1. The Law of Reflection

1.1. Equipment

Ray Optics light source, Ray Table, Ray Optics mirror, sticky tac

1.2. Introduction

The shape and location of the image created by reflection from a mirror of any object is determined by just a few simple principles. One of these principles you already know: light propagates in a straight line. You will have an opportunity to learn the remaining principles in this experiment.

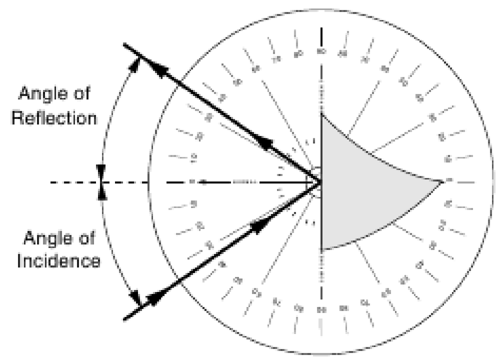


Figure 1.1.: Angles of Incidence and Reflection.

To determine the basic principles underlying any phenomenon, it is best to observe that phenomenon in its simplest possible form. In this experiment, you will observe the reflection of a single ray of light from a plane mirror. The principles you discover will be applied, in later experiments, to more complicated examples of reflection.

1.3. Procedure

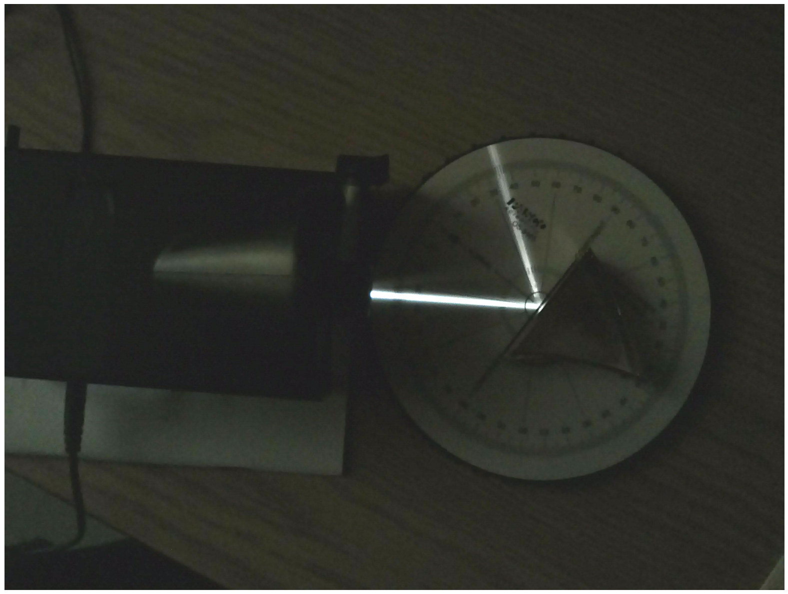
1. The goals is to set up the equipment as shown in Figure 1.2. Use sticky tac to prevent the ray table from moving on the table.

2. Adjust the components so a single ray of light is aligned with the bold arrow labeled "Normal" on the Ray Table Degree Scale.

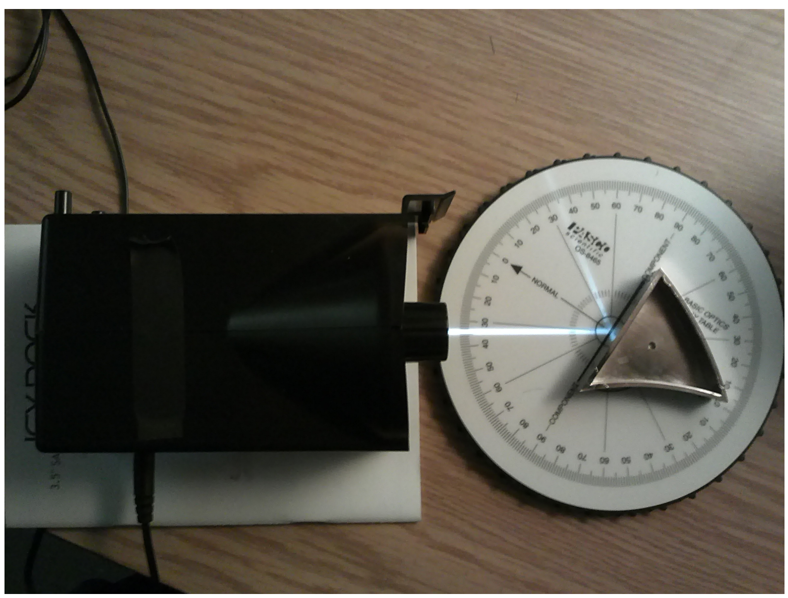
3. Carefully align the flat reflecting surface of the mirror with the bold line labeled Component on the Ray Table. The reflected ray should travel back along the Normal line.

