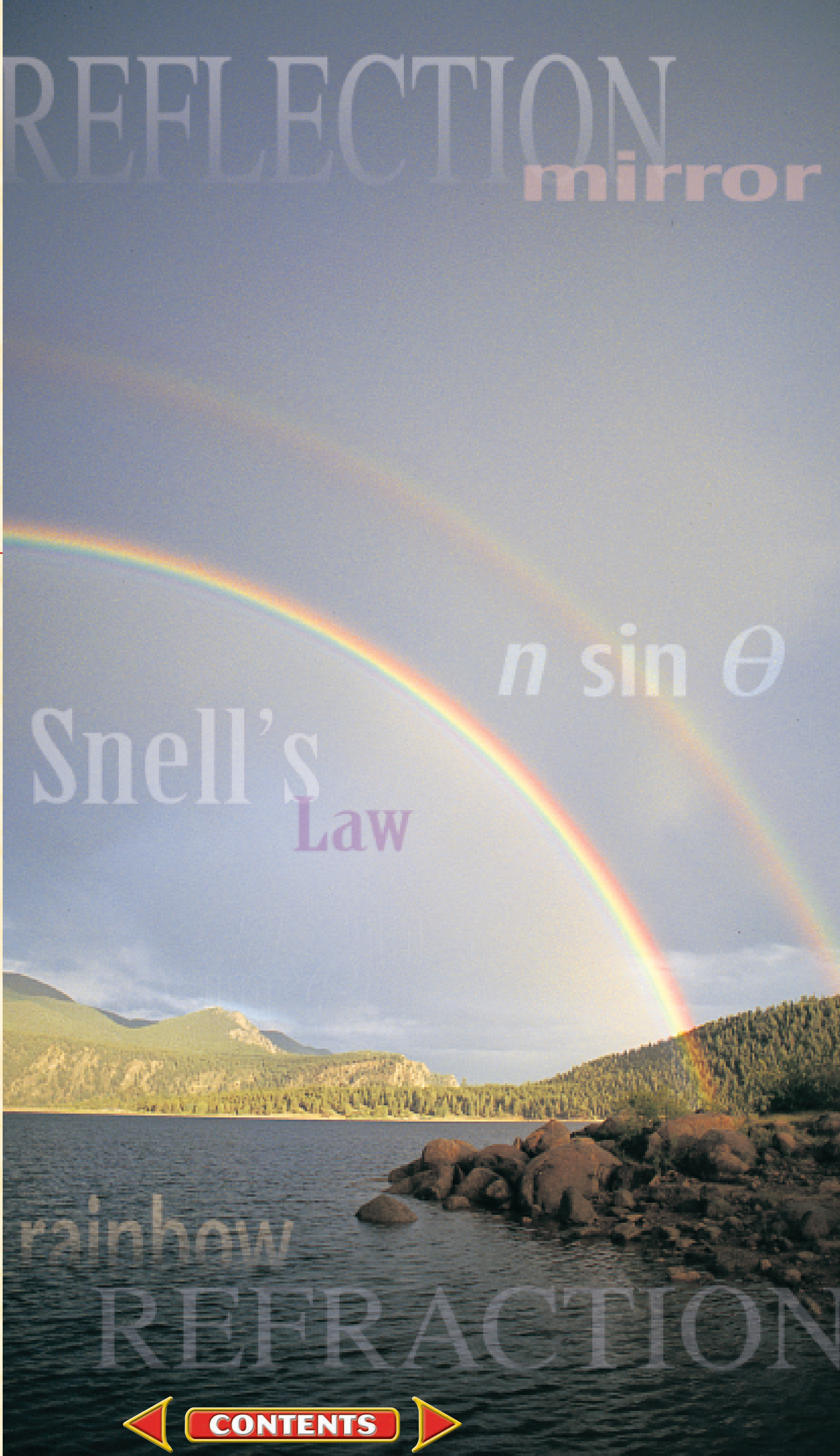
A Smile in the Sky

Rainbows are created by a combination of refraction and reflection in raindrops. When you look at a rainbow, you see violet on the inside and red on the outside. How does the rainbow form, and why are the colors separated?

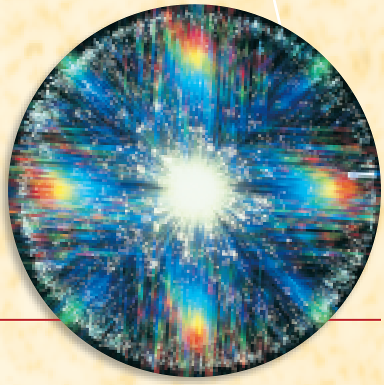
➥ *Look at the text on page 409 for the answer.*



CONTENTS

CHAPTER

17 Reflection and Refraction



It has just stopped raining. The air is still wet. The late afternoon sun comes out behind you. As you look to the horizon, you see an arc of many colors—a rainbow. Has anything, in the sky or on Earth, captured the human imagination more than a rainbow? Yet you can produce this ethereal phenomenon at home. All you need is simultaneous sun and rain. Even the spray from a hose or lawn sprinkler will do. Stand with the sun low and behind you and look into the water drops. Each drop of water separates sunlight into a spectrum: violet at the inside of the arc, then blue, green, yellow, and, at the outside, red. Even though each water drop separates the light into many colors, you see only one color from each drop.

Look carefully at the photo, and you will see more. The sky is brighter inside the rainbow than it is outside. There is also a secondary rainbow. This rainbow, fainter than the primary rainbow, presents the colors in reversed order.

The same principles that produce these rainbows are also responsible for some mysterious observations you might make. Perhaps you've observed mirages or heat images dance above sand or pavement, or the illusion of a drinking straw bending as it entered the water in a glass. Or perhaps you've observed multiple reflections in a mirror or windows, or the multiple lights and colors seen in the fiber-optic bundle pictured above. In this chapter, you will learn how to describe light waves as they bounce off surfaces. You will also learn how to describe the motion of light waves as they enter and leave transparent substances.

WHAT YOU'LL LEARN

- You will study how light is bent when it moves from one medium to another.
- You will understand why total internal reflection occurs.
- You will discover what effects are caused by changes in the index of refraction.

WHY IT'S IMPORTANT

- Your view of the world, from your reflection in a mirror to your use of a phone or computer, depends on the various ways light interacts with the matter around you.

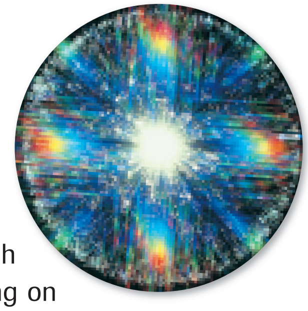
PHYSICS Online

To find out more about reflection and refraction, visit the Glencoe Science Web site at science.glencoe.com

CLICK HERE

CONTENTS

17.1 How Light Behaves at a Boundary



Light travels in straight lines and at very high velocities. Its velocity varies however, depending on the medium through which it moves. In this sense, light acts just like any other wave moving from one medium to another. What happens to light striking a surface between air and glass?

OBJECTIVES

- **Explain** the law of reflection.
- **Distinguish** between diffuse and regular reflection and **provide** examples.
- **Calculate** the index of refraction in a medium.

Pocket Lab

Reflections

Toss a tennis ball or a handball against a wall so that it will bounce to a lab partner, but first predict where the ball must hit on the wall to bounce in the right direction. If your partner moves closer (or farther) from the wall, does your rule still work?

Compare and Contrast Write a general rule that seems to work. Does your rule for the bouncing ball work for predicting the path of light? How is it similar?

The Law of Reflection

In **Figure 17–1** a mirror has been placed on the table in front of a protractor. A laser beam strikes the mirror and is reflected from it. What can you say about the angles the beams make with the mirror? If you look carefully, you can see that each makes an angle of 60° relative to a line perpendicular to the mirror. This line is called the normal to the surface, or normal. The angle that the incoming beam makes with the normal, the angle of incidence, is equal to the angle the outgoing beam makes, the angle of reflection.

When two parallel beams strike the mirror, as in **Figure 17–2a,** the two reflected beams also are parallel, which means that the angle of reflection was the same for the two beams, as shown in **Figure 17–2c.** A smooth surface such as the mirror causes **regular reflection,** in which light is reflected back to the observer in parallel beams.

