29

Reflection and Refraction

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

In other situations, as when light passes from air into water, waves travel from one medium into another. If the waves strike the surface of the medium at an angle, their direction changes in the second medium. These waves are *refracted*.

In most cases, waves are both reflected and 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 us see why reflection occurs.

29.1

Reflection

When a wave reaches the boundary between two media, some or all of the wave bounces back into the first medium. This is **reflection**. For example, suppose you fasten a spring to a wall and send a pulse along its length (Figure 29–1). The wall is a very rigid medium compared to the spring. As a result, all the wave energy is transmitted back along the spring rather than into the wall. Waves that travel along the spring are *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. These waves are *partially reflected*.

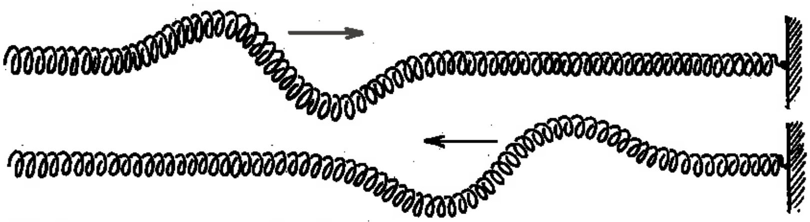

Fig. 29–1 A wave is totally reflected when it reaches a completely rigid boundary.

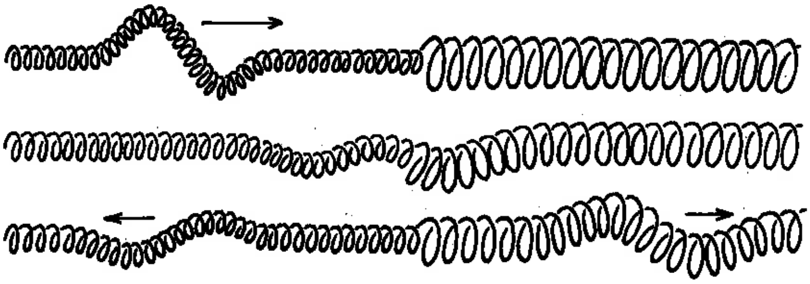

Fig. 29–2 When the wave reaches the heavy spring, it is partially reflected. Part of the wave energy bounces back along the first spring, while the other part travels along the heavy spring.

A metal surface is rigid to light waves that shine upon it. Light energy does not propagate into the metal, and 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. Smooth surfaces of these metals are therefore used as mirrors.

Materials such as glass and water are not as rigid to light waves. Like the different springs of Figure 29–2, wave energy is both reflected and transmitted at the boundary. When light falls perpendicularly on the surface of still water, about 2 percent is reflected and the rest transmitted. When light strikes glass perpendicularly, about 4 percent is reflected. Except for slight losses, the rest is transmitted.

29.2 The Law of Reflection

In one dimension, reflected waves simply 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.

The direction of incident and reflected waves is best described by straight lines called *rays*. Incident rays and reflected rays make equal angles with a line perpendicular to the surface, called the **normal** (Figure 29–3). The angle made by the incident ray and the normal, called the **angle of incidence**, is equal to the angle made by the reflected ray and the normal, called the **angle of reflection**. That is:

angle of incidence = angle of reflection

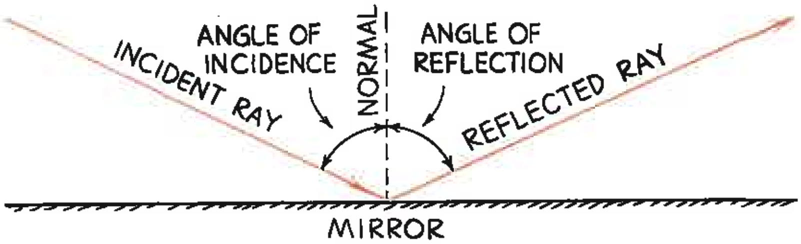

Fig. 29–3 In reflection, the angle between the incident ray and the normal is equal to the angle between the reflected ray and the normal.

This relationship is called the **law of reflection**. 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.

29.3 Mirrors

Consider a candle flame placed in front of a plane (flat) mirror. Rays of light are reflected from its 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 someone's 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. The image of the candle the person sees in the mirror is called a **virtual image**, because light does not actually pass through the image position but behaves virtually as if it did.

Your eye cannot ordinarily tell the difference between an object and its reflected image. This is because the light that enters your eye is entering in exactly the same manner, physically, as it would if there really were an object there. Notice that the image is as far behind the mirror as the object is in front of the mirror. Notice also that the image and object have the same size.

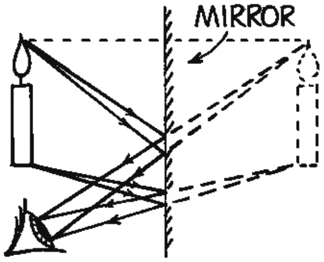

Fig. 29–4 A virtual image is formed behind the plane mirror and is located at the position where the extended reflected rays (broken lines) converge.

When you view yourself in a mirror, for example, the size of 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.

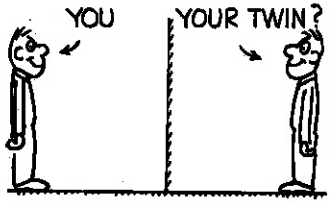

Fig. 29–5 For reflection in a plane mirror, object size equals image size and object distance equals image distance.

When the mirror is curved, the sizes and distances of object and image are no longer equal. This text will not treat curved mirrors, except to say that the law of reflection still holds. The angle of incidence is equal to the angle of reflection (Figure 29–6). Note that for a curved mirror, unlike a plane mirror, the normals (shown as dashed black lines) at different points on the surface are not parallel to each other.

