PHYSICS 176

UNIVERSITY PHYSICS LAB II

Experiment 11

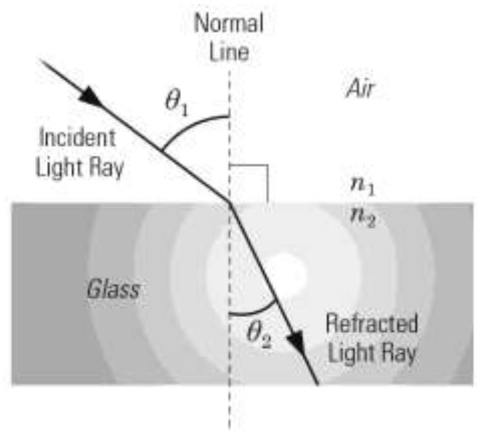
Geometrical Optics: Refraction and Lenses

Equipment

Light source, spinning wheel, D-shaped acrylic and Rhomboid-shaped acrylic plates, protractor.

Introduction

Snell's Law



Light crossing a boundary between two transparent materials changes direction if the speed of light within those materials is different. This direction change is known as *refraction*.

Light traveling from a material in which it has high speed (like air) to a material in which it has slower speed (like glass) experiences refraction *toward* the normal line perpendicular to the boundary, and light traveling from a material in which it has slower speed to a material in which it has greater speed experiences refraction *away* from the normal line.

The amount of refraction experienced by light as it passes between two transparent materials is dependent on the angle at which the light is incident upon the boundary between the materials and the *index of refraction* of each material. The formula relating these quantities is known as Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

where n_1 and n_2 are the indices of refraction of the first and second material, θ_1 is the incident angle the incoming light ray makes relative to the normal line, and θ_2 is the angle the refracted light ray makes relative to the normal line.

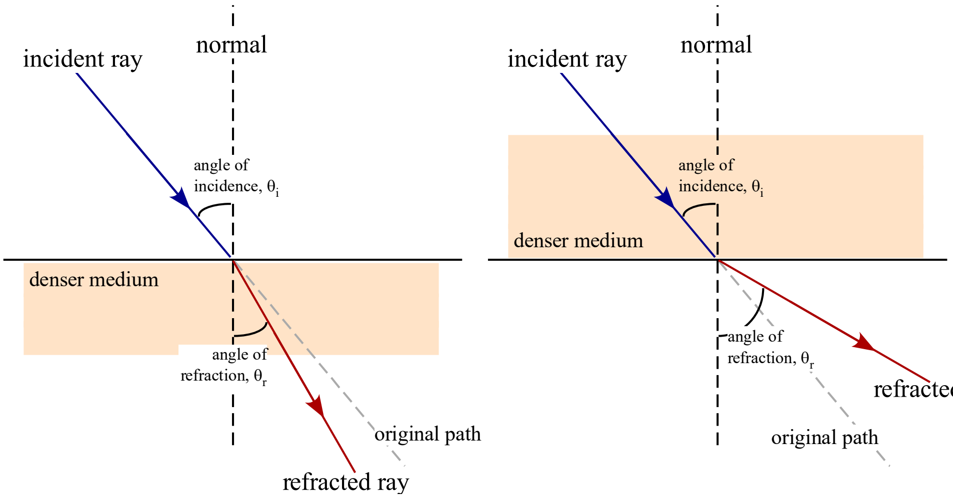
In this experiment, you will use Snell's law to determine the index of refraction of a D-shaped piece of transparent material. For the purpose of this experiment, we will assume that the index of refraction of air is effectively equal to 1.00.

Refraction

Refraction is the bending of the path of light when it passes from one material to another. The most common example of refraction is the bending of light when it travels from water to air, which causes submerged objects to appear displaced from their actual positions.

Refraction is commonly explained in terms of the wave theory of light and is based on the fact that light travels faster in some media than in others. When a ray of light traveling through air strikes the surface of a piece of glass at an angle, one side of the wave front enters the glass before the other and it slows down, while the other side continues to move at its original speed until it too reaches the glass. As a result, the light ray bends inside the glass

The original ray is called the incident ray; the bent ray is called the refracted ray. Their directions are specified with the angle to the normal, as illustrated.

