29 REFLECTION AND REFRACTION

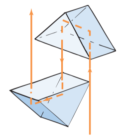
Objectives

- Describe what happens when a wave reaches a boundary between two media. (29.1)
- Describe the law of refraction. (29.2)
- Describe the type of images that are produced by plane mirrors. (29.3)
- Describe what happens when light is incident on a rough surface. (29.4)
- Describe what happens to sound energy that is not reflected. (29.5)
- Describe what happens when a wave that is traveling at an angle changes its speed upon crossing a boundary between two media. (29.6)
- Describe what causes sound waves to refract. (29.7)
- Describe what causes the refraction of light. (29.8)
- Describe what causes the appearance of a mirage. (29.9)
- Describe what causes the dispersion of light. (29.10)
- Describe the conditions necessary for seeing a rainbow. (29.11)
- Describe what causes total internal reflection to occur. (29.12)

As a brief treatment of light, this chapter can stand on its own. In this case, emphasize the behavior rather than the nature of light.

PAUL

29 REFLECTION AND REFRACTION



THE BIG IDEA When waves interact with matter, they can be reflected, transmitted, or a combination of both. Waves that are transmitted can be refracted.

When you shine a beam of light on a mirror, the light doesn't travel through the mirror, but is returned by the mirror's surface back into the air. When sound waves strike a canyon wall, they bounce back to you as an echo. When a wave transmitted along a spring reaches a wall, it reverses direction. In all these situations, waves remain in one medium rather than enter a new medium. These waves are *reflected*.

In other situations, such as when light passes from air into a transparent medium like water, waves travel from one medium into another. When waves strike the surface of a medium at an angle, their direction changes as they enter the second medium. These waves are *refracted*. This is evident when a pencil in a glass of water appears to be bent.

Usually waves are partly reflected and partly refracted when they fall on a transparent medium. When light shines on water, for example, some of the light is reflected and some is refracted. To understand this, let's see how reflection occurs.

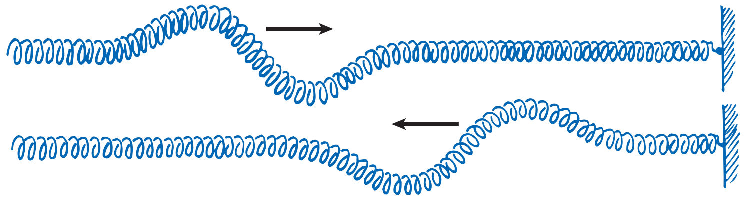
discover!

How Can You Make an Object Invisible?

1. Obtain two small heat-resistant beakers, one smaller than the other.
2. Place the smaller beaker inside the larger beaker.
3. Pour light vegetable oil or baby oil into both beakers until the smaller beaker is completely submerged.

Analyze and Conclude

1. **Observing** What did you observe when the oil filled both beakers?
2. **Predicting** Do you think you would observe the same results if the beakers were filled with other clear liquids?
3. **Making Generalizations** What makes an object visible?

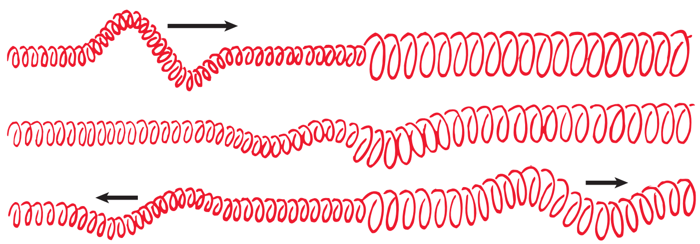


◀ **FIGURE 29.1**
A wave is totally reflected when it reaches a completely rigid boundary.

29.1 Reflection

When a wave reaches a boundary between two media, usually some or all of the wave bounces back into the first medium. The return of a wave back into its original medium is called **reflection.** Suppose you fasten a spring to a wall and send a pulse along the spring's length, as illustrated in Figure 29.1. The wall is a very rigid medium compared with the spring. As a result, all the wave energy is reflected back along the spring rather than transmitted into the wall. Waves that travel along the spring are almost *totally reflected* at the wall.

If the wall is replaced with a less rigid medium, such as the heavy spring shown in Figure 29.2, some energy is transmitted into the new medium. Some of the wave energy is still reflected. The incoming wave is *partially reflected.*



◀ **FIGURE 29.2**
When the wave reaches the heavy spring, it is partially reflected and partially transmitted.

A metal surface is rigid to light waves that shine upon it. Light energy does not propagate into the metal, but instead is returned in a reflected wave. The wave reflected from a metal surface has almost the full intensity of the incoming wave, apart from small energy losses due to the friction of the vibrating electrons in the surface. This is why metals such as silver and aluminum are so shiny. They reflect almost all the frequencies of visible light.

Other materials such as glass and water are not as rigid to light waves. When light shines perpendicularly on the surface of still water, about 2% of its energy is reflected and the rest is transmitted. When light strikes glass perpendicularly, about 4% of its energy is reflected. Except for slight losses, the rest is transmitted.

CONCEPT CHECK What happens when a wave reaches a boundary between two media?

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discover!

MATERIALS two heat-resistant beakers, light vegetable oil or baby oil.

ANALYZE AND CONCLUDE

1. When the oil filled both beakers, the smaller beaker became invisible.
2. Only if the index of refraction of the liquid matched that of glass
3. In this case, the optical discontinuity at the boundary of the two materials makes a clear object visible.

29.1 Reflection

Key Term
reflection

▶ **Teaching Tip** Explain that waves follow the laws of conservation of momentum and of energy.

Demonstrations of reflection are important. Point out the changes in speed of the transmitted waves.
PAUL

CONCEPT CHECK When a wave reaches a boundary between two media, usually some or all of the wave bounces back into the first medium.

Teaching Resources

- **Reading and Study Workbook**
- **Transparency** *68*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Conceptual Physics Alive! DVDs** *Reflection and Refraction*

29.2 The Law of Reflection

Key Terms
normal, angle of incidence, angle of reflection, law of reflection

▶ **Teaching Tip** Introduce the law of reflection by giving examples such as a billiard ball (with no spin) bouncing off the cushion of a billiard table at an angle and a ball bouncing on the ground or off a wall. In each case, the angle of reflection equals the angle of incidence.

▶ **Teaching Tip** Stress that the angles mentioned are the angles between the ray and the line that is perpendicular to the surface, i.e., the normal.

CONCEPT CHECK The law of reflection states that the angle of incidence and the angle of reflection are equal to each other.

Teaching Resources
- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

29.3 Mirrors

Key Term
virtual image

▶ **Teaching Tip** Discuss how a pane of glass both transmits and reflects light. Reflection is more noticeable when it is dark on the other side of the glass, and less noticeable when it's light on the other side. Stress that the percentage of light reflected (about 4%) is the same in both cases, but in the first case the 4% is more noticeable.

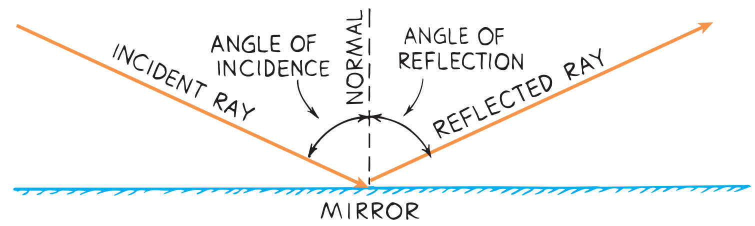


FIGURE 29.3 ▶
In reflection, the angle between the incident ray and the normal is equal to the angle between the reflected ray and the normal.

29.2 The Law of Reflection

In one dimension, reflected waves travel back in the direction from which they came. Let a ball drop to the floor, and it bounces straight up along its initial path. In two dimensions, the situation is a little different. A pool ball hitting the side of a pool table at an angle bounces back at the same angle in a new direction. Likewise with light.

The direction of incident and reflected waves is best described by straight-line *rays.* Incident rays and reflected rays make equal angles with a line perpendicular to the surface, called the **normal,** as shown in Figure 29.3. The angle between the incident ray and the normal, called the **angle of incidence,** is equal to the angle between the reflected ray and the normal, called the **angle of reflection.**

$$\text{angle of incidence} = \text{angle of reflection}$$

The **law of reflection** describes the relationship between the angle of incidence and angle of reflection. **The law of reflection states that the angle of incidence and the angle of reflection are equal to each other.** The incident ray, the normal, and the reflected ray all lie in the same plane. The law of reflection applies to both partially reflected and totally reflected waves.

think!

If you look at your blue shirt in a mirror, what is the color of its image? What does this tell you about the frequency of light incident upon a mirror compared with the frequency of the light after it is reflected?
Answer: 29.2

CONCEPT CHECK **What is the law of reflection?**

29.3 Mirrors

Consider a candle flame placed in front of a plane (flat) mirror. Rays of light leaving the candle are reflected from the mirror surface in all directions. The number of rays is infinite, and every one obeys the law of reflection. Figure 29.4 shows only two rays that originate at the tip of the candle flame and reflect from the mirror to your eye. Note that the rays diverge (spread apart) from the tip of the flame, and continue diverging from the mirror upon reflection. These divergent rays *appear* to originate from a point located behind the mirror.

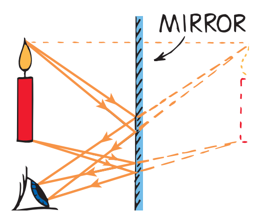


FIGURE 29.4 ▲
A virtual image is formed behind the plane mirror and is located at the position where the extended reflected rays (broken lines) converge.

discover!