4. With the mirror properly aligned, the bold arrow on the Ray Table is normal (at right angles) to the plane of the reflecting surface. The angles of incidence and reflection are measured with respect to the Normal as shown in Figure 1.1

5. Rotate the Ray Table and observe the light ray; an example of this is shown in Figure 1.2. Determine and record a reasonable value for the error in the angle measurements and state this in the data table.



(a)



(b)

Figure 1.2.: Reflection Law setup photographs showing equipment and light ray after alignment under different light conditions.

Table 1.1.: Data: Measurements of Incidence and Reflection angles.

	Incidence [°]	Reflection_1[°]	Reflection_2[°]	Average Reflection Angle [°]
error ±° →				
	0.0			
	10.0			
	20.0			
	30.0			
	40.0			
	50.0			
	60.0			
	70.0			
	80.0			
	90.0			

6. The angles of incidence and reflection are measured with respect to the normal to the reflecting surface. By rotating the Ray Table, set the angle of incidence to each of the settings shown in Table 1.1.

7. For each angle of incidence, record the angle of reflection. Repeat your measurements with the incident ray coming from the opposite side of the normal .

1.4. Questions

1. Are the two reflection angle columns the same? If the results for the two trials are not identical, to what do you attribute the differences?

2. The law of reflection states that the incident ray, the normal and the reflected ray all lie in the same plane. How this is shown in your experiment?

3. You were asked to measure the angle of reflection when the ray was incident on either side of the 0 normal to the surface of the mirror. What advantages does this provide?

4. Physicists expend a great deal of energy in attempts to increase the accuracy with which an exact law can be proven valid. How might you test the Law of Reflection to a higher level of accuracy than in the experiment you just performed?

5. What is the definition of the "correlation coefficient r"?

6. Average the two reflection angle values and calculate the correlation coefficient r for how the reflection angle depends on the incidence angle. State the answer below.

7. If you were asked to plot "angle of reflection" as a function of "angle of incidence", what would be the value of the intercept a and the slope b be according to theory?

1.5. Theory: Cylindrical Mirrors

A concave cylindrical mirror focuses incoming parallel rays at its focal point. The focal length f is the distance from the focal point to the center of the mirror surface. The radius of curvature R of the mirror is twice the focal length, as shown in Figure 1.3:

$$R = 2f$$

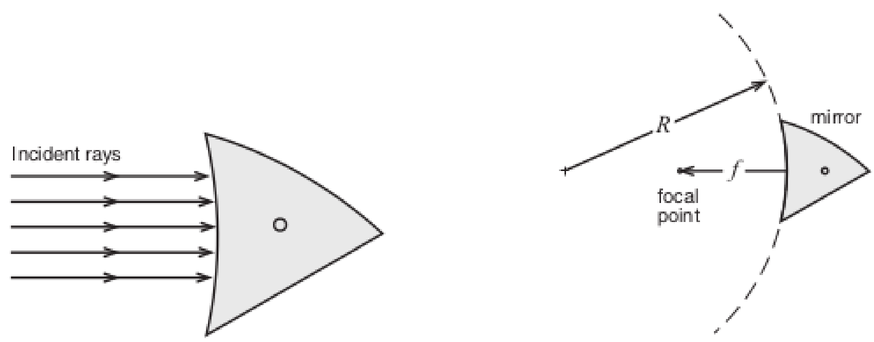


Figure 1.3.: Concave cylindrical mirror and reflection. Three rays may work better than the five shown in the diagram.

1.5.1. Procedure

1. Turn the wheel on the light source to three parallel rays[1]. Direct the rays straight into the concave mirror so that the light is reflected back toward the ray box similar to Figure 1.3. Be aware of where the rays focus.

2. Trace the surface of the mirror and the incident and reflected rays by marking two or more positions on each. Label the rays and surface.

3. The place where the five reflected rays cross each other is the focal point of the mirror. Mark the focal point.

4. Indicate the incoming and the outgoing rays with arrows in the appropriate directions. (You can now remove the light source and mirror from the paper.)

[1] You can choose five rays if the rays are good and parallel.

5. Measure the focal length, the distance from the center of the concave mirror surface (where the middle ray hit the mirror) to the intersection of the rays. Record and report the result in a table with error.

6. Use a compass to draw a circle that matches the curvature of the mirror. Set the compass to different widths and find the width that matches the curve. Measure the radius of curvature and record it in a table with error.