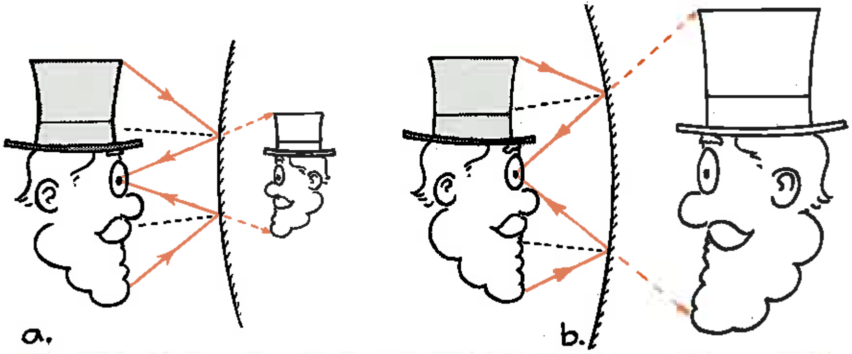

Fig. 29–6 (a) The virtual image formed by a *convex* mirror (a mirror that curves outward) is smaller and closer to the mirror than the object. (b) When the object is close to a *concave* mirror (a mirror that curves inward like a "cave"), the virtual image is larger and farther away than the object. In any case the law of reflection holds for each ray.

▶ **Questions**

1. 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 to its frequency when reflected?

2. If you wish to take a picture of your image while standing 2 m in front of a plane mirror, for what distance should you set your camera to provide sharpest focus?

▶ **Answers**

1. The color of the image will be the same as the color of the object. This is evidence that the frequency of light does not change when it undergoes reflection.

2. You should set your camera for a distance of 4 m. The situation is equivalent to your standing 2 m in front of an open window and viewing your twin standing 2 m in back of the window.

29.4 Diffuse Reflection

When light is incident on a rough surface, it is reflected in many directions. This is called **diffuse reflection** (Figure 29–7). Although the reflection of each single ray obeys the law of reflection, the many different angles that light rays encounter in striking a rough surface cause reflection in many directions.

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 therefore may be polished for long wavelengths, but not polished for short wavelengths. The wire-mesh "dish" shown in Figure 29–8 is very rough for light waves, not mirrorlike at all. Yet for long-wavelength radio waves it is polished. It acts as a mirror to radio waves and is an excellent reflector. Whether a surface is a diffuse reflector or a polished reflector depends on the size of the waves it reflects.

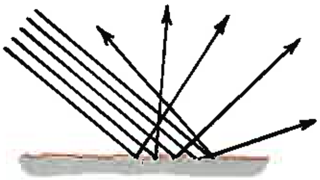

Fig. 29–7 Diffuse reflection from a rough surface.

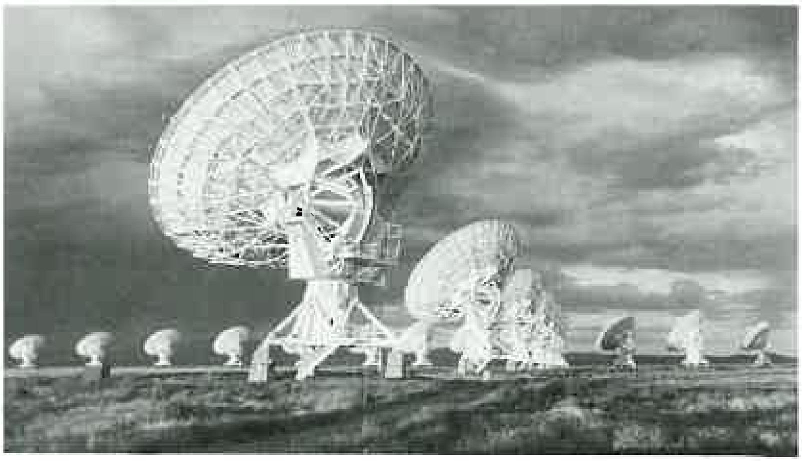

Fig. 29–8 The open-mesh parabolic dish acts like a diffuse reflector for light waves but like a polished reflector for long-wavelength radio waves.

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. This roughness is evident in the microscopic view of an ordinary paper surface (Figure 29–9). Rays of light incident on this page encounter millions of tiny flat surfaces facing in all directions. The light is therefore reflected in all directions. This is very nice, for it allows us to read the page from any direction or position. We see most of the things around us by diffuse reflection.

Fig. 29–9 A microscopic view of the surface of ordinary paper.

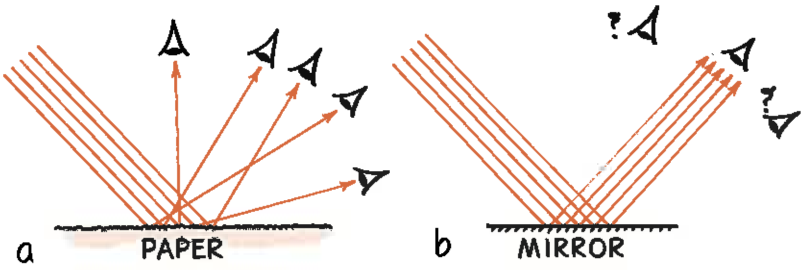

Fig. 29–10 (a) If you shine a beam of light on paper, you can see diffusely reflected light at any position. (b) However, your eye must be at the right place to see a reflected beam from a small mirror.

29.5 Reflection of Sound

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

Sound reflects from all surfaces—the walls, ceiling, floor, furniture, and people—of a room. Designers of interiors of buildings, whether office buildings, factories, or auditoriums, need an understanding of the reflective properties of surfaces. The study of these properties is the field of *acoustics*.