Where Is Your Mirror Image?

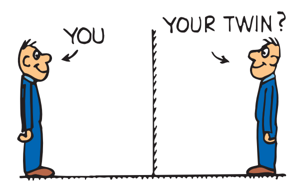
1. Look at your face in a mirror.
2. Now look at something on the surface of the mirror, such as a dust speck.
3. Do you have to adjust your eyes to refocus from looking at your image to looking at the dust on the mirror surface?
4. **Think** Is your image farther away than the mirror surface?

Your experience is that light travels in straight lines. Therefore, you perceive the candle flame to be located behind the mirror. A **virtual image** is an image that appears to be in a location where light does not really reach. **Plane mirrors produce only virtual images.**

Your eye cannot ordinarily tell the difference between an object and its virtual image because the light that enters your eye is entering in exactly the same manner as it would without the mirror if there really were an object where you see the image. Notice that the image is as far behind the mirror as the object is in front of the mirror, and the image and object are the same size. As illustrated in Figure 29.5, when you view yourself in a mirror, your image is the same size your identical twin would appear if located as far behind the mirror as you are in front—as long as the mirror is flat.

Note in Figure 29.6a that Majorie and her image have the same color of clothing—evidence that the light doesn't change frequency upon reflection. Interestingly, her left-right axis is no more reversed than her up-down axis. The axis that is reversed, as shown in Figure 29.6b is front-back. That's why it seems her left hand faces the right hand of her image.

FIGURE 29.5
For reflection in a plane mirror, object size equals image size and object distance equals image distance.



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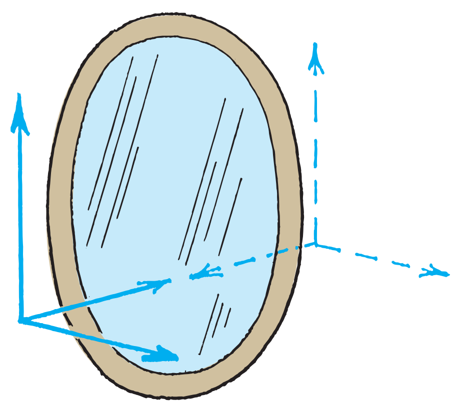

b

FIGURE 29.6
a. Marjorie's image is as far behind the mirror as she is in front. **b.** Her front-back axis is the only axis that is reversed.

discover!

MATERIALS plane mirror

EXPECTED OUTCOME Students will notice that they must adjust their eyes as they look from their images to the mirror's surface.

THINK Yes, your image is formed some distance behind the mirror.

Interesting thought: Because of the finite speed of light, your image in the mirror is always younger than you.
PAUL

Teaching Tip Use a ray diagram to show that the image formed by a plane mirror is as far behind the mirror as the object is in front.

Ask **Why will a camera with automatic focus give poor results if you take a picture of yourself in a mirror?** *The sonar or infrared beam will reflect from the surface of the mirror and so the camera will focus on the mirror surface. Since your image in the mirror is farther away than the mirror, the photograph will show a poorly focused image.*

If students are careful they will learn something about their image in a mirror that all their lives has likely escaped their notice: The size of the mirror needed to see their full height is independent of their distance from it.
PAUL

▶ **Teaching Tip** As you discuss Figure 29.7, point out that the law of reflection along every facet of a curved surface is the same as for a flat surface. A single ray of light does not distinguish between a large area and the tiny part with which it interacts, just as Earth appears flat to a single observer on its surface.

CONCEPT CHECK Plane mirrors produce only virtual images.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *29-1, 29-2*
- **Laboratory Manual** *77, 78, 79, 80*
- **Transparency** *69*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Questions** *29-1, 29-2*

29.4 Diffuse Reflection

Key Term
diffuse reflection

▶ **Teaching Tip** Introduce diffuse reflection by describing the appearance of a highly waxed floor and the appearance of the same floor when the wax has worn off.

▶ **Teaching Tip** Using a ray diagram, show that reflection from a rough surface is diffuse.

▶ **Teaching Tip** Explain that we see most of our environment because of diffuse reflection.

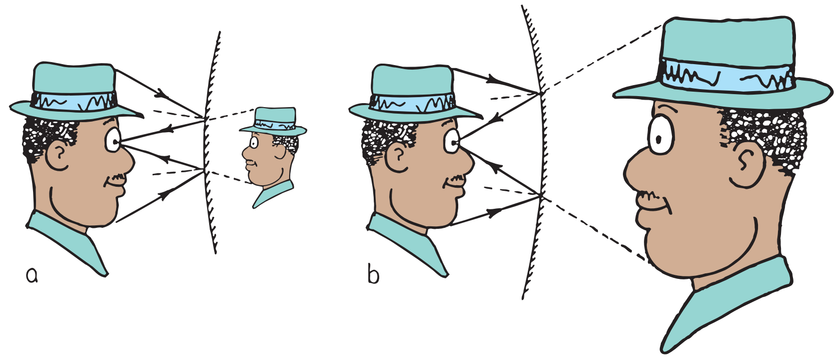

FIGURE 29.7 ▶
The law of reflection holds for curved mirrors. **a.** The image formed by a convex mirror is smaller than the object. **b.** When the object is close to a concave mirror, the image can be larger than the object.

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The law of reflection still holds for curved mirrors, as illustrated in Figure 29.7. However, when the mirror is curved, the sizes and distances of object and image are no longer equal. The virtual image formed by a *convex* mirror (a mirror that curves outward) is smaller and closer to the mirror than the object is. When the object is close to a *concave* mirror (a mirror that curves inward like a "cave"), the virtual image can be larger and more distant than the object.

CONCEPT CHECK What kind of images do mirrors produce?

29.4 Diffuse Reflection

When light is incident on a rough surface, it is reflected in many directions. **Diffuse reflection,** as shown in Figure 29.8, is the reflection of light from a rough surface. Although each ray obeys the law of reflection, the many different angles that incident light rays encounter at the surface cause reflection in many directions.

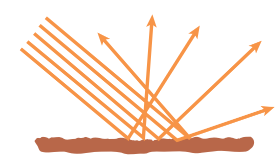

FIGURE 29.8 ▶
Diffuse reflection occurs when light is incident on a rough surface.

What constitutes a rough surface for some rays may be a polished surface for others. If the differences in elevations in a surface are small (less than about one-eighth the wavelength of the light that falls on it), the surface is considered polished. A surface may be polished for long wavelengths, but not polished for short wavelengths. Whether a surface is a diffuse reflector or a polished reflector depends on the wavelength of the waves it reflects.

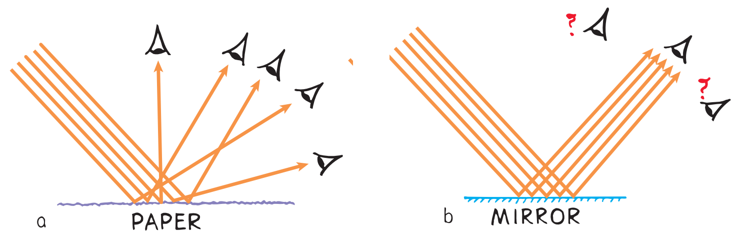

FIGURE 29.9 ▲
Diffuse reflection allows us to see most things around us. **a.** Light is diffusely reflected from paper in many directions. **b.** Light incident on a smooth mirror is only reflected in one direction.

Light that reflects from this page is diffuse. The page may be smooth to a long radio wave, but to the short wavelengths of visible light, it is rough. Rays of light incident on this page encounter millions of tiny flat surfaces facing in all directions, so they are reflected in all directions, as illustrated in Figure 29.9. A microscopic view of an ordinary paper surface is shown in Figure 29.10. Diffuse reflection allows us to read the page from any direction or position. We see most of the things around us by diffuse reflection.

FIGURE 29.10 ▲
Ordinary paper, like this textbook page, has a rough surface that can be viewed with a microscope.

CONCEPT CHECK What happens when light is incident on a rough surface?

29.5 Reflection of Sound

An echo is reflected sound. The fraction of sound energy reflected from a surface is more when the surface is rigid and smooth, and less when the surface is soft and irregular. **Sound energy that is not reflected is absorbed or transmitted.**

Sound reflects from all surfaces—the walls, ceiling, floor, furniture, and people—of a room. People who design the interiors of buildings, whether office buildings, factories, or auditoriums, need to understand the reflective properties of surfaces. The study of sound is called *acoustics*.

When the walls of a room, auditorium, or concert hall are too reflective, the sound becomes garbled. This is due to multiple reflections of sound waves called **reverberations.** But when the reflective surfaces are more absorbent, the sound level is lower, and the hall sounds dull and lifeless. Reflection of sound in a room makes it sound lively and full, as you have probably found out while singing in the shower. In the design of an auditorium or concert hall, a balance between reverberation and absorption is desired.

▶ **Teaching Tip** Ask your students if they have ever noticed that it is difficult to see the road ahead while driving in a car on a rainy night. When the road is dry, it is rough, and light from the car headlights is diffused—some of it returns to the driver. But on a rainy night, the road has water on the surface that acts as a mirror. The light is not diffusely reflected back to the driver, but is reflected ahead by the mirror-like surface. This has disadvantages to both approaching drivers, and to yourself. Instead of the light from headlights being diffused in many directions, it is reflected into the eyes of oncoming motorists.