7. If there is time, repeat steps 1-4 three more times for the concave mirror.

8. Repeat steps 1–4 for the convex mirror. Note that the reflected rays will diverge and not cross. Use a ruler to extend the reflected rays back behind the mirror's surface. The focal point is where these extended rays cross.

1.5.2. Analysis

- Obtain averages (or the single value if multiple trials were not taken) for the radii of both curved surfaces with error. Do the same for the focal length.
- Use these values to for the ratio of $\frac{R}{f}$. Does this value match the predicted ratio?

1.5.3. Question

1. What is the value of the radius of curvature of a plane mirror?

2. The Law of Refraction

2.1. Equipment

Light ray box, Ray Table, sticky tac, Cylindrical Lens.

2.2. Introduction

As you have seen, the direction of light propagation changes abruptly when light encounters a reflective surface. The direction also changes abruptly when light passes across a boundary between two different media of propagation, such as between any combination of air, acrylic, glass or water. In this case, the change of direction is called *refraction*. As with reflection, a simple law characterizes the behavior of a refracted ray of light. According to the Law of Refraction, also known as Snell's Law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

The quantities n_1 and n_2 are constants[1], called indices of refraction, that depend on the two media through which the light is passing. The angles θ_1 and θ_2 are the angles that the ray of light ray makes with the normal to the boundary between the two media as shown in Figure 2.1 for the situation where $n_2 > n_1$. In this experiment you will test the validity of this law, and also measure the index of refraction for acrylic n_2.

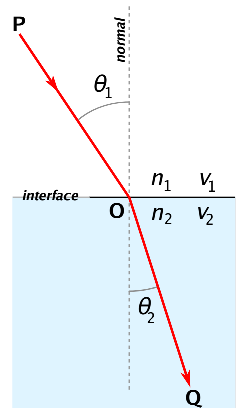


Figure 2.1.: Light ray traversing boundary between two media where $n_2 > n_1$.

2.3. Procedure

1. To alleviate slippage, sticky tac should be used under the ray table.
2. Set up the equipment as shown in Figure 2.2 but leave the cylindrical lens off. Adjust the components so a single ray of light follows over the center of the bold "Normal" line.
3. Align the flat surface of the Cylindrical Lens with the line labeled component. Observe the reflected ray and use it to improve alignment. With the lens properly aligned, the radial lines extending from the center of the Degree Scale will all be perpendicular to the circular surface of the lens.

[1] for the purposes of this lab, anyway...

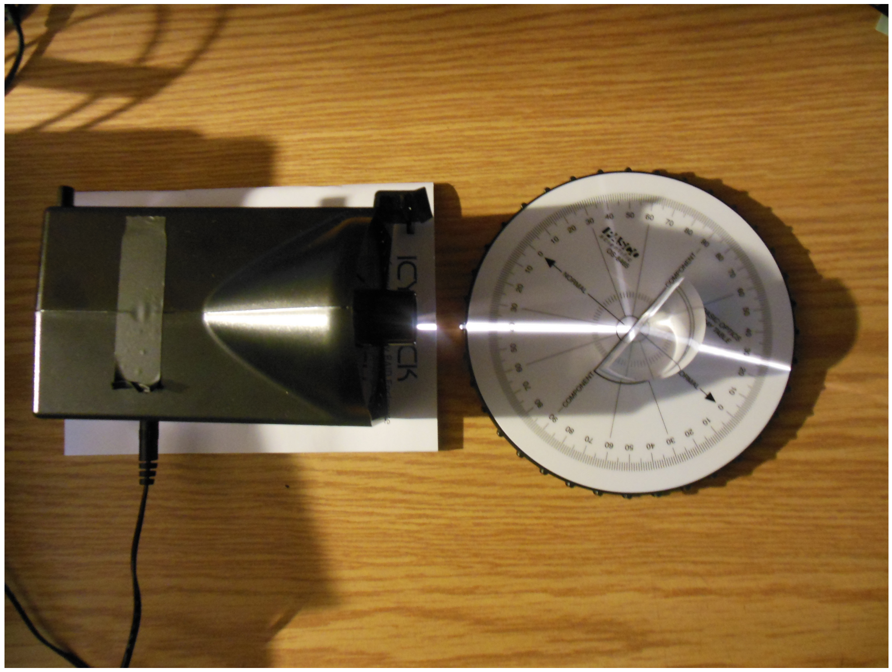


Figure 2.2.: Refraction experiment equipment configuration

Angle of Incidence θ_1	Trial 1: Angle of Refraction	Trial 2: Angle of Refraction	Average θ_2
0.0	±	±	±
10.0	±	±	±
20.0	±	±	±
30.0	±	±	±
40.0	±	±	±
50.0	±	±	±
60.0	±	±	±
70.0	±	±	±
80.0	±	±	±
90.0	±	±	±

Table 2.1.: Data table for Refraction Experiment

4. Without disturbing the alignment of the lens, rotate the ray table to alter the angle of incidence to each angle θ_1 shown in Table 2.1.