If the walls of a room, auditorium, or concert hall are too reflective, the sound becomes garbled. This is due to multiple reflections called **reverberations**. On the other hand, if the reflective surfaces are too absorbent, the sound level would be low, and the hall would sound 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.

The walls of concert halls are often designed with grooves so that the sound waves are diffused (Figure 29–11 top). 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 disks 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 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.

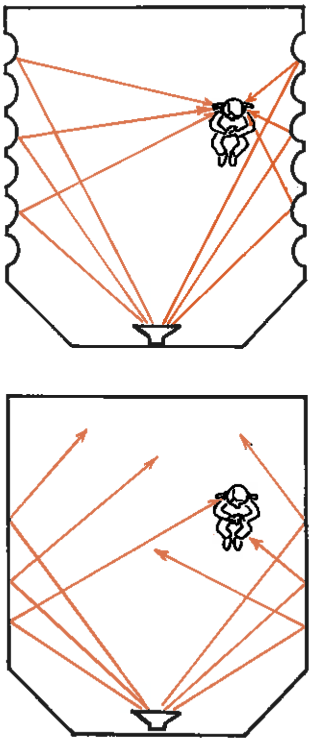

Fig. 29–11 (Top) With grooved walls, sound reflects from many small sections of the wall to a listener. (Bottom) With flat walls, an intense reflected sound comes from only one part of the wall.
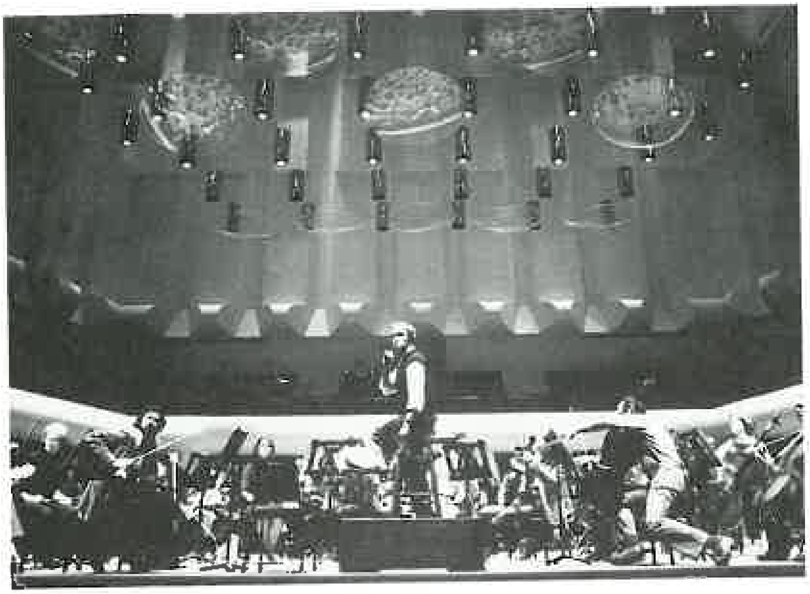
Fig. 29–12 The disks above the orchestra in Davies Symphony Hall in San Francisco reflect both light and sound. Adjusting them is quite simple: What you see is what you hear.

29.6 Refraction

Take a pair of wheels off an old toy cart and roll them along the pavement and onto a mowed lawn. They roll more slowly on the lawn because of the interaction of the wheels with the blades of grass. If you roll them at an angle (Figure 29–13), they will be deflected from their straight-line course. The direction of the rolling wheels is shown in the illustration. Note that on meeting the lawn, the left wheel is slowed down first. This is because it meets the grass while the right wheel is still rolling on the pavement. The wheels pivot, and the path is bent toward the normal (the dashed black line perpendicular to the grass-pavement boundary). They then continue across the lawn in a straight line at reduced speed.

Water waves similarly bend when one part of the waves is made to travel more slowly (or faster) than another part. This is **refraction**. Waves travel faster in deep water than in shallow water. Figure 29–14 left shows a view from above of straight wave crests (the bright lines) moving toward the top 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 that some reflection from the boundary is also taking place.

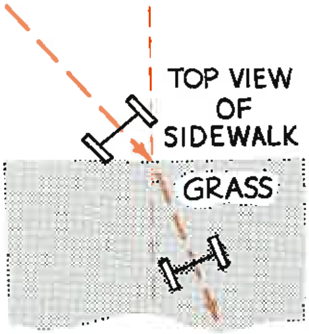

Fig. 29–13 The direction of the rolling wheels changes when one part slows down before the other part.

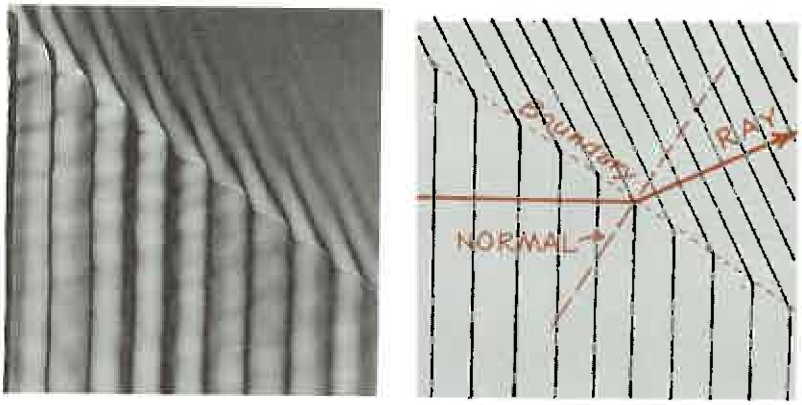

Fig. 29–14 (Left) Photograph of the refraction of a water wave at a boundary where the wave speed changes because the water depth changes. (Right) Diagram of wavefronts and a sample ray. The ray is perpendicular to the wavefront it intersects.