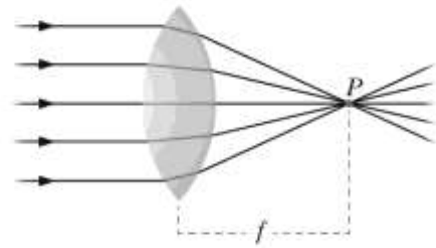


The speed at which a given transparent medium transmits light waves is related to its optical density (not to be confused with mass density). Materials are classified by their index of refraction. The index of refraction, n, of a transparent medium is the ratio of the speed of light in a vacuum, c, to the speed of light in the medium:

$$n = \frac{c}{v} \tag{2}$$

In general, a ray is refracted toward the normal when it passes into a denser medium and away from the normal when it passes into a less dense medium, as illustrated.

Focal Length of a Converging Lens



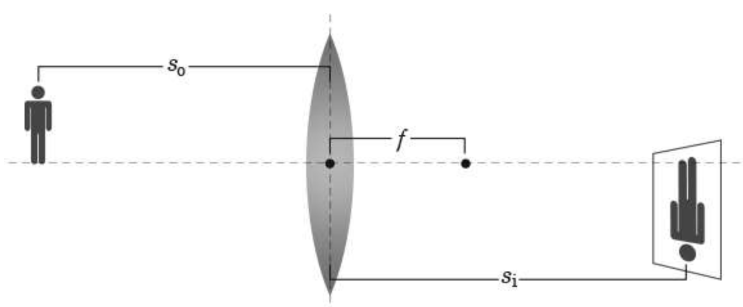
Parallel light rays entering a converging (*double-convex*) lens change direction as the rays are refracted at both the front (*incident*) and back (*emergent*) surfaces of the lens. If we assume that the path of the light entering the lens is perpendicular to the plane of the lens, the final refracted angle of the ray as it leaves the lens will direct it to a *focal point P* along the optical axis. The distance from the lens to *P* is known as the *focal length f* of the lens.

This behavior is a result of refraction, the geometric properties of the lens shape, and angles at which the incoming light rays strike the surface of the lens. Given the shape of the lens, its focal length can be quantified using a complex formula involving the curvature at each lens surface, the thickness of the lens, and the index of refraction for both air and the lens material. However, if we assume that the thickness of the lens is very small, the equation simplifies to a form involving only the distance between the lens and the object and the lens and the image produced by the lens.

This form is called the *thin lens* equation:

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i} \tag{3}$$

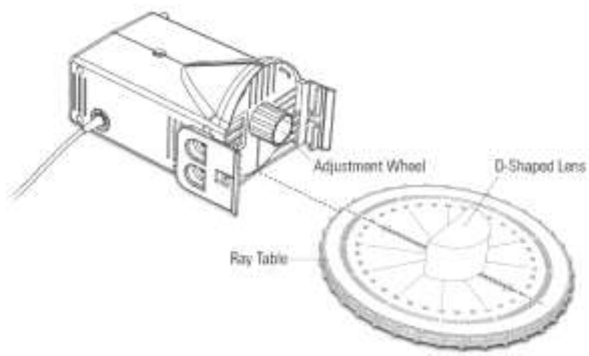
Here f is the lens focal length, s_o is the distance from the lens to an object, and s_i is the distance from the lens to the point at which the image of the object is in focus.

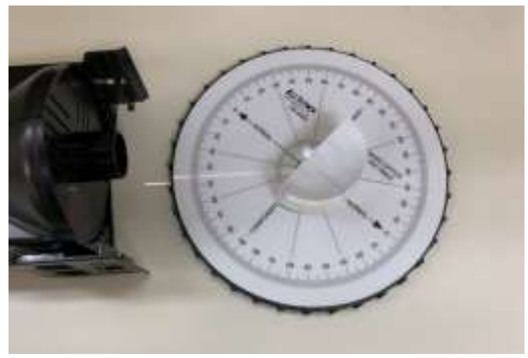


Procedure A: Snell's Law

1. Plug in the light source to turn it on, and then turn the wheel on the front of the light source so that a single light ray is emitted. Place the light source flat on the lab table.

