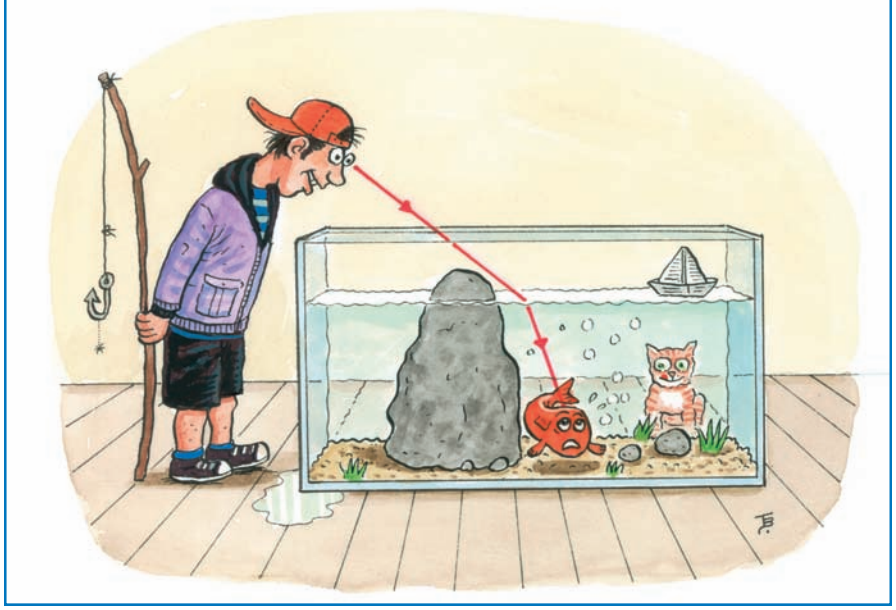
Section 8 Refraction of Light

What Do You See?



Learning Outcomes

In this section, you will

- **Observe** refraction.
- **Measure** angles of incidence and refraction.
- **Measure** the critical angle.
- **Observe** total internal reflection.

What Do You Think?

The Hope Diamond is valued at about 100 million dollars. A piece of cut glass of about the same size is worth only a few dollars.

- **How can a jeweler tell the difference between a diamond and cut glass?**

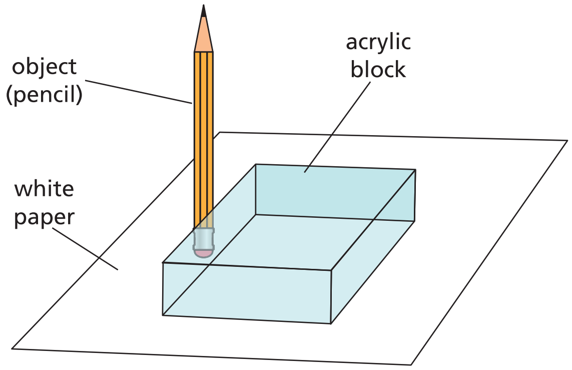
Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your responses with your small group and with your class.

Investigate

In this section, you will use an acrylic block and the light from a laser beam to observe the refraction of light.

1. Place an acrylic block on a piece of white paper on your desk. Have one member of your group hold a pencil or some other thin, tall object behind the acrylic block while you look at the object through the block.

   a) Describe what you see as you move your head back and forth sideways. Record your observations in your *Active Physics* log.



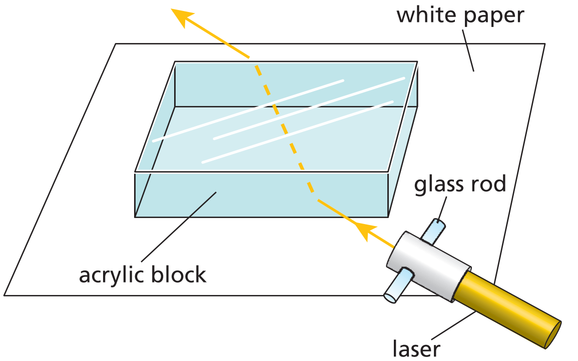
2. Trace the outside of the acrylic block on the paper. Carefully aim a laser pointer, or the light from a ray box, so the light beam moves horizontally, as you did in previous sections. Remember to follow the safety rules when using lasers and never allow any of the transmitted or reflected light to fall on a student's eye.

