# Lab 25:
# Geometric Optics

College Physics For AP® Courses

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**In this lab you will learn**

- how to use Snell's law to determine the index of refraction of a given material
- how to determine the focal length of a converging lens

## Activity 1: Pre-Assessment

1. When looking at an object on the bottom of a pool, the object appears to be in a different location than where it actually is. Why is this?
2. Why does the sun appear larger and redder during sunrise and sunset?
3. **Discuss the answers to questions 1 and 2 with the class.**

## Activity 1: Snell's Law

A **light ray** is a simplified model of light where each ray is a line drawn perpendicular to the wave front of the actual light and pointing in the direction of propagation of the light. The speed of a light ray through a given material or medium is given by the **index of refraction** of that material, defined as

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

where *n* is the index of refraction, *c* is the speed of light in a vacuum, and *v* is the speed of light through that material. Light rays can change direction when traveling through different media. Consider a light ray traveling from one medium to another. The incoming ray in the first medium is known as an **incident ray**. When the incident ray strikes the interface (or boundary) between the two media, the ray splits into a **reflected ray** that corresponds to the ray reflected back from the interface via the original medium, and a **refracted ray** that corresponds to the light that gets transmitted through the interface into the second medium. Suppose the incident ray makes an angle $\theta_1$ with respect to the **normal to the interface**, which is the line perpendicular to the interface surface. The reflected ray reflects off the surface with the same angle $\theta_1$ while the refracted ray passes through the second material with an angle $\theta_2$ with respect to the normal. The relationship between $\theta_1$ and $\theta_2$ is given by **Snell's law**

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

where $n_1$ and $n_2$ are the indices of refraction of the two materials. Figure 25.1 illustrates the refraction of a light ray when traveling between two different materials.

In this activity you will investigate how light is reflected and refracted through different materials.

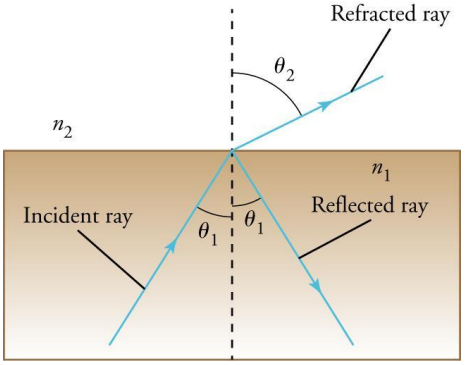



**Figure 25.1:** An incident ray traveling through a material with an index of reflected $n_1$ at an angle $\theta_1$ with respect to the normal to the interface. The angle of reflection of the reflected wave equals the incident angle. The refracted wave passes into the second material with an index of refraction $n_2$ at an angle $\theta_2$ with respect to the interface.

**For this activity, you will need the following:**

- Laser source (such as a laser pointer)
- Piece of glass in the shape of a half-cylinder
- Protractor
- Paper
- Pencil to sketch the outline of the glass

**Safety Precautions**

- Take care to avoid shining the laser in anyone's eyes, as this can cause permanent damage to the retina.
- Be careful with the edge of the glass half-cylinder, as it can cause cuts.
- Notify your teacher immediately if any of the glass breaks.

For this activity, you will work *in groups of four students.*

**Structured Inquiry**

**Step 1:** First draw the outline of the half-cylinder piece of glass on your paper. The outline should resemble a semicircle. Next, use the protractor to label several angles with respect to the flat end of the half circle.
**Step 2: Hypothesize/Predict:** Given that light travels faster through air than through glass, will the incident angle be larger or smaller than the refracted angle? Write your hypothesis in your notebook.
**Step 3: Student-Led Planning:** Shine your laser light through the non-curved sides of the glass and record the angle at which the light exits the glass from the other side. Do this for several incident angles.
**Step 4: Critical Analysis:** Use the measurement of the incident and refracted angles to determine the index of refraction of the glass, given that the index of refraction of air is $n_{\text{air}} \approx 1$. Is this consistent with your hypothesis in Step 2?

