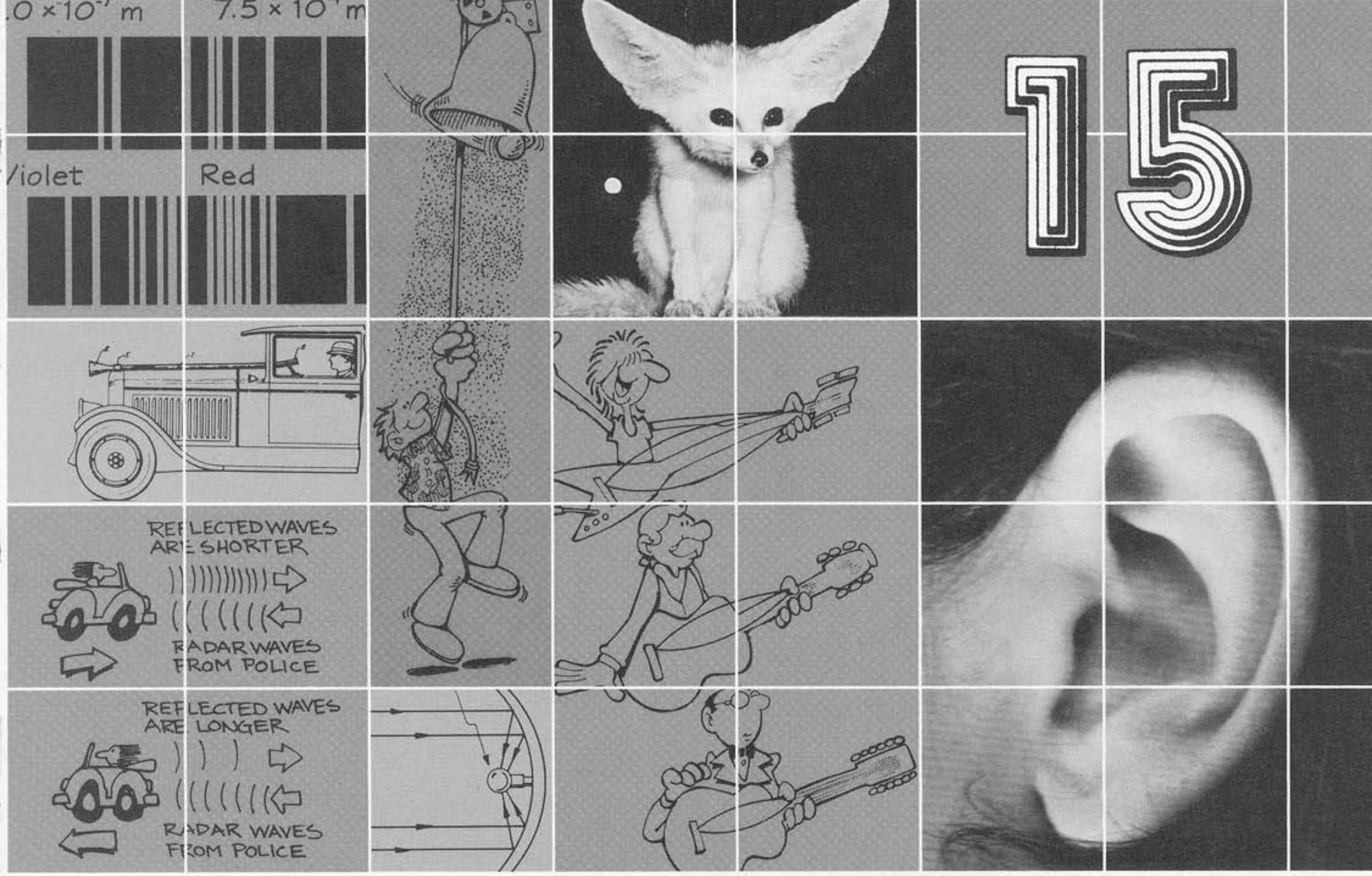


15

Waves: Sound and Electromagnetic

After sitting in the sun for several hours, you have a sunburn. So, you decide to get a cold drink and relax in front of the television. As you sit down, you hear your roommate shout and the refrigerator door slam. (You left it open again!) In spite of the jackhammer vibrating the house and everything in it as it breaks up the concrete on the street outside, you try to relax while watching the evening news. Following a report on a new design for police radar comes the details of the destruction from yesterday's earthquake and tsunami. Whew! Perhaps you could relax better if you popped some corn in the microwave oven.

Sunburn, television, sound, jackhammer vibrations, radar, earthquakes, tidal waves, and microwaves. Each of these phenomena involves the transfer of energy from a source to a receiver without a transfer of matter. Each can be described in terms of the wave model developed in Chapter 14. Frequency and wavelength distinguish sound from earthquakes, radar from sunlight. Reflection, refraction, superposition, and resonance describe the behavior of sound and light as effectively as they described our observations of springs and water waves. The photographs and sketches of springs and water waves serve as guides as we construct mental images of phenomena we can sense but not necessarily see.

We begin by looking at the two major categories of wave phenomena: *mechanical waves* and *electromagnetic waves.* By ordering waves according to frequency, the *wave spectrum* organizes the different types of waves within each of these categories. For each wave category, we will describe phenomena due to reflection, refraction, absorption, standing waves, and the Doppler effect. *Sound* will be used to illustrate mechanical waves. *Light, microwaves,* and *radar* will illustrate electromagnetic waves.

WAVE CLASSIFICATION

Sunburn, television, sound, jackhammer vibrations, radar, earthquakes, tsunami, and microwaves—some of these phenomena are easier to imagine than others. Jackhammers and earthquakes shake the ground and the ground shakes you. You can watch tsunami waves move across the ocean. Even sound seems quite real as you strum a guitar and feel the vibrating strings. By contrast, other phenomena seem more abstract. It is hard to imagine how energy travels from the sun to our bodies, from the television tower in the next city to that box in the living room, from the police car to your car. Light, television signals, radar, and microwaves seem almost magical. The two categories of waves, mechanical and electromagnetic, reflect our sense of the concrete and the abstract.

Mechanical Waves

Sound, jackhammer vibrations, earthquakes, and tsunamis are all examples of mechanical waves, waves created when chunks of matter—vocal chords, jackhammers, rock, or water—vibrate. This matter collides with other matter, which collides with other matter, and so forth, as the disturbance is transmitted through the surrounding material. **Mechanical waves** can be produced and transmitted by matter in any form: solid, liquid, or gas. Table 15-1 lists several examples of mechanical waves, common sources of each, and whether these waves are transverse, longitudinal, or both.

The various kinds of mechanical waves differ in the frequencies at which they commonly occur. If you count water waves as they strike the beach, you find that they rarely exceed a frequency of one per second, or 1 hertz (Hz). Earthquakes and jackhammers produce waves in the ground that range from 1 to about 50 Hz. Vibrations that produce sound audible to the human ear range from 20 to 20,000 Hz. Dogs hear sounds at still higher frequencies.

We can arrange these frequencies in order from low to high, in a classification scheme called a **wave spectrum.** Figure 15-1 shows the wave spectrum for mechanical waves. Mechanical waves with frequencies below those of audible sound are called *infrasonic waves* and include the water waves and earthquakes discussed in the last chapter. Mechanical waves at frequencies

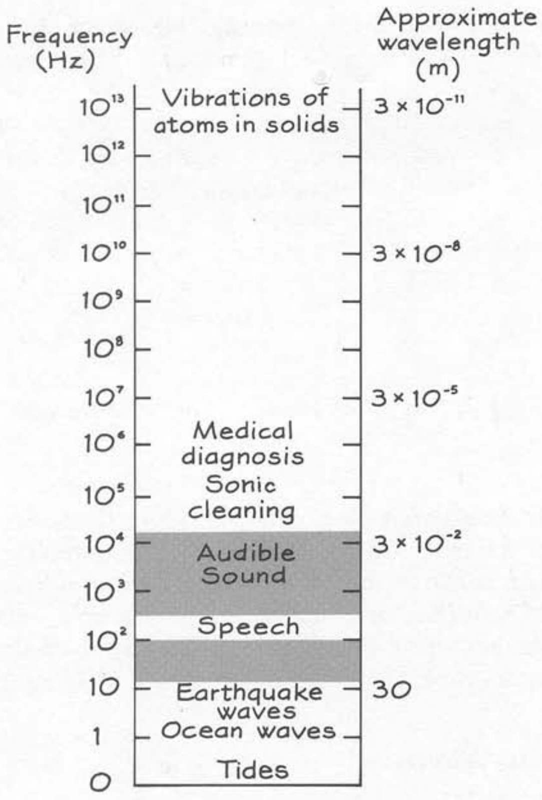


Figure 15-1
Mechanical wave spectrum.

Table 15-1 Examples of Mechanical Waves

Type of Wave	Source	Longitudinal/Transverse
Water waves	Objects thrown in water; wind-water interaction	Transverse on surface; longitudinal below surface
Earthquake waves	Sudden fault movement in earth	Transverse and longitudinal
Sound	Vibrations of certain objects, including musical instruments and vocal chords	Longitudinal
Ultrasound	Vibrations of certain objects, such as bats' vocal chords and ship sonar	Longitudinal

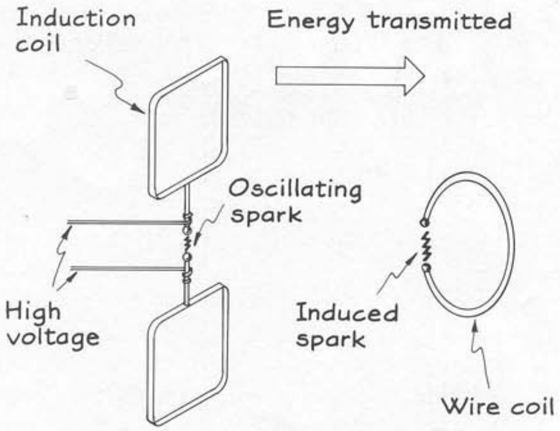


Figure 15-2

An oscillating spark at the left induces a similar spark on the right. Oscillating electrical charges produce electromagnetic waves.

larger than audible sound are called *ultrasonic waves*. These waves have found wide application in industry—welding, cleaning, and detecting flaws in a variety of materials. Ultrasonic imaging is used in medicine, primarily in situations where X rays are ineffective or dangerous. (For example, ultrasound is used to examine the development of a fetus.) Wavelengths, estimated from the media that usually transmit each kind of wave, are included in Figure 15-1.