In drawing a diagram of a wave, as in Figure 29–14 right, it is convenient to draw lines that represent the positions of different crests. Such lines are called **wave fronts.*** 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 rays in Figure 29–14 right show 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.

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, for example, 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 (Figure 29–15). Sound waves therefore tend to bend away from warm ground, making it appear that the sound does not carry well.

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* Wave fronts also can be considered to represent the positions of different troughs—or any continuous portions of the wave that are all vibrating the same way at the same time.

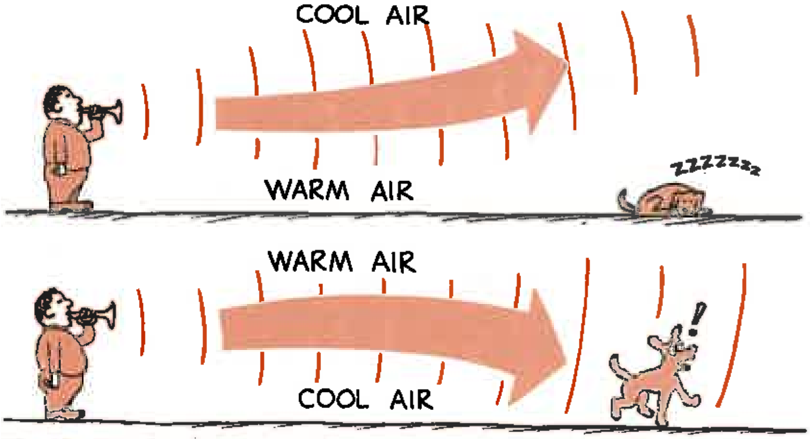

Fig. 29–15 The wave fronts of sound are bent in air of uneven temperature.

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. The higher speed of the wave fronts above cause a bending of the sound toward the earth. When this happens, sound can be heard over considerably longer distances.

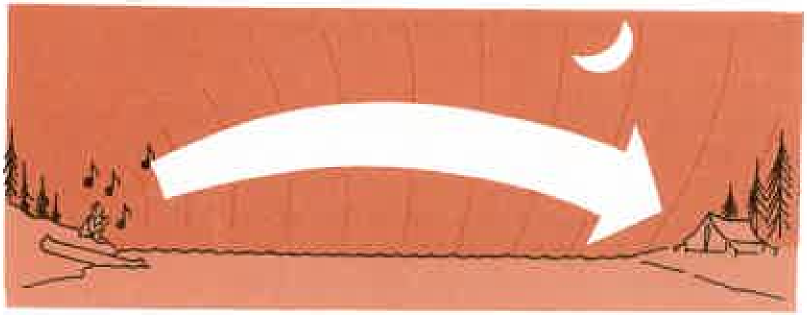

Fig. 29–16 At night, when the air is cooler over the surface of the lake, sound is refracted toward the ground and carries unusually well.

▶ **Question**

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**

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. If the wind speed were greater near the ground, the refraction would be upward.

29.8 Refraction of Light

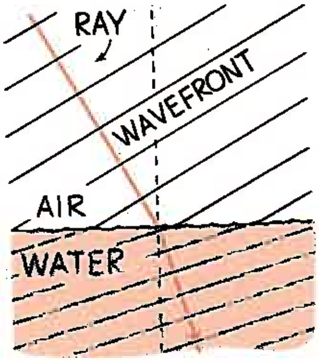

Fig. 29–17 As a light wave passes from air into water, its speed decreases. Note that the refracted ray is closer to the normal than is the incident ray.

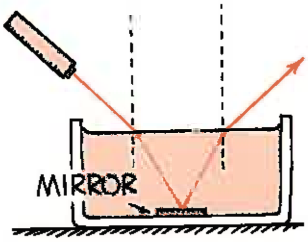

Fig. 29–18 The laser beam bends toward the normal when it enters the water, and away from the normal when it leaves.

A pond or swimming pool both appear shallower than they are. A pencil in a glass of water appears bent, the air above a hot stove shimmers, and the stars twinkle. These effects are caused by the change in the speed of light and hence the change in the direction of light when it passes from one medium to another. In other words, these effects are due to the refraction of light.*

Figure 29–17 shows rays and wave fronts of light that is refracted as it passes 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. 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 cart wheels in Figure 29–13. When light enters a medium in which its speed decreases, the rays bend toward the normal. But when light enters a medium in which its speed increases—as when light passes from water into air—the rays bend away from the normal (Figure 29–18).

Note that the path of light shown in Figure 29–18 would be the same if the light were shone into the water where it now exits. 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 you should know that the person can see you by that device also.

As Figure 29–19 left shows, a thick pane of glass appears to be only two thirds its real thickness when viewed straight on. (For

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* The ratio n of the speed of light in vacuum to the speed in a given material is called the *index of refraction* of that material.

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

The quantitative law of refraction, called *Snell's law*, was first worked out in 1621 by W. Snell, a Dutch astronomer and mathematician. According to Snell's law,

$$n \sin \theta = n' \sin \theta'$$

where n and n' are the indices of refraction of the media on either side of the boundary, and θ and θ' are the respective angles of incidence and refraction. If three of these values are known, the fourth can be calculated from this relationship.

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. Look at a fish in water from a bank, and the fish appears to be nearer the surface than it really is (Figure 29–19 right). It will also seem closer. These effects are due to the refraction of light whenever it crosses the boundary between air and another transparent medium.