   Place a glass rod in the light beam so that the beam spreads up and down.

3. Shine the laser pointer or light from the ray box through the acrylic block. Be sure the beam leaves the acrylic block on the side opposite the side the beam enters.

   a) Mark the path of each beam. You may wish to use a series of dots as you did before.

   b) Label each path on both sides of the acrylic block so you will know that they go together.



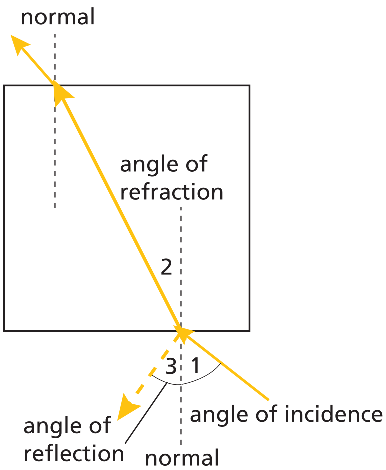
   You may notice that some of the incident light is reflected off the acrylic block. Use a series of dots to mark the reflected ray.

4. Remove the acrylic block.

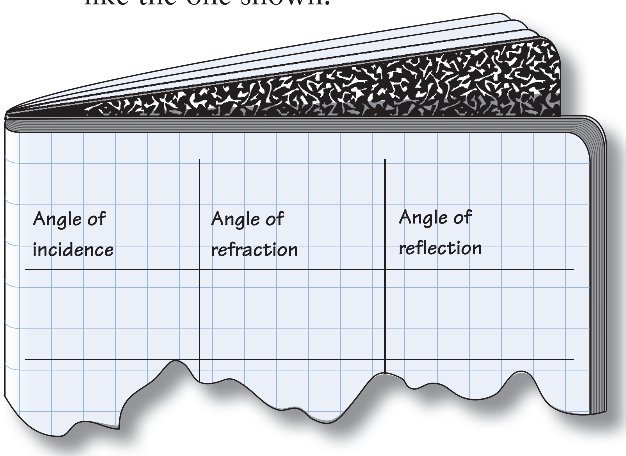
   a) Connect the paths you traced to show the light beam hitting the front surface of the acrylic block, traveling through the acrylic block, and emerging from the acrylic block. You cannot see the laser beam traveling through the acrylic block, but you can tell where the beam entered and left. To get the path of the laser beam through the block, just connect these points with a straight line. Note that the direction of the beam is not the same as that in air. The light has been *refracted* by the block.

   b) Draw perpendicular lines (the normals) at the point where rays enter and leave the acrylic block. Label these lines as normal.

   c) Measure the angles of incidence (the angle between the incident ray and the normal in the air), reflection (the angle between the reflected ray and the normal in the air), and refraction (the angle between the refracted ray and the normal in the acrylic block).



   d) Record your measurements in a table like the one shown.



5. Repeat *Steps 2, 3*, and *4* for two more (different) angles of incidence. Use a separate sheet of paper for each trial.

a) Draw a graph of angle of refraction (y-axis) versus the angle of incidence (x-axis).

b) Use your graph to predict the angle of refraction if the angle of incidence is 45°.

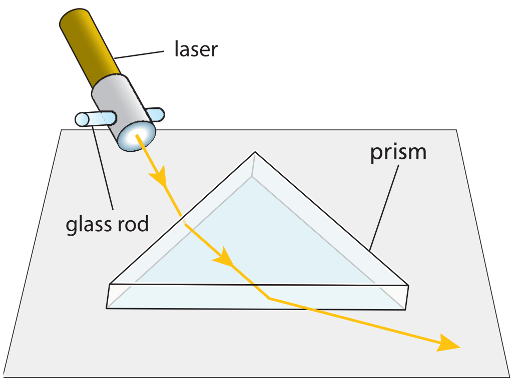
c) Set up the acrylic block and light source so the angle of incidence is 45°. Find the angle of refraction. Compare the angle of refraction to your prediction.