Electromagnetic Waves

In the 1880s Heinrich Hertz performed a series of experiments with electricity and magnetism. Using a device called an induction coil, he became adept at producing vibrating electric charges, commonly called sparks, across an air gap. Near this oscillating spark Hertz placed a coil of wire, which also had a

Table 15-2 Examples of Electromagnetic Waves

Type of Wave	Vibrating Charged Source	Longitudinal/Transverse
Radio, television	Charges in an antenna	Transverse
Microwave	Molecules	Transverse
Infrared	Atoms	Transverse
Visible light	Atoms	Transverse
Ultraviolet	Atoms	Transverse
X rays	Electrons	Transverse
Gamma rays	Atomic nuclei	Transverse

small air gap (Figure 15-2). Each time a spark occurred across the induction coil, a spark was produced across the wire coil as well. Energy had been transmitted from one coil to the other, although no mass had been transferred. Our interpretation of this phenomenon is that oscillating electrical charges produce waves.

Light, television signals, radar, and microwaves are all examples of **electromagnetic waves,** waves created by vibrating electric charges. These charges can be a single charged particle like an electron or a chunk of electrically charged matter like an atom or molecule that has a net electric charge. One electric charge can affect another at a distance, even when there is no matter between them. Consequently, electromagnetic waves are transmitted through empty space as well as through matter. Light waves from the sun, for example, cross millions of kilometers of emptiness before reaching us. Table 15-2 lists several examples of electromagnetic waves and common sources of each type. As shown in the table, all electromagnetic waves are transverse.

Electromagnetic waves range in frequency from less than 100 Hz (radio waves) to more than a million million million times this amount (gamma rays). Figure 15-3 shows the complete electromagnetic wave spectrum. Visible light, perhaps the most famous member of the spectrum, actually occupies an extremely narrow range of frequencies. It extends from the lower frequencies of red light (4.5×10^{14} Hz) to the higher frequencies of violet light (7.5×10^{14} Hz). Differences we perceive as **color** are, in fact, differences in frequency. Like mechanical waves, electromagnetic waves travel at different speeds in different materials. However, in a vacuum all electromagnetic waves travel at 3×10^8 meters per second (m/s) (commonly called the speed of light). Wavelengths for electromagnetic waves in a vacuum are included in Figure 15-3.

SELF-CHECK 15A

Use Figures 15-1 and 15-3 to estimate the frequencies of human speech and of microwaves. What, besides frequency, is different about these two kinds of waves?

Wave Receivers

All waves transfer energy from a source to a receiver, but some receivers are more sensitive than others. Our eyes and photographic film detect visible light but seem unaffected by the shorter wavelengths in microwaves. A television antenna absorbs the longer waves emitted by a television station but virtually ignores the shorter wavelengths of visible light. Microwaves can pop corn, while gamma rays cannot.

To understand why receivers are more sensitive to some wavelengths than others, consider an example using water waves. Suppose you are sitting in a fishing boat that is 2 meters (m) long. While you are fishing, a water wave

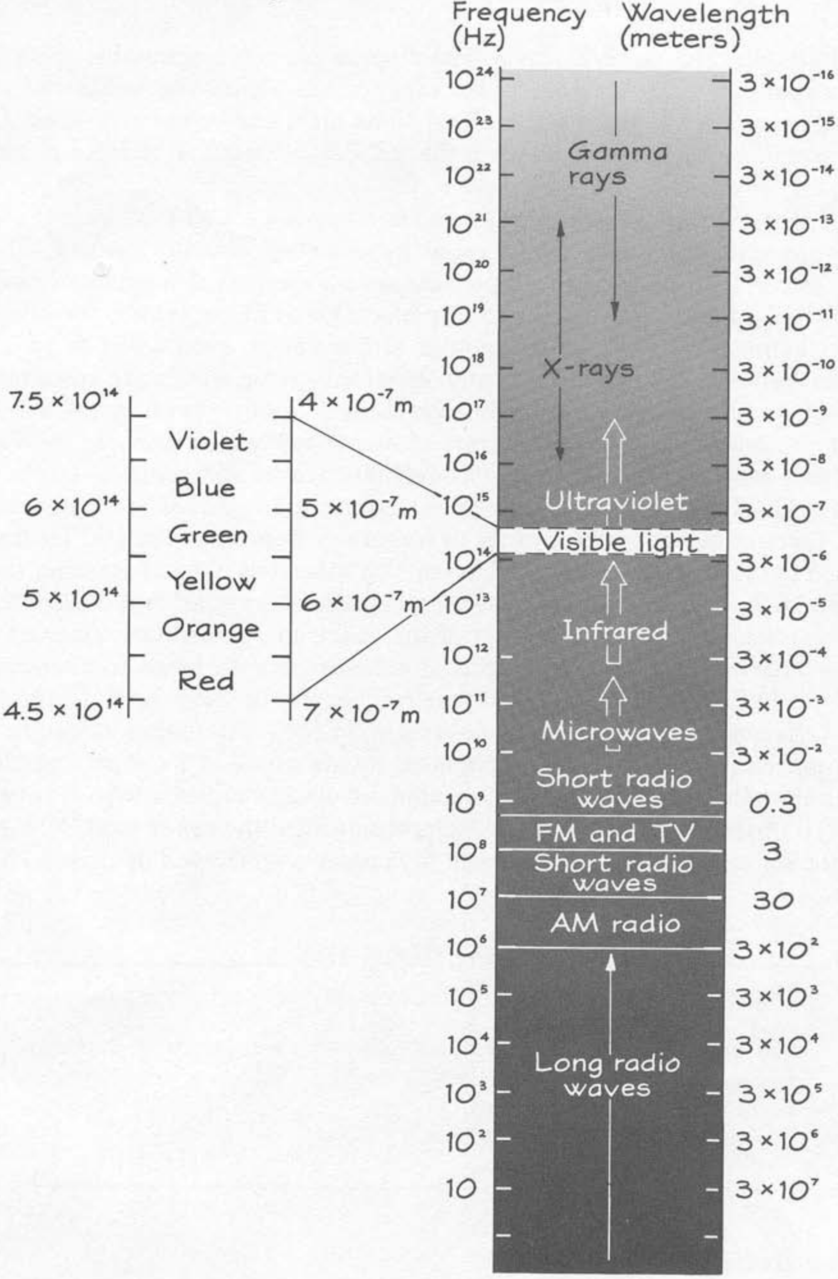


Figure 15-3
Electromagnetic wave spectrum.

with a wavelength of 20 m passes beneath you (Figure 15-4(a)). Your boat slowly rises and falls with the wave. Since the wavelength of the water waves is much longer than your boat, chances are your fishing will not be interrupted much. A wave with a 10-m wavelength will be only slightly more noticeable, while waves that are 4 to 5 m long will become apparent (Figure 15-4(b)). When the wavelength of the wave is approximately equal to the length of the fishing boat, fishing becomes virtually impossible (Figure 15-4(c)). The bow of the boat oscillates as every wave passes by. If the water waves become

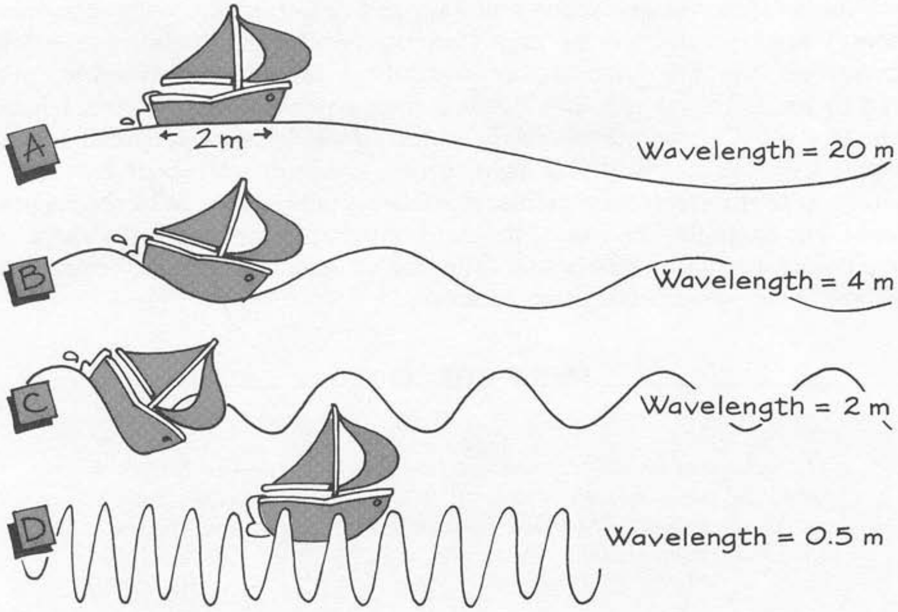


Figure 15-4

The closer the length of the boat is to the wavelength of the waves, the more easily it detects the waves.

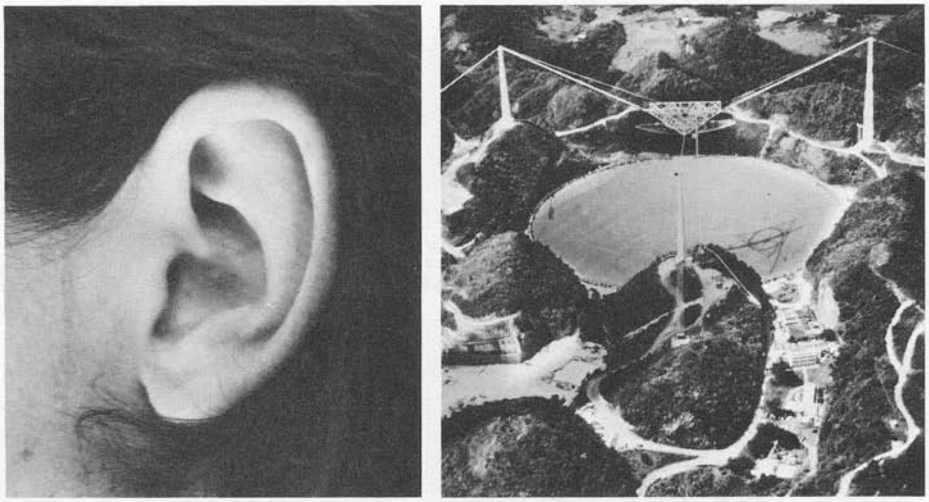


Figure 15-5

considerably shorter than the boat, the boat floats along the top of the crests (Figure 15-4(d)) and the waves again pass unnoticed. You notice only the waves whose wavelength is close to the length of the boat.