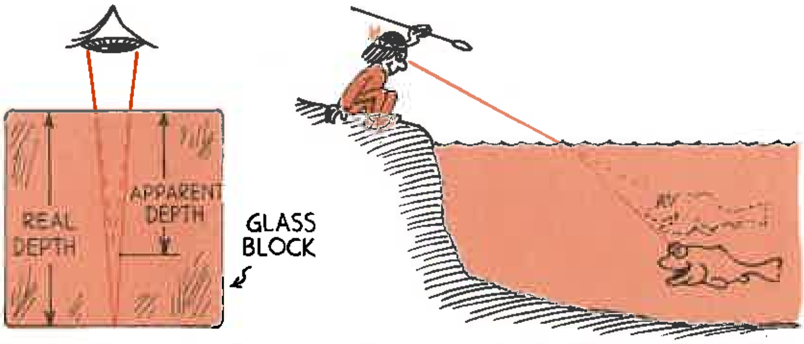


Fig. 29–19 Because of refraction, the apparent depth of the glass block is less than the real depth (left), and the fish appears to be nearer than it actually is (right).

29.9 Atmospheric Refraction

Although the speed of light in air is only 0.03 percent less than its speed in a vacuum, there are situations in which atmospheric refraction is quite noticeable. One of the most interesting occurs in the **mirage**. On hot days there may be a layer of very hot air in contact with the ground. Since the molecules in hot air are farther apart, the light travels faster through it than through cooler air above. The speeding up of the part of the wave nearest the ground produces a gradual bending of the light rays. The tree in Figure 29–20 would appear upside down (as well as right-side-up) 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.

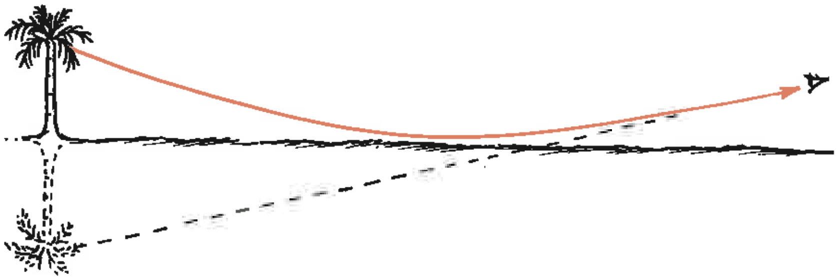


Fig. 29–20 The refraction of light in air produces a mirage.

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.

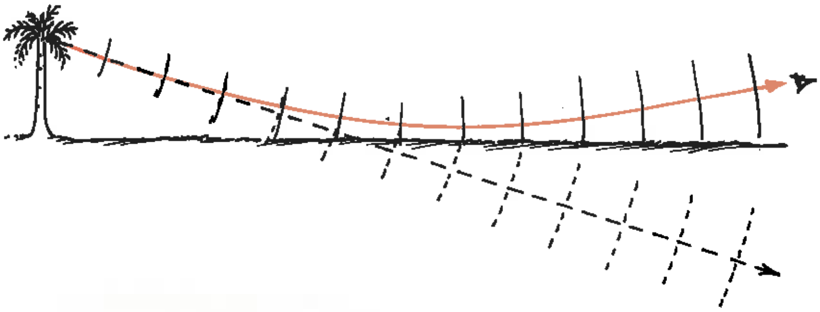


Fig. 29–21 Wave fronts of light travel faster in the hot air near the ground, thereby bending the rays of light upward.

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." A mirage is formed by real light and can be photographed (see Figure 29–22).

Fig. 29–22 A mirage.

When you see shimmering images in air over a hot pavement or hot stove, you are seeing the effects of atmospheric refraction. The speed of light alters as it travels through varying temperatures of air. The twinkling of stars in the nighttime sky is produced by variations in the speed of light as it passes through unstable layers in the atmosphere.

Whenever 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 the earth's atmosphere (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.

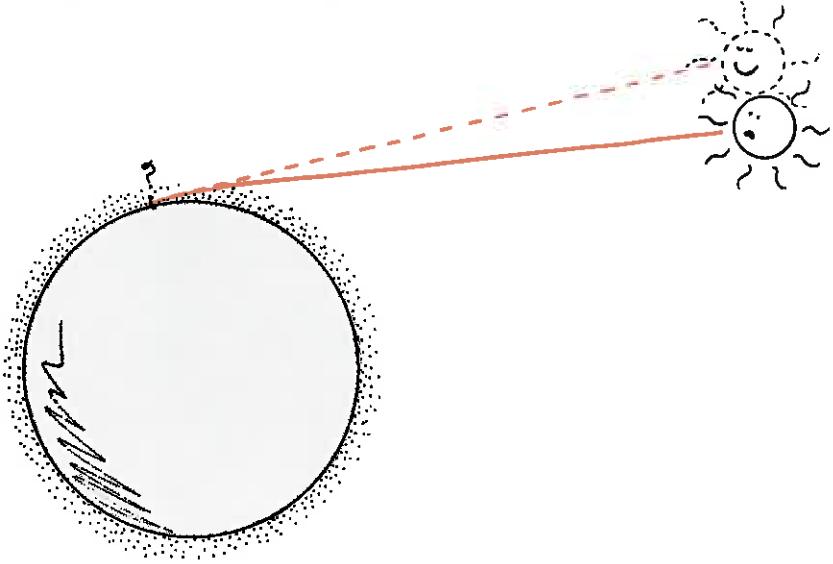


Fig. 29–23 When the sun is already below the horizon, you can still see it.

Fig. 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 (Figure 29–24).

▸ **Question**

If the speed of light were the same in the various temperatures and densities of air, would there still be mirages, slightly longer daytimes, and a pumpkin sun at sunset?

▸ **Answer**

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

29.10 Dispersion in a Prism

Chapters 27 and 28 discussed how the 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 travel more slowly in the medium. This is because in the process of absorption and re-emission, there is more interaction with the medium. 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 travels about 1 percent more slowly in ordinary glass than red light. The colors between red and violet travel at their own 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 is called **dispersion** (Figure 29–25).