5. For each angle of incidence, measure the angle of refracted ray. Record this in the Trial 1 column.

6. Repeat the measurement with the incident ray striking the acrylic block from the opposite side of the normal and record the refracted ray's angle in the Trial 2 column.

7. Calculate the average angle of refraction θ_2 with error. The error value can be calculated using the "propagation of errors" rules shown in the appendix or a separate pdf.

2.4. Analysis: Plot and Questions

1. Is the ray bent when it passes out of the lens through the curved surface of the lens? What does this tell you about the shape of the curved surface of the lens?

2. Are your results for the two trials the same? If not, to what do you attribute the differences?

3. **Plot**: Use xmgrace to construct a graph with $\sin\theta_1$ (sine of incident angle) on the x-axis and $\sin\theta_2$ (sine of refracted angle, average) on the y-axis. Put error bars on the data points.

4. Use the regression tool in xmgrace to determine and show the best fit straight line[2] for each of yourdata.

5. Explain how your graph is consistent with the Law of Refraction

6. State the slope of your best fit line: ___________±____________

7. Assume that the index of refraction for air is equal to 1.0). From the value of the slope calculate the index of refraction for the acrylic lens. State this value with error as in $n_2 \pm \sigma_{n2}$:

8. In performing the experiment, what difficulties did you encounter in measuring the angle of refraction for large angles of incidence?

9. How does averaging the results of measurements taken with the incident ray striking from either side of the normal improve the accuracy of the results?

10. How did you use the Law of Reflection to test the alignment of the Cylindrical Lens?

11. Was the incident light ray both refracted and reflected for all incident angles?

12. Was the brightness of the refracted and reflected rays constant as the angle of incidence θ_1 changed? If not, how did it change with increasing θ_1?

13. What branch of physics allows one to calculate the percentage of and incident beam that is reflected and refracted at the boundary between two media?

14. The law of refraction has two parts; state both.

15. Use the index of refraction calculator at `http://refractiveindex.info/legacy` to determine the index of refraction for PMMA (under plastics), aluminum, the alloy Aluminum Copper and air for wavelength $\lambda = 589$nm.

[2]Remember to remove the "join the dots" line.

3. Image Formation in a Plane Mirror

3.1. Purpose

1. Determine the location of a mirror's virtual image by ray tracing.
2. Compare image and object distances for a mirror.

3.2. Equipment

Ray Light box[1], ray Optics Mirror, 11x17 inch paper, ruler (15" or longer if available), diverging lens (double concave) from Pasco Optics kit.

3.3. Introduction

Looking into a mirror and seeing a nearly exact image of yourself hardly seems like the result of simple physical principles, but it is. The nature of the image you see in a mirror is understandable in terms of the principles you have already learned: the Law of Reflection and the straight-line propagation of light.

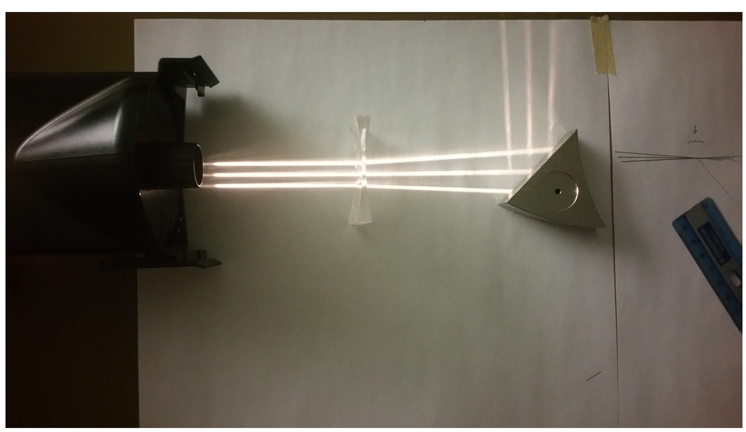
In this experiment you will investigate how the apparent location of an image reflected from a plane mirror relates to the location of the object, and how this relationship is a direct result of the basic principles you have already studied. Additionally a virtual object will be utilized.