If we think of the fishing boat as an energy receiver, its behavior can be explained in terms of resonance. The bow of the boat oscillates more when the water waves push in time with its natural frequency. This natural frequency depends, in part, on the length of the boat. Consequently, waves that are about the same length as the energy receiver oscillate at frequencies near the natural frequency of the receiver. To be most effective, a wave detector needs to be about the same size as the wavelength of the waves it is to detect. Several examples are shown in Figure 15-5.

Radio antennae are about 1 m long and detect waves that range from about 1 m to several meters long. Microwave detectors are at most a few centimeters long and detect waves of about the same length. When we proceed to electromagnetic waves of very short wavelengths, we cannot build detectors small enough. Fortunately, nature does! Infrared radiation is best detected by molecules. Visible light, with wavelengths of about 8×10^{-7} meters, is best detected by atoms. A similar analysis applies to mechanical waves. For example, the size of the eardrum is appropriate for the range of frequencies we call audible sound. The size of detectors is closely related to the size of the wavelength being received.

SELF-CHECK 15B

The directions for installing automobile radio antennae frequently instruct the owner to set the antenna differently for FM reception than for AM reception. Why? Use Figure 15-3 to determine which would need the longer antenna, FM or AM.

SOUND

Pleasant music soothes us, unexpected noises frighten us, the roar of the crowd excites us. Friends recognize us by our voices. Sound waves may well be the most familiar type of wave we experience. While sound is not the only way to communicate, it carries a large fraction of our thoughts, feelings, and opinions. We need only compare the social barriers faced by the deaf with those encountered by the blind to realize how much human beings depend upon this form of wave motion.

Historically, sound was one of the first phenomena to which the wave model was successfully applied. The spread of sound in all directions from a source was likened to the spread of circular water waves from a pebble dropped into a quiet pond. Early interest in musical instruments contributed enormously to our understanding of standing waves and resonance. The concepts and images used to describe water and mechanical waves in a spring prove valuable in understanding the behavior of sound.

Describing Sound Waves

A bell is placed inside a jar to which a vacuum pump has been attached. Initially the jar is filled with air and we hear the bell ringing. The jar is then sealed and the pump begins removing the air inside it. Gradually, the sound dies out. Although we can still see the clapper as it pounds away on the bell, we can no longer hear any sound. Sound requires a medium.

Sound waves are longitudinal waves, capable of traveling through solids, liquids, and gases. We imagine atoms and molecules to be evenly spaced in matter, much like the evenly spaced coils in a spring. When a bell rings, its motion alternately compresses (squeezes together) and rarefies (pulls apart) the molecules in the surrounding air. A series of compressions and rarefactions travels through the air (Figure 15-6), much as compressions traveled in the spring. Each molecule vibrates parallel to the direction in which the sound energy is transmitted. When the compressions and rarefactions reach your ear, they establish vibrations in the eardrum that are eventually transformed into nerve impulses sent on to the brain.

The speed of sound has been measured in a variety of materials, some of which are listed in Table 15-3. Since wave speed depends on the medium, the speed of sound varies considerably in different materials. The speed of sound in air increases as the temperature of the air increases. At high temperatures the air molecules move rapidly and transfer the wave energy to their neighbors more quickly than at low temperatures. Sound travels progressively faster as we move from gases to liquids to solids because of the stronger restoring forces. The stronger the molecular bond, the more rapidly the motion of one molecule influences the next. Sound waves travel most rapidly in solids.

We describe sounds in terms of loudness and pitch. **Loudness** refers to our perception of the amount of energy carried by the sound wave. Consequently, it is related to the amplitude of the wave. As the energy carried by the sound wave increases, so does the amount by which molecules are compressed in each disturbance. **Pitch** describes how we perceive frequency or

Figure 15-6
A vibrating bell produces a series of compressions and rarefactions that travel to your ears.

Table 15-3 Speed of Sound in Various Materials

Material	Speed of Sound (m/s)
Gases (0°C)	
Carbon dioxide	259
Oxygen	316
Air	331
Helium	965
Liquids (25°C)	
Mercury	1450
Water	1498
Seawater	1531
Solids	
Rubber	1800
Lead	2100
Gold	3000
Glass	5000-6000
Granite	6000

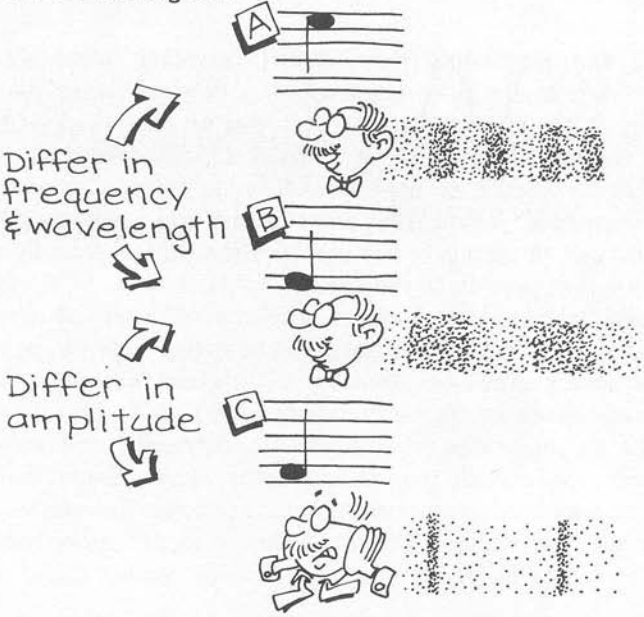


Figure 15-7

The sound in **(c)** has a larger amplitude than the sound in **(b).** The sound in **(a)** has a higher frequency and shorter wavelength than the sound in **(b).**

wavelength. A higher-pitched sound has a higher frequency and shorter wavelength than a lower-pitched sound. (Sound waves of differing amplitude, frequency, and wavelength are shown in Figure 15-7.)

Sound Waves in Matter

"Hello" you shout as you stare up at the surrounding canyon walls. "Hello" comes the echo back to you. "Hey, turn down that radio!" comes a familiar yell—funny how your neighbors always complain more in the evening than during the day. "I can't hear you through that ski mask" you tell a friend as you get on the lift. Like water waves, sound waves can be reflected, refracted, and absorbed as they move from one material to another.

Reflected waves have the same wavelengths as incident waves, but they travel in the opposite direction—back toward the energy source. Echoes reveal these characteristics. Your echo sounds similar to your voice; its energy is simply traveling back toward you rather than away from you. Sound can be reflected from any hard surface, from the walls in a hallway as well as the walls in a canyon. However, your ear can distinguish the echo as being separate from the original sound only when the original and reflected waves reach your ears at least 0.1 second (s) apart. In most buildings, the reflected waves reach your ear more quickly. Consequently, the reflections mix with the original waves, contributing to what we call the *brightness* of a sound instead of producing an echo.

A less well known application of sound reflection is the use of curved surfaces to focus sound. Figure 15-8 shows waves reflected by a curved barrier. Energy carried by the entire wave front is reflected to a single point, called the **focal point.** Sound waves behave in much the same fashion (Figure 15-9). Curved surfaces used in a directional microphone focus the incoming sound waves, allowing the microphone to pick up more sound. Ears, both

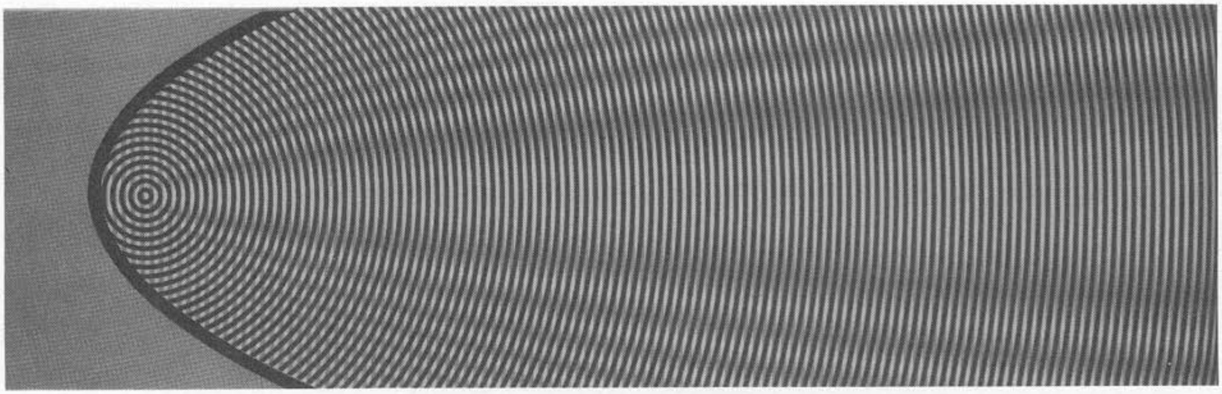


Figure 15-8

Waves reflected from a curved surface can be focused to a single point, called the focal point.

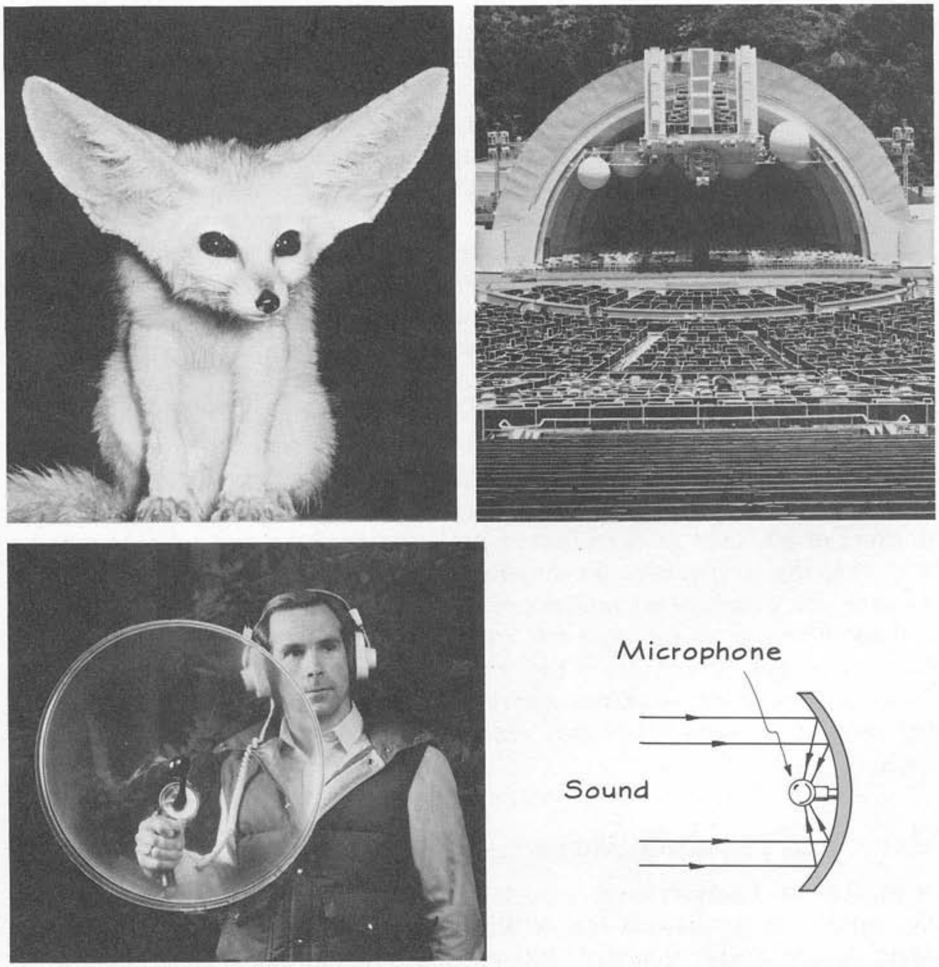


Figure 15-9

Directional microphones and ears take advantage of curved reflectors.