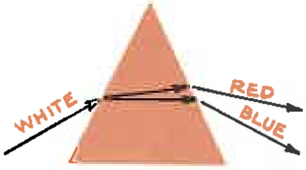
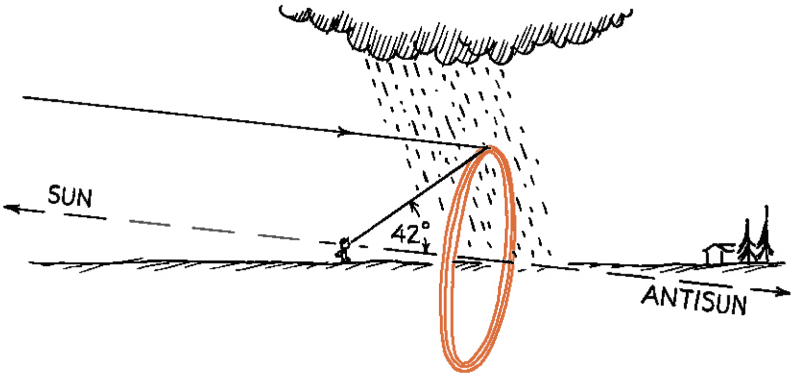


Fig. 29–25 Dispersion through a prism.

29.11 The Rainbow

A spectacular illustration of dispersion is the rainbow. The conditions for seeing a rainbow are that the sun be shining in one part of the sky and that rain be falling in the opposite part of the sky. When you turn your back to the sun, you see the spectrum of colors in a bow. From an airplane the bow may form a complete circle. The colors are dispersed from the sunlight by thousands of tiny drops that act like prisms.

Fig. 29–26 The rainbow is seen in a part of the sky opposite the sun and is centered around the imaginary line extending from the sun to the observer.



To understand how light is dispersed by raindrops, 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 water. 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.

Each drop disperses a full spectrum of colors. An observer, however, is in a position to see only a single color from each drop (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°.

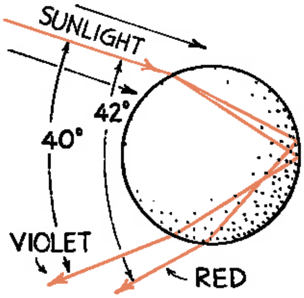


Fig. 29–27 Dispersion of sunlight by a single drop.

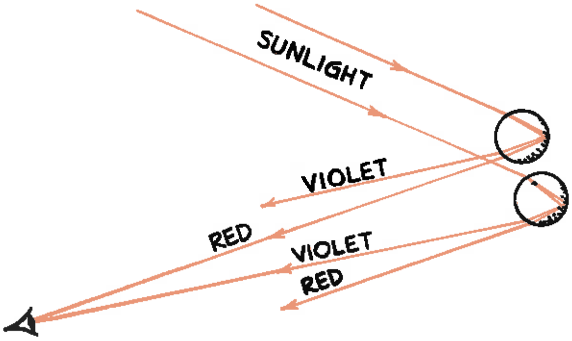


Fig. 29–28 Sunlight strikes two sample drops and emerges as dispersed light. The observer sees red from the upper drop and violet from the lower drop. Millions of drops produce the whole spectrum.

You don't need to look only upward at 42° to see dispersed red light. You could see red by looking sideways at the same angle or anywhere along a circular arc swept out at a 42° angle (Figure 29–29). 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.

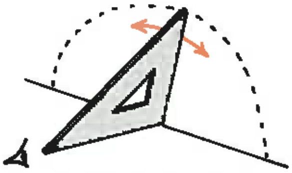


Fig. 29–29 Only raindrops along the dashed arc disperse red light to the observer at a 42° angle.

A secondary rainbow larger than the primary rainbow can often be seen. The colors are reversed for the secondary bow, with violet on the outside and red on the inside. The secondary bow is formed by similar circumstances and is a result of double

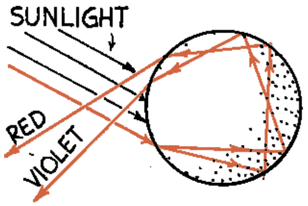


Fig. 29–30 Double reflection in a drop produces a secondary bow.

reflection within the raindrops. Because some light is refracted out the back during the extra reflection, the secondary bow is much dimmer.

▶ **Question**

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

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. Put the bathroom light out. 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.

At a certain angle, called the **critical angle**, you'll notice that the beam no longer emerges into the air above the surface. Instead, it grazes the surface. For water, the critical angle is 48° between the incident ray and the normal to the surface. When the flashlight is tipped beyond the critical angle, you'll notice that the beam cannot enter the air; it is only reflected. The beam is experiencing **total internal reflection**. The only light emerging from the water surface is that which is diffusely reflected from the bottom of the bathtub.

Figure 29–31 shows the refraction and reflection of light for different angles of incidence. The proportions of light refracted and reflected are indicated by the relative lengths of the solid arrows. Note that 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 29–32, 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.

▶ **Answer**

No.

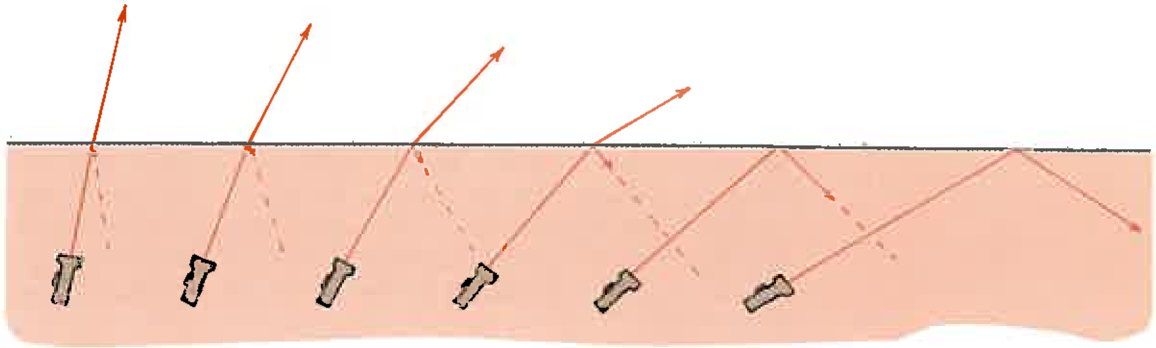


Fig. 29–31 Light emitted in the water at angles below the critical angle is partly refracted and partly reflected at the surface. At the critical angle (second sketch from right), the emerging beam skims the surface. Past the critical angle (far right), there is total internal reflection.