Ask Would your book be easier to read if the pages were shinier? Why or why not? *No; there would be more glare and less diffusely reflected light.*

CONCEPT CHECK When light is incident on a rough surface, it is reflected in many directions.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Questions** *29-3, 29-4*

29.5 Reflection of Sound

Key Term
reverberation

▶ **Teaching Tip** Explain that the law of reflection also applies to sound. Discuss echoes, and the effects of multiple echoes—reverberations.

Ask **Why does your voice sound fuller when you sing in the shower?** *Each note lasts slightly longer as your voice reverberates between the walls.*

▶ **Teaching Tip** Walls that reflect sound diffusely are preferred in concert halls. Point out the interesting interplay between sound and light on the plates shown in Figure 29.12. Since both light and sound obey the same law of reflection, where light is seen is where sound is heard.

CONCEPT CHECK Sound energy that is not reflected is absorbed or transmitted.

Teaching Resources

- **Reading and Study Workbook**
- **Problem-Solving Exercises in Physics** *14-2*
- **Presentation***EXPRESS*
- **Interactive Textbook**

29.6 Refraction

Key Terms
refraction, wave front

Common Misconception
Both sound and light travel only in straight lines.

FACT Both light and sound waves change direction when they enter new media at angles greater than 0°.

▶ **Teaching Tip** Emphasize that the refraction of any wave depends on it changing its speed.

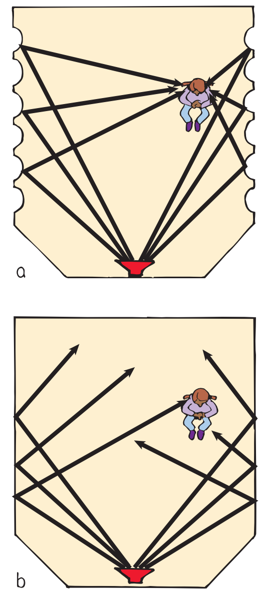

FIGURE 29.11 ▲
The walls of a concert hall are carefully designed. **a.** With grooved walls, sound reflects from many small sections of the wall to a listener. **b.** With flat walls, an intense reflected sound comes from only one part of the wall.

The walls of concert halls are often designed with grooves so that the sound waves are diffused. This is illustrated in Figure 29.11a. In this way a person in the audience receives a small amount of reflected sound from many parts of the wall, rather than a larger amount of sound from one part of the wall.

Highly reflective surfaces are often placed behind and above the stage to direct sound out to an audience. The large shiny plastic plates in Figure 29.12 also reflect light. A listener can look up at these reflectors and see the reflected images of the members of the orchestra. (The plastic reflectors are somewhat curved, which increases the field of view.) Both sound and light obey the same law of reflection, so if a reflector is oriented so that you can *see* a particular musical instrument, rest assured that you will *hear* it also. Sound from the instrument will follow the line of sight to the reflector and then to you.

CONCEPT CHECK **What happens to sound energy that is not reflected?**

◀ **FIGURE 29.12**
The shiny plates above the orchestra in Davies Symphony Hall in San Francisco reflect both light and sound.

29.6 Refraction

Suppose you take a rear axle with its wheels attached off an old toy cart and let it roll along a pavement that slopes gently downward and onto a downward-sloping mowed lawn. It rolls more slowly on the lawn because of the interaction of the wheels with the blades of grass. If you roll it at an angle, as shown in Figure 29.13, it will be deflected from its straight-line course. The direction of the axle and rolling wheels is shown in the illustration. Note that the wheel that first meets the lawn slows down first—because it interacts with the grass while the opposite wheel is still rolling on the pavement. The axle pivots, and the path bends toward the normal (the thin dashed line perpendicular to the grass-pavement boundary). The axle then continues across the lawn in a straight line at reduced speed.

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When a wave that is traveling at an angle changes its speed upon crossing a boundary between two media, it bends. Water waves bend, or refract, when one part of each wave is made to travel slower (or faster) than another part. **Refraction** is the bending of a wave as it crosses the boundary between two media at an angle. Water waves travel faster in deep water than in shallow water. Figure 29.14a shows a view from above of straight wave crests (the bright lines) moving toward the right edge of the photo. They are moving from deep water across a diagonal boundary into shallow water. At the boundary, the wave speed and direction of travel are abruptly altered. Since the wave moves more slowly in shallow water, the crests are closer together. If you look carefully, you'll see some reflection from the boundary.

In drawing a diagram of a wave, it is convenient to draw lines, called **wave fronts,**[29.6] that represent the positions of different crests. At each point along a wave front, the wave is moving perpendicular to the wave front. The direction of motion of the wave can thus be represented by rays that are perpendicular to the wave fronts. The ray in Figure 29.14b shows how the water wave changes direction after it crosses the boundary between deep and shallow water. Sometimes we analyze waves in terms of wave fronts, and at other times in terms of rays. Both are useful models for understanding wave behavior.

CONCEPT CHECK What causes a wave to bend?

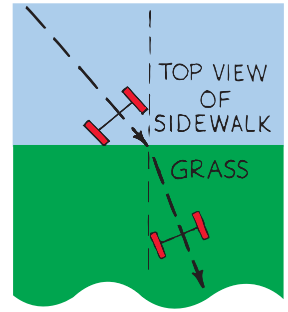
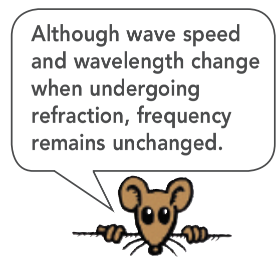
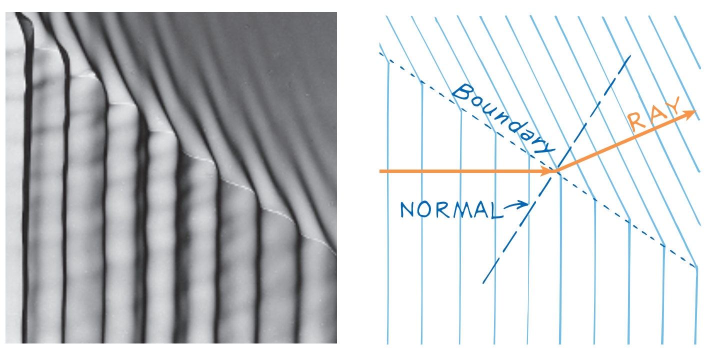


FIGURE 29.13 ▲
The direction of the rolling wheels changes when one wheel slows down before the other one.





a b

FIGURE 29.14 ▲
Water waves travel faster in deep water than in shallow water. **a.** The wave refracts at the boundary where the depth changes. **b.** The sample ray is perpendicular to the wave front it intersects.

▶ **Teaching Tip** As you discuss Figure 29.14, sketch the lines that are perpendicular to the wave front before and after the wave enters the new medium. Then add the normal to the boundary and show the change in direction.

CONCEPT CHECK When a wave that is traveling at an angle changes its speed upon crossing a boundary between two media, it bends.

Teaching Resources
- **Reading and Study Workbook**
- **Transparency** *70*
- **Presentation***EXPRESS*
- **Interactive Textbook**

29.7 Refraction of Sound

▶ **Teaching Tip** Note the sound of a bugle being refracted both upward and downward in Figure 29.15. The reason for refraction is the change in speed through different air densities. Different wind speeds can also cause sound refraction. The upper illustration could represent faster ground winds, and the lower illustration faster upper winds. Listing all variables helps.

▶ **Teaching Tip** Discuss the useful application of sound refraction in medicine ultrasound imaging, and how it can replace the use of X-rays in examining internal organs. This technique is useful in examining unborn children in pregnant women and is relatively free of dangerous side effects.

▶ **Teaching Tip** Sound refraction makes detecting submarines with sonar very difficult. Thermal gradients in the ocean and the resulting refractions of sonar waves leaves gaps or "blind spots" in the water, which are used to advantage by submarines. Otherwise, submarines would easily be detected by sonar.

Ask **What is the key factor for refraction (of any kind of wave)?** *A change in wave speed*

CONCEPT CHECK Sound waves are refracted when parts of a wave front travel at different speeds.

Teaching Resources
- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

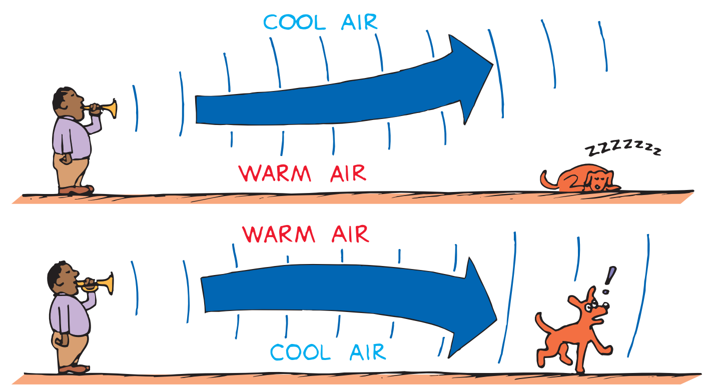


FIGURE 29.15 ▶
The wave fronts of sound are bent in air of uneven temperature.

think!

Suppose you are downwind from a factory whistle. In which case will the whistle sound louder—if the wind speed near the ground is more than the wind speed several meters above the ground, or if it is less?
Answer: 29.7

29.7 Refraction of Sound

Sound waves are refracted when parts of a wave front travel at different speeds. This happens in uneven winds or when sound is traveling through air of uneven temperature. On a warm day the air near the ground may be appreciably warmer than the air above. Since sound travels faster in warmer air, the speed of sound near the ground is increased. The refraction is not abrupt but gradual, as shown in Figure 29.15. Sound waves therefore tend to bend away from warm ground, making it appear that the sound does not carry well.