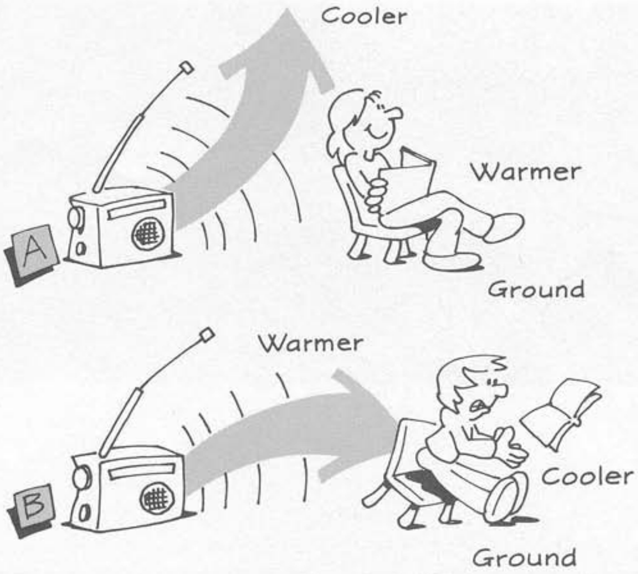


Figure 15-10
Sound waves are refracted **(a)** upward during the day and **(b)** downward at night.

human and animal, are shaped to focus as much sound as possible on the eardrum. In outdoor amphitheaters orchestras are often placed in front of a curved reflecting surface to direct more sound back toward the audience.

Since the speed of sound in air varies with the air temperature, sound is often refracted by the atmosphere. During the day, the air near the ground is warmed more than the upper levels. Since sound travels more quickly in warm air than in cool air, sound waves are gradually refracted upward (Figure 15-10(a)). At night, the reverse occurs. Air near the ground cools more rapidly and sound waves are refracted downward (Figure 15-10(b)). Refraction enables sound to travel farther along the ground at night than during the day. There is an explanation for your neighbor's complaints!

Waves are absorbed when the energy stored in the disturbance is dissipated into thermal energy found in the motion of molecules within matter. Though sound waves are easily transmitted through air, pockets of air within solids act as extremely effective sound absorbers. Sound waves enter the pockets of air, only to be reflected back and forth by the solid boundaries enclosing the air pockets. Eventually, the organized vibrations of the wave become the disorganized motions of the air molecules. Sound has been absorbed. Acoustic tiles designed to muffle room noise are made from porous foam or loosely woven fibers that create many such air pockets. Rugs and foam rubber are also excellent absorbers of sound. Architects take the absorbing properties of materials into account in designing buildings and concert halls.

Music and Standing Waves

A small-necked bottle stands under a dripping water faucet. Each time a drop hits the bottle, it makes a sound. When the bottle is empty, the pitch of the sound is low; but as the bottle fills up, the pitch becomes higher. As the air space above the water shortens, the pitch of the sound rises.

Figure 15-11
Which instrument produces lower frequency sounds?

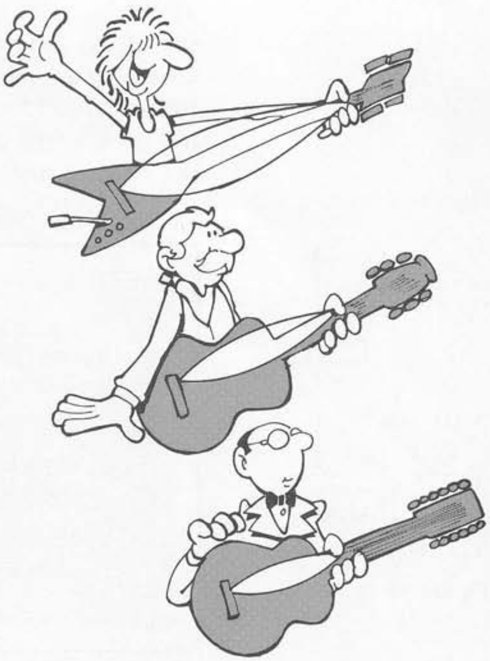


Figure 15-12
As the string gets shorter, the wavelength associated with the fundamental frequency decreases. The shorter the string, the higher the pitch produced.

Musical instruments display the same relationship between length and pitch. Without ever hearing them, you know that the instrument on the left in Figure 15-11 can play lower notes than the one on the right. Within a family of instruments like the string family, the longer bass viols have a range that extends much lower than the shorter violins. This relationship between the size of the instrument and pitch can be explained in terms of standing waves and resonance.

Consider how different pitches are produced on a single string. To vary the pitch of a string, a guitarist presses the string against the guitar neck at different points, thereby changing the length of the string that is free to vibrate when plucked. A guitar string vibrates in much the same way as the spring we discussed in Chapter 14. Both ends of the string are fixed, one at the bottom where the string is tied off and the other wherever the guitarist places his or her finger. When the guitarist plucks the string, standing waves are produced at the resonant frequencies characteristic of that length string. These standing waves cause the wooden body of the guitar to vibrate, causing the air within it to vibrate, and eventually causing a sound wave to be transmitted to your ears. The sound we hear can ultimately be traced back to the standing waves possible in the guitar string.

The fundamental frequency produced in a guitar string varies with the length of the string (Figure 15-12). Since one-half of a standing wave is the minimum wavelength that can fit in each length of string, the wavelength associated with the fundamental frequency is twice the length of the string. As the string gets shorter, this wavelength gets shorter. Since frequencies increase as wavelengths decrease, short strings must have higher fundamental frequencies than longer strings. As the guitarist moves his or her fingers along the neck of the guitar, he or she lengthens and shortens the string to produce the desired pitch.

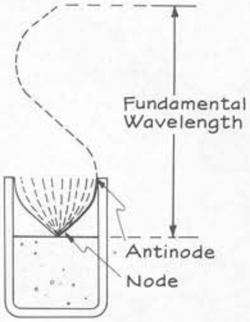


Figure 15-13

SELF-CHECK 15C

The standing waves produced in a bottle are somewhat different than those in a guitar string. Instead of nodes at each end, the bottle allows a node at the water level and an antinode at the open end, as shown in Figure 15-13.

a. How is the wavelength of the fundamental frequency related to the length of the air column above the water?

b. How does the fundamental frequency change as the bottle fills up with water? Does this match your experience?

The analysis can be extended to wind instruments. Trumpets and sousaphones, for example, are long tubes that for convenience have been folded up about themselves. Air inside the tubes can be made to vibrate in a standing wave pattern with a node at the mouthpiece end and an antinode at the bell. Valves are used to change the lengths of the air columns. Since trumpets are made from much shorter tubes than sousaphones, their range of frequencies extends higher.

While the fundamental frequency in a violin string or air column is the dominant pitch we hear, other pitches are often present simultaneously. In a violin string, for example, the only constraint on the standing waves is that they have nodes at each end. A number of different frequencies satisfy this requirement. When a string vibrates, many frequencies are produced simultaneously but at different amplitudes. These vibrations are picked up by the wooden sound box, which further augments or diminishes their amplitudes to produce a sound wave in air that is relatively complex. Figure 15-14 contrasts the contributions of the lowest two frequencies for a violin and piano when each is playing the A above middle C. These different contributions lead to significantly different waveforms (Figure 15-15). While pianos and violins can play the same pitch, they do not produce the same sound waves. Differences in the higher frequencies establish the quality of the sound, the characteristic that enables us to distinguish one instrument from another.

The Sound of a Siren

WHEEE . . . OOOH—As the ambulance speeds by, its siren goes from a higher pitch to a lower one. Our most common experience with the Doppler

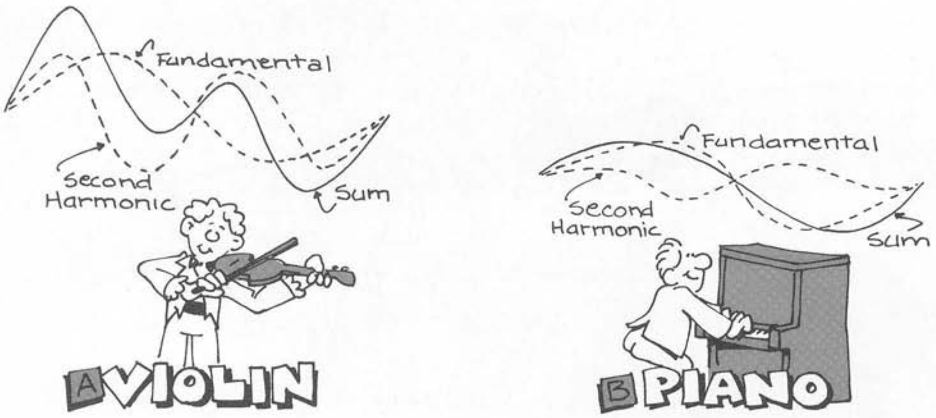


Figure 15-14

The sound we hear depends on the amplitude of the harmonics. **(a)** For a violin, the amplitude of the second harmonic is the same as the fundamental. **(b)** For a piano, the amplitude of the second harmonic is tiny compared to the amplitude of the fundamental. These differences produce two very different looking waves.