What happens when light strikes another surface that seems to be smooth, such as the page of this book or a wall painted white? As in **Figure 17–2b,** there is no reflected beam. Rather, there is a fuzzy round dot because the light was reflected into a wide range of angles, as illustrated in **Figure 17–2d.** On the scale of the wavelength of light, even these seemingly smooth surfaces are rough, and therefore they result in **diffuse reflection.** Where there is regular reflection, as in a mirror, you can see your face. But no matter how much light is reflected off bright white paint, it will still result in diffuse reflection, and you will never be able to use the wall as a mirror.

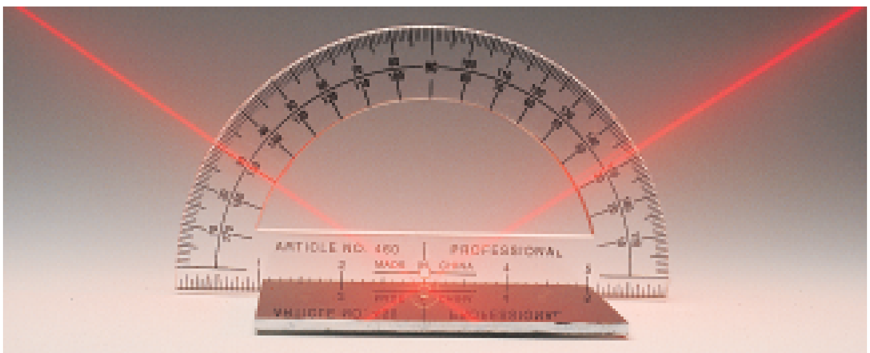


FIGURE 17–1 A light ray reflecting from a mirror shows that the angle of incidence equals the angle of reflection.

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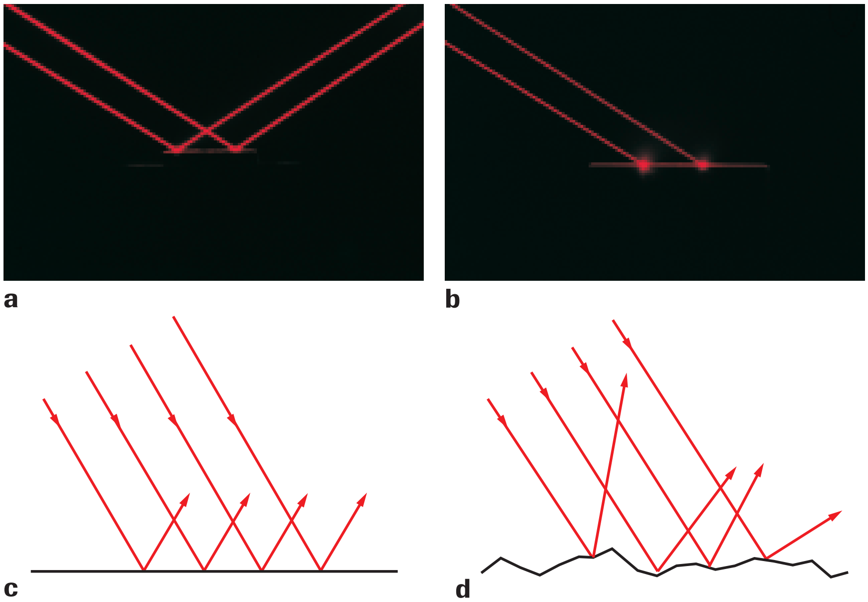


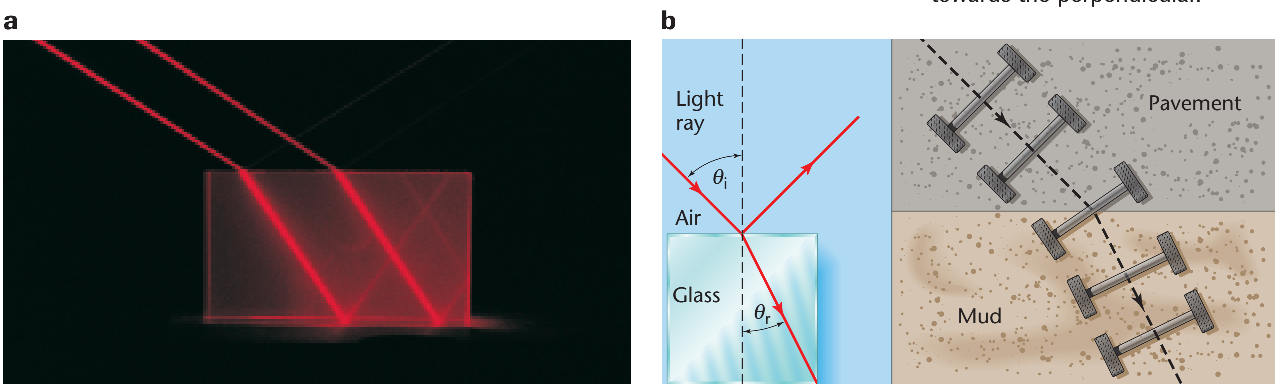
FIGURE 17–2 When parallel light rays strike a mirror surface, they reflect as parallel rays **(a) (c).** When parallel light rays strike a rough surface, they are randomly reflected **(b) (d).**

Refraction of Light

When light strikes the top of a block of plastic, as in **Figure 17–3a,** faint beams of light are reflected from the surface, but a bright beam goes into the block. It doesn't go in as a straight line, however; the beam is bent at the surface. Recall from Chapter 14 that this change in direction, or bending of a wave, at the boundary between two media is called refraction.

Note that when a light beam goes from air to glass at an angle, it is bent toward the normal, as shown in **Figure 17–3b.** The beam in the first medium is called the incident ray, and the beam in the second medium is called the refracted ray. In this case, the angle of incidence is larger than the **angle of refraction,** which is the angle that the refracted ray makes with the normal to the surface. If the angle of refraction is smaller than the angle of incidence, then the new medium is said to be more **optically dense.** Later in the chapter you'll learn that the speed of light is slower in more optically dense materials.

FIGURE 17–3 Light is refracted toward the normal as it enters denser medium. Compare the deflection of a set of wheels as it crosses a pavement-mud boundary. The first wheel that enters the mud is slowed, causing the wheels to change direction towards the perpendicular.



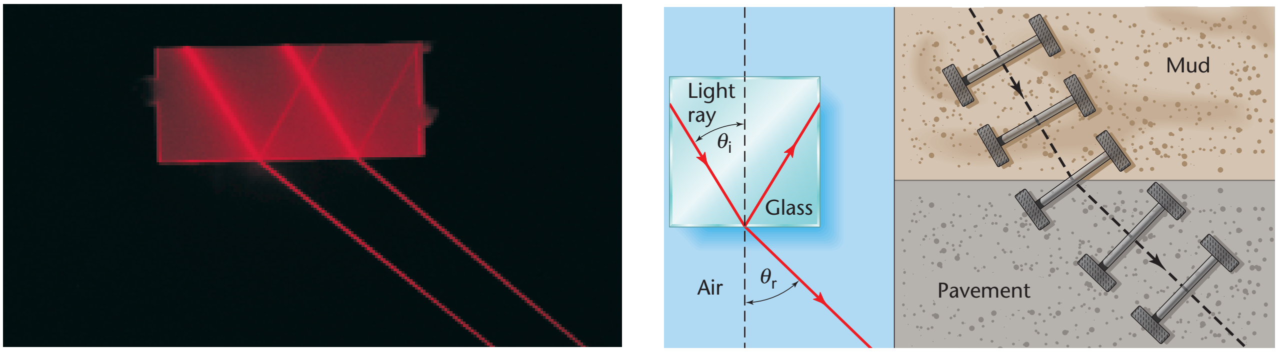


FIGURE 17–4 Light is refracted away from the normal as it enters a less-dense medium. Compare the deflection of a set of wheels as it crosses a mud-pavement boundary. The first wheel to leave the mud speeds up, and the direction of the wheels changes away from the perpendicular.

What happens when a light ray passes from glass to air? As you can see in **Figure 17–4,** the rays are refracted away from the normal. The angle of refraction is larger than the angle of incidence.

When light strikes a surface along the perpendicular, the angle of incidence is zero, and the angle of refraction will also be zero. The refracted ray leaves perpendicular to the surface and does not change direction.

Snell's Law

When light passes from one medium to another, it may be reflected and refracted. The degree to which it is bent depends on the angle of incidence, and the properties of the medium as shown in **Figure 17–5.** How does the angle of refraction depend on the angle of incidence? The answer to this question was found by Dutch scientist Willebrord Snell in 1621. **Snell's law** states that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant. For light going from the vacuum into another medium, the constant, n, is called the **index of refraction.** Snell's law, is written as

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

where θ_r is the angle of refraction, n the index of refraction, and θ_i is the angle of incidence. In the more general case, the relationship is written as

Snell's Law $\quad n_i \sin \theta_i = n_r \sin \theta_r.$

F.Y.I.