6. Some of the incident light reflected off the acrylic block. Does the law of reflection hold true for the light reflected from the surface of the acrylic block?

7. Replace the acrylic block with the 45°-90°-45° glass prism, lying flat on a piece of paper. Aim the laser beam as shown in the diagram so that the beam enters a short side of the triangle and leaves on the long side.

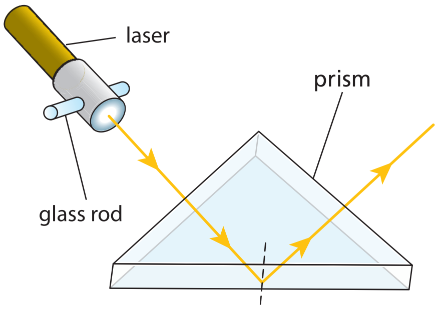
a) Trace the outline of the prism and make some dots to mark the incident ray and refracted ray.

b) Draw the normals where the incident ray enters the prism and where the refracted ray leaves the prism.



8. Put the prism on a new sheet of paper. Now direct the laser beam so that it approaches the side of the prism along the normal (that is, perpendicular to the side as shown). Note that the laser beam no longer exits at the bottom but now exits the prism from the other side.

a) Trace the outline of the prism and make some dots to mark the incident ray and refracted ray.

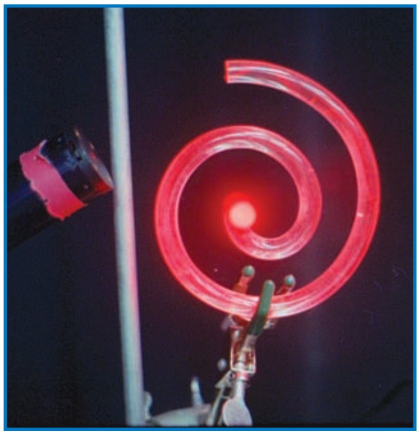


Note that the long side of the prism is acting as a mirror. This situation is called *total internal reflection* because the inside of the prism acts like a perfect mirror (total reflection) and the reflected light stays inside the prism (until it gets to the other side).

b) Extend the lines indicating the incident rays and refracted rays to see where they hit the bottom of the prism. Draw the normal at that point. Does the law of reflection describe what happens at the bottom of the prism?

9. Swivel the incident beam at various angles and determine when the beam refracted at the bottom just disappears. (This may be difficult to find precisely because the refracted beam gets weak just before it disappears.) The angle of incidence at the bottom of the prism when the refracted beam at the bottom just disappears—skimming the bottom—is called the *critical angle* of refraction.

10. It is possible to bend a long, thin acrylic rod so the light enters the narrow end of the acrylic rod, reflects off one side of the acrylic rod, then reflects off the other and back again, emerging from the other narrow end. Try to bend a long acrylic rod so that the light is reflected as described. A flexible glass or plastic rod used in this manner is called an optical fiber. You may have seen such fibers on lamps in novelty stores.

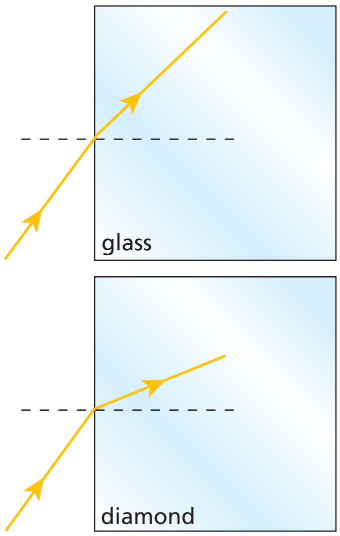


Physics Talk

SNELL'S LAW (THE LAW OF REFRACTION)

A light ray refracts (bends) when it goes from one material to another. You have explored light going from air to acrylic and from acrylic back into air. This bending occurs whether the substances are acrylic, glass, water, or diamond. The amount of bending depends on the properties of the two materials. Each transparent material has a specific property called the **index of refraction**.