2. Place the spinning wheel in front of the light source so it is not more than 10 cm from the light source, and then adjust its position so that the single light ray crosses its exact center, i.e. along the "normal" line of D-shaped plate (left Figure below).





3. Set the D-shaped plate in the marked outline on the spinning table, with its frosted side of against the table.

4. Rotate the ray table so the light ray enters the lens at the center of its flat surface with an incident angle of 10° (right Figure above). Use the degree scale on the wheel to locate it.

   NOTE: The light ray refracts as it crosses the boundary from air to the lens material, but it does not *refract as it crosses the boundary from lens to air. This is because the circular shape of the lens causes the incident angle of the light ray at the lens–air boundary to be zero.*

5. Use the degree scale on the wheel to measure the incident and refraction angles. Record both angles in row 1 of Table 1 in the Data Analysis section below.

6. Rotate the ray table to increase the incident angle by 5° so the light ray enters the lens at the center of its flat surface with an incident angle of 15°.

7. Measure and record the new incident and refraction angles in row 2 of Table 1.

8. Repeat the data collection steps three additional times, increasing the incident angle by 5° each time, measure up to an incident angle of 30 degrees. Record the incident and corresponding refraction angles for each trial into Table 1.

Data Analysis

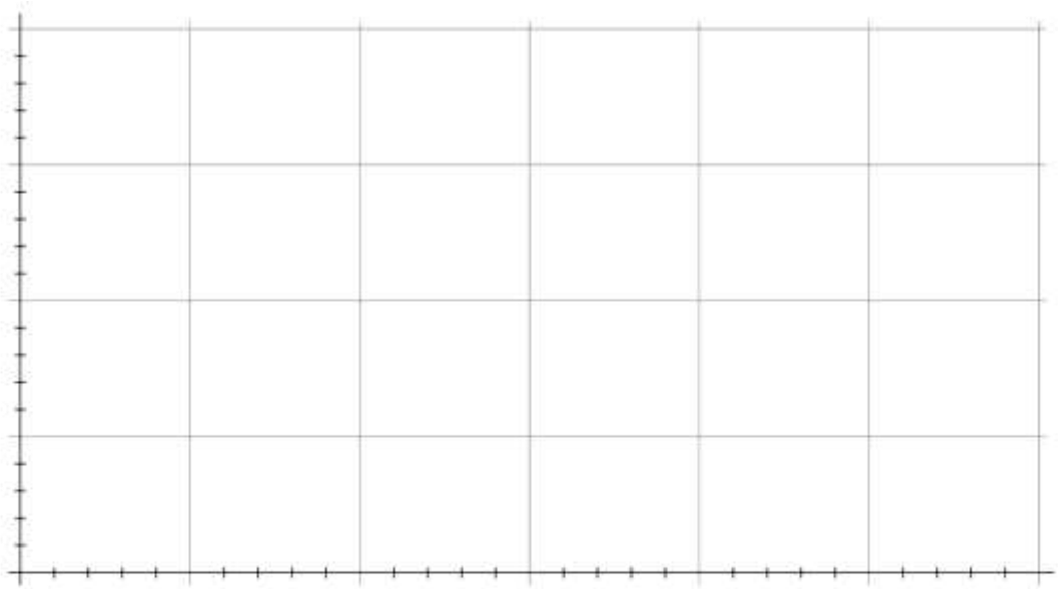
Table 1: Incident and refraction angles of a light ray crossing from air into an unknown transparent medium

Trial	Incident Angle (°)	Refraction Angle (°)	$sin\theta_1$	$sin\theta_2$
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

9. Calculate the sine of the incident angle θ_1 and refraction angle θ_2 for each trial. Record your results into Table 1.