Another of Snell's accomplishments was the development of a method for determining distances by trigonometric triangulation. This led to modern mapmaking.

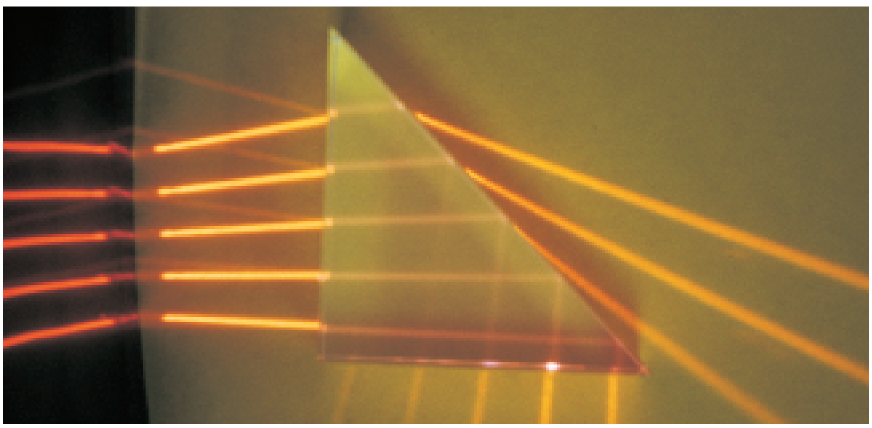


FIGURE 17–5 When light passes from one medium to another, the angle of refraction depends upon the angle of incidence. This is shown very clearly by the rays of light leaving the glass prism.

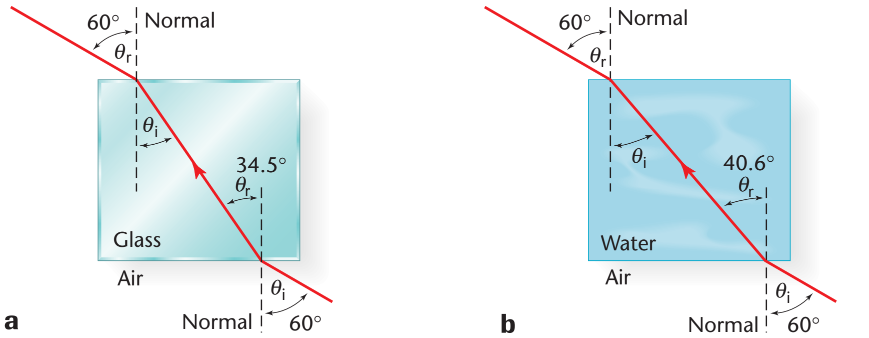


FIGURE 17–6 The index of refraction for glass is greater than that for water. As a result, the bending will be greater when light passes into or exits from the glass.

Here, n_i is the index of refraction of the medium in which the incident ray travels, the first medium, and n_r is the index of refraction of the medium in which the refracted ray moves, the second medium. **Figure 17–6** shows rays of light entering and leaving glass and water from air. Note how θ_i is always used for the angle the incident ray makes with the surface, regardless of the medium. From the angles of refraction, how would you expect the index of refraction of water to compare to that of glass?

The index of refraction of a substance often can be measured in the laboratory. To do this, direct a ray of light onto the substance's surface. Measure the angle of incidence and the angle of refraction. Then use Snell's law to find the index of refraction. **Table 17–1** presents indices of refraction for some common materials. Note that the index of refraction for air is only slightly larger than that of a vacuum. For all but the most precise measurements, you can set the index of refraction of air to 1.00.

TABLE 17–1
Indices of Refraction

Medium	n
vacuum	1.00
air	1.0003
water	1.33
ethanol	1.36
crown glass	1.52
quartz	1.54
flint glass	1.61
diamond	2.42

PROBLEM SOLVING STRATEGIES

Drawing Ray Diagrams

1. Draw a diagram showing the two media, as in **Figure 17–7.** Label the media, and indicate the two indices of refraction, n_i and n_r.
2. Draw the incident ray to the point where it hits the surface, then draw a normal to the surface at that point.
3. Use a protractor to measure the angle of incidence.
4. Use Snell's law to calculate the angle of refraction.
5. Use a protractor to draw the refracted ray leaving the surface at the point where the incident ray entered.
6. Evaluate your work. Make sure your answer agrees with the qualitative statement of Snell's law: light moving from a smaller n to a larger n is bent toward the normal; light moving from a larger n to a smaller n is bent away from the normal.

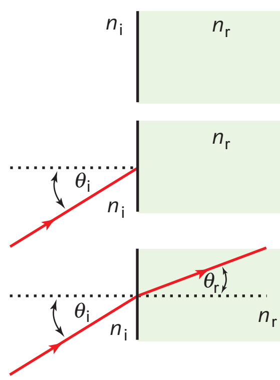


FIGURE 17–7 These are the steps to follow to draw a ray diagram.

When solving problems involving the reflection and refraction of light, you will use a ray diagram. This will help you set up the problem, assign symbols for the various quantities, and check your results. When drawing ray diagrams, use the Problem Solving Strategy outlined on page 397.

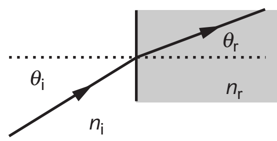
Example Problem

Snell's Law

A light beam in air hits a sheet of crown glass at an angle of 30.0°. At what angle is it refracted?

Sketch the Problem

- Draw a picture of the beam moving from the air to the crown glass.
- Draw a ray diagram.
- Check to make sure that the angle in the medium with the larger n is smaller.



Calculate Your Answer

Known:

$\theta_i = 30.0°$

$n_i = 1.00$

$n_r = 1.52$

Unknown:

Angle of refraction θ_r = ?

Strategy:

Use Snell's law written to be solved for the sine of the angle of refraction.

Calculations:

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

$$\sin \theta_r = \left(\frac{n_i}{n_r}\right) \sin \theta_i$$

$$= \left(\frac{1.00}{1.52}\right)(0.500)$$

$$= 0.329$$

Use your calculator or trigonometry tables to find the angle of refraction.

$$\theta_r = 19.2°$$

Check Your Answer

- Are the units correct? Angles are expressed in degrees.
- Is the magnitude realistic? The index of refraction, n_r, is greater than the index of refraction, n_i. Therefore, the angle of refraction, θ_r, must be less than the angle of incidence, θ_i.

Bending of Light

Problem

How is the index of refraction of light in water determined?

Materials

graph paper
felt-tip pen
ruler
semicircular plastic dish
water

Procedure

Part I

1. Draw a line dividing the graph paper in half.
2. Use the felt-tip pen to draw a vertical line at the center of the straight edge of the plastic dish. This line will be your object.
3. Place the edge of the dish along the straight line so that the dish is on the bottom half of the paper. Trace the outline of the dish on the paper.
4. Mark the position of the object on your paper.
5. Add water until the dish is 3/4 full.
6. Lay a ruler on the bottom half of the paper. Adjust the position until the edge of the ruler seems to point at the object when you look through the water.
7. Have a lab partner check to verify that the ruler position is accurate.
8. Draw a line along the ruler edge to the edge of the dish.
9. Repeat steps **6–8** for a different position of the ruler.

Part II

1. Wipe the vertical line from the dish and draw a vertical line at the center of the curved edge. This is your new object.
2. Repeat all steps from Part I, but this time sight the ruler on the top half of the paper.
3. Dispose of the water as instructed by your teacher. Dry and put away materials that can be reused.

Data and Observations

1. Look at the sight lines you drew in Part I. Did the light bend when moving from water to air?
2. For Part II, do the sight lines point directly toward the object?
3. For Part II, draw a line from the object position to the point where each sight line touches the dish.
4. Draw the normal at each point where the sight line touched the dish.
5. Measure the angles from the normal for the angles in air and water.

Analyze and Conclude

1. **Interpreting Data** Explain why the light did not bend in Part I. (**Hint:** Draw the normal to the surface.)
2. **Calculating Values** Calculate *n*, using Snell's law.

Apply

1. Could a flat piece of material be used for focusing light? Make a drawing to support your answer.

Pocket Lab

Refraction

Place a small hexagonal nut in the center of the bottom of a 1000-mL beaker. Pour water into the beaker until it is half full of water. Look through the sides of the beaker at the nut while placing a ruler along the tabletop so that the edge of the ruler appears to point to the center of the nut. Do you think that the ruler really points to the nut? Look from the top to see where the ruler points. Place a golf ball on the nut. Look through the sides of the beaker at the ball and adjust the edge of the ruler to point to the edge of the ball. Look from the top.