A diamond with a high index of refraction (lots of bending when light comes in from the air) can be distinguished from glass with lower index of refraction (less bending when light comes in from the air). If neighboring materials have nearly the same index of refraction, the bending is small as light travels from one material to the other. For example, if you submerge your acrylic block in a container of water (use a container with flat sides), you will find that the amount of bending of light when it goes from water to acrylic or from acrylic back into water is relatively small. The index of refraction for water is close to that for acrylic. The index of refraction for air is 1.0003. For water, the index of refraction is 1.33; for acrylic it is about 1.5, and for diamond about 2.5.



Light entering glass and diamond at the same angle bends much more when it enters the diamond.

The relationship between the index of refraction and the ratio of the sine of angle of incidence to the sine of angle of refraction for each of the two materials is called the **law of refraction** or **Snell's law**.

Physics Words

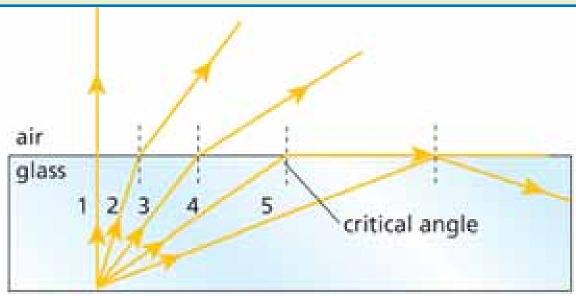
index of refraction: a property of the materials at an interface that determine the relationship between the angle of incidence and the angle of refraction.

Snell's law: the relationship between the index of refraction and the ratio of the sine of angle of incidence to the sine of angle of refraction at the boundary of the two media where refraction takes place.

Snell's law states that as light enters a substance such as acrylic (high index of refraction) from air (low index of refraction), the light bends toward the normal. When light leaves a substance such as acrylic (high index of refraction) and enters the air (low index of refraction), it bends away from the normal. The larger the difference in the index of refraction for the two materials, the larger the difference between the angle of incidence and the angle of refraction.

If the light is entering material such as air (with a low index of refraction) from a substance with a higher index of refraction, the angle in that substance may be such that the angle of refraction is 90°. In this special case, the angle in the substance is called the **critical angle**. If the angle in the substance is greater than this critical angle, then the light does not enter the air but reflects back into the substance as if the surface were a perfect mirror. This is the basis for optical fibers in which laser light reflects off the inner walls of glass or plastic and travels down the fiber, regardless of the bend in the fiber.

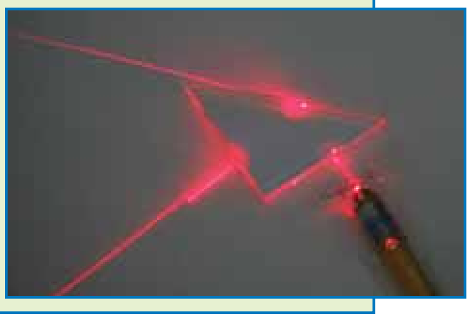
You noticed in the investigation at every air-glass interface, some of the light was reflected and some of the light was refracted. The exception to this was the light's angle of incidence was greater than the critical angle. In this case, all of the light was reflected back into the glass. The result is **total internal reflection**.



In the diagram, rays 1-3 leave the glass and bend away from the normal as they enter the air. Ray 4 leaves the glass and bends away from the normal such that its angle of refraction is 90°. The angle of incidence is defined as the critical angle. Ray 5 has an angle of incidence greater than the critical angle. It reflects back into the glass. The angle of incidence is equal to the angle of reflection.