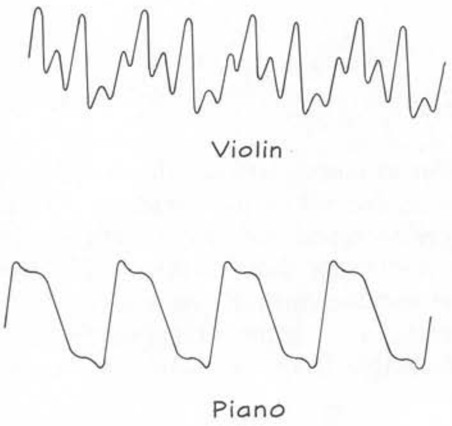


Figure 15-15

Two very different looking waves lead to two very different sounding sounds. Here the piano and violin play the same pitch!

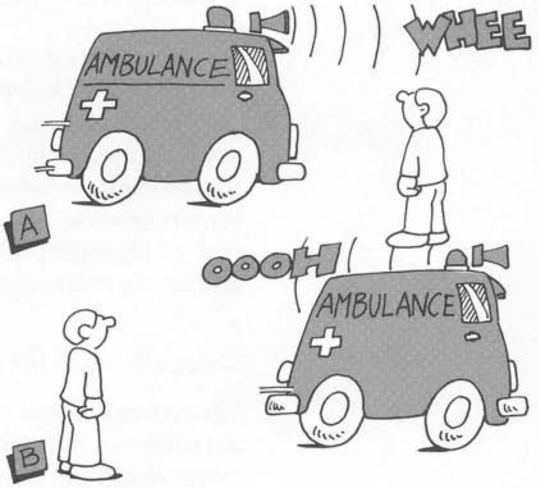
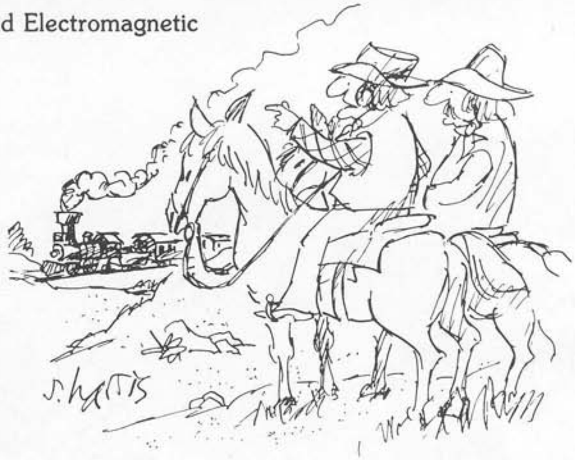


Figure 15-16

The frequency of the sound we hear depends on the velocity at which the ambulance travels.

effect occurs with sound. A drawn-out note like an ambulance siren or train whistle changes pitch as it travels past a stationary observer. Compared to the single note it produces when the ambulance is stationary, the siren sounds higher as the ambulance approaches the observer and lower as it moves away from the observer.

Like the water waves described in Chapter 14, sound waves are affected by the motion of the source or receiver. As the source moves toward the receiver, the sound wave compressions become more closely spaced and the receiver hears a higher pitch than that being emitted by the source. As the source recedes, the compressions are more widely spaced, and the receiver hears a lower pitch (Figure 15-16). The frequency of the sound we hear depends on the relative velocity between the source and ourselves.



"I LOVE HEARING THAT LONESOME WAIL OF THE TRAIN WHISTLE AS THE MAGNITUDE OF THE FREQUENCY OF THE WAVE CHANGES DUE TO THE DOPPLER EFFECT."

ELECTROMAGNETIC WAVES

All wave motion is defined as the transfer of energy without the transfer of matter. Nevertheless, mechanical waves do depend on the presence of matter. A bell clanging in a vacuum produces no sound. Electromagnetic waves are different—they do not depend on matter for their existence. Light is transferred continuously between the sun and the earth. Radio and television signals provide astronauts a link with home. X rays, gamma rays, visible light, and radio waves continually bring us messages from the stars, crossing an emptiness more vast than we can imagine.

Describing Electromagnetic Waves

Electromagnetic waves are created by vibrating electric charges. A vibrating electron can induce vibrations in another electron, which in turn induces vibrations in yet another electron, and so forth. Energy, but no mass, is transferred from one electron to another. Because electrical interactions occur at a distance, this energy can be transferred across empty space (as well as across matter). Electromagnetic waves are very hard to imagine.

To provide a medium analogous to water for water waves or air for sound waves, physicists use the concepts of electric and magnetic fields. Electrically charged objects create an electric field around themselves. This field describes their ability to influence other charged objects across empty space. When the object vibrates, it produces a disturbance that moves through this electric field, much as a water wave moves across water. When the disturbance in the field reaches another charged object, it can induce that object to vibrate. In a sense, electric fields provide us with a way of picturing the empty space surrounding the charged objects and the way in which energy can be transferred between them.

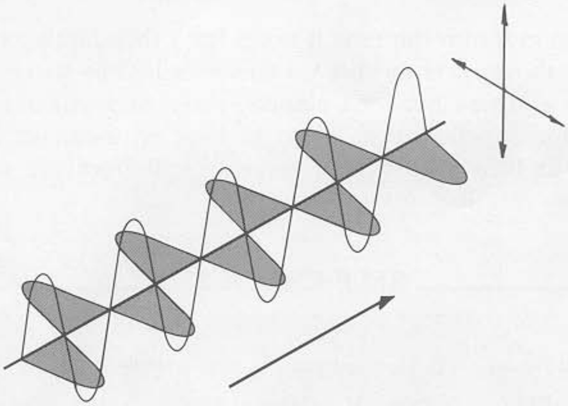


Figure 15-17

Two fields, one electric and the other magnetic, vibrate at right angles to one another as an electromagnetic wave is transmitted in the third direction. All electromagnetic waves are transverse.

Electromagnetic waves are actually a result of both electric and magnetic fields. A moving electrical charge produces a magnetic field and an electric field. This magnetic field can influence another moving electrical charge in yet a different way than the electrical field. Consequently, two disturbances are actually propagated—one through the electric field and a second through the magnetic field. Physicists picture electromagnetic waves in terms of changes in these two fields, as illustrated in Figure 15-17. The energy transferred by the wave travels perpendicular to the direction in which either field vibrates. All electromagnetic waves are transverse.

In a vacuum, all electromagnetic waves travel at the same speed—3×10^8 m/s, or 186,000 miles per second. In matter, electromagnetic waves travel at somewhat lower speeds. Like sound, light travels at different speeds in air at different temperatures. Representative speeds are included in Table 15-4. For distances on earth, these speeds are enormous. Consequently, electromagnetic waves seem to us to travel instantaneously from one point to

Table 15-4 Speed of Light in Various Materials

Material	Speed of Light (m/s)
Vacuum	2.998×10^8
Air	2.997×10^8
Liquids (20°C)	
Water	2.250×10^8
Glycerine	2.040×10^8
Carbon disulfide	1.840×10^8
Solids	
Ice	2.290×10^8
Quartz	1.940×10^8
Crown glass	1.970×10^8
Diamond	1.240×10^8

another. We can measure the time it takes for a thunderclap to reach us, but the lightning flash appears to take no time at all. Only when we look at distances as large as those between planets, stars, and galaxies does the finite speed of electromagnetic waves begin to take on meaning. Light from the moon reaches us in a little over a second; light from the sun, in about 8 minutes.

SELF-CHECK 15D

The nearest star, Alpha Centauri, is 4.2×10^{16} m away. If we received a radio message from Alpha Centauri today, how long ago would it have been sent?

Light in Matter

Our young son has just realized that there is not another baby in the mirror. He reaches out and finds the cold hard surface of the glass rather than the soft skin he expected. The hiker has just realized that the lake in the distance is a mirage. With each step he takes, the lake fades farther into the distance. You left your bicycle in the sun again—its black seat is hot. Reflection, refraction, and absorption describe the behavior of electromagnetic waves as effectively as they describe waves in sound and water.

We see most objects by virtue of reflected light. Light from a lamp strikes the table, for example, and is reflected to our eyes. Light waves moving parallel to one another before striking the table are reflected in all directions (Figure 15-18). Within this apparent chaos lies the information our eye-brain system uses to tell us that we are looking at a table. Light reflected by each point along the table's surface obeys the law of reflection—the angle of reflection equals the angle of incidence. The uneven, bumpy surface of the table offers a different angle of incidence at each point. Consequently, the pattern of reflected waves carries information about each and every point on the table's surface—information we learn to interpret in a fraction of a second.

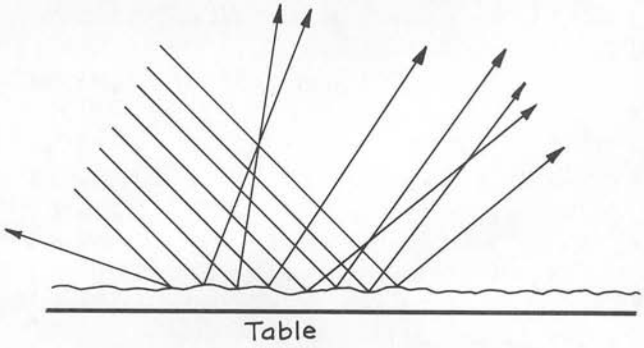


Figure 15-18

The bumps in the reflecting surface affect the way in which parallel rays of light are reflected. Each surface creates a unique pattern of reflected waves.

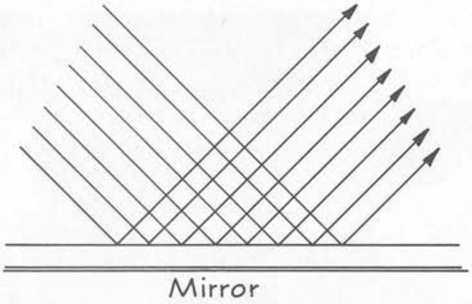


Figure 15-19

Mirror surfaces are so smooth that parallel rays of light remain parallel to one another after reflection. The mirror imposes no pattern of its own on the reflected light.

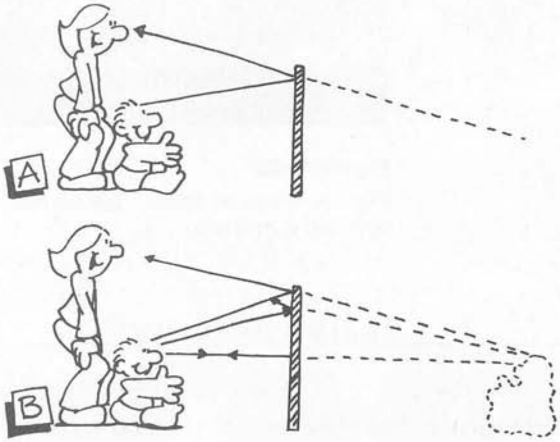


Figure 15-20

Our eyes trace light along straight lines. A light ray reflected by a mirror appears to have come from behind the mirror, as shown by the dotted line. We see an image that appears to be behind the mirror.