Analyze and Conclude Describe your observations. Make a drawing to show why the ball appears to be so wide.

Practice Problems

1. Light in air is incident upon a piece of crown glass at an angle of 45.0°. What is the angle of refraction?
2. A ray of light passes from air into water at an angle of 30.0°. Find the angle of refraction.
3. A ray of light is incident upon a diamond at 45.0°.
   a. What is the angle of refraction?
   b. Compare your answer for 3a to your answer for problem 1. Does glass or diamond bend light more?
4. A block of unknown material is submerged in water. Light in the water is incident on the block at an angle of 31°. The angle of refraction in the block is 27°. What is the index of refraction of the unknown material?

Index of Refraction and the Speed of Light

The index of refraction is a measure of how much light bends when it passes into a medium from a vacuum. But the index is also a measure of how fast light travels in the medium. To learn how these two are connected, you must explore the connections between the ray model and the wave model of light.

A ray, as you know, is the path of an extremely narrow beam of light. If you have a broader beam of light that is always the same width, then you can visualize this beam as a series of parallel, straight wave fronts. Each wave front represents the crest of the electromagnetic wave and is perpendicular to the direction of the ray. Therefore, the spacing between wavefronts is one wavelength. Recall from Chapter 14, that when a wave moves from one medium to another in which the wave speed is different, the frequency of the wave is unchanged, but the wavelength changes according to the equation $v = \lambda f$. Thus, in a vacuum, $v_{vacuum} = c$, and $\lambda_{vacuum} = c/f$. But if light travels at speed $v_{material}$ in a medium, then $\lambda_{material} = v_{material}/f$.

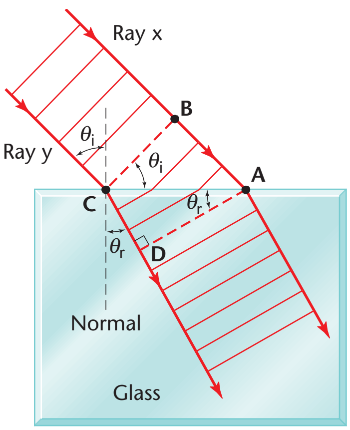


FIGURE 17–8 In this diagram, the refraction of two parallel light rays incident on a piece of glass is shown.

Figure 17–8 shows a beam of light, originally in a vacuum, that strikes a glass plate at an angle of incidence θ_i. The line BC represents the last wavefront totally in the vacuum, and the line AD represents the first wavefront entirely in the glass. In this example, these lines are three wavelengths apart. But the wavelength in glass is smaller than that in the vacuum, so the distance CD is shorter than the distance BA, and the wavefronts that are partially in the vacuum and partially in the glass are bent at the boundary. You can see that the direction of the ray is bent toward the normal when light moves from a vacuum into matter. But by how much is it bent?

First find the relative lengths of CD and BA, which are separated by three wavelengths. They are related in the following way.

$$\frac{BA}{CD} = \frac{3\lambda_{vacuum}}{3\lambda_{glass}} = \frac{3c/f}{3v_{glass}/f} = \frac{c}{v_{glass}}$$

Thus, these two lengths are related by the speed of light in the vacuum and in the glass.

Next find the relationship between the sines of the angles of incidence and refraction. Consider the two triangles, ABC and ADC. The sine of an angle is the length of the opposite side divided by the length of the hypotenuse. Thus, $\sin\theta_i = BA/CA$ and $\sin\theta_r = CD/CA$. Therefore, using Snell's law, the following is true.

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{BA/CA}{CD/CA} = \frac{BA}{CD}$$

You already know that $BA/CD = c/v_{glass}$, and, according to Snell's law, because the index of refraction of the vacuum is 1.00, the following is true.

$$\frac{\sin\theta_i}{\sin\theta_r} = n \text{ and } \frac{\sin\theta_i}{\sin\theta_r} = \frac{c}{v_{glass}}$$

$$\text{so, } n = \frac{c}{v_{glass}}, \text{ or in general,}$$

Index of Refraction $n_{substance} = \dfrac{c}{v_{substance}}$

Therefore, it is possible to calculate the speed of light in many substances.

Example Problem

Speed of Light in Matter

Find the speed of light in water.

Calculate Your Answer

Known:

$n_{water} = 1.33$

$c = 3.00 \times 10^8$ m/s

Unknown:

Speed of light in water, $v_{water} = ?$

Strategy:

Use the relationship that the index of refraction of water equals the ratio of the speed of light in vacuum to the speed of light in water.

Calculations:

$n_{water} = c/v_{water}$

$v_{water} = c/n_{water}$

$= \dfrac{(3.00 \times 10^8 \text{ m/s})}{1.33}$

$= 2.26 \times 10^8$ m/s

Check Your Answer

- Is the magnitude realistic? Light slows as it passes through water. Therefore, the speed must be less than 3.00×10^8 m/s.

HELP WANTED

OPTOMETRIST

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St. Louis, MO 63141

Practice Problems

5. Use **Table 17–1** to find the speed of light in the following.
   a. ethanol **b.** quartz **c.** flint glass
6. The speed of light in one type of plastic is 2.00×10^8 m/s. What is the index of refraction of the plastic?
7. What is the speed of light for the unknown material in problem 4?
8. Suppose two pulses of light were "racing" each other, one in air, the other in a vacuum. You could tell the winner if the time difference were 10 ns (10×10^{-9} s). How long would the race have to be to determine the winner?

The speed of light for some materials is listed in **Table 17–2.**

TABLE 17–2

Speed of Light in Various Materials

Material	v m/s
Vacuum	3.00×10^8
Air	3.00×10^8
Ice	2.29×10^8
Glycerine	2.04×10^8
Crown glass	1.97×10^8
Rock salt	1.95×10^8

17.1 Section Review

1. Give examples of diffuse and regular reflectors.
2. If you double the angle of incidence, the angle of reflection also doubles. Does the angle of refraction double as well?
3. You notice that when a light ray enters a certain liquid from water, it is bent toward the normal, but when it enters the same liquid from crown glass, it is bent away from the normal. What can you conclude about its index of refraction?
4. **Critical Thinking** Could an index of refraction ever be less than 1? What would that imply about the velocity of light in that medium?

Applications of Reflected and Refracted Light

17.2

Modern societies depend on communication systems. The telephone has become necessary for both homes and businesses. In many cities, however, the underground pipes containing telephone wires are so full that no new customers can be added. Now the old wires can be replaced by a bundle of optical fibers that can carry thousands of telephone conversations at once. Moreover, illegal tapping of optical fibers is almost impossible. This application of the reflection of light is revolutionizing our communication systems.

OBJECTIVES

- **Explain** total internal reflection.
- **Define** the critical angle.
- **Explain** effects caused by the refraction of light in a medium with varying refractive indices.
- **Explain** dispersion of light in terms of the index of refraction.

Total Internal Reflection

What happens when a ray of light passes from a more optically dense medium into air? You have learned that the light is bent away from the normal. In other words, the angle of refraction is larger than the angle of incidence. The fact that the angle of refraction is larger than the angle of incidence leads to an interesting phenomenon known as **total internal reflection,** which occurs when light passes from a more optically dense medium to a less optically dense medium at an angle so great that there is no refracted ray. **Figure 17–9** shows how this happens. Ray 1 is incident upon the surface of the water at angle θ_i. Ray 1 leaves by the angle of refraction, θ_r. Ray 2 is incident at such a large angle, θ_i, that the refracted ray lies along the surface of the water. The angle of refraction is 90°. What is θ_i?