10. Plot a graph of $sin\ \theta_1$ versus $sin\ \theta_2$ in the blank Graph 1 axes below or on a separate piece of graph paper. Be sure to label both axes with the correct scale and units (if any).

Graph 1: Sine of incident angle versus sine of refraction angle for a light ray crossing from air into an unknown transparent medium



11. Draw a line of best fit through your data in Graph 1. Determine and record the equation of the line here:

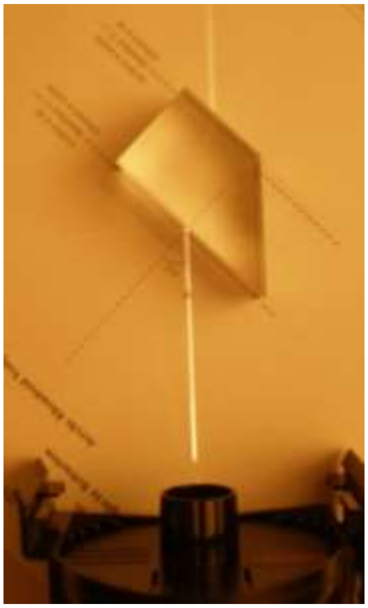
Best fit line equation: ______________________________

12. Use the slope from the best fit line to determine an experimental value for the index of refraction n_2 of the D-shaped transparent material:

$$\text{slope} = \frac{n_2}{n_1} \qquad \text{where } n_1 = 1.00 \text{ (index of refraction for air)}$$

Index of Refraction of the D-shaped plate n_2: ______________________________

PROCEDURE B: The Bending of Light by Refraction



1. Put the acrylic rhomboid plate on top of the illustration shown on page 8.

1. Place the Basic Optics Light Source on the paper and shine a single ray of light along the illustrated incident ray.

2. Trace the ray that comes out at the other side of the acrylic.

3. Remove the acrylic piece and connect the two rays to show the path that light followed while inside the acrylic.

4. Make arrows on the rays to illustrate the direction of travel.

5. Analyze the side labeled ‘Interface 1’: This is the first bending of the light, as it traveled from air into the acrylic.

- Use the protractor to measure the angle of refraction that the light ray makes with the normal line at this interface. Record it in the Data Table.

6. Analyze the side labeled ‘Interface 2’: This is the second bending of the light, as it traveled from inside the acrylic back out into the air.

- At the point where the light ray exited the acrylic, use the protractor to trace the normal line to the surface at that point. Extend the line to the inside of the acrylic.
- Use the protractor to measure the angles of incidence and refraction with respect to the normal line at this interface. Record them in the Data Table.

7. Repeat the process for an initial incident angle larger than 45° and then for an initial incident angle smaller than 45°.

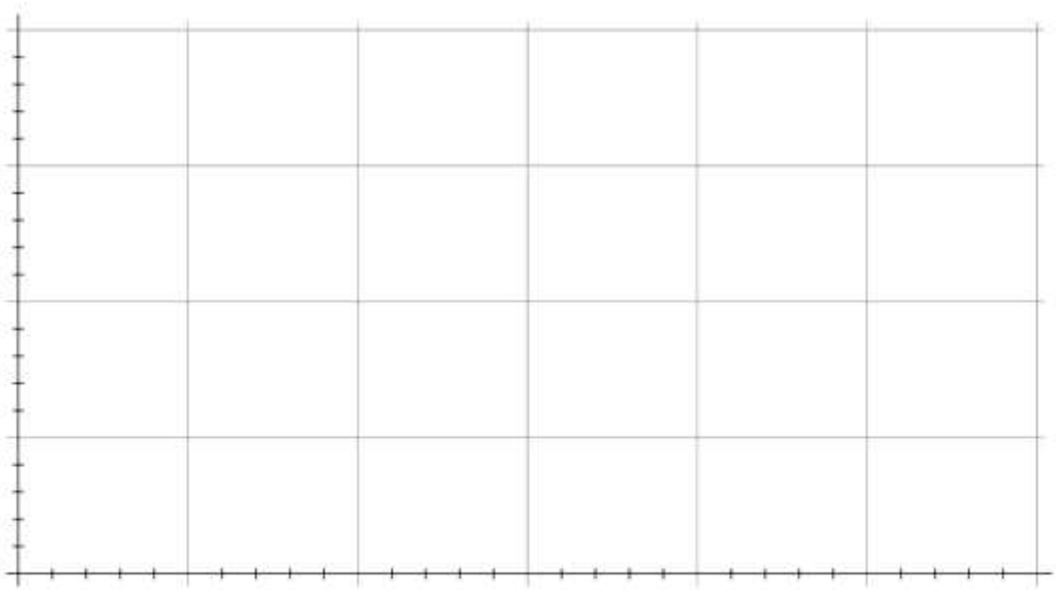
- It may help to print a new template (page 8) for each trial. Use the available 'Extra Rhomboid Template' for the repetitions.