On a cold day or at night, when the layer of air near the ground is colder than the air above, the speed of sound near the ground is reduced. As illustrated in Figure 29.16, the higher speed of the wave fronts above cause a bending of the sound toward Earth. When this happens, sound can be heard over considerably longer distances.

CONCEPT CHECK **What causes sound waves to refract?**

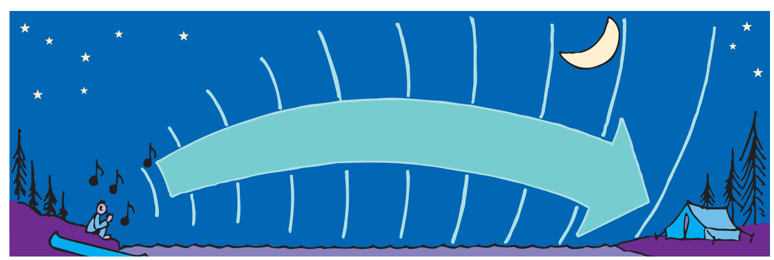


FIGURE 29.16 ▲
At night, when the air is cooler over the surface of the lake, sound is refracted toward the ground and carries unusually well.

29.8 Refraction of Light

Ponds or swimming pools appear shallower than they actually are. A pencil in a glass of water appears bent, the air above a hot stove seems to shimmer, and stars twinkle. These effects are due to the refraction of light. **Changes in the speed of light as it passes from one medium to another, or variations in the temperatures and densities of the same medium, cause refraction**. The directions of the light rays change because of refraction.[29.8]

Figure 29.17 shows rays and wave fronts of light refracted as they pass from air into water. (The wave fronts would be curved if the source of light were close, just as the wave fronts of water waves near a stone thrown into the water are curved. If we assume that the source of light is the sun, then it is so far away that the wave fronts are practically straight lines.) Note that the left portions of the wave fronts are the first to slow down when they enter the water (or right portion if you look along the direction of travel). The refracted ray of light, which is at right angles to the refracted wave fronts, is closer to the normal than is the incident ray.

Compare the refraction in this case to the bending of the axle's path in Figure 29.13. When light rays enter a medium in which their speed decreases, as when passing from air into water, the rays bend toward the normal. But when light rays enter a medium in which their speed increases, as when passing from water into air, the rays bend away from the normal.

Figure 29.18 shows a laser beam entering a container of water at the left and exiting at the right. The path would be the same if the light entered from the right and exited at the left. The light paths are reversible for both reflection and refraction. If you can see somebody by way of a reflective or refractive device, such as a mirror or a prism, then that person can see you (or your eyes) by looking through the device also.

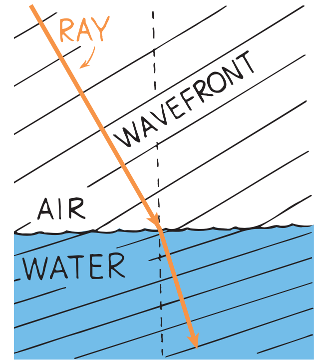
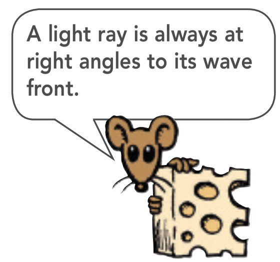


FIGURE 29.17 As a light wave passes from air into water, its speed decreases.



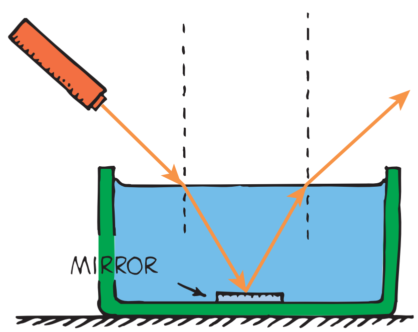
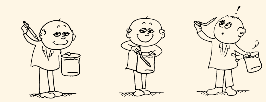


FIGURE 29.18 The laser beam bends toward the normal when it enters the water, and away from the normal when it leaves.

29.8 Refraction of Light



Teaching Tip Refer back to Figure 27.7 on page 538. Stress that different frequencies of light travel at different speeds in a transparent material—red slowest, and blue and violet fastest.

Teaching Tip Students might be interested to see how light behaves in mirrors that are silvered on the back: Light first refracts as it enters the glass and then reflects off the back surface. As it leaves the glass, it refracts again.

Teaching Tip When discussing Figure 29.19, explain that if you extend the ray from the fish's eye backward, you see that the fish sees the person to be higher than he or she really is.

Demonstration

Show a thick root beer mug filled with root beer (or cola). Because of significant refraction of light in passing from the glass mug to the air, the mug appears to contain more root beer than it actually does (Figure 29.19c). You can demonstrate this by immersing the mug in a tank of water. Because the light doesn't change speed as much in traveling through the glass mug to the water, you can better see the glass thickness.

CONCEPT CHECK Changes in the speed of light as it passes from one medium to another, or variations in the temperatures and densities of the same medium, cause refraction.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *29-3, 29-4, 29-5*
- **Transparency** *70*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Questions** *29-5, 29-6, 29-7*

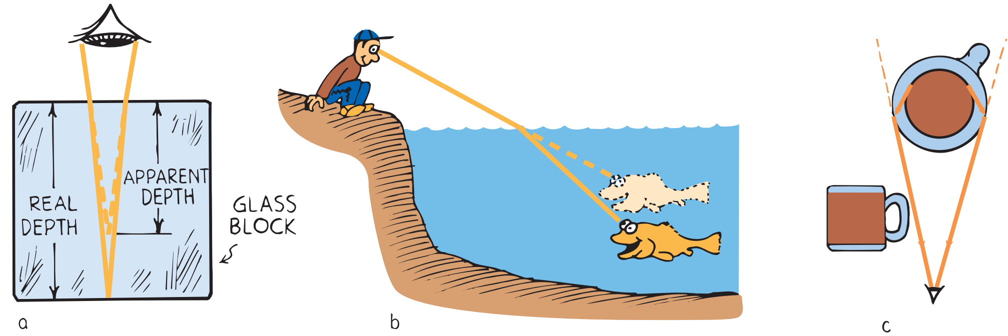


FIGURE 29.19 There are many effects of refraction. **a.** The apparent depth of the glass block is less than the real depth. **b.** The fish appears to be nearer than it actually is. **c.** The full glass mug appears to hold more root beer than it actually does.

As Figure 29.19a shows, a thick pane of glass appears to be only two-thirds its real thickness when viewed straight on. (For clarity, the diameter of the eye pupil is made larger than true scale.) Similarly, water in a pond or pool appears to be only three-quarters its true depth. In Figure 29.19b, the fish in the water appears to be nearer to the surface than it really is. It also seems closer. Another illusion is shown in Figure 29.19c. Light from the root beer is refracted through the sides of the thick glass, making the glass appear thinner than it is. The eye, accustomed to perceiving light traveling along straight lines, perceives the root beer to be at the outer edge of the glass, along the broken lines. These effects are due to the refraction of light whenever it crosses a boundary between air and another transparent medium.

CONCEPT CHECK **What causes the refraction of light?**

29.9 Atmospheric Refraction

Although the speed of light in air is only 0.03% less than its speed in a vacuum, in some situations atmospheric refraction is quite noticeable. One interesting example is the appearance of a distorted image called a **mirage.** **A mirage is caused by the refraction of light in Earth's atmosphere.** On hot days there may be a layer of very hot air in contact with the ground. Since molecules in hot air are farther apart, light travels faster through it than through the cooler air above. The speeding up of the part of the wave nearest the ground produces a gradual bending of the light rays. This can produce an image, say, of the palm tree in Figure 29.20. The image appears upside down to an observer at the right, just as if it were reflected from a surface of water. But the light is not reflected; it is refracted.

Wave fronts of light are shown in Figure 29.21. The refraction of light in air in this case is very much like the refraction of sound in Figure 29.15. Undeflected wave fronts would travel at one speed and in the direction shown by the broken lines. Their greater speed near the ground, however, causes the light ray to bend upward as shown.

think!

If the speed of light were the same for the various temperatures and densities of air, would there still be mirages?
Answer: 29.9

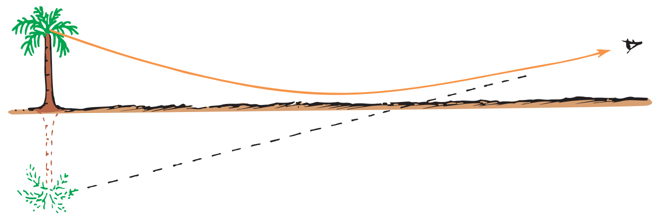


FIGURE 29.20 The refraction of light in air produces a mirage.

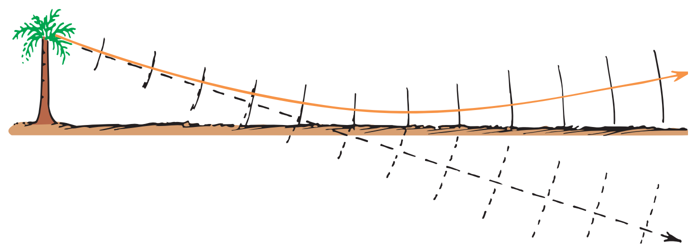


FIGURE 29.21 Wave fronts of light travel faster in the hot air near the ground, thereby bending the rays of light upward.