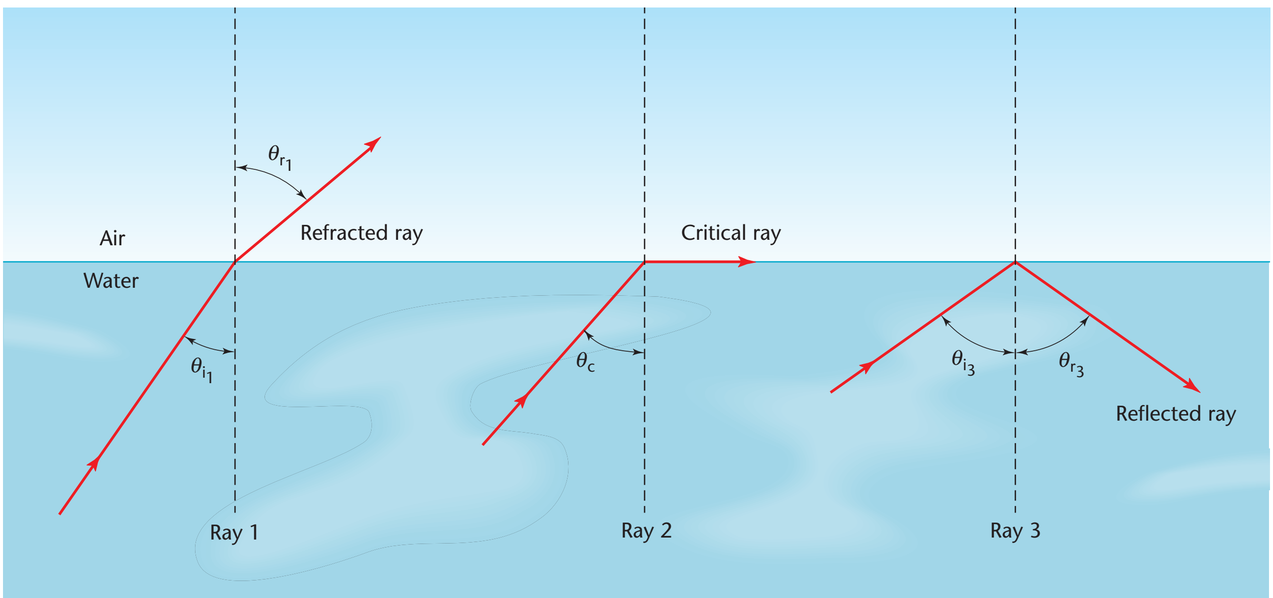


FIGURE 17–9 Ray 1 is refracted. Ray 2 is refracted along the boundary of the medium and forms the critical angle. An angle of incidence greater than the critical angle results in the total internal reflection of ray 3.

For light traveling from one medium into another, Snell's law is $n_{\mathrm{i}} \sin \theta_{\mathrm{i}} = n_{\mathrm{r}} \sin \theta_{\mathrm{r}}$. For this example, $n_{\mathrm{water}} \sin \theta_{\mathrm{i}} = n_{\mathrm{air}} \sin \theta_{\mathrm{r}}$ or $(1.33)(\sin \theta_{\mathrm{i}}) = (1.00)(\sin 90°)$.

Solving the equation for $\sin \theta_{\mathrm{i}}$,

$$\sin \theta_{\mathrm{i}} = \frac{(1.00)(\sin 90°)}{1.33}$$

$$= 0.752$$

so $\theta_{\mathrm{i}} = 48.8°$. When an incident ray of light passing from water to air makes an angle of 48.8°, the angle of refraction is 90°.

The incident angle that causes the refracted ray to lie right along the boundary of the substance, angle θ_{c}, is unique to the substance. It is known as the **critical angle** of the substance. The critical angle, θ_{c}, of any substance may be calculated as follows.

$$n_{\mathrm{i}} \sin \theta_{\mathrm{i}} = n_{\mathrm{r}} \sin \theta_{\mathrm{r}}$$

In this situation, $\theta_{\mathrm{i}} = \theta_{\mathrm{c}}$, $n_{\mathrm{r}} = 1.00$, and $\theta_{\mathrm{r}} = 90.0°$. Therefore, the following is true.

$$\sin \theta_{\mathrm{c}} = \frac{(1.00)(\sin 90.0°)}{n_{\mathrm{i}}}$$

$$= \frac{1.00}{n_{\mathrm{i}}}$$

For crown glass, the critical angle can be calculated as follows.

$$\sin \theta_{\mathrm{c}} = \frac{1.00}{1.52}$$

$$= 0.658$$

$$\text{and } \theta_{\mathrm{c}} = 41.1°$$

Any ray that reaches the surface of water at an angle greater than the critical angle cannot leave the water, as shown in **Figure 17–9.** All of the light from ray 3 is reflected. Total internal reflection has occurred.

Total internal reflection causes some curious effects. Suppose you look at the surface of a tank of water from under the water. A submerged object near the surface may appear to be inverted. Likewise, if a swimmer is near the surface of a quiet pool, the swimmer may not be visible to an observer standing near the side of the pool. These effects of total internal reflection gave rise to the field of fiber optics.

Effects of Refraction

Many interesting effects are caused by the refraction of light. Mirages, the apparent shift in the position of objects immersed in liquids, and the daylight that lingers after the sun is below the horizon are all caused by the refraction of light.

F.Y.I.

Most binoculars contain two prisms mounted at right angles to each other so that the light can be redirected from the object to the eye-piece by total internal reflection.

Pocket Lab

Cool Images

Caution: *Avoid staring directly into the laser beam or at bright reflections.*

Can you light an electric bulb without any electrical connection and can you make the image of the bulb in a mirror glow? Try this activity to find out. Place a 100-watt bulb in an electric socket but do not turn on the electricity. Place this next to a mirror. Sit so that you can see both the bulb and its reflection. Aim a penlight laser at the bulb.

Observe and Infer Did you notice that the bulb glowed red and that the image also glowed? What would happen if you aimed the laser at the image? Try it. Use a ray diagram to explain your results.

How It Works

Optical Fibers

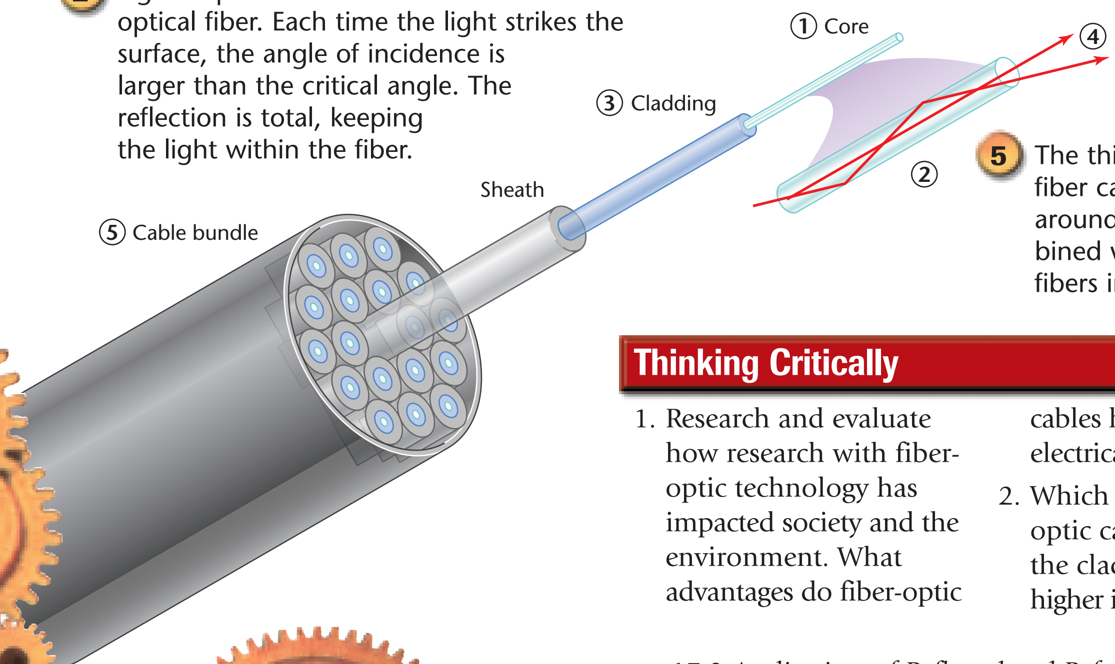
Fiber-optic technology has been applied to many fields. Physicians are able to use optical fibers to treat illnesses and as surgical tools to perform delicate operations. In the field of telecommunications, optical fibers can transmit audio and video information, as well as other data, as coded light signals. An information flow equivalent to 25 000 telephone conversations can be carried by a fiber the thickness of a human hair. Facsimile systems, oscilloscopes, photographic typesetting machines, and computer graphics systems also use optical fibers. For this reason, optical fibers are being used to transmit telephone, computer, and video signals within buildings; from city to city; and even across oceans. Even plants have been shown to use total internal reflection to transport light to cells that utilize light energy.

1. The core of an optical fiber is made of either glass or plastic. Because it transmits light over a variety of distances, this core must be highly transparent.

2. Light impulses from a source enter one end of the optical fiber. Each time the light strikes the surface, the angle of incidence is larger than the critical angle. The reflection is total, keeping the light within the fiber.

