Lab 4
Thin Lenses and Refraction of Light

Learning Goals:

- to determine the relationship between object distance and image distance for a thin
- convex lens
- to use a light source, optics bench, lens, and viewing screen to measure object distance,
- image distance, and image size.
- to use lens combinations in contact or separate to form images
- to use the thin lens formula $1/f = 1/o + 1/i$ in air and in water.
- to trace the rays of light from an object through the eye onto a retina-like screen

Apparatus:

Instrument	Instrumental error	Instrumental Resolution
Light Source, Viewing Screen,		
Optics Bench and lens holder	± 1%	0.1 cm
100, 200 and -150mm Convex lenses	± 1%	1 mm
Human Eye Model, Water, Light source, Flashlight		
Corneal lens (140 mm); 62 mm & 120 mm Crystalline lenses	±1%	1 mm
Calipers	±1%	1 mm
Ruler	±1%	1 mm

Theory:

Refraction and Snell's Law

Refraction is the bending of light as it travels from one medium to another (air to glass, glass to water, etc.). This bending of light is the result of light moving slower through different materials. This "slowing down" of light is determined by a dimensionless constant known as the *index of refraction* ≡ **n** for a specific medium. The index of refraction is mathematically defined as:

$$\textbf{(1)} \qquad \mathbf{n = c/v}$$

where

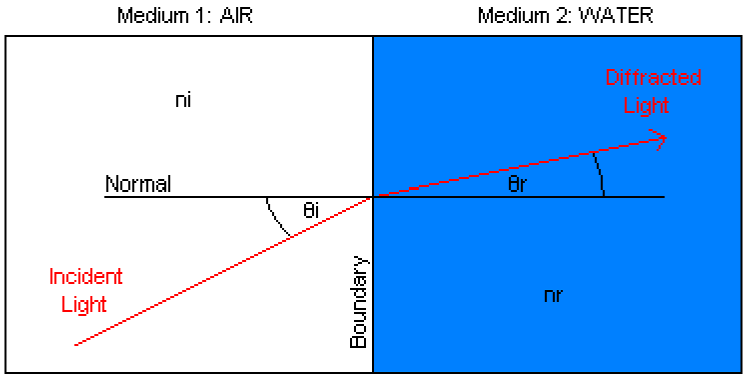
$\mathbf{n}$ ≡ "index of refraction"
$\mathbf{c}$ ≡ "speed of light (in a vacuum)" ≈ 3×10^8 [m/s]
$\mathbf{v}$ ≡ "speed of light (through the medium)" ≤ $\mathbf{c}$

When light travels from one medium to another, the light also bends depending on its angle at the boundary between the two media. For instance, if light travels through air at a specific *angle of incidence* ≡ $\boldsymbol{\theta_i}$, and strikes the surface of water, the light will refract and move along a different angle through the water (because the light slows down in the water). The new angle is called the *angle of refraction* ≡ $\boldsymbol{\theta_r}$. Be aware that both angles are measured from the line perpendicular to the boundary, called the *normal* (see figure below). These angles and indices of refraction are related by *Snell's Law*:

$$\textbf{(2)} \qquad \mathbf{n_i} \sin(\boldsymbol{\theta_i}) = \mathbf{n_r} \sin(\boldsymbol{\theta_r})$$