A motorist experiences a similar situation when driving along a hot road that appears to be wet ahead. The sky appears to be reflected from a wet surface but, in fact, light from the sky is being refracted through a layer of hot air. A mirage is not, as some people mistakenly believe, a "trick of the mind." As Figure 29.22 illustrates, a mirage is formed by real light and can be photographed.

FIGURE 29.22 A driver might see a mirage on a hot day. The "wet" street is actually dry.

When you watch the sun set, you see the sun for several minutes after it has really sunk below the horizon. This is because light is refracted by Earth's atmosphere, as shown in Figure 29.23. Since the density of the atmosphere changes gradually, the refracted rays bend gradually to produce a curved path. The same thing occurs at sunrise, so our daytimes are about 5 minutes longer because of atmospheric refraction.

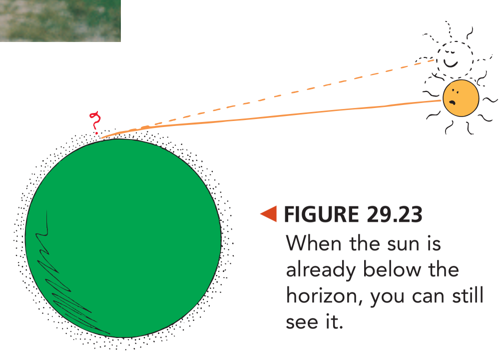


FIGURE 29.23 When the sun is already below the horizon, you can still see it.

29.9 Atmospheric Refraction

Key Term
mirage

▶ **Teaching Tip** Discuss the effects of refraction in the atmosphere—mirages. Make sure that students understand that these effects are real, and not tricks of the mind, as evidenced by the fact that they can be captured on photographic film.

▶ **Teaching Tip** Students often say they can see the "heat waves" near the ground or near other hot surfaces. Explain that what they are actually seeing are air convection currents much like those that occur in heated water.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Questions** *29-8, 29-9*

▶ **Teaching Tip** Discuss the role of atmospheric refraction in sunsets and in the "pumpkin" sun (or moon) often seen low in the sky as shown in Figure 29.24.

CONCEPT CHECK A mirage is caused by the refraction of light in Earth's atmosphere.

29.10 Dispersion in a Prism

Key Term
dispersion

Common Misconception
A prism changes white light into colors.

FACT A prism separates white light into its constituent colors.

▶ **Teaching Tip** Explain that the separation of light by a prism occurs because the sides of the triangular prism are not parallel. Light does not separate as it passes through a window because the sides of the glass are parallel to each other.

CONCEPT CHECK Since different frequencies of light travel at different speeds in transparent materials, they will refract differently and bend at different angles.

discover!

EXPECTED OUTCOME When looking across a hot stove or hot pavement, students should see shimmering images, or "heat waves." These mirages and the twinkling of stars are both produced by the refraction of light in the atmosphere.

THINK Many observatories are located at higher altitudes to limit the effects of atmospheric refraction.

FIGURE 29.24 ▲
Atmospheric refraction produces a "pumpkin" sun.

When the sun (or moon) is near the horizon, the rays from the lower edge are bent more than the rays from the upper edge. This produces a shortening of the vertical diameter and makes the sun (or moon) look elliptical instead of round, as in Figure 29.24.

CONCEPT CHECK What causes the appearance of a mirage?

29.10 Dispersion in a Prism

Chapter 27 discussed how the average speed of light is less than *c* in a transparent medium. How much less depends on the medium and the frequency of the light. Light of frequencies closer to the natural frequency of the electron oscillators in a medium travels more slowly in the medium. This is because there are more interactions with the medium in the process of absorption and reemission. Since the natural or resonant frequency of most transparent materials is in the ultraviolet part of the spectrum, visible light of higher frequencies travels more slowly than light of lower frequencies. Violet light travels about 1% slower in ordinary glass than red light. Light waves of colors between red and violet travel at their own intermediate speeds.

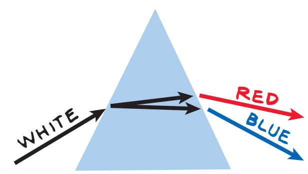


FIGURE 29.25 ▶
Dispersion through a prism occurs because different frequencies of light travel at different speeds.

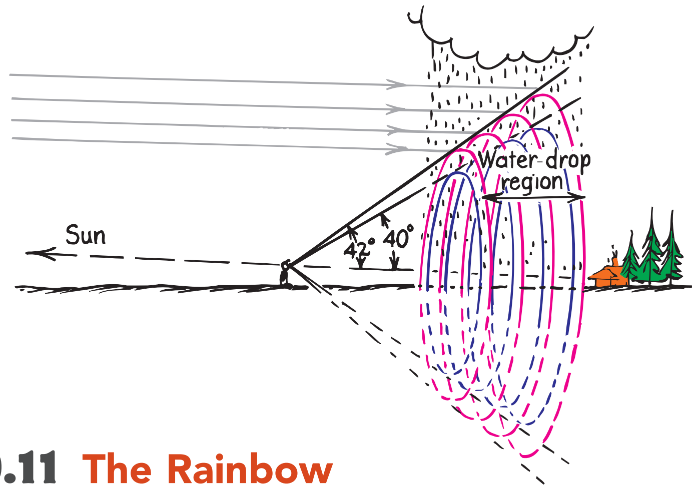
Since different frequencies of light travel at different speeds in transparent materials, they will refract differently and bend at different angles. When light is bent twice at nonparallel boundaries, as in a prism, the separation of the different colors of light is quite apparent. This separation of light into colors arranged according to their frequency, as illustrated in Figure 29.25, is called **dispersion.**

CONCEPT CHECK What causes dispersion of light?

discover!

Why Do Stars Twinkle?

1. Look across a hot stove or hot pavement. Describe what you observe. What is a possible explanation for what you are seeing?
2. The next time you are outside on a clear night try to notice the twinkling of stars in the nighttime sky. What causes this twinkling?
3. **Think** Why are many observatories located atop mountains?



◀ **FIGURE 29.26**
The rainbow is seen in a part of the sky opposite the sun and is centered on the imaginary line extending from the sun to the observer.

29.11 The Rainbow

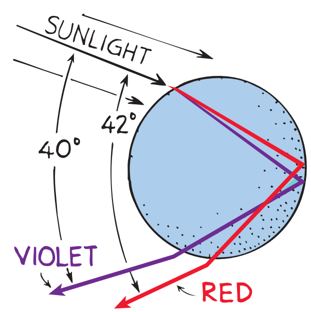
A spectacular illustration of dispersion is the rainbow. **In order for you to see a rainbow, the sun must be shining in one part of the sky, and the water droplets in a cloud or in falling rain must be in the opposite part of the sky.** When you turn your back to the sun, you see the spectrum of colors in a bow. As illustrated in Figure 29.26, all rainbows would be completely round if the ground were not in the way.

think!

If light traveled at the same speed in raindrops as it does in air, would we still have rainbows?
Answer: 29.11.1

Dispersion by a Raindrop Consider an individual spherical raindrop, as shown in Figure 29.27. Follow the ray of sunlight as it enters the drop near its top surface. Some of the light here is reflected (not shown), and the rest is refracted into the drop. At this first refraction, the light is dispersed into its spectral colors. Violet is bent the most and red the least. The rays reach the opposite part of the drop to be partly refracted out into the air (not shown) and partly reflected back into the water. Part of the rays that arrive at the lower surface of the drop are refracted into the air. This second refraction is similar to that of a prism, where refraction at the second surface increases the dispersion already produced at the first surface. This twice-refracted, once-reflected light is concentrated in a narrow range of angles.

FIGURE 29.27 ▶
Dispersion of sunlight by a water drop produces a rainbow.



29.11 The Rainbow

▶ **Teaching Tip** Point out that there are not distinct bands of color in the rainbow, but rather the colors merge from one hue to another. We separate the rainbow into the colors we have learned to identify.

▶ **Teaching Tip** State that all rainbows are complete circles, but the ground gets in the way so only half of the circle is seen.

I have seen complete circles of both primary and secondary bows from a helicopter over Kauai. Spectacular!
PAUL

▶ **Teaching Tip** Explain that rainbows cannot be seen when the sun is more than 42° above the horizon because the bow is below the horizon where no water drops are to be seen. Hence rainbows are normally seen early and late in the day. We don't see rainbows in midday in summer in most parts of the world (except from an airplane, where they are seen as full circles).

▶ **Teaching Tip** Point out a significant, yet commonly unnoticed, feature about the rainbow—the disk segment bounded by the bow is appreciably brighter than the rest of the sky. The rainbow is similar to the chromatic aberration around a bright spot of projected white light.

Observing a Rainbow Each drop disperses a full spectrum of colors. An observer, however, is in a position to see only a single color from any one drop, as illustrated in Figure 29.28. If violet light from a single drop enters your eye, red light from the same drop falls below your eye. To see red light you have to look at a drop higher in the sky. You'll see the color red when the angle between a beam of sunlight and the dispersed light is 42°. The color violet is seen when the angle between the sunbeam and dispersed light is 40°.