It turns out that the index of refraction is also related to the speed with which light travels in vacuum and also to the average speed with which light travels through the material. The relationship is expressed as

$$\text{index of refraction} = \frac{\text{speed of light in vacuum}}{\text{speed of light in the material}}$$



The speed of light in a vacuum is 2.99×10^8 m/s, a very high speed! In fact, it is the fastest speed that anything can attain.

Physics Words

critical angle: the angle of incidence, for a light ray passing from one medium to another, that has an angle of refraction of 90°.

total internal reflection: a phenomenon in which the refracting medium acts like a perfect mirror and the reflected light stays inside the medium.

Checking Up

1. Why do light rays bend when they travel from one substance to another?
2. Explain how you can measure a diamond's index of refraction.
3. Explain Snell's law.

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
◆			

Using Snell's Law to Analyze Your *Investigate* Data

The law of refraction (Snell's law) can be expressed in mathematical terms. The expression involves the trigonometric sine of the angle of incidence (θ_i), the sine of the angle of refraction (θ_r), and the index of refraction of each of the two materials. This relationship can be mathematically expressed as

$$n_i \sin\theta_i = n_r \sin\theta_r$$

$$\text{or} \quad \frac{\sin\theta_i}{\sin\theta_r} = \frac{n_r}{n_i}$$

1. Using your data from this section, find the sine of the angles using a calculator. (Use the SIN button and be sure the calculator is set for angles in degrees.)
2. For each angle of incidence and angle of refraction pair, calculate the ratio

$$\frac{\sin\theta_i}{\sin\theta_r}$$

3. According to the law of refraction, this ratio should be the same for all pairs of angles. The ratio should equal the ratio of the two indexes of refraction $\frac{n_r}{n_i}$.

   Does this relationship work for your combination of air and acrylic?

What Do You See Now?

The cartoon at the beginning of *Section 8* shows how a person can see a fish behind a rock due to the bending of light. In the cartoon, the arrow shows the direction the person is looking. The light actually travels from the fish to the person's eye. Should the cartoonist reverse the arrow?

What Do You Think Now?

At the beginning of the section, you were asked the following:

- **How can a jeweler tell the difference between a diamond and cut glass?**

Now that you know how refraction occurs, what would be different between diamond and cut glass to allow a jeweler to recognize a diamond? How does your answer relate to Snell's law and critical angles?

Physics

Essential Questions

What does it mean?

In this section, you learned that light travels in straight lines until it interacts with materials. When light travels from one medium to another, its direction can be changed by the process of refraction. Explain what you mean by the term "refraction of light."

How do you know?

Physicists prefer to find quantitative relationships among basic properties based on observations and experiments. How are the angle of incidence and the angle of refraction related? Tell how you know this from your experiments in the *Investigate*.

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Waves and interactions	* Interactions of matter, energy and fields	Experimental evidence is consistent with models and theories

* When scientists observe new phenomena, they often have to modify previously stated general principles. Does light always travel in straight lines? How do your observations of refraction modify your statement about the general principle that light travels in straight lines?

Why should you care?

The aspect of light behavior such as refraction is very general and occurs in many different situations. Give some examples of the use of refraction in everyday life. How can the refraction of light be used as part of the entertainment in your sound and light show?

Reflecting on the Section and the Challenge

The bending of light as it goes from one material into another material is called refraction. It is mathematically expressed by Snell's law, which involves the material property called the index of refraction. The higher the index of refraction, the slower the average speed of the light traveling in that material.

As you design your light show for the *Chapter Challenge*, you may find creative uses of refraction. You may decide to have light bending in such a way that it spells out a letter or word or forms a picture. You may wish to have the light travel from air into glass to change its direction. You may have it bend by different amounts by replacing one material with another. Regardless of how you use refraction effects, you can now explain the physics principles behind them.