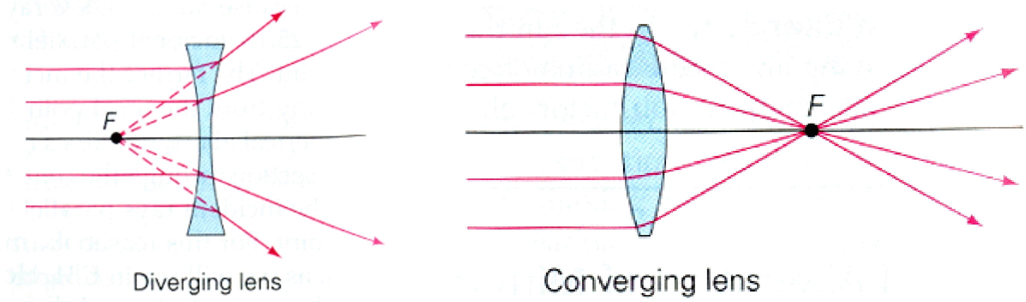
where

$\mathbf{n_i}$ ≡ "index of refraction (first medium)"
$\boldsymbol{\theta_i}$ ≡ "angle of incidence"
$\mathbf{n_r}$ ≡ "index of refraction (second medium)"
$\boldsymbol{\theta_r}$ ≡ "angle of refraction"



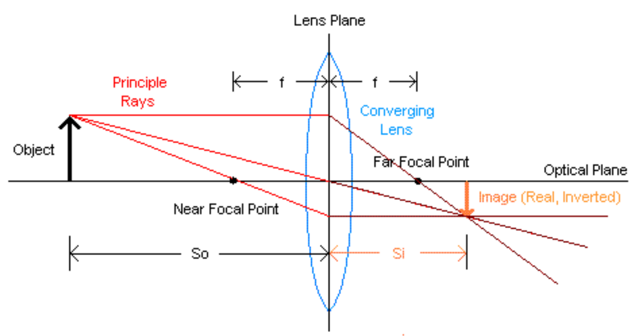
<u>Thin Lenses</u>

Lenses are curved pieces of glass which are used to refract light using Snell's Law. Light will bend when it <u>enters</u> the glass lens from a different medium (perhaps air), and will bend again when it <u>exits</u> the glass back into that medium. A *convex lens* (or *converging lens*) bends light in such a way that incident light rays bend <u>toward</u> a particular point, or converge. A *concave lens* (or *diverging lens*) bends light rays <u>away from</u> a particular point, causing them to diverge. The point which rays of light bend toward (or away from) for a particular lens is called its *focal point* ≡ **f**.



The shape of the lens determines how the light refracts (converges or diverges). Notice how the light bends according to Snell's Law within the glass lenses above.

When light rays from an *object* strikes a lens, the light refracts about the focal points of the lens in a specific way. Where the light rays converge to (or diverge from) is where an *image* exists. The size and position of this image is found using ray tracing methods, which tracks how the light moves through the lens and where it refracts. See the figure below for how an image is determined for a converging lens by tracing *principle rays*.



An object is always represented by an upright arrow (the black arrow, in this case). By tracing the principle rays, we can roughly determine image location (orange arrow). Since this is a converging lens, the focal points (black dots) on either side of the lens indicate how the light will refract. The top principle ray is parallel to the *optical plane*, and refracts through the far focal point. The middle ray passes directly through the center of the lens without bending. The bottom ray passes through the near focal point, and emerges parallel to the optical plane. The single point where these principle rays meet is the image (orange arrow). Notice that the image is *inverted* (upside down) and has a smaller height than the object.

When rays of light <u>converge</u> (as above), the image is said to be *real*. This real image could actually be seen on a screen if one were positioned at the image location.

Supposing that the quantities in the above figure ($\mathbf{s_o = p}$, $\mathbf{s_i = q}$, object height, image height) can be measured, the *focal length* ≡ **f** (distance from lens to focal point) can be determined using the *thin lens equation* (Note: diverging lenses always have a negative focal length):

$$\textbf{(3)} \qquad (1/\mathbf{f}) = (1/\mathbf{q}) + (1/\mathbf{p})$$

where

$\mathbf{f}$ ≡ "focal length"
$\mathbf{s_o = p}$ ≡ "object distance (from lens)"
$\mathbf{s_i = q}$ ≡ "image distance (from lens)"