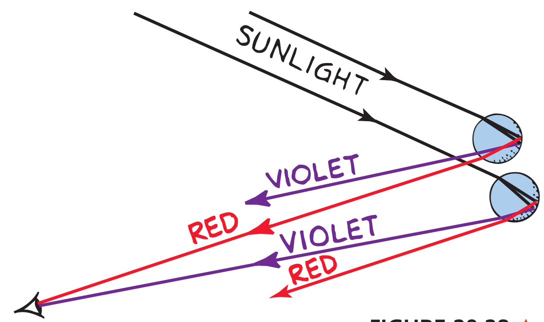


FIGURE 29.28 ▲
Sunlight strikes two sample drops and emerges as dispersed light.

You don't need to look only upward at 42° to see dispersed red light. You can see red by looking sideways at the same angle or anywhere along a circular arc swept out at a 42° angle. The dispersed light of other colors is along similar arcs, each at their own slightly different angle. Altogether, the arcs for each color form the familiar rainbow shape.

If you rotate the triangle shown in Figure 29.29, you sweep out the portion of a cone, with your eye at the apex. The raindrops that disperse light to you lie at the far edges of such a cone. The thicker the region of water drops, the thicker the conical edge you look through, and the more vivid the rainbow.

Your cone of vision that intersects the raindrops creating your rainbow is different from that of a person next to you. So when a friend says, "Look at the beautiful rainbow," you can reply, "Okay, move aside so I can see it too." Everybody sees his or her own personal rainbow.

So when you move, your rainbow moves with you. This means you can never approach the side of a rainbow, or see it end-on as in the exaggerated view of Figure 29.26. You *can't* get to its end. Hence the expression "looking for the pot of gold at the end of the rainbow" means pursuing something you can never reach.

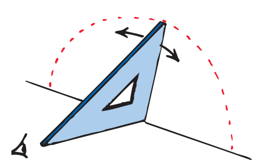


FIGURE 29.29 ▲
Only raindrops along the dashed arc disperse red light to the observer at a 42° angle.

▶ **Teaching Tip** The different sizes of raindrops affect the proportions of color seen in a rainbow. Drops between 0.5 and 1 mm in diameter create the most brilliant colors. Drops of 1–2 mm in diameter show very bright violet and blue with scarcely any green. Larger drops produce poor rainbows because they depart from a truly spherical shape due to flattening caused by air pressure and the oscillations they undergo. In drops smaller than 0.5 mm, red is weak. In the 0.02–0.3 mm range, red is not seen. At 0.08 to 0.10 mm, the bow is pale with only violet vivid. Smaller drops produce weak bows with a distinct white stripe. And as a pair of polarized sunglasses will show, rainbows are polarized.

▶ **Teaching Tip** You may wish to extend the topic of rainbows to the similar phenomenon of the moon's halo. Explain how the halo is produced by refraction of moonlight through ice crystals in the atmosphere. Note the important difference: Whereas both refraction and internal reflection produce rainbows, only refraction produces halos. And, whereas the observer is between the sun and the drops for seeing a rainbow, the ice crystals that produce halos are between the observer and the moon. Moonlight is refracted through ice crystals high in the atmosphere—evidence of the coldness up there even on a hot summer night.

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FIGURE 29.30 Light from droplets inside the rainbow form a bright disk with the colored rainbow at its edge. The sky appears darker outside the rainbow because there is no light exiting raindrops in the way that produces the main rainbow. Notice the dimmer secondary bow.

Often a larger, secondary bow with colors reversed can be seen arching at a greater angle around the primary bow. You can see the secondary bow in Figure 29.30. The secondary bow is formed by similar circumstances and is a result of double reflection within the raindrops, as illustrated in Figure 29.31. Because most of the light is refracted out the back of the water drop during the extra reflection, the secondary bow is much dimmer.

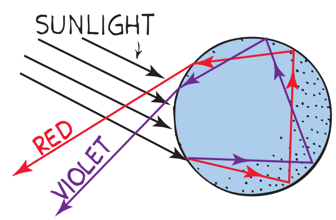


FIGURE 29.31 Double reflection in a water drop produces a secondary bow that is much dimmer than the primary bow.

CONCEPT CHECK: What are the conditions necessary for seeing a rainbow?

think!

Point to a wall with your arm extended to approximate a 42° angle to the normal of the wall. Rotate your arm in a full circle while keeping the same 42° angle. What shape does your arm describe? What shape on the wall does your finger sweep out?
Answer: 29.11.2

29.12 Total Internal Reflection

When you're in a physics mood and you're going to take a bath, fill the tub extra deep and bring a waterproof flashlight into the tub with you. Turn the bathroom light off. Shine the submerged light straight up and then slowly tip it and note how the intensity of the emerging beam diminishes and how more light is reflected from the water surface to the bottom of the tub.

CONCEPT CHECK: In order for you to see a rainbow, the sun must be shining in one part of the sky, and the water droplets in a cloud or in falling rain must be in the opposite part of the sky.

Teaching Resources
- **Reading and Study Workbook**
- **Transparency** *71*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *29-10*

29.12 Total Internal Reflection

Key Terms
critical angle, total internal reflection, optical fiber

Demonstration

Show examples of reflection, refraction, and total internal reflection with a light source (laser), some prisms, and a tank of water with some fluorescent dye added.

▶ **Teaching Tip** Tell students that because of the higher frequencies of light compared to electric currents, a pair of glass fibers as thin as a human hair can carry 1300 simultaneous telephone conversations, while a conventional copper cable can carry only 24. Signals in copper cables must be boosted every 4 to 6 km, whereas re-amplification in light wave systems occurs at 10- to 50-km intervals. For infrared optical fibers, the distance between regenerators may be hundreds or even thousands of kilometers.

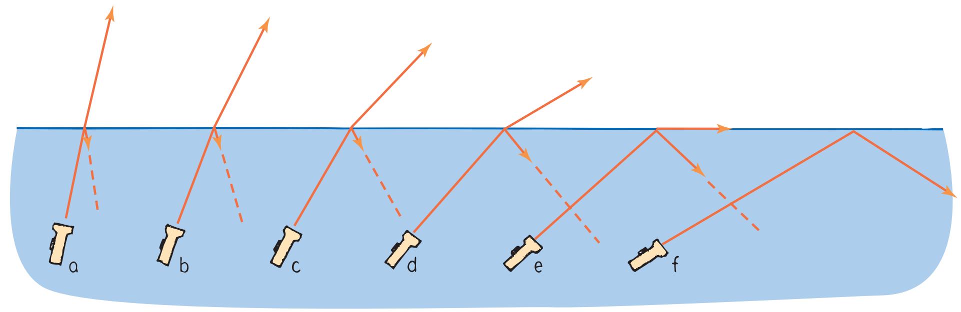


FIGURE 29.32 ▲
You can observe total internal reflection in your bathtub. **a–d.** Light emitted in the water at angles below the critical angle is partly refracted and partly reflected at the surface. **e.** At the critical angle, the emerging beam skims the surface. **f.** Past the critical angle, there is total internal reflection.

The Critical Angle At a certain angle, called the critical angle, you'll notice that the beam no longer emerges into the air above the surface. The **critical angle** is the angle of incidence that results in the light being refracted at an angle of 90° with respect to the normal. As a result, the intensity of the emerging beam reduces to zero. When the flashlight is tipped beyond the critical angle (48° from the normal in water), the beam cannot enter the air; it is only reflected. The beam is experiencing **total internal reflection,** which is the complete reflection of light back into its original medium. **Total internal reflection occurs when the angle of incidence is larger than the critical angle.** The only light emerging from the water surface is that which is diffusely reflected from the bottom of the bathtub.

This procedure is shown in Figure 29.32. The proportions of light refracted and reflected are indicated by the relative lengths of the solid arrows. The light reflected beneath the surface obeys the law of reflection: The angle of incidence is equal to the angle of reflection.

The critical angle for glass is about 43°, depending on the type of glass. This means that within the glass, rays of light that are more than 43° from the normal to a surface will be totally internally reflected at that surface. Rays of light in the glass prisms shown in Figure 29.33, for example, meet the back surface at 45° and are totally internally reflected. They will stay inside the glass until they meet a surface at an angle between 0° (straight on) and 43° to the normal.

Total internal reflection is as the name implies: total—100%. Silvered or aluminized mirrors reflect only 90 to 95% of incident light, and are marred by dust and dirt; prisms are more efficient. This is the main reason prisms are used instead of mirrors in many optical instruments. Figure 29.33 illustrates how prisms can be used to reflect light.

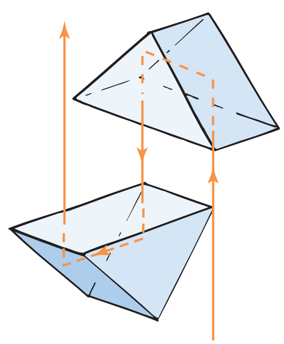


FIGURE 29.33 ▲
Prisms are more efficient at reflecting light than mirrors because of total internal reflection.

Total Internal Reflection in Diamonds The critical angle for a diamond is 24.6°, smaller than in other common substances. This small critical angle means that light inside a diamond is more likely to be totally internally reflected than to escape. All light rays more than 24.6° from the normal to a surface in a diamond are kept inside by total internal reflection.