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 they are used instead of mirrors in many optical instruments.

The critical angle for a diamond is 24.6°, smaller than any other known substance. This small critical angle means that light inside a diamond is most likely to be totally internally reflected. All light rays more than 24.6° from the normal to a surface in a diamond stay inside by total internal reflection. 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. That's why you see unexpected flashes from a diamond. A small critical angle plus the pronounced refraction because of the unusually low speed of light in diamond produce wide dispersion and a wide array of colors with less overlap between adjacent colors. The colors seen in a diamond are therefore more brilliant.

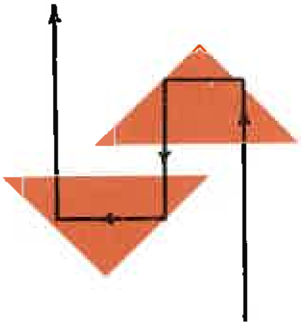


Fig. 29–32 Total internal reflection in glass prisms.

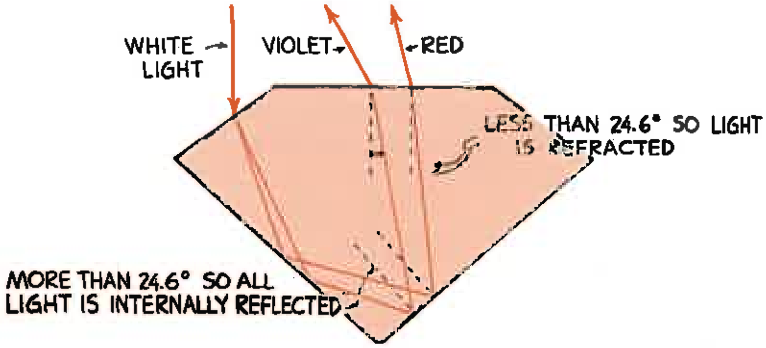


Fig. 29–33 Paths of light in a diamond.

Total internal reflection underlies the usefulness of **optical fibers**, which have been called *light pipes*. As the name implies, these transparent fibers pipe light from one place to another. They do this by a series of total internal reflections, much like the ricocheting of a bullet down a steel pipe. Optical fibers are useful for getting light to inaccessible places. Mechanics and machinists use them to look at the interior of engines, and physicians use them to look inside a patient's body. Light shines down some of the fibers to illuminate the scene and is reflected back along others.

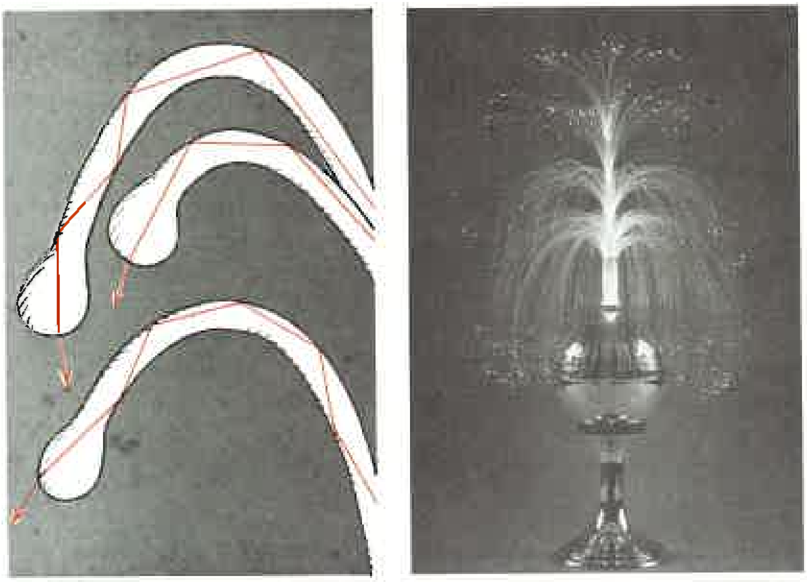


Fig. 29–34 In an optical fiber, light is piped from one end to the other by a succession of total internal reflections.

Optical fibers are important in communications because they are more efficient than copper wire or coaxial cable. In many cities, thin glass fibers have replaced thick, bulky, and expensive copper cables to carry thousands of simultaneous telephone messages between major switching centers. More information can be carried in the short wavelengths of visible light than in the vibrations of electric current. Optical fibers are more and more replacing electric circuits in communications technology.

29 Chapter Review

Concept Summary

In reflection, a wave reaches the boundary between two media and bounces back into the first medium.

- At a boundary, usually part of a wave is reflected and part passes into the second medium.
- According to the law of reflection, the angle of incidence is equal to the angle of reflection.
- A plane mirror forms a virtual image of an object; the image appears to be as far in back of the mirror as the object is in front of it, and is the same size as the object.
- Light that falls on a rough surface is reflected diffusely.
- The field of acoustics is concerned with how different surfaces reflect sound.

In refraction, a wave reaches the boundary between two media and changes direction as it passes into the second medium.