Physics to Go

1. A light ray goes from the air into an acrylic block. In general, which is larger, the angle of incidence or the angle of refraction?

2. a) Make a sketch of a ray of light as it enters a piece of acrylic block and is refracted.

   b) Now turn the ray around so it goes backward. What was the angle of refraction is now the angle of incidence. Does the turned-around ray follow the path of the original ray?

3. A light ray enters an acrylic block from the air. Make a diagram to show the angle of incidence, the angle of refraction, and the normal at the edge of the acrylic block.

4. Light rays enter an acrylic block from the air. Make drawings to show rays with angles of incidence of 30° and 60°. Use your data from this section to find the angle of refraction for each of these rays. For each incident ray, sketch the refracted ray that passes through the acrylic block.

5. a) Light is passing from the air into an acrylic block. What is the maximum possible angle of incidence that will permit light to pass into the acrylic block? Refer to your data for refraction of a light ray entering the acrylic block from the air.

   b) Make a sketch to show your answer. Include the refracted ray (inside the acrylic block) in your sketch.

6. a) A ray of light is already inside an acrylic block and is heading out. What is the name of the maximum possible angle of incidence that will permit the light to pass out of the acrylic block?

   b) If you make the angle of incidence greater than this special angle, what happens to the light?

   c) Make a sketch to show your answer. Be sure to show what happened to the light.

7. a) Make a drawing of a light ray that enters the front side of a rectangular piece of acrylic block and leaves through the back side.

   b) What is the relationship between the direction of the ray that enters the acrylic block and the direction of the ray that leaves the acrylic block?

8. You have seen the colored bands that a prism, cut glass, or water produce from sunlight. Light that you see as different colors has different wavelengths. Since refraction makes these bands, what can you say about the way light of different wavelengths refracts?

9. **Active Physics Plus** Light enters a piece of glass ($n = 1.50$) from air ($n = 1.00$) at an angle of 45°. Calculate the angle of refraction in glass using Snell's law.

10. Active Physics *Plus* To investigate whether a stone in a ring is a real diamond ($n = 2.42$) or a piece of cut glass ($n = 1.50$), a student/physicist observes a laser beam emerging from the stone. The angle of incidence in the stone is 20°. The angle of refraction in air is 56°. What does the physicist conclude from this data? Is the stone in the ring a diamond or glass?

11. Active Physics *Plus* Compare the angle of refraction in water ($n = 1.33$), glass ($n = 1.50$), and diamond ($n = 2.42$) if the angle of incidence is 45° for each.

12. ***Preparing for the Chapter Challenge***

Design a light effect that uses refraction of light. You may wish to look at one of the suggestions in *Inquiring Further* for ideas. Explain your light effect using what you have learned about refraction in this section.

Inquiring Further

1. **Setting up a special effect using total internal reflection**

Find some small-diameter, clear, flexible tubing, about 2 m long. Plug one end of the tube. Pour clear gelatin in the other end, through a funnel, before the gelatin has had time to set. Arrange the tubing into an interesting shape and let the gelatin set. You may wish to mount your tube on a support or a sturdy piece of cardboard, which can be covered with interesting reflective material, such as iridescent paper. Fasten one end of the tube so laser light can easily shine straight into it. When the gelatin has set, turn on the laser. What do you see? This light-trapping phenomenon is called total internal reflection.

2. **Using different media to observe refraction**

Place your acrylic block in a clear, rectangular container of water. The water container should be large enough so that the acrylic block can be turned in different directions. Shine a laser beam perpendicular to the side of the water container so the beam hits the acrylic block. Rotate the acrylic block and observe how the angle of incidence and angle of refraction change when the block is immersed in water. Explain what is happening.

3. **The "magic" reappearing penny**

Place a penny in the bottom of an opaque drinking glass. Position your eye so that the penny is just out of view when you look over the rim of the glass. Predict what will happen when you fill the glass with water. Then try it and see what happens. How can you explain the results?