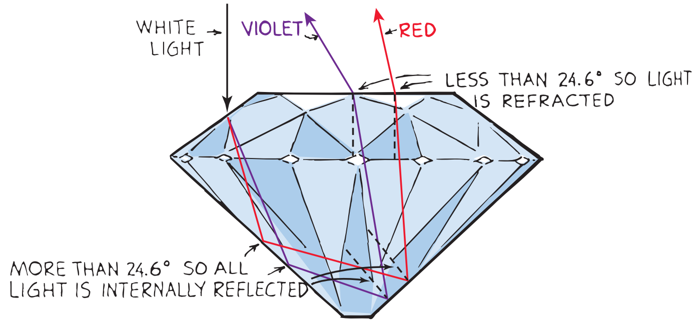
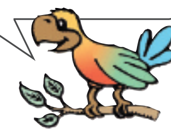


FIGURE 29.34
The brilliance of diamonds is a result of total internal reflection.

As shown in Figure 29.34, when a diamond is cut as a gemstone, light that enters at one facet is usually totally internally reflected several times, without any loss in intensity, before exiting from another facet in another direction. A small critical angle, plus the pronounced refraction because of the unusually low speed of light in diamond, produces wide dispersion and a wide array of brilliant colors.

Light travels slowly in a diamond, but even more slowly in a silicon carbide crystal called *carborundum*.



Optical Fibers **Optical fibers,** sometimes called *light pipes,* are transparent fibers that pipe light from one place to another. As illustrated in Figure 29.35, they do this by a series of total internal reflections. Optical fibers are useful for getting light to inaccessible places. Mechanics and machinists use them to look at the interiors of engines, and physicians use them to look inside a patient's body. Light that shines down some of the fibers illuminates the scene and is reflected back along others.

Optical fibers are important in communications and have been replacing bulky and expensive copper cables to carry telephone messages between major switching centers. More information can be carried in the high frequencies of visible light than in the lower frequencies of electric current.

CONCEPT CHECK **What causes total internal reflection to occur?**

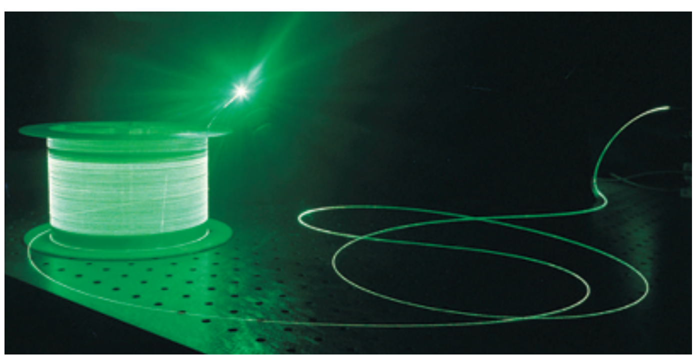
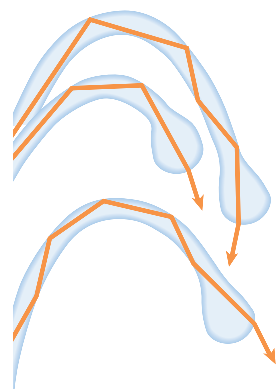


FIGURE 29.35
In an optical fiber, light is piped from one end to the other by a succession of total internal reflections.



Teaching Tip Show an example of light pipes, such as that shown in Figure 29.35. Discuss some of the many applications of these fibers, or "light pipes."

CONCEPT CHECK Total internal reflection occurs when the angle of incidence is larger than the critical angle.

Teaching Resources
- **Reading and Study Workbook**
- **Problem-Solving Exercises in Physics** ***14-3***
- **Presentation*EXPRESS***
- **Interactive Textbook**

29 REVIEW

Teaching Resources

- Teacher*EXPRESS*
- Virtual Physics Lab *26*
- Conceptual Physics Alive! DVDs *Reflection and Refraction*

29 REVIEW

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Concept Summary

- When a wave reaches a boundary between two media, usually some or all of the wave bounces back into the first medium.
- The law of reflection states that the angle of incidence and the angle of reflection are equal to each other.
- Plane mirrors produce only virtual images.
- When light is incident on a rough surface, it is reflected in many directions.
- Sound energy that is not reflected is absorbed or transmitted.
- When a wave that is traveling at an angle changes its speed upon crossing a boundary between two media, it bends.
- Sound waves are refracted when parts of a wave front travel at different speeds.
- Changes in the speed of light as it passes from one medium to another, or variations in the temperatures and densities of the same medium, cause refraction.
- A mirage is caused by the refraction of light in Earth's atmosphere.
- Since different frequencies of light travel at different speeds in transparent materials, they will refract differently.
- In order for you to see a rainbow, the sun must be shining in one part of the sky, and water droplets must be in the opposite part of the sky.
- Total internal reflection occurs when the angle of incidence is larger than the critical angle.

Key Terms

reflection *(p. 579)*
normal *(p. 580)*
angle of incidence *(p. 580)*
angle of reflection *(p. 580)*
law of reflection *(p. 580)*
virtual image *(p. 581)*
diffuse reflection *(p. 582)*
reverberation *(p. 583)*
refraction *(p. 585)*
wave front *(p. 585)*
mirage *(p. 588)*
dispersion *(p. 590)*
critical angle *(p. 594)*
total internal reflection *(p. 594)*
optical fiber *(p. 595)*

think! Answers

29.2 The color of the image will be the same as the color of the object because the frequency of light is not changed by reflection.

29.7 You'll hear the whistle better if the wind speed near the ground is less than the wind speed higher up. For this condition, the sound will be refracted toward the ground.

29.9 No! There would be no refraction if light traveled at the same speed in air of different temperatures and densities.

29.11.1 No. If there is no change in speed, there is no refraction. If there is no refraction, there is no dispersion of light and hence, no rainbow!

29.11.2 Your arm describes a cone, and your finger sweeps out a circle. Likewise with rainbows.

29 ASSESS

Check Concepts

Section 29.1

1. What becomes of a wave's energy when the wave is totally reflected at a boundary? When it is partially reflected at a boundary?

2. Why do smooth metal surfaces make good mirrors?

3. When light strikes perpendicular to the surface of a pane of glass, how much light is reflected and how much is transmitted at the first surface?

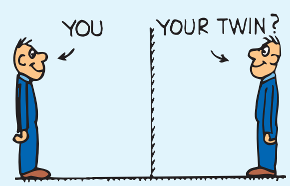
Section 29.2

4. What is meant by the normal to a surface?

5. What is the law of reflection?

Section 29.3

6. When you view your image in a plane mirror, how far behind the mirror is your image compared with your distance in front of the mirror?



7. In what way does the law of reflection hold for *curved* mirrors?

Section 29.4

8. In what way does the law of reflection hold for diffuse reflection? Explain.

9. What is meant by the idea that a surface may be polished for some waves and rough for others?

Section 29.5

10. Distinguish between an echo and a reverberation.

11. Does the law of reflection hold for both sound waves and light waves?

Section 29.6

12. Distinguish between reflection and refraction.

13. When a wave crosses a surface at an angle from one medium into another, why does it change directions as it moves across the boundary into the new medium?

14. What is the orientation of a ray in relation to the wave front of a wave?

Section 29.7

15. Give an example where refraction is abrupt, and another where refraction is gradual.

Section 29.8

16. Does refraction occur for both sound waves and light waves?

17. If light had the same speed in air and in water, would light be refracted in passing from air into water?

18. If you can see the face of a friend who is underwater, can she also see you?

29 ASSESS

Check Concepts

1. It reverses direction and goes back through the original medium; part goes into the second medium.

2. They reflect almost all the colors of visible light.

3. 4%; 96% (at first surface)

4. Any line that is perpendicular to the surface

5. Angle of incidence = angle of reflection

6. Same distance

7. The law of reflection still holds, but the normals at different points are not parallel to one another.

8. Each single ray obeys the law of reflection.

9. The surface is considered polished if its irregularities are less than $1/8\lambda$ of the incident wave.

10. Echo—single reflection; reverberation—multiple reflections

11. Yes; and for all other types of waves

12. Reflection—waves travel back in the original medium; refraction—waves enter a new medium

13. Different parts of the wave change speed at different times.

14. Perpendicular

15. Abrupt—light traveling from air into water (sharp boundary); gradual—light traveling through the atmosphere

16. Yes (and for all other types of waves too)

17. No; refraction depends on change in wave speed.

18. Yes (eyes at least); the directions of rays are reversible.

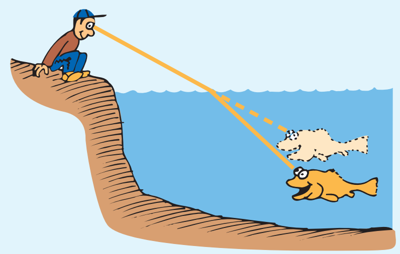
19. Shallower
20. Refraction; it only appears to be a reflection.
21. Longer
22. High frequencies
23. Blue interacts more and slows more than red.
24. The observer must be between a low sun and the water drops.
25. Both refract and disperse light.
26. The angle at which light doesn't refract, but reflects.
27. They literally pipe light along the fiber.

Think and Rank

28. B, C, A
29. B, C, A
30. C, B, A

29 ASSESS (continued)

19. Does refraction tend to make objects submerged in water seem shallower or deeper than they really are?



Section 29.9

20. Is a mirage a result of refraction or reflection? Explain.

21. Is daytime a bit longer or is it a bit shorter because of atmospheric refraction?

Section 29.10

22. As light passes through a transparent medium, it undergoes an absorption-reemission process (discussed earlier, in Figure 27.7). Which interacts more with the medium, light of high frequencies or light of low frequencies? (Do high frequencies or low frequencies lag behind?)