Also, the *magnification* ≡ **M** (the multiple of the change in height from object to image) can be found by (Note: inverted images always have a negative magnification):

$$\textbf{(4)} \qquad \mathbf{M} = (\mathbf{-q/p}) = (\mathbf{h_i/h_o})$$

where

$\mathbf{M}$ ≡ "magnification"
$\mathbf{s_o = p}$ ≡ "object distance (from lens)"
$\mathbf{s_i = q}$ ≡ "image distance (from lens)"
$\mathbf{h_i}$ ≡ "image height"
$\mathbf{h_o}$ ≡ "object height"

When two or more thin lenses are placed closely together, they form a *combination lens*. They collectively act as a single lens with a new focal point, which is determined by the focal points of the individual lenses. For a two-lens combination, the *combination focal point* ≡ $\mathbf{f_{combo}}$ can be found using:

$$\textbf{(5)} \qquad (1/\mathbf{f_{combo}}) = (1/\mathbf{f_1}) + (1/\mathbf{f_2})$$

where

$\mathbf{f_{combo}}$ ≡ "combination focal point"
$\mathbf{f_1}$ ≡ "focal point of first lens"
$\mathbf{f_2}$ ≡ "focal point of second lens"

Prelab:

1. In the middle of the base line below, draw a thin converging lens. Five centimeters from the middle of the lens and on both sides, draw a point and label it F. Draw a line traveling from left to right and parallel to the base line that passes through the lens and then changes direction to intersect point F.

____.

2. On the base line above draw a 3 cm tall house located ten centimeters to the left of the lens so that its foundation rests on the base line. To the right of the lens, draw an inverted house located ten centimeters from the lens so that its foundation rests on the base line.

3. Fill in the blanks using the drawing above:
   a. The focal length of the converging lens is _____cm.
   a. The object distance is ______cm.
   b. The image distance is _______cm.
   c. The height of the object is _______cm.
   d. The height of the image is _________cm.

4. In the middle of the base line below, draw a thin converging lens. Five centimeters from the middle of the lens and on both sides, draw a point and label it F.

____.

5. On the base line above draw a 3 cm tall house located 15.0 centimeters to the left of the lens so that its foundation rests on the base line. To the right of the lens, draw an inverted house located 7.5 centimeters from the lens so that its foundation rests on the base line.

6. Fill in the blanks using the drawing above:
   a. The focal length of the converging lens is _____cm.
   e. The object distance is ______cm.
   f. The image distance is _______cm.
   g. The height of the object is _______cm.
   h. The height of the image is _________cm.

7. Two converging lenses can be used to form an image of an object. Of the following seven choices, circle the two that are <u>not</u> factors which determine the location and the size of the image
   a. the size of the object
   b. the focal length of each lens
   c. the space between the lenses
   d. the distance between the object and the lens closest to it
   e. the height of the lens
   f. the shape of the lens

Procedures:

Background Part I Optical Bench:

Thin convex lenses focus light entering on one side to a point on the opposite side. If the light entering the lens is parallel to the axis of the lens, the light will focus at a point on the axis of the lens on the opposite side. The distance from the center of the lens to this focus is called the focal length of the lens. A 100 mm lens will focus light parallel to its axis 100 mm from its center. The location and size of an image formed by all the rays of light coming from an object on one side of the lens will depend on the location and size of the object in reference to the focal length of the lens. The image of an object can be brought into focus on a screen using a system of two lenses.

Procedure: (Part I Optical Bench)

1. Mount the Four-in-One Light Source at the zero point (left end) of the Optics Bench.
2. Connect the power supply.
3. Mount the Viewing Screen at the other end of the bench.
4. Adjust the light source in its bracket so the crossed-arrow object is illuminated and pointing toward the viewing screen.
5. Place the 100-mm Convex Lens on the optics bench 500 mm from the light source.
6. In a darkened room, move the viewing screen so the image of the crossed arrow is in sharp focus on the screen. Observe the image.
7. Move the lens to several different positions, each time focusing the image onto the viewing screen. Observe the image.