- Refraction is caused by a difference in the speed of the wave in the two media.
- The speed of light in materials depends on frequency, causing different colors of white light to refract differently and spread out to form a visible spectrum.

In total internal reflection, a wave is incident on a boundary at an angle such that none of the wave can be refracted and there is reflection only.

Important Terms

angle of incidence (29.2)
angle of reflection (29.2)
critical angle (29.12)
diffuse reflection (29.4)
dispersion (29.10)
law of reflection (29.2)
mirage (29.9)
normal (29.2)
optical fiber (29.12)
reflection (29.1)
refraction (29.6)
reverberation (29.5)
total internal reflection (29.12)
virtual image (29.3)
wave front (29.6)

Review Questions

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? (29.1)

2. Why do smooth metal surfaces make good mirrors? (29.1)

3. When light strikes the surface of a pane of glass perpendicularly, how much light is reflected and how much is transmitted? (29.1)

4. What is meant by the normal to a surface? (29.2)

5. What is the law of reflection? (29.2)

6. When you view your image in the mirror, how far behind the mirror is your image compared to your distance in front of the mirror? (29.3)

7. Does the law of reflection hold for *curved* mirrors? (29.3)

8. Does the law of reflection hold for diffuse reflection? Explain. (29.4)

9. What is meant by the idea that a surface may be polished for some waves and rough for others? (29.4)

N 10. Distinguish between an echo and a reverberation. (29.5)

11. Does the law of reflection hold for both sound waves and light waves? (29.5)

12. Distinguish between reflection and refraction. (29.1, 29.6)

13. When a wave crosses a surface at an angle from one medium into another, why does it "pivot" as it moves across the boundary into the new medium? (29.6)

14. What is the orientation of a ray in relation to the wave front of a wave? (29.6)

15. Give an example where refraction is abrupt, and another where refraction is gradual. (29.6–29.7)

16. Does refraction occur for both sound waves and light waves? (29.7–29.8)

17. If light had the same speed in air and in water, would light be refracted in passing from air into water? (29.8)

18. If you can see the face of a friend who is underwater, can your friend also see you? (29.8)

19. Does refraction tend to make objects submerged in water seem shallower or deeper than they really are? (29.8)

20. Is a mirage a result of refraction or reflection? Explain. (29.9)

21. Is daytime a bit longer or a bit shorter because of atmospheric refraction? (29.9)

22. As light passes through glass or water, do the high or low frequencies of light interact more in the process of absorption and reemission, and therefore lag behind? (29.10)

23. Why does blue light refract at greater angles than red light in transparent materials? (29.10)

24. What conditions are necessary for viewing a rainbow in the sky? (29.11)

25. How is a raindrop similar to a prism? (29.11)

26. What is meant by the *critical angle* in terms of refraction and total internal reflection? (29.12)

27. Why are dispersed colors so brilliant in a diamond? (29.12)

28. Why are optical fibers often called *light pipes*? (29.12)

Activities

1. Stand a pair of mirrors on edge with the faces parallel to each other. Place an object such as a coin between the mirrors, and look at the reflections in each mirror. Neat?

2. What must be the minimum length of a plane mirror in order for you to see a full view of yourself? To find out, stand in front of a mirror and put 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 to your height. If a full-length mirror is not handy, put pieces of tape on a smaller mirror where you see the top of your head and the bottom of your chin.

3. What effect does your distance from the plane mirror have in the answer to Activity 2? (*Hint:* Move closer and farther from your initial position. Be sure that the top of your head lines up with the top piece of tape. How does the bottom alignment compare? At greater distances, is your image smaller than, larger than, or the same size as the space between the pieces of tape allow? Surprised?)

Think and Explain

1. Why are metals generally shiny?

2. When light strikes glass perpendicularly, about 4% is reflected at each surface. How much light is transmitted through a pane of window glass?

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

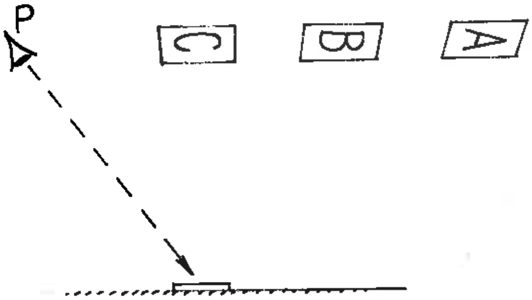


Fig. A

4. 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?)

5. Why is the lettering on the front of some vehicles "backward" (see Figure B)?

Fig. B

6. Suppose you walk toward a mirror at one meter per second. How fast do you and your image approach each other? (The answer is *not* one meter per second.)

7. 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.

8. 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?

9. A bat flying in a cave emits a sound and receives its echo in one second. How far away is the cave wall?

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

11. 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.

12. 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.

30 Lenses

A light ray bends as it enters glass and bends again as it leaves. The bending, or refraction, is due to the difference in the speed of light in glass and in air. Glass of certain shapes can form images which appear larger, smaller, closer, or farther than the object being viewed. Magnifying glasses have been used for centuries and were well known to the early Greeks and medieval Arabs. Today, eyeglasses allow millions of people to read in comfort, and cameras, projectors, telescopes, and microscopes widen our view of the world.

30.1 Converging and Diverging Lenses

If a piece of glass has just the right shape, it can bend parallel rays of light so that they all cross—or appear to have crossed—at a single point. A piece of glass that does this is called a **lens**.

The special shape of a lens can be understood by considering a lens to be a large number of portions of triangular prisms (Figure 30–1). When arranged properly, the prisms refract incoming parallel rays so they converge to (or diverge from) a single point. The arrangement shown at the left is thicker in the middle and converges the light. The arrangement at the right, however, is thinner in the middle than at the edges; it diverges the light.

Fig. 30–1 A lens may be thought of as a set of prisms that converge light (left) or diverge light (right).