3. The outer covering of an optic fiber is called cladding. Cladding prevents light from scattering once it is in the core.

4. Light exits the cable at the opposite end, where a device, which could be the human eye, receives the light.



5. The thin, flexible optical fiber can be easily bent around corners or combined with many other fibers into a cable.

Thinking Critically

1. Research and evaluate how research with fiber-optic technology has impacted society and the environment. What advantages do fiber-optic cables have over their electrical counterparts?
2. Which part of a fiber-optic cable—the core or the cladding—has a higher index of refraction?

FIGURE 17–10 Mirages are caused by the refracting properties of a nonuniform atmosphere.

F.Y.I.

The blue color of the sky during the daylight hours results from the intense scattering of blue light from the sun. In the early morning and late evening, this blue light must travel through more air and the amount of blue you see is reduced by this scattering. This allows you to see the beautiful yellows, oranges, and reds of the sunrises and sunsets.

Have you ever seen the mirage effect shown in **Figure 17–10?** A driver looking almost parallel to the road sees what looks like a puddle of water. The puddle, however, disappears as the car approaches. The mirage is the result of the sun heating the road. The hot road, in turn, heats the air above it, while the air farther above the road remains cool. The index of refraction of air at 30°C, for example, is 1.00026, while that of air at 15°C is 1.00028. Thus, there is a continuous change in the index of refraction of the air. A ray of light aimed toward the road encounters the smaller index of refraction and is bent away from the normal, that is, it is bent to be more parallel to the road, as shown in **Figure 17–11.** The motorist actually sees light from the sky, which looks like light reflected from a puddle.

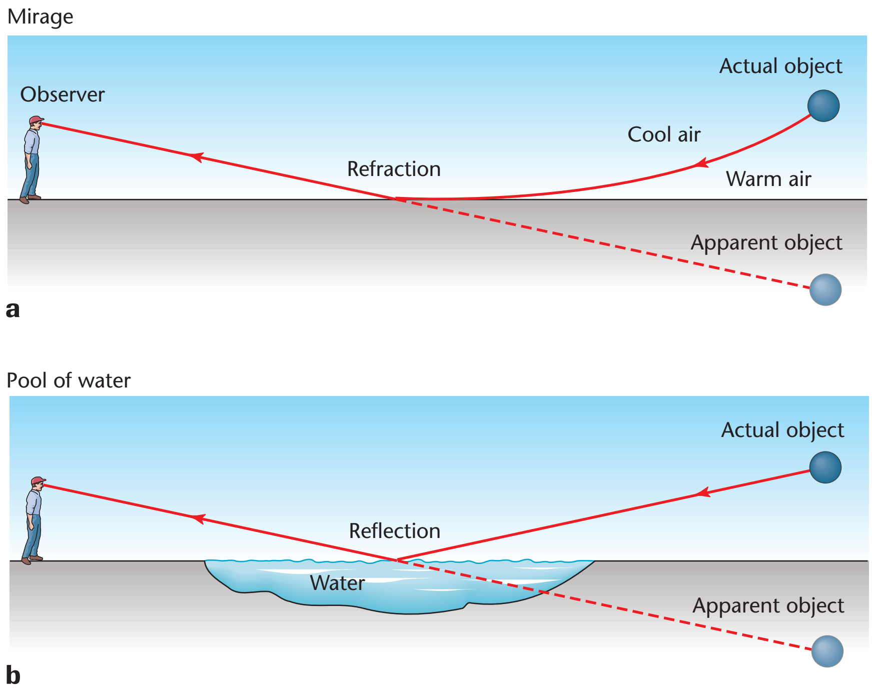


FIGURE 17–11 Refraction of light in air of different densities **(a)** produces an effect similar to the reflection of light off a pool of water **(b).**

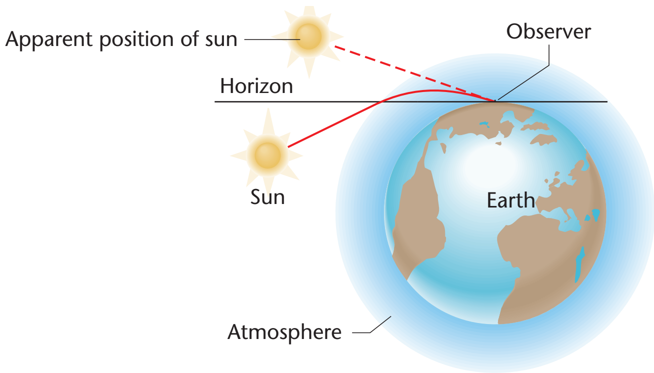


FIGURE 17–12 After the sun has actually set, it is still visible because of refraction of light over the horizon through the atmosphere.

An object submerged in a liquid is not where it appears to be. As a result of refraction, an object may appear to be much closer to the surface of the liquid than it actually is. Refraction also makes a spoon placed in a glass of water appear to be bent.

Light travels at a slightly slower speed in Earth's atmosphere than it does in outer space. As a result, sunlight is refracted by the atmosphere. In the morning, this refraction causes sunlight to reach us before the sun is actually above the horizon, as shown in **Figure 17–12.** In the evening, the sunlight is bent above the horizon after the sun has actually set. Thus, daylight is extended in the morning and evening because of the refraction of light.

Dispersion of Light

How can a prism produce such beautiful colors? Did they come from the glass? Were they in the light itself? Although the formation of colors by light passing through glass, water, and other clear materials had been observed long before his time, Sir Isaac Newton was the first to discover how the colors were formed. He found that sunlight was separated into the spectrum of colors when it passed through a prism, as in **Figure 17–13.** To show that the colors weren't in the prism itself, Newton used the

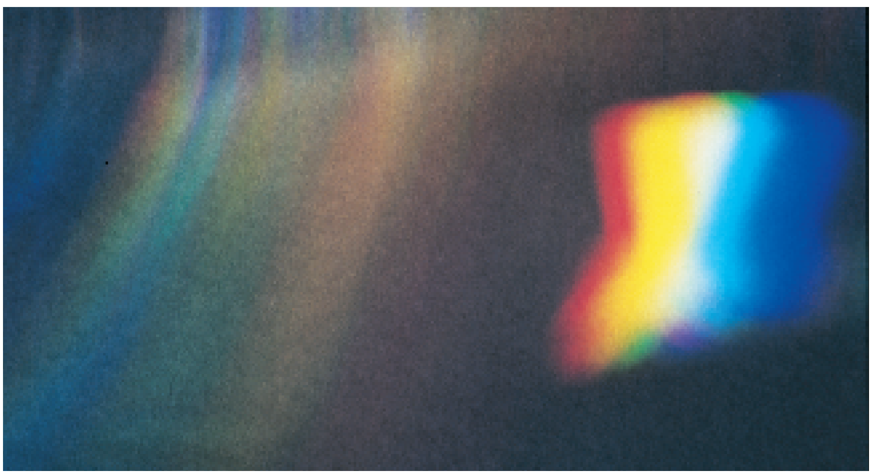
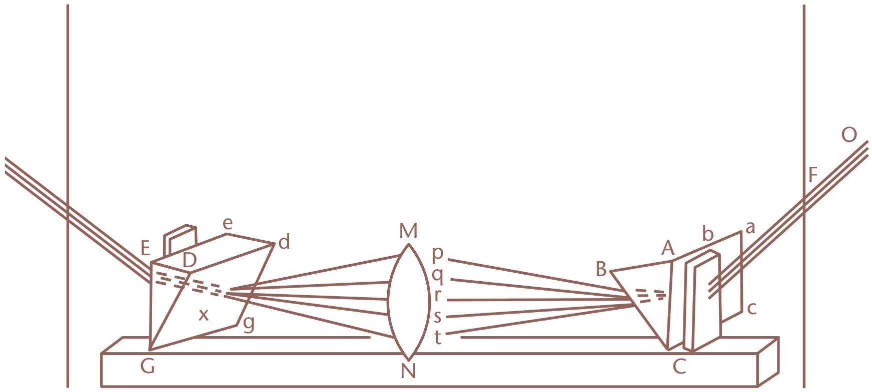


FIGURE 17–13 White light directed through a prism is dispersed into bands of different colors.

FIGURE 17–14 This old sketch illustrates Sir Isaac Newton's demonstration with prisms. Prism ABC separates white light into colors. Prism EDG combines the colors back into white light.



apparatus shown in **Figure 17–14.** When spectrum, p,q,r,s,t, produced by prism ABC, was directed through a lens onto a second prism, DEG, white light came out of the second prism. Thus, Newton showed that white light could be separated into all the colors of the rainbow, and that those colors could be added together again to produce white light.