Observations (Part I Optical Bench) (record in notebook)

A) Describe what happens to the image size when you change the position of the lens.
B) Describe whether the image is upright or inverted.

8. Reposition the lens to the 500 mm position. Position the viewing screen so the image of the crossed arrow is in sharp focus.
9. Record the distance from the *lens to the viewing screen* as the image distance.
10. Measure and record the *height of the image* on the viewing screen.
11. Repeat the experiment setting the object distance to the values shown in the table and record the corresponding image distance and image height. *The object distance is measured from the lens to the illuminated crossed arrows on the light box.*

Data (Part I Optical Bench) (record in notebook)

Object Distance (mm)	Image Distance (mm)	Object Height (mm)	Image Height (mm	Object Distance (mm)	Image Distance (mm)	Object Height (mm)	Image Height (mm)
500				250			
475				200			
450				150			
400				125			
350				120			
300							

12. Make a graph (in notebook) showing the Image Distance (vertical axis) versus Object Distance (horizontal axis). Sketch a curve fit for the data. If the curve fit is unsatisfactory, try graphing 1/p on the x-axis and 1/q on the y-axis with a linear curve fit. Note the intercept for this new graph.

Observations (Part I Optical Bench) (record in notebook)

C. Describe from the graph the value the *image distance* approaches as the *object distance* becomes larger.

D. Describe from the graph the value the *object distance* approaches as the *image distance* becomes larger.

E. Describe the significance of the values given in the previous two questions.

F. Describe the relationship between *image distance* and *object distance* (Directly related or inversely related?) Give evidence supporting your answer using the suggested linear curve fit adjustments.

G. Describe the relationship between *object distance* and *image height*. (Directly related or inversely related?) Give evidence supporting your answer.

H. Describe where you would place the object to obtain an image that is as far away from the lens as the object is.

I. Describe where you would place the object to obtain an image as far away from the lens as possible.

J. Describe where would you place the object to obtain an image located at the focal length of the lens (100 mm)?

K. Using your answer from above and your experiences in this activity, explain why 'fixed lens' cameras require that the subject of the photo be a minimum distance from the lens.

13. Place both the 100mm and 200mm lenses approximate 60 cm apart on the optical bench.

14. Place the light source approximately 20 cm from the 100mm lens and the screen approximately 40 cm from the 200 mm lens.
15. Adjust these three distances slightly to form a real, right side up image on the screen.

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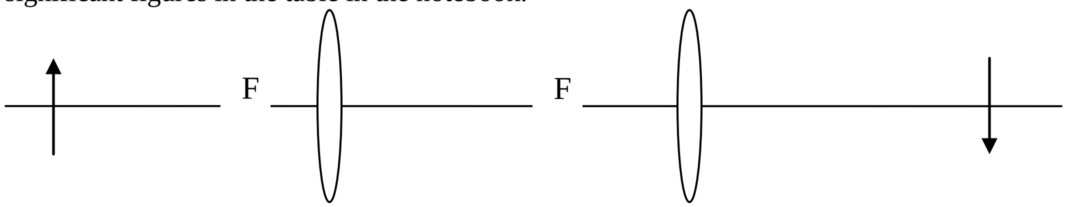
16. Record these distances and the object and image heights to three significant figures in the data table in the notebook.

17. Move lenses closer together or farther apart and repeat procedures 15. and 16. for three additional sets of distances and note whether or not the image is inverted and record data to three significant figures in the table in the notebook.



Data: (Part I Optical Bench record in note book)

Trial #	1	2	3	4
Distance from object to 100mm lens (cm)	20.0			
Distance between 100mm and 200mm lenses (cm)	60.0			
Distance from 200mm lens to screen (cm)	40.0			
Size of object (cm)				
Size of image (cm)				
Image right side up (+) or inverted (-)	+			

18. Remove the 200 mm lens from the optical bench

19. Place the light source approximately 20 cm from the 100mm lens and place the screen approximately 20 cm away from the opposite side of the lens. This first image should be in focus on the screen. This first image acted as the object for the 200mm lens when it was on the optical bench 60.0 cm away from the 100 mm lens. This first image was 40.0 cm away from the 200 mm lens and became the second image 40.0 cm away from the 200 mm lens.