3.4. Procedure

1. Use electrical tape to block the light emitted upward from the filament if you desire.
2. Tape together two sheets of 11x17 inch paper along the long side as shown. Place the light ray box in the upper left of the paper.
3. Set up the equipment as shown in Figure 3.1. Positioning of the ray box, lens and mirror is important. The location of both the virtual object and virtual image must be on the paper. Estimate where your rays will intersect.
   a) Additional paper can be added later if needed
   b) Attempt to have the lens center and the center ray coincide, along with the center of the mirror.
   c) Attempt to have the lens's axis purpendicular to the central ray.
4. Set the ray box to provide three rays.
5. Place a diverging lens from the Pasco kit in the path of the rays. This will generate diverging rays and a virtual object. The meeting point for these rays will serve as a virtual object: the filament's apparent location.
6. Mark the centers or edges of all three rays in two locations. This could possibly be done before putting the mirror on. Make these marks far apart to improve ray direction accuracy.
7. Position the mirror so that all three light rays are reflected from its flat surface as shown in Figure 3.1b.

[1] Leave collimator in, removal often damages the plastic case unfortunately.

(a) Light Ray box on upper left of paper



(b) Position for the mirror: the diverging rays between the lens and mirror must meet somewhere on the paper to locate the virtual object.

Figure 3.1.: Mirror Image equipment configuration

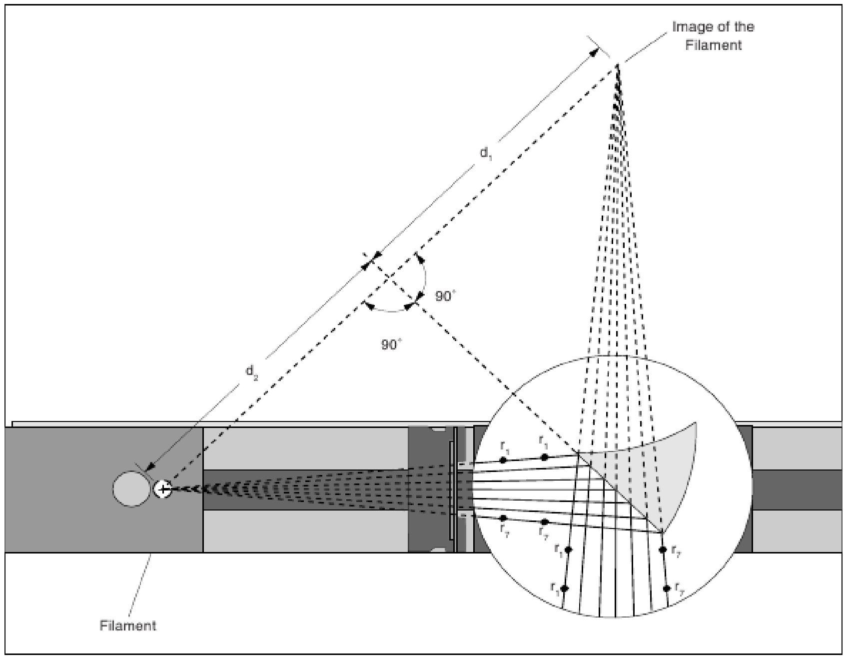


Figure 3.2.: Mirror image ray tracing and analysis. Note that the diverging lens is not present, the light ray box has had the collimating lens removed. In this case the object is real: the actual filament position can be used.

8. Without moving the mirror, trace a line on the paper to mark the position of the flat surface of the mirror.
9. With a pencil, mark two points along the reflected rays. If necessary, label the points so you know which points belong to which ray.
10. Remove the mirror and reconstruct the rays using a pencil and straight-edge. Draw dotted lines to extend the incident and reflected rays to where they intersect.
11. Estimate the center of the various intersecting rays if the back-traced lines do not meet at a single location.
12. On your drawing, label the position of the virtual object and the apparent position of its reflected image. Draw a line joining these points or locations similar to what is shown in Figure 3.2.
13. Extend the line of the mirror's surface up to the line drawn in step 12. Consult Figure 3.2.
14. Measure d_1 and d_2 as shown in Figure 3.2 and calculate their ratio. See questions below.

3.5. Questions

1. What is the perpendicular distance from the filament to the plane of the mirror? This corresponds to distance d_1 in Figure 3.2.

2. What is the perpendicular distance from the image of the filament to the plane of the mirror? This corresponds to distance d_2 in Figure 3.2.

3. What is the relationship between object and image location for reflection in a plane mirror?

4. If one wall of a room consists of a large, flat mirror, how much larger does the room appear to be than it actually is?

5. A mirror reverses what image property with respect to the object?
   a) right/left
   b) depth

6. How does the size of the image reflected from a plane mirror relate to the size of the object?