The separation of light into its spectrum is called **dispersion.** Red light is bent the least as it goes through a prism, while violet is bent the most. This means that the index of refraction depends on the color, or the wavelength, of light. The index of refraction is smaller for red than it is for violet. Because the index of refraction and light speed are related, it further means that the speed of light in matter depends on the wavelength of the light.

Glass is not the only substance that disperses light. A diamond not only has one of the highest refractive indices of any material, but it also has one of the largest variations in the index. Thus, it disperses light more than most other materials. The intense colors visible when light is dispersed in a diamond are the reason why these gems are said to have "fire."

Different light sources have different spectra. A prism can be used to determine the spectrum of a source. Light from an incandescent lamp, for example, contains all visible wavelengths of light. When this light passes through a prism, a continuous band of color is seen. A fluorescent lamp produces both a continuous spectrum and light emitted at four individual wavelengths. Thus, its spectrum contains both a continuous band and bright lines at specific colors.

A prism is not the only means of dispersing light. A rainbow is a spectrum formed when sunlight is dispersed by water droplets in the atmosphere. Sunlight that falls on a water droplet is refracted. Because of dispersion, each color is refracted at a slightly different angle, as shown in **Figure 17–15a**. At the back surface of the droplet, the light undergoes total internal reflection. On the way out of the droplet, the light is once more refracted and dispersed. Although each droplet produces a complete spectrum, an observer will see only a certain wavelength of light

Pocket Lab

Personal Rainbow

You can make your own personal rainbow when the sun is out and low in the sky for easier viewing. Adjust a garden hose to produce a gentle spray. Face away from the sun so that you can see your shadow. Spray the water upwards above your shadow and watch closely until you see the colors. By moving the spray in an arc from side to side, you will produce your own personal rainbow.

Analyze and Conclude Did you notice the order of the colors in the spectrum of visible lights? Could you easily see each of the colors ROYGBIV? Which color was on the inside edge? Which color was on the outside edge?

from each droplet. The wavelength depends on the relative positions of sun, droplet, and observer. Because there are millions of droplets in the sky, a complete spectrum is visible. The droplets reflecting red light make an angle of 42° in relation to the direction of the sun's rays; the droplets reflecting blue light make an angle of 40°, as shown in **Figure 17–15b.**

Sometimes you can see a faint second-order rainbow. Light rays that are reflected twice inside the drop produce this sight. A third bow is possible but normally is too weak to observe.

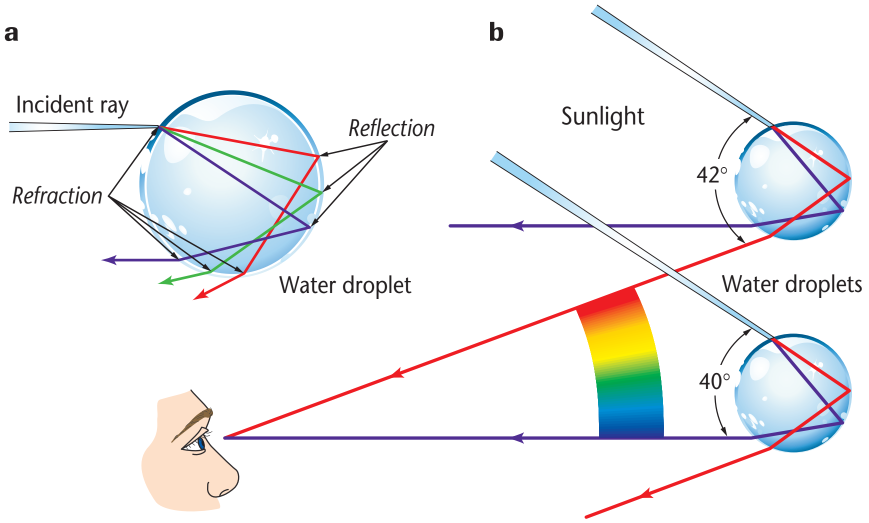


FIGURE 17–15 Refraction occurs when rays pass into and out of a raindrop. Reflection occurs at the inside surface **(a).** The observer sees only certain wavelengths from each drop **(b).** (Ray angles have been exaggerated for clarity.)

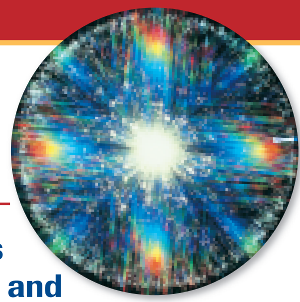
A Smile in the Sky

Answers question from page 392.

17.2 Section Review

1. If you were to use quartz and crown glass to make an optical fiber, which would you use for the coating layer? Why?
2. Is there a critical angle for light going from glass to water? From water to glass?
3. Interpret the role of light's ability to refract in industry and medicine.
4. Why can you see the image of the sun just above the horizon when the sun, itself, has already set?
5. **Critical Thinking** In what direction can you see a rainbow on a rainy late afternoon?

CHAPTER 17 REVIEW



Key Terms

17.1
- regular reflection
- diffuse reflection
- angle of refraction
- optically dense
- Snell's law
- index of refraction

17.2
- total internal reflection
- critical angle
- dispersion

Summary

17.1 How Light Behaves at a Boundary

- The law of reflection states that the angle of reflection is equal to the angle of incidence.
- Refraction is the bending of light rays at the boundary between two media. Refraction occurs only when the incident ray strikes the boundary at an angle.
- When light goes from a medium with a small n to one with a large n, it is bent toward the normal. Light going from materials with a large n to those with a small n is bent away from the normal.
- Snell's law states $n_i \sin \theta_i = n_r \sin \theta_r$.

17.2 Applications of Reflected and Refracted Light

- Total internal reflection occurs when light is incident on a boundary from the medium with the larger index of refraction. If the angle of incidence is greater than the critical angle, no light leaves; it is all reflected.
- Light waves of different wavelengths have slightly different refractive indices. Thus, they are refracted at different angles. Light falling on a prism is dispersed into a spectrum of colors.

Key Equations

17.1

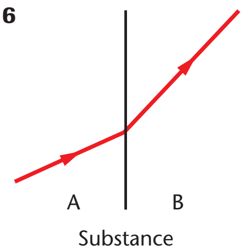
$$n_i \sin \theta_i = n_r \sin \theta_r \qquad n_{substance} = \frac{c}{v_{substance}}$$

Reviewing Concepts

Section 17.1

1. What behaviors does light exhibit?
2. How does regular reflection differ from diffuse reflection?
3. Does the law of reflection hold for diffuse reflection? Explain.
4. What is meant by the phrase "normal to the surface"? Copy **Figure 17–16** onto your paper. Draw a normal and label the angle of incidence and the angle of refraction for light moving from substance A to substance B.

FIGURE 17–16



5. How does the angle of incidence compare with the angle of refraction when a light ray passes from air into glass at a non-zero angle?
6. How does the angle of incidence compare with the angle of refraction when a light ray leaves glass and enters air at a non-zero angle?
7. Describe what happens to a light wave when it meets and travels through a different medium.
8. State Snell's law in your own words.
9. Derive $n = \sin \theta_i / \sin \theta_r$ from the general form of Snell's law, $n_A \sin \theta_A = n_B \sin \theta_B$. State any assumptions and restrictions.

CONTENTS

Section 17.2

10. What is the critical angle of incidence?

11. What happens to a ray of light with an angle of incidence greater than the critical angle?

12. Explain mirages.

13. Although the light coming from the sun is refracted while passing through Earth's atmosphere, the light is not separated into its spectrum. What does this tell us about the speeds of different colors of light traveling through air?

14. What evidence is there that diamonds have a slightly different index of refraction for each color of light?

Applying Concepts

15. A dry road is a diffuse reflector, while a wet road is not. Sketch a car with its headlights illuminating the road ahead. Show why the wet road would appear darker to the driver than the dry road would.

16. Why is it desirable that the pages of a book be rough rather than smooth and glossy?

17. Is it necessary to measure the volume of a glass block to find its optical density? Explain.

18. A light ray strikes the boundary between two transparent media. What is the angle of incidence for which there is no refraction?

19. In the example problem Snell's law, a ray of light is incident upon crown glass at 30.0°. The angle of refraction is 19.2°. Assume that the glass is rectangular in shape. Construct a diagram to show the incident ray, the refracted ray, and the normal. Continue the ray through the glass until it reaches the opposite edge.