**Guided Inquiry**

**Step 1: Hypothesize/Predict:** Given the index of refraction for the glass, what incident angle will correspond to an angle of refraction of $90°$ (the critical angle)? Write your hypothesis in your notebook.

**Step 2: Student-Led Planning:** How would you position the laser so that total internal reflection is achieved? Discuss with your group, and then keep experimenting until total internal reflection is achieved. Describe each of your trials in your notebook as you complete each one.

**Step 3: Critical Analysis:** Is there any refracted light at the angle calculated in Step 1? How would this angle change if the index of refraction of the glass were doubled? Discuss your results with your group.

## Assessments

1. The _____ of a material determines how fast light propagates through that material.
2. Suppose light is traveling through air into a material with an index of refraction of *n* = 2, and the angle of incidence is $1°$.
   a. What will the angle of the refracted light be?
   b. What is the speed of light in the material?

## Activity 2: Pre-Assessment

1. To focus sunlight to a point, would you use a concave or convex lens?
2. Do nearsighted people (those who can only focus on nearby things) need to wear glasses with concave or convex lenses?
3. **Discuss the answers to questions 1 and 2 with the class.**

## Activity 2: Lenses and Images

A device that leads to a convergence or divergence of light rays is known as a **lens.** A lens that leads to a convergence of parallel light rays is known as a **convex lens**, whereas a lens that diverges parallel light rays is known as a **concave lens**. For a convex lens, parallel light rays entering the lens converge to a point, known as the **focal point**, on the other side of the lens. Similarly, light diverging from a concave lens appears as if it is originating from a single point on the other side of the lens, also known as the focal point. For both type of lenses, the **focal length** *f* of a lens is the distance from the lens center to the focal point (Figure 25.2).

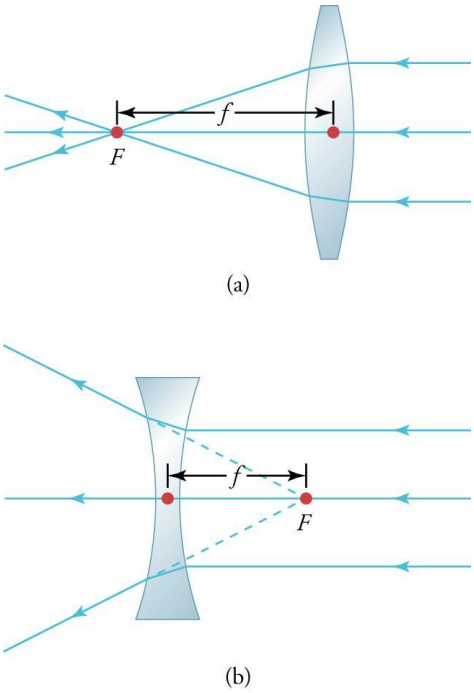



**Figure 25.2:** Locations of the focal point *F* and focal length *f* for (a) a convex lens and (b) a concave lens.

The focal length for a lens in air can be determined from the **lens maker's equation**

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + (n-1)\frac{d}{nR_1R_2}\right]$$

where *n* is the index of refraction of the lens, $R_1$ is the radius of curvature of the lens surface that is nearest to the source of light, $R_2$ is the radius of curvature of the lens surface farthest away from the light source, and *d* is the thickness of the lens along the lens axis between the two surfaces. For a very small value of *d*, the lens maker's equation reduces to an equation known as the **thin lens approximation.**

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Note that the signs of $R_1$ and $R_2$ usually follow the following sign convention: The value is positive if the vertex (peak) lies to the left of the center of curvature, and it is negative if the vertex lies to the right of the center of curvature.

If an object of height $h_o$ is placed at a distance $d_o$ from the lens, then an **image** is formed at a distance $d_i$ from the lens. The distance of the image can be related to the distance of the object and the focal length by the **thin lens equation**.