Mirrors allow us to see the baby instead of the mirror because they make little impression of their own on the light waves. Light waves moving parallel to one another before striking the mirror are still parallel once they are reflected (Figure 15-19). The mirror surface is so smooth that it imposes little, if any, pattern on the light it reflects. Consequently, light that has first been reflected by a baby will still carry information about the baby when it is reflected by the mirror. We see the baby instead of the mirror.

The information reflected by the mirror creates an image of the baby that appears to be located behind the mirror. This arises from the way we interpret light's motion. Experience with light sources has led us to expect light to travel along straight lines. Figure 15-20(a) shows one path the light waves travel as they strike the baby's head and are then reflected by the mirror. As we gaze into the mirror, the reflected light seems to travel along a straight-line path that originates behind the mirror, as shown by the dotted line. Our eyes trace that straight-line path, not the real path traveled by the light. Light waves traveling along paths that diverge from a single point on the baby's head appear to be diverging from a point behind the mirror (Figure 15-20(b)). The image we see is formed at that point. The same is true for light emerging from all other points along the baby's body. Thus, a complete image is formed behind the mirror. Only with experience do we come to realize that we are seeing just an image and not the real object.

Figure 15-21
Light is refracted as it strikes the glass surface of a prism.

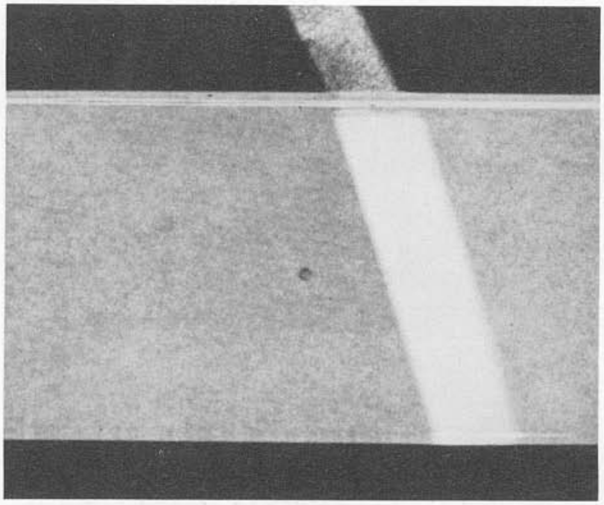


Figure 15-22
Light is refracted toward the normal as it enters the medium.

SELF-CHECK 15E

Advertisements describe the effectiveness of furniture waxes in terms of the clarity of the images you see. Explain how a wax can help turn a table into a mirror.

Figure 15-21 shows several narrow beams of light as they strike a prism. A small part of the light is reflected at the glass surface, but most is transmitted into the prism. Light that is perpendicular to the surface continues to travel along the same path. Light incident at other angles, however, bends. Light, like sound and water waves, is refracted as it moves from one medium to another. You have seen this phenomenon often in swimming pools: The submerged part of your body looks shortened, due to the bending of light as it emerges from the water into the air.

Like other wave phenomena, light waves are refracted due to the change in wave speed that occurs as waves enter new media. Light travels more slowly in glass than in air. If we trace a single beam of light (Figure 15-22), we see the light refracted toward the normal as it enters the medium and away from the normal as it moves back into the air. Light waves, however, display a characteristic called **dispersion.** The speeds at which light waves move in matter depend on their wavelengths. The differences are small, but sufficient to refract each wavelength of light at a slightly different angle. White light, a mixture of all wavelengths, is separated into its colors. Red light

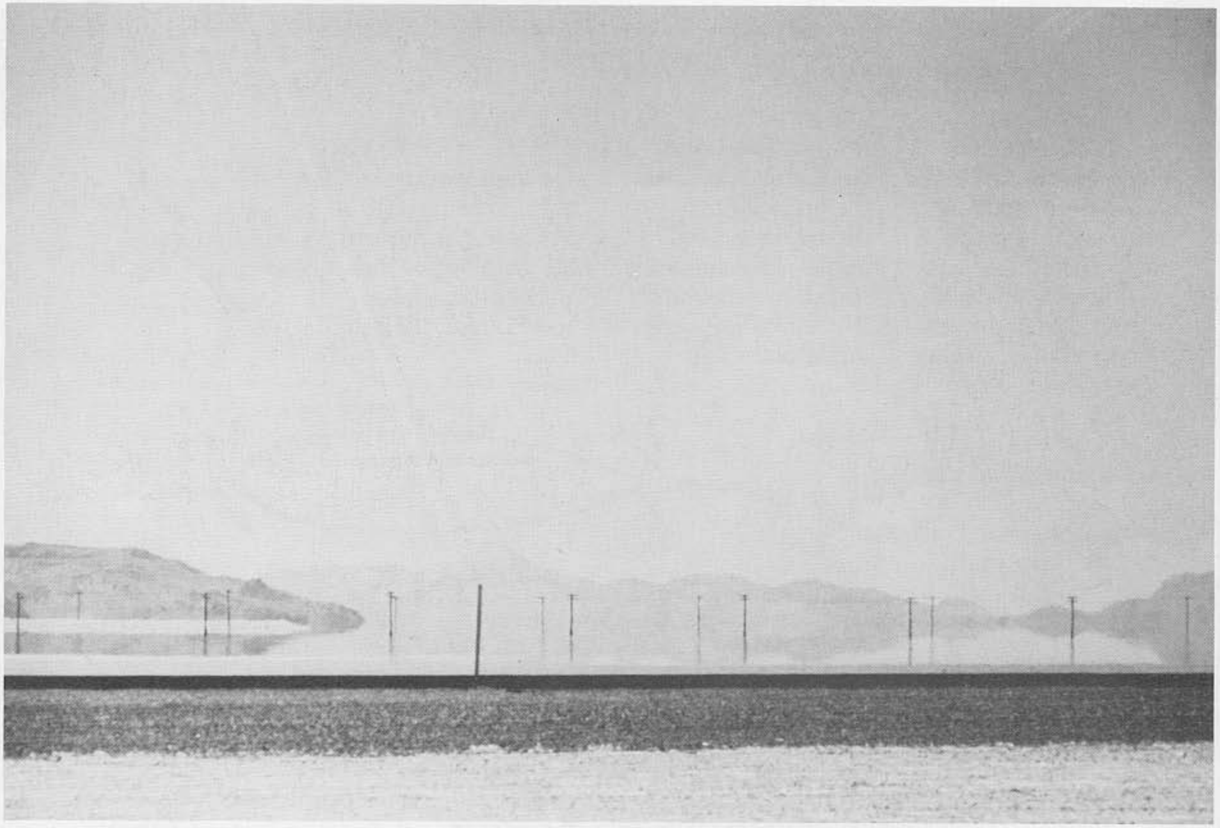


Figure 15-23

Mirages are formed when light from the sky is refracted upward by warmer layers of air. Our eyes trace the refracted light along straight lines, creating an image that appears to be located on the ground in front of us.

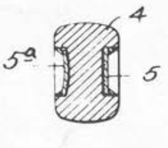
is refracted the least; violet light, the most. If we replace the prism with a drop of water, we have a rainbow!

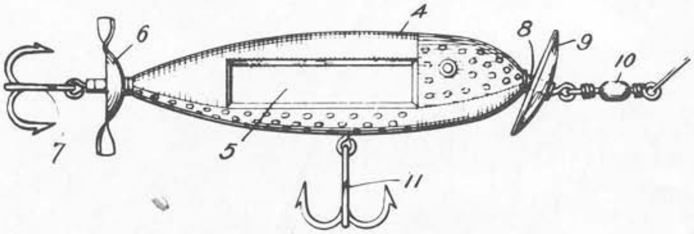
Like sound, light waves experience atmospheric refraction due to the fact that the speed of light in air increases as the temperature of air increases. Mirages are caused by this refraction. Air near the surface of hot sand is warmer than the air above it. Light traveling downward from the sky is refracted as it encounters warmer layers, until its path is actually bent back upward (Figure 15-23). Hikers see this reflected light and trace its path backward along a straight line to the ground. Seeing an image of the sky on the ground, they naturally assume it is a reflection from the surface of a lake. Drivers see the same effect as they drive along asphalt highways on hot, sunny days.

Electromagnetic waves are absorbed when the energy stored in the electromagnetic disturbance is dissipated into thermal energy. The hot bicycle seat provides us evidence of how effectively this process can occur. Infrared radiation and visible light have wavelengths that correspond roughly to the sizes of atoms and molecules. Consequently, the energy stored in and transmitted by these electromagnetic waves is easily transformed into the thermal energy associated with the motions of atoms and molecules. In Chapter 10 we called this process radiation-absorption.

"SEEING" THE BAIT

In 1916 William Zeigler thought of a way to use the law of reflection to catch a fish. His artificial fish bait looks similar to many others except for the mirror (5) in the middle. A fish would swim near the bait and see its own reflection. Thinking that another fish would grab the bait before it could, the fish would bite, thus becoming someone's dinner. The law of reflection tells us that the angle of incidence equals the angle of reflection, so fish approaching the mirror from any angle other than straight on would not see their own reflections. One must wonder, then, about why Mr. Zeigler put the hooks on the back and bottom of his bait.





Standing Waves in Microwave Ovens

Oops . . . you forgot to take the casserole out of the freezer. Guess you will have to use the microwave oven. You shove the casserole in, close the door, set the timer, and push the button. Twenty minutes later it is done—steam rises as you lift the casserole out of the oven. You take a huge helping from the center and take your first bite. Ugh! It is still cold. A quick check shows that the casserole is plenty hot around the outside but still cold in several spots near the center. What happened?

Microwave cooking, one of the more recent additions to kitchen technology, is based on the principle of wave absorption. Microwaves, with a frequency of about 2×10^9 Hz, stimulate the water and fat molecules in foods to vibrate. The thermal energy generated by these vibrations cooks the food, often in a fraction of the time required in a conventional oven. Glass and plastic containers, as well as the surrounding air, absorb very little of the energy carried by the microwaves, so most of the energy goes directly into the food being cooked. One of the major disadvantages, however, has been the uneven cooking typical of many oven designs.