8. Enter the values for the angles in air and the angles in acrylic into a data table. Notice that it does not matter whether the air or the acrylic was the incident of the refractive side. Just make sure you enter them in the correct table.

9. Plot the $\sin\theta_{\text{air}}$ versus $\sin\theta_{\text{acrylic}}$ and determine the slope of the line going through the data points (you may use a separate piece of graph paper or graphing program).

10. From the slope of the line, calculate the value of the index of refraction of the plate using

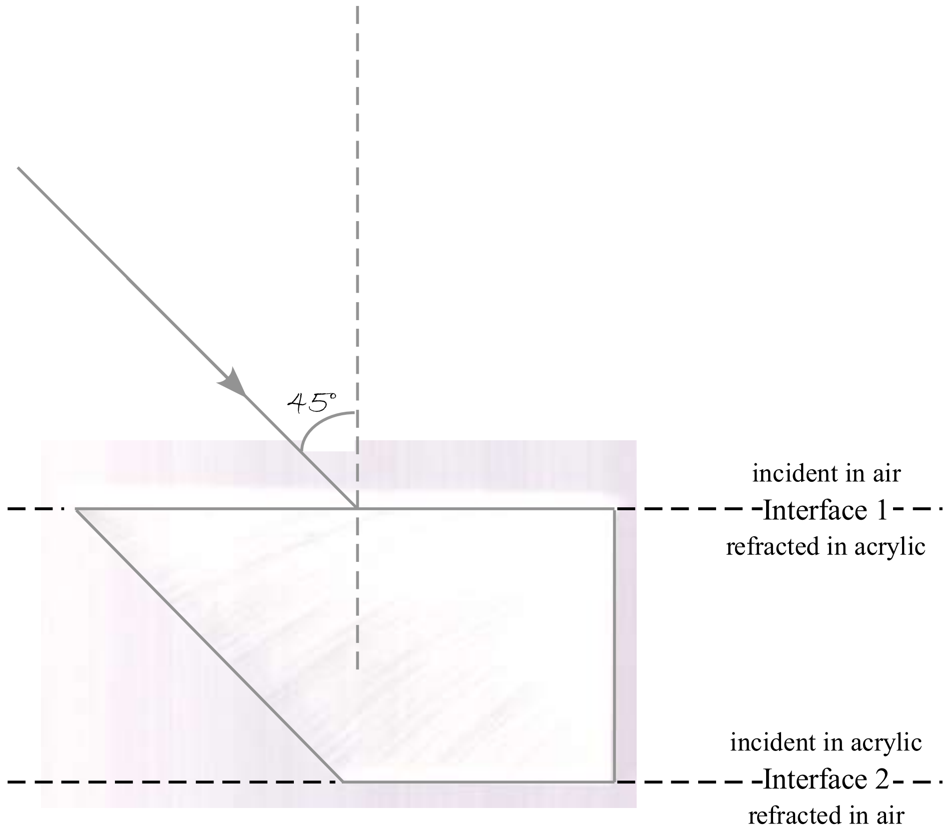
$\text{slope} = \frac{n_2}{n_1}$ where $n_1 = 1.00$ (index of refraction for air)



Index of Refraction of the Rhomboid-shaped plate n_2: ______________________________