- **a.** Construct a normal at this point. What is the angle at which the refracted ray is incident upon the opposite edge of the glass?
- **b.** Assume that the material outside the opposite edge is air. What is the angle at which the ray leaves the glass?
- **c.** As the ray leaves the glass, is it refracted away from or toward the normal?
- **d.** How is the orientation of the ray leaving the glass related to the ray entering the glass?

20. Assume that the angle of incidence in problem 19 remains the same. What happens to the angle of refraction as the index of refraction increases?

21. Which substance, A or B, in **Figure 17–16** has a larger index of refraction? Explain.

22. How does the speed of light change as the index of refraction increases?

23. How does the size of the critical angle change as the index of refraction increases?

24. Which two pairs of media, air and water or air and glass, have the smaller critical angle?

25. Examine **Figure 17–5.** Why do the two left-hand bottom rays that enter the prism exit vertically, while the two top rays exit horizontally? (**Hint:** If you look carefully, you will find that the middle ray has both vertical and horizontal intensity and that there is a trace of the other ray moving vertically.)

26. If you crack the windshield in your car, you will see a silvery line along the crack. The two pieces of glass have separated at the crack, and there is air between them. The silvery line indicates that light is reflecting off the crack. Draw a ray diagram to explain why this occurs. What phenomenon does this illustrate?

27. According to legend, Erik the Red sailed from Iceland and discovered Greenland after he had seen the land in a mirage. Describe how the mirage might have occurred.

28. A prism bends violet light more than it bends red light. Explain.

29. Which color of light travels fastest in glass: red, green, or blue?

30. Why would you never see a rainbow in the southern sky if you were in the northern hemisphere?

Problems

Section 17.1

31. A ray of light strikes a mirror at an angle of 53° to the normal.

- **a.** What is the angle of reflection?
- **b.** What is the angle between the incident ray and the reflected ray?

32. A ray of light incident upon a mirror makes an angle of 36.0° with the mirror. What is the angle between the incident ray and the reflected ray?

33. A ray of light has an angle of incidence of 30.0° on a block of quartz and an angle of refraction of 20.0°. What is the index of refraction for this block of quartz?

34. A ray of light travels from air into a liquid. The ray is incident upon the liquid at an angle of 30.0°. The angle of refraction is 22.0°.
a. What is the index of refraction of the liquid?
b. Refer to **Table 17–1.** What might the liquid be?

35. A ray of light is incident at an angle of 60.0° upon the surface of a piece of crown glass. What is the angle of refraction?

36. A light ray strikes the surface of a pond at an angle of incidence of 36.0°. At what angle is the ray refracted?

37. Light is incident at an angle of 60.0° on the surface of a diamond. Find the angle of refraction.

38. A ray of light has an angle of incidence of 33.0° on the surface of crown glass. What is the angle of refraction into the air?

39. A ray of light passes from water into crown glass at an angle of 23.2°. Find the angle of refraction.

40. Light goes from flint glass into ethanol. The angle of refraction in the ethanol is 25.0°. What is the angle of incidence in the glass?

41. A beam of light strikes the flat, glass side of a water-filled aquarium at an angle of 40.0° to the normal. For glass, $n = 1.50$. At what angle does the beam
a. enter the glass?
b. enter the water?

42. What is the speed of light in diamond?

43. The speed of light in chloroform is 1.99×10^8 m/s. What is its index of refraction?

44. A thick sheet of plastic, $n = 1.500$, is used as the side of an aquarium tank. Light reflected from a fish in the water has an angle of incidence of 35.0°. At what angle does the light enter the air?

45. A light source, S, is located 2.0 m below the surface of a swimming pool and 1.5 m from one edge of the pool. The pool is filled to the top with water.
a. At what angle does the light reaching the edge of the pool leave the water?
b. Does this cause the light viewed from this angle to appear deeper or shallower than it actually is?

46. A ray of light is incident upon a 60°–60°–60° glass prism, $n = 1.5$, **Figure 17–17.**
a. Using Snell's law determine the angle θ_r to the nearest degree.
b. Using elementary geometry, determine the values of angles A, B, and C.
c. Determine the angle, θ_{exit}.

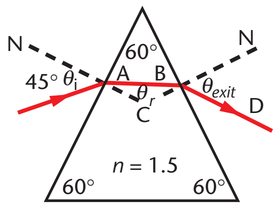


FIGURE 17–17

47. A sheet of plastic, $n = 1.5$, 25 mm thick is used in a bank teller's window. A ray of light strikes the sheet at an angle of 45°. The ray leaves the sheet at 45° but at a different location. Use a ray diagram to find the distance between the ray that leaves and the one that would have left if the plastic were not there.

48. The speed of light in a clear plastic is 1.90×10^8 m/s. A ray of light strikes the plastic at an angle of 22.0°. At what angle is the ray refracted?

49. How many more minutes would it take light from the sun to reach Earth if the space between them were filled with water rather than a vacuum? The sun is 1.5×10^8 km from Earth.

Section 17.2

50. Find the critical angle for diamond.

51. A block of glass has a critical angle of 45.0°. What is its index of refraction?

52. A ray of light in a tank of water has an angle of incidence of 55.0°. What is the angle of refraction in air?

53. The critical angle for a special glass in air is 41.0°. What is the critical angle if the glass is immersed in water?

54. A diamond's index of refraction for red light, 656 nm, is 2.410, while that for blue light, 434 nm, is 2.450. Suppose white light is incident on the diamond at 30.0°. Find the angles of refraction for these two colors.

55. The index of refraction of crown glass is 1.53 for violet light, and it is 1.51 for red light.

a. What is the speed of violet light in crown glass?

b. What is the speed of red light in crown glass?

56. Just before sunset, you see a rainbow in the water being sprayed from a lawn sprinkler. Carefully draw your location and the locations of the sun and the water coming from the sprinkler.

57. A light ray enters a rectangle of crown glass, as illustrated in **Figure 17–18.** Use a ray diagram to trace the path of the ray until it leaves the glass.

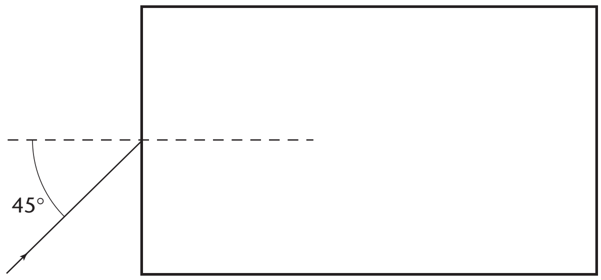


FIGURE 17–18

58. Crown glass's index of refraction for red light is 1.514, while that for blue light is 1.528. White light is incident on the glass at 30.0°.

a. Find the angles of refraction for these two colors.

b. Compare the difference between the angles of reflection and refraction for the crown glass and diamond. Angles for diamond were calculated in problem 54.

c. Use the results to explain why diamonds are said to have "fire."

Extra Practice For more practice solving problems, go to Extra Practice Problems, Appendix B.

Critical Thinking Problems

59. How much dispersion is there when light goes through a slab of glass? For dense flint glass, $n = 1.7708$ for blue light ($\lambda = 435.8$ nm) and $n = 1.7273$ for red light ($\lambda = 643.8$ nm). White light in air ($n = 1.0003$) is incident at exactly 45°. Find the angles of refraction for the two colors, then find the difference in those angles in degrees. You should use five significant digits in all calculations.

60. Suppose the glass slab in problem 59 were rectangular. At what angles would the two colors leave the glass?

61. Find the critical angle for ice ($n = 1.31$). In a very cold world, would fiber-optic cables made of ice be better or worse than those made of glass? Explain.

Going Further

Using a Computer or Programmable Calculator Explore why the region inside the rainbow is brighter than the outside. First, **Figure 17–15** shows the path of a light ray that strikes a water drop of radius *r* and distance *d* from the center. Confirm that the angle through which the ray is bent is given by

$$\phi = 180° - 4\,\theta_r + 2\,\theta_i$$

where θ_i is the angle of incidence of the ray on the drop and θ_r is the angle of refraction. Next, demonstrate that $\sin\theta_i = d/r$, and that Snell's law then gives $\sin\theta_r = d/nr$. The index of refraction for water is 1.331 for red light and 1.337 for blue. Use your computer or calculator to find the angles θ_i, θ_r, and ϕ for at least ten values of d/r from 0 to 1. Plot ϕ versus d/r. You should find that the minimum angle through which the ray is bent is about 138°. Write a paragraph that shows how your results explain the brightness inside the rainbow.

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