You can understand this uneven cooking in terms of standing waves. Microwaves generated by most microwave ovens have a wavelength of about 13 centimeters. Consequently, three to four complete wavelengths can fit into the oven cavity. To prevent leakage of microwaves to the outside, the oven's interior is lined with metal, which is an excellent reflector. The waves emitted by the microwave source interfere with the waves reflected from the sides, and a standing wave pattern is produced. Energy is distributed unevenly

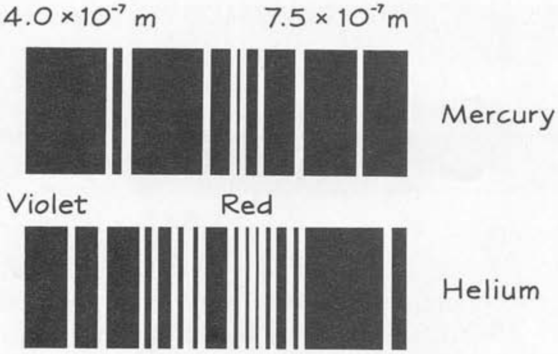


Figure 15-24

Light emitted by each chemical element has a light spectrum characteristic of that element.

about the oven's interior, with most of the energy concentrated at antinodes and little energy located at nodes. Your casserole's cold spot was located at a node.

Because of safety concerns, metal interiors are likely to remain an essential feature in microwave oven design. It would therefore be impractical to try to eliminate standing waves. Most recipes suggest rotating the food once or twice during cooking, thus rotating areas from nodes to antinodes for more even energy absorption. Some manufacturers have added rotating platforms that move the food continuously as it is being cooked. A second solution is to move the standing wave pattern itself. A rotating microwave source produces a standing wave pattern that moves about the food, moving nodes to different sections of the dish. Rotating fans have also been used. These fans reflect microwaves in continually changing directions, so that the standing wave patterns change as well.

The Expanding Universe and Police Radar

Electromagnetic waves, like mechanical waves, experience a shift in apparent frequency when either the source or the receiver is moving. This electromagnetic Doppler effect is used to measure the speeds of objects that are approaching or receding from us—objects as diverse as galaxies and automobiles.

For more than a century, astronomers have analyzed the light emitted by stars. The visible light emitted by a glowing gas, such as hydrogen or helium, is a mixture of different wavelengths. Each gas has its own characteristic mixture. When the light is passed through a prism, the different wavelengths are separated, creating a pattern characteristic of that gas, called its **line spectrum** (Figure 15-24). By comparing light from stars and galaxies with the spectra of known gases, astronomers can tell what chemical elements are present.

Astronomers found perplexing data when they analyzed light from very distant stars and galaxies. A spectrum would show all the lines characteristic

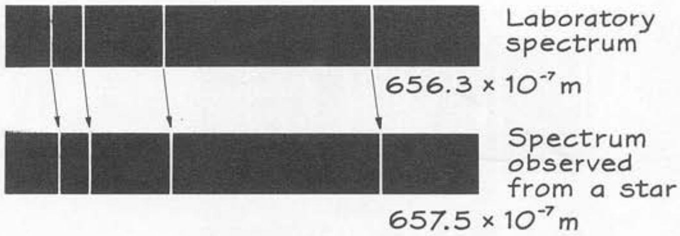


Figure 15-25

Light emitted by distant stars and galaxies shows shifts in frequencies characteristic of the Doppler effect. Astronomers believe that these shifts arise from the motion of stars and galaxies outward from the origin of the big bang.

of hydrogen, for example, but the lines were uniformly shifted to lower frequencies (Figure 15-25). Described in terms of wavelength, the lines were shifted toward the red end of the spectrum; thus the effect was called the **red shift.** The red shift is consistent with a model of the universe in which all galaxies are moving outward, away from one another. Like the sound of a train whistle as the train moves away from you, light is shifted toward lower frequencies as galaxies recede from us.

A more down-to-earth illustration of the electromagnetic Doppler effect is police radar. A police officer who wants to measure the speed of a car uses the shift in frequency of radar waves reflected by the moving car. Because of the car's motion, the reflected waves are shifted compared to the frequency emitted by the radar unit (Figure 15-26). By comparing the frequency of the radar emitted by the antenna with the frequency of the reflected waves, a computer built directly into the radar system can calculate the car's speed. As the car's speed increases, so does the magnitude of the shift in frequency.

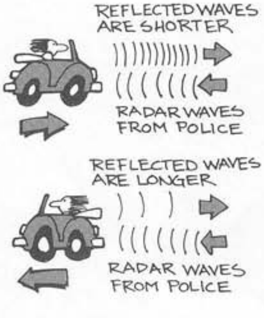


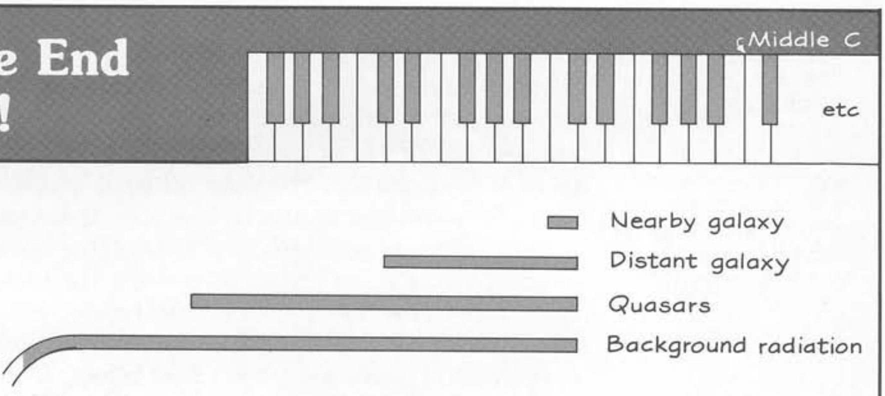
Figure 15-26

Police radar measures the speed of cars by looking at the shift in frequency of radar waves reflected by the moving car.

When the police car is stationary, the frequency change provides all the required information with which to calculate the car's speed relative to the ground. When both cars are moving, however, the frequency shift allows calculation only of the relative speed between the two cars. In order to determine the car's speed relative to the ground, moving radar units emit two signals. One is reflected by the moving car, allowing the radar unit to calculate the relative speed between the two cars. The second signal is reflected by the road and allows the radar unit to calculate the police car's speed relative to the ground. Given the two speeds, the computer can calculate the car's speed relative to the ground. From galaxies to automobiles, the Doppler effect allows us to measure the relative speed between objects.

The success of the wave model in describing a wide range of phenomena is indeed impressive. Starting with waves in springs and waves in water, we have been able to build mental pictures of sound and light waves. We cannot see the vibrations of atoms and molecules that combine to produce sound; but we can understand how sound behaves in terms of these vibrations. Wave reflection, refraction, and superposition provide an effective way of understanding echoes, sound transmission at night, and the design of musical instruments. We cannot see the electric and magnetic fields whose motions create electromagnetic waves, but we can understand how light, radar, and microwaves behave in terms of waves. Chapter 16 examines two additional wave phenomena—diffraction and interference—and their role in convincing physicists of the wave nature of light.

Right Off the End of the Piano!



If electromagnetic radiation could be emitted by playing a piano, the visible spectrum would occupy about one full octave. The Doppler shifts observed by astronomers can be huge—literally taking us right off the end of the piano!

Red shifts have proven enormously useful to astronomers, providing what seems to be profound evidence in support of the big-bang model of the universe (see Chapter 8). As we look deep into space, the extent of the red shift becomes staggering. It is hard to appreciate the size of these shifts, however, without a benchmark—a reference frame for comparison. Fortunately, the piano provides a useful analogy.

Suppose that a train whistle emits a pitch corresponding to middle C on the piano. As the train moves away from us at 25 m/s (90 kilometers per hour), its whistle sounds about one half-step (one note) lower to us than the sound emitted by the train. We hear B below middle C. For sound this shift is one of the larger Doppler shifts we encounter. Most are far less. To hear a shift of a full octave, for example, the train would have to move about 500 kilometers per hour. Most ordinary objects do not move at such high speeds. For astronomers, however, Doppler shifts of light can be this large or even larger. Let's compare their observations with the more familiar shifts observed for sound.

We do not normally think of electromagnetic radiation in terms of octaves. However, for comparisons involving the Doppler shift, such a construct is quite useful. A musical octave ranges from one frequency to twice that frequency. Middle C, for example, has a frequency of 256 Hz. The C below middle C has a frequency of 128 Hz. In the electromagnetic spectrum, visible light has a range equivalent to about one octave (4×10^{14} Hz to 8×10^{14} Hz). Above and below this octave, we would find the other forms of electromagnetic radiation.

Consider the red shifts observed by astronomers. Beginning close to home, nearby galaxies emit light that is red-shifted about one step or so. The light drops in frequency by one note on our electromagnetic piano. As we progress to more distant galaxies, the red shift becomes larger. The farthest galaxies that have been observed so far have a red shift equivalent to the change of an octave. These shifts indicate that distant galaxies are moving away from us at speeds of about 6×10^7 m/s. If we look still deeper in space, the most distant quasars have red shifts equivalent to a couple of octaves. They are moving away from us at enormous speeds—up to 90% of the speed of light.

In 1965 Arno Penzias and Robert Wilson detected radio waves that seemed to come from even deeper in space. This radiation is coming to us from all directions, so we call it *background radiation*. Its red shift is so large that it falls right off the end of our piano! Presumably released at the time of the big bang itself, this radiation and its red shift hold clues to events that occurred an estimated 20 billion years ago.

CHAPTER SUMMARY

Wave phenomena can be separated into two categories: mechanical waves and electromagnetic waves. *Mechanical waves* are produced in matter in any form—solid, liquid, or gas. One piece of matter is displaced and the disturbance is transmitted throughout all parts of the surrounding matter. Electromagnetic waves are produced in empty space as well as in matter. Vibrating electrical charges produce disturbances that are transmitted across space. By ordering waves according to frequency, the *wave spectrum* organizes the different types of waves within each category.

Mechanical waves include water waves, earthquake waves, and sound waves. *Sound waves* are longitudinal waves. Displacing one atom or molecule produces a series of compressions and rarefactions that are transmitted by the surrounding matter. We use the terms *loudness* and *pitch* to describe our perceptions of the amplitudes and frequencies of sound waves. Sound waves are reflected in echoes, refracted by the atmosphere, and absorbed by trapped pockets of air. All musical instruments are designed to produce standing waves that establish the pitch and character of musical sounds. The lengths of the vibrating strings or air columns determine the fundamental frequencies. The fundamental frequency establishes the pitch; higher harmonics contribute to the character of the sound. Sirens and train whistles provide daily examples of the Doppler effect.