DATA ANALYSIS B: The Bending of Light by Refraction

Acrylic Rhomboid Template

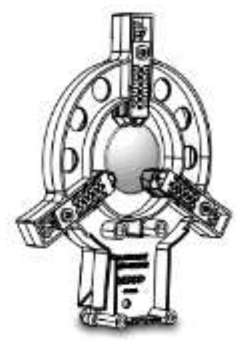


REFRACTION

INTERFACE 1 — From air into acrylic		INTERFACE 2 — From acrylic into air	
Incident angle (in air)	Refracted angle (in acrylic)	Incident angle (in acrylic)	Refracted angle (in air)
45°			

Procedure C: Focal Length of a Converging Lens

1. Lay the optics track flat on your lab table and mount the light source to it so that the "screen zero" (see the bottom of the light source for the screen zero indicator) is aligned with the 0-cm mark on the track. Make sure the crossed-arrow image on the light source points down the length of the track.



2. Mount the lens in the center of the holder using the three adjustable arms, and then mount the holder on the track so that the lens is aligned with the 35-cm mark. The lens in this photo is not the lens that will be used, the lens that will be used is in the plastic container in the kit. Make sure you use the converging lens.

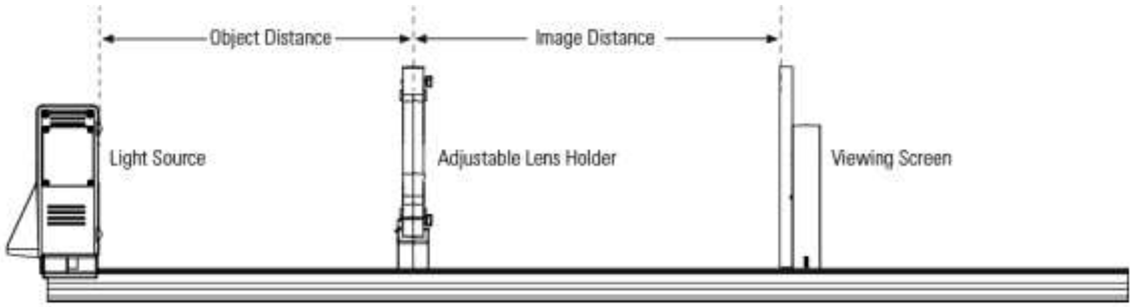
3. Mount the viewing screen to the track on the opposite side of the lens as the light source, with the front of the screen facing the lens.

4. Plug in the light source to turn it on.

5. Slide the viewing screen up and down the length of the optics track until the image of the crossed-arrow target is in the best focus on the screen.

6. Using the graduated scale on the optics track, determine the object distance s_o and the image distance s_i. Record these values in Table 1 in the Data Analysis section below.

   NOTE: Object distance is measured from the position of the lens to the front of the light source, and image distance is measured from the position of the lens to the front of the viewing screen.



7. Slide the lens holder 5 cm farther down the track, away from the light source. (Do not change the light source position.)

8. Slide the viewing screen up and down the length of the optics track until the image of the crossed-arrow target is again in focus on the screen.

9. Record the new object distance and image distance next to Trial 2 in the Table below.

10. Repeat the data collection steps, increasing the distance between the lens holder and the light source by 5 cm in each trial. Repeat 7 times, until you reach 65cm. Record the object distance and corresponding image distance for each trial into the table.