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

A **ray diagram** is a diagram that is used to locate the point on an image formed by a lens by tracing the path that light takes from the object. To draw an image from a given object

1. draw a ray from the top of the object parallel to the axis of the lens; this ray changes direction at the lens and passes through the focal point;
2. draw a ray from the top of the object through the center of the lens; this ray passes through the lens in a straight line; and
3. draw a ray from the top of the object through the focal point *on the same side of the lens as the object*; this ray changes direction at the lens and travels parallel to the axis of the lens.

   Find the intersection point of the three rays. The image is located where the three rays intersect at a distance $d_i$ from the lens and at a height $h_i$ from the axis of the lens. In this case, the image will appear inverted from the original object. The entire process is illustrated for a convex lens in Figure 25.3. In this activity you will determine the focal length of a convex lens.

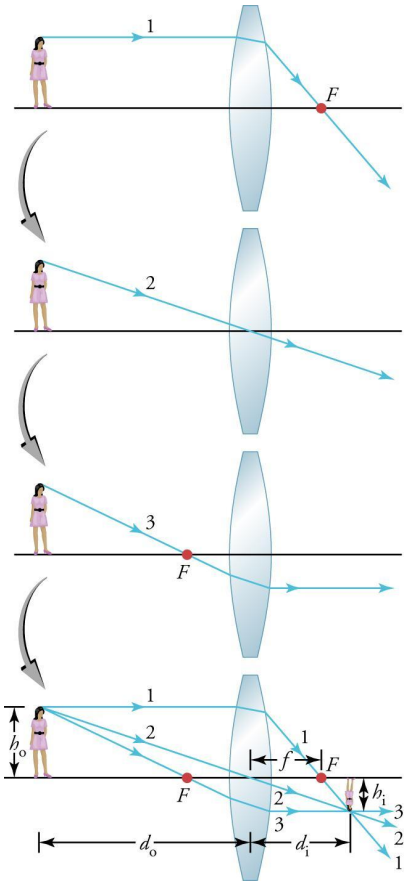



**Figure 25.3:** A ray diagram showing how to construct an image from an object.

**For this activity, you will need the following:**

- Light source, such as a clear lamp or candle
- Converging lenses with focal lengths between 15 and 25 cm
- Lens holders
- Yard or Meter stick
- Index card for a screen (5 × 7 inches or larger)

**Safety Precautions**

- Be careful with the flame from the candle to avoid burns.
- Notify your teacher immediately if any of the glass breaks.

For this activity, you will work *in groups of four students*.

**Structured Inquiry**

**Step 1:** Working with your group, place a lens in the lens holder. Now, place your light source at a given distance (no more than 1 meter) from your lens. On the other side of the lens, use your index card to find the distance where you see a clear image. Record your results.

**Step 2: Hypothesize/Predict:** If you increase the distance of the light source from the lens, how does the distance of the image change? What about if you decrease the distance between the light source and the lens? Make predictions on the distance of the image from the lens based on the results in Step 1. Create an appropriate table in your notebook to record your data.

**Step 3: Student-Led Planning:** Working with your group, you will now test your hypothesis from Step 2 by placing the light source at various distances from the lens. What distances would make the most sense to test?

**Step 4:** On graph paper, plot the inverse of the image distance vs. light source distance and draw a straight line through the data points. The intersection of the line with the *y*-axis should be equal to the focal length. Repeat Steps 1–3 for lenses of different focal lengths.

**Step 5: Critical Analysis:** Was your hypothesis supported by your results? How does the measured focal length compare to the known focal length of the lens? Does the focal length of a given lens change as the distance between the light source and lens changes? Can the image ever be farther away from the lens than the light source? Why or why not? Write all of your answers in your notebook.

## Assessments

1. The focal length of a given lens is $f = 5$ cm. If an object is located $d_o = 20 \text{ cm}$ away from the lens, where will the image be located?
2. Parallel rays going through a concave lens will _____.
3. What happens when a light ray passes through the center of a thin lens?