23. Why does blue light refract at greater angles than red light in transparent materials?

Section 29.11

24. What conditions are necessary for viewing a rainbow in the sky?

25. How is a raindrop similar to a prism?

Section 29.12

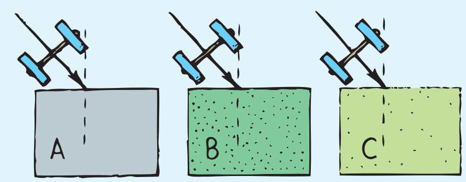
26. What is the *critical angle* in terms of refraction and total internal reflection?

27. Why are optical fibers often called *light pipes?*

Think and Rank

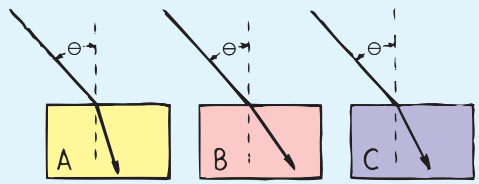
Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

28. Wheels from a toy cart are rolled from a concrete sidewalk onto the following surfaces.
(A) a paved driveway
(B) a grass lawn
(C) close-cropped grass (like that on a golf-course putting green)

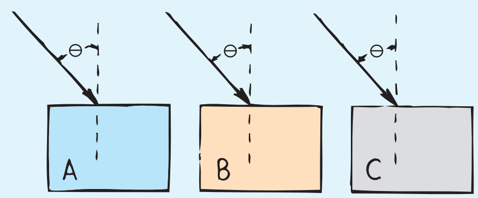


Due to slowing, each set of wheels bends at the boundary and is deflected from its original course. Rank the surfaces according to the amount each set of wheels bends at the boundary, from greatest amount of bending to least amount of bending.

29. Identical rays of light enter three transparent blocks composed of different materials. Light slows upon entering the blocks. Rank the blocks according to the speed light travels in each, from highest speed to lowest speed.



30. Identical rays of light in air are refracted upon entering three transparent materials.
   (A) water, where speed slows to $0.75c$
   (B) ethyl alcohol (speed $0.74c$)
   (C) crown glass (speed $0.66c$)

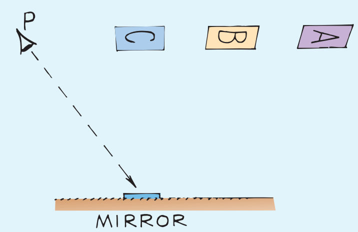


Rank the materials according to how much the light ray bends toward the normal, from most bending to least bending.

Think and Explain

31. On a steamy mirror, wipe an area just large enough to allow you to see your full face. How tall will the wiped area be compared with the vertical dimension of your face?

32. Suppose that a mirror and three lettered cards are set up as in the figure. If a person's eye is at point P, which of the lettered cards will be seen reflected in the mirror? Explain.



33. In the photograph below we see the bird and its reflection. Why don't we see the bird's feet in the reflection?

34. Contrast the types of reflection from a rough road and from the smooth surface of a wet road to explain why it is difficult for a motorist to see the roadway ahead when driving on a rainy night.

35. Cameras with automatic focus bounce a sonar (sound) beam from the object being photographed and compute distance from the time interval between sending and receiving the signal. Why will these cameras not focus properly for photographs of mirror images?

Think and Explain

31. The wiped area will be half the height of your face (see Activity 53).

32. By the law of reflection, only light from card B reaches his or her eyes.

33. The bird's feet are out of view of the water and therefore are not reflected as the rest of the body is.

34. A dry road causes diffuse reflection of headlight beams and only a small part of the reflected light returns to the driver's eyes. A wet road acts more like a plane mirror, so most of the light is reflected ahead (causing glare for oncoming motorists!).

35. Sound is bounced from the mirror surface rather than from the image, so sonar cameras will not ordinarily focus properly for a mirror image.

36. Only his right leg is lifted while he stands on his left leg behind the mirror.

37. Sound, like any wave, spreads as it travels and is diluted with distance.

38. Louder; waves heading upward go faster and bend downward (Figure 29.15).

39. No; the reflected view of an object is seen from a lower angle, as from a point as far below the reflecting surface as the viewer is above it. The geometrical difference is most noticeable when closer objects and their reflections are viewed.

40. Below; the fish appears to be closer to the surface than it really is, because of the refraction of light that leaves the fish and travels to your eye in the air above the water. No; laser light will travel back along the same path as the light from the fish, so you would have to aim directly at the fish's image.

41. Both show illusions, but the encased bottle shows a truer view (refraction at curved bottle shrinks cola a bit). More refraction occurs for the bottle in air, which shows much more cola than exists.

42. The slower speed of light in denser air causes downward refraction, which lengthens the amount of daylight hours.

43. Red light is faster and therefore exits first.

44. No; from every vantage point, the rainbow forms part (or all) of a circle.

45. Yes; your head is directly between the sun and the center of the bow.

29 ASSESS *(continued)*

36. In the photograph below, Peter Hopkinson is standing astride a large mirror and boosts class interest with this zany demonstration. How does he accomplish his apparent levitation in midair?

37. Why is an echo weaker than the original sound?

38. Suppose you are standing downwind from a barking dog on a windy day. The wind blows faster well above the ground than close to the ground. Refraction will change the sound of the dog's bark. Will the sound of the bark be somewhat louder or somewhat diminished? Defend your answer.

39. Does the reflection of a scene in calm water look exactly the same as the scene itself only upside down? (*Hint:* Place a mirror on the floor between you and a table. Do you see the top of the table in the reflected image?)

40. If you were spearing a fish with a spear, would you aim above, below, or directly at the observed fish to make a direct hit? Would your answer be the same if you used laser light to "spear" the fish? Defend your answer.

41. The photo below shows two identical cola bottles, each with the *same* amount of cola. The right bottle is in air, and the left bottle is encased in solid plastic that has nearly the same index of refraction as glass (the speed of light in the plastic and in glass are nearly the same). Which bottle shows an illusion of the amount of cola? How does the other bottle give a truer view of its contents?

42. How do the different speeds of light in thin air and dense air affect the length of daylight?

43. Very short pulses of red light and blue light enter a glass block normal to its surface at the same time. Which pulse exits first?

44. When you stand with your back to the sun, you see a rainbow as a circular arc. Could you move off to one side and then see the rainbow as the segment of an ellipse rather than the segment of a circle (such as Figure 29.26 suggests)? Defend your answer.

45. A rainbow viewed from an airplane may form a complete circle. Will the shadow of the airplane appear at the center of the circle? Explain with the help of Figure 29.26.

600

46. Two observers standing apart from each other do not see the same rainbow. Explain.

47. Why is a secondary rainbow dimmer than the primary bow?

Think and Solve

48. When light strikes glass perpendicularly, about 4% of the light is reflected at each surface. Show that the amount of light transmitted through a pane of window glass is approximately 92%.

49. Suppose you walk toward a mirror at 1 m/s. How fast do you and your image approach each other? (The answer is *not* 1 m/s.)

50. A radio wave sent into space strikes an asteroid and is reflected back to Earth 1 second after being emitted. How far away is the asteroid?

51. A spider hangs by a strand of silk at eye level 20 cm in front of a plane mirror. You are behind the spider, 50 cm from the mirror. Show that the distance between your eye and the image of the spider in the mirror is 70 cm.

52. The average speed of light slows to $0.75c$ when it enters a particular piece of plastic.
   a. What change occurs in the frequency of light in the plastic?
   b. What change occurs in the wavelength?

Activities

53. Stand in front of a mirror and put two pieces of tape on the glass: one piece where you see the top of your head, and the other where you see the bottom of your feet. Compare the distance between the pieces of tape with your height. If a full-length mirror is not handy, use a smaller mirror and find the minimum length of mirror to see your face. Mark where you see the top of your head and the bottom of your chin. Then compare the distance between the marks with the length of your face. What must be the minimum length of a plane mirror in order for you to see a full view of yourself?

54. What effect does your distance from the mirror have on the answer to Activity 53? (*Hint:* Move closer and farther from your initial position. Be sure the top of your head lines up with the top piece of tape. At greater distances, is your image smaller than, larger than, or the same size as the space between the pieces of tape?) Are you surprised?

55. Look at a diamond under bright light. Turn the stone and note the flashes of color that refract, reflect, and refract toward you. When the flash encounters only one eye instead of two, your brain registers it differently than for both eyes. The one-eyed flash is a sparkle! What causes the brilliant sparkle of a diamond?

More Problem-Solving Practice
Appendix F

46. The centers of each rainbow are as far apart as the viewers. Only eyes in the same location see *exactly* the same rainbow.

47. The intensity of the light is diminished by the extra internal reflection.

Think and Solve

48. Each boundary reflects 4%: 96% gets through the first boundary, and 96% of 96%, or 92.2%, gets through the second boundary.

49. Relative to each other, you and your image approach at 2 m/s.

50. Time going or returning is 0.5 s; distance = ct = $(3 \times 10^8 \text{ m/s}) \times (0.5 \text{ s}) = 1.5 \times 10^8$ m away.

51. By addition: 50 cm + 20 cm = 70 cm. (The spider's image is 20 cm in back of the mirror.)

52. **a.** None; there is no change in frequency by refraction.
   b. $\lambda = v/f = 0.75c/f$; there is no change in frequency f, so the wavelength λ is reduced to 0.75 the initial wavelength.

Activities

53. Half your height

54. No difference

55. Its high index of refraction and small critical angle

Teaching Resources
- Computer Test Bank
- Chapter and Unit Tests