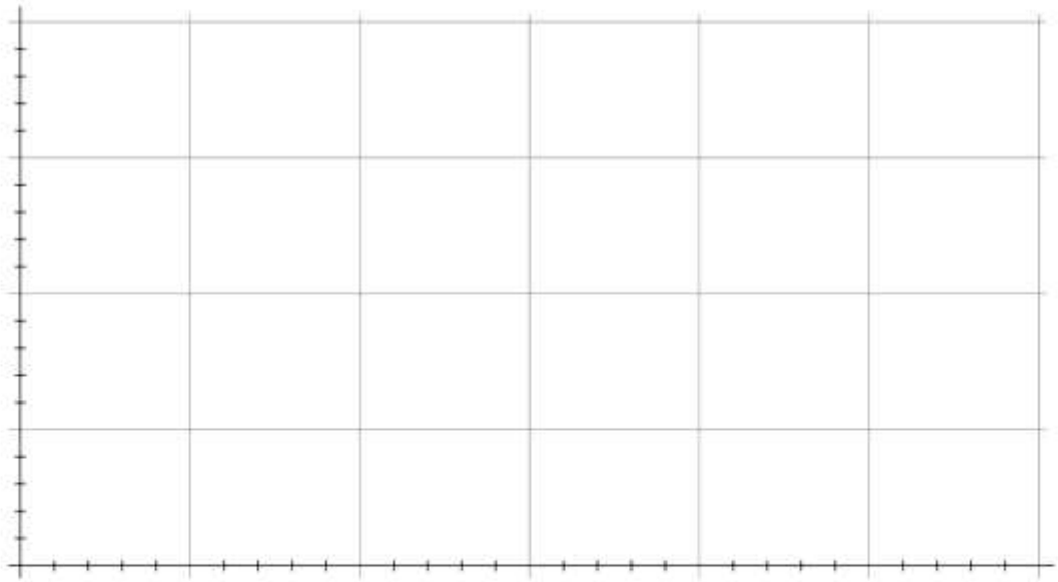
Data Analysis C: Focal Length of a Converging Lens

Trial	Object Distance s_o	Image Distance s_i	$1/s_o$	$1/s_i$
1				
2				
3				
4				
5				
6				
7				

1. Calculate the inverse of each object distance and image distance value in Table 1. Record your results in the $1/s_o$ and $1/s_i$ columns of the table.

2. Plot a graph of $1/s_o$ versus $1/s_i$ in the blank Graph 1 axes below. Be sure to label both axes with the correct scale and units. You are also allowed to use a separate piece of graph paper or graphing software.

Graph 1: Inverse object distance versus inverse image distance using a converging lens



3. Draw the line of best fit through the data in graph 1. Determine and record the line of best fit here:

4. Use the y-intercept from the line of best fit line to determine an experimental value for the focal length f of your lens:

$$y - intercept = 1/f$$

QUESTIONS PROCEDURE A: Snell's Law

1. What is your experimental value for the index of refraction of your transparent material? How did you determine this value from your data?

2. Below is a list of refractive indices for common materials. Use this table and your experimental value for the index of refraction to determine a potential candidate for your transparent material. Calculate the percent error between your experimental value and the index of refraction value of your candidate.

Material	Index of Refraction
Quartz	1.41
Acrylic glass	1.49
Polycarbonate	1.58
Dense crown glass	1.67
Diamond	2.42

$$\text{Percent error} = \left|\frac{\text{Theoretical} - \text{Experimental}}{\text{Theoretical}}\right| \times 100$$

3. What are factors that might have caused error in your measured value of index of refraction?

QUESTIONS PROCEDURE B: The Bending of Light by Refraction

1. Look at Interface 1: When traveling from air into acrylic, did the refracted ray bent toward or away from the normal line?

2. Look at Interface 2: When traveling from acrylic into air, did the refracted ray bent toward or away from the normal line?

3. Compare your index of refraction of acrylic to the actual index of refraction of acrylic, and find the percent difference.

QUESTIONS PROCEDURE C: Focal Length of a Converging Lens

1. What is your experimental value for the focal length of your lens? How did you determine this value from your data?

2. What are factors that might have caused error in your measured value of the focal length? Explain how each factor you list could have been avoided or minimized.

3. Ask your teacher for the actual value of the focal length of your lens. Calculate the percent error between your experimental value and the actual value.

$$\text{Percent error} = \left|\frac{\text{Actual} - \text{Experimental}}{\text{Actual}}\right| \times 100$$

4. What do you predict happens to the image distance from a converging lens as the object distance approaches the focal length of the lens? Justify your answer: use mathematical reasoning or data from your experiment, or both, to support your answer.