20. Determine where the first image was formed in the second trial of the data table above and record its value in the table below to three significant figures.

Data (Part I Optical Bench: record in notebook)

Trial #	1	2
Distance from object to 100mm lens (cm)	20.0	
Distance between 100mm and 200mm lenses (cm)	60.0	
Distance from 200mm lens to location of second image (cm)	40.0	
Distance from 100mm lens to location of first image (cm)	20.0	
Distance from location of first image to 200 mm lens (cm)	40.0	

Procedure (Part I Optical Bench) (ctd)

21. Place a 100mm lens and a -150mm lens **in contact** with each other on the optical bench and place an object approximately 60 cm from this lens combination.

22. Locate the image of the object on a screen on the optical bench, adjusting the object and image distances for the sharpest image.

23. Record the object and image distances and sizes and calculate the focal length of this lens combination and the linear magnification.

Data (Part I Optical Bench) (record in notebook)

Distance from object to 100mm and -150mm lenses (cm)	
Distance from 100mm and -150mm lenses to screen (cm)	
Calculated value of effective focal length of lens combination (mm)	

Data (Part I Optical Bench) (record in notebook)

Object size (cm)	
Image Size (cm)	
Linear magnification H_i/H_o	

Background Part II Human Eye Model

A model of the human eye human eye having water and two lenses demonstrates the formation of an image on a retina-like screen. The lens in the front of the eye is the corneal lens. In the model, it is a glass, plano-convex lens with air on the convex side and water on the flat side. The lens in the eye surrounded by eye fluid is the crystalline lens. In the model it is a plastic double–convex lens with water on both sides.

The eye model is a system of lenses having five components: the front curved surface of the glass corneal lens, the flat rear surface of the glass corneal lens, the front curved surface of the plastic crystalline lens, the rear curved surface of the plastic crystalline lens, the water and the plastic screen (the retina).

The light from object o_1 in front of the eye is focused by the first curved surface of the corneal lens to produce the image i_1. This image becomes the object o_2 for the back flat surface of the corneal lens. The image produced by the flat surface i_2 becomes the object o_3 for the front curved surface of the crystalline lens. The image i_3 produced by the back second curved surface of the crystalline lens appears on the retina-like screen.

The light from an illuminated object in front of the eye model will pass thrugh the eye and produce a sharp image on the retina screen if the distances, curvatures and indicies of refraction are in corect proportion.

Procedure 2 (Part II: Human eye model)

1. Arrange the eye model for normal, **far** vision (i.e., the 140 mm corneal lens, the 120 mm crystalline lens in the septum slot and the retina screen in the normal position). Position the eye model on the optical bench facing an illuminated distant object. Observe the image on the retina screen and comment on its size and clarity in the data table in the notebook.
2. Fill the eye model with water and again observe the image on the retina screen. Test which crystalline les produces the clearest image. Comment in the data table in the notebook if the image is in sharper focus on the retina screen with or without the water, with the 62 mm or 120 mm the crystalline lens.
3. Draw a sketch of this setup showing the distant object, the shape of the two lens' surfaces the distances between the lenses and the image on the retina screen. Indicate on the sketch the different media (air, glass, water and plastic) that the light travels through. Represent light coming from the distant object with rays parallel to the optical axis. For thin lenses, all distances are measured from the center of the lens.

Data (Part II Human Eve Model) record in Notebook

Medium in eye	O_1 Distance between object and corneal lens	Distance between corneal lens and crystalline lens	Distance between crystalline lens and retina screen	Image size and quality
air	___________cm.	___________cm.	___________cm.	
water	___________cm.	___________cm.	___________cm.	