Electromagnetic waves can be described as disturbances in the electric and magnetic fields that surround a moving electric charge. Light, radar, and microwaves are three of the many kinds of electromagnetic waves. They differ from one another in frequency. Different *colors* of light have different frequencies as well. Light can be reflected, refracted, and absorbed by matter. The light reflected from objects to our eyes allows us to see the objects. Reflections from very smooth surfaces give rise to mirror images. Atmospheric refraction leads to the formation of mirages. Absorption of light and infrared radiation leads to the process of heat transfer called radiation-absorption. Absorption of microwaves is used to heat food in microwave ovens. Reflected waves in microwave ovens produce standing waves, resulting in uneven cooking. The electromagnetic Doppler effect is used extensively in measuring speeds—speeds of galaxies as well as speeds of cars.

ANSWERS TO SELF-CHECKS

15A. Human speech involves frequencies around 200–400 Hz. Microwaves include frequencies from 10^{10}–10^{12} Hz. Human speech involves mechanical waves. Microwaves are electromagnetic waves.

15B. AM waves have a lower frequency, and hence a longer wavelength, than FM waves. To be effective, an energy receiver needs to be about the same size as the waves it is to detect. Since AM and FM waves have different wavelengths, the radio antenna will need to be adjusted differently for best reception of each range. The antenna will have to be longer for AM reception.

15C. a. The fundamental frequency will have a wavelength that is four times the length of the air column.

b. As the bottle fills up, the length of the air column shortens. Consequently, the fundamental frequency will have a shorter wavelength and hence a higher frequency. The pitch of the sound goes up.

15D.
$$\text{Time} = \frac{\text{distance}}{\text{speed of light}} = \frac{4.2 \times 10^{16}\ \text{m}}{3 \times 10^{8}\ \text{m/s}} = 1.4 \times 10^{8}\ \text{s}$$

One year is equal to 3.2×10^7 s, so about 4.4 years have elapsed since the message was sent from Alpha Centauri.

15E. The furniture wax fills in the low spots in the wood grain, producing a much smoother surface. As the surface becomes smoother, light waves are reflected more regularly and an image is formed.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define the following terms:
Mechanical waves
Wave spectrum
Electromagnetic waves

A2. Give examples of mechanical waves and electromagnetic waves.

A3. Describe how the size of a wave receiver is related to the wavelength of a wave. Explain the reason for this relationship.

A4. Describe the differences between mechanical and electromagnetic waves.

A5. Describe how a curved surface can focus waves.

A6. Use refraction to explain why sound travels further along the ground at night than during the day.

A7. Explain how the frequency of a sound wave is related to the size of the wave source.

A8. Explain how the Doppler effect is related to the changing pitch of a siren as it passes at high speed.

A9. How are electric and magnetic fields used to describe the motion of electromagnetic waves?

A10. Use the law of reflection to show how an image is formed by a mirror.

A11. Why do standing waves affect microwave cooking?

A12. Describe how the Doppler effect allows us to measure the speed of distant galaxies and passing automobiles.

B. Using the Chapter Material

B1. In Chapter 14 we studied waves on springs. Are these waves mechanical or electromagnetic? Explain how you reached your conclusion.

B2. Cyclotron radiation is a type of wave produced by electrons that are traveling in a circle. Is cyclotron radiation a mechanical or electromagnetic wave? Explain how you reached your answer.

B3. One way in which astronomers study the universe is to detect radio waves emitted by the hydrogen molecule. The wavelength of this wave is 0.21 m. Would you expect the astronomers' detectors to be larger or smaller than AM radio antennae? Why?

B4. A microphone is a detector of sound. Would you expect the size of a microphone to be greater, smaller, or approximately the same size as the human ear? Explain.

B5. A supernova is the explosion of a star. If a supernova occurs somewhere in space, will sound from it be detected on earth? Can light from the supernova be detected here?

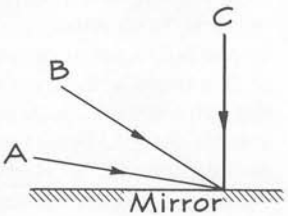
B6. Medieval musical instruments called krumhorns are shown above. One is an alto; the other is a higher-pitched soprano. Using physical principles, describe why you can determine which is the alto.

B7. Sound can be heard across a still lake much better than across a lake which has lots of waves. Apply reflection of sound to explain why.

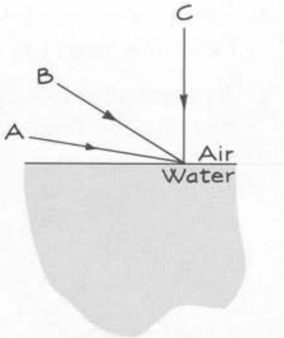
B8. A car is traveling down the road with its horn blaring. What would you need to know so that you could measure the car's speed from the Doppler shift of the horn's sound?

B9. What frequency of electromagnetic wave would be produced by electrons vibrating at 60 Hz? 120 Hz? 240 Hz? What would be the speed, in a vacuum, of each of these electromagnetic waves?

B10. Each of the light waves shown below is striking a mirror as shown. Draw the direction of the reflected wave.



B11. Light travels more rapidly in air than in water. Draw the direction of the light waves in water for each of those shown in air in the next column.



C. Extensions to New Situations

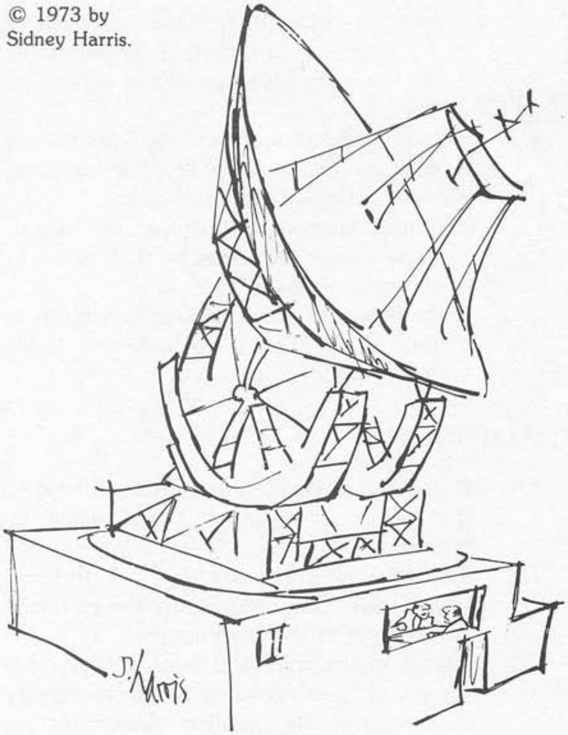
C1. When lightning occurs, it creates two types of waves—sound and light. Because these waves travel at different speeds, their arrival times can be used to estimate the distance to the lightning flash. Light travels at 3×10^8 m/s and sound moves at about 300 m/s. Suppose we hear thunder about 2 s after we see the lightning flash.
   a. How far does sound travel in 2 s?
   b. How long would it take light to travel this same distance?
   c. Approximately how far away did the lightning flash occur?
   d. Can you make up a general rule to determine the approximate distance to a flash of lightning?

C2. The sitar, an Indian musical instrument, has a number of strings that are never plucked by the player. These strings are called *sympathetic strings* and are identical to strings that are plucked. Use the idea of resonance to explain why the sympathetic strings vibrate (and produce music) even though they are never touched by the sitarist.

C3. Could you ever sing and cause a stringed instrument to sound even though you do not touch it? Explain how and why.

C4. In a television commercial for a particular brand of audio tape, a recording of a singer is shown shattering a wine glass. Use the concept of resonance to describe how one can shatter glass with sound.

C5. The speed of electromagnetic waves is used to define astronomical distances. The distance that light, or any other electromagnetic wave, travels in 1 year through



"AS I UNDERSTAND IT, THEY WANT AN IMMEDIATE ANSWER. ONLY TROUBLE IS, THE MESSAGE WAS SENT OUT 3 MILLION YEARS AGO."

empty space is called a *light-year.* The nearest star, Alpha Centauri, is 4 light-years away.

a. How far away is Alpha Centauri in kilometers?
b. In 1974 the radio telescope at Arecibo, Puerto Rico, sent a message toward a star cluster called M13, which is 27,000 light-years away. Within a day the following telegram arrived at Arecibo: "Message received. Help is on its way. M13." Why did the astronomers think this message was a prank?

C6. Suppose a movie set has a mirror on it. You wish to take a picture of the actor's image in the mirror but do not want images of the camera, lights, or crew. How should you arrange the mirror, actor, lights, and camera?

C7. Alternating current in the United States oscillates at 60 Hz.

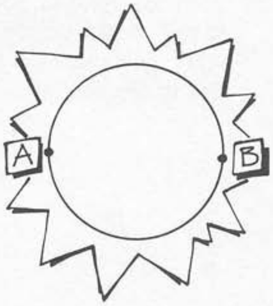
a. What frequency electromagnetic wave is produced around your lamp cord?
b. This frequency must be all around us because of all the wires. Why do we not normally receive it on our radios and televisions?

C8. Each of our hearts contains a natural pacemaker, which stimulates our heart to beat about 60 to 80 times per minute. If this natural method fails, an electronic pacemaker can be inserted. The electronic device detects electromagnetic nerve signals in the heart. If no signal is detected, the electronic pacemaker fires. Why could it be dangerous or fatal for an electronic pacemaker to be near sources of strong electromagnetic waves, like microwave ovens?

C9. Your neighbor is playing music rather loudly, so you close your windows. Now you hear only the bass portion of the music.

a. What size objects will vibrate in resonance with the bass?
b. What objects of this size are between you and the music?
c. Would you expect these objects to vibrate at high or low frequencies?
d. Why do the bass pitches but not the higher pitches reach you when the window is closed?

C10. Astronomers have looked carefully at the spectrum of light emitted by the sun. They have discovered that rays of light from edges A and B have shifts in their frequencies. The frequencies emitted at A are greater than normal, while those from B are less.



a. Which side, A or B, is moving toward the earth?
b. Which side is moving away from the earth?

c. What do these measurements tell you about the sun's motion?

C11. In Chapter 14 we stated an equation for the frequency shift of a wave emitted by a moving source. This equation is used to calculate the speed of a car from which police radar has been reflected. For this problem, we can rewrite this equation as:

$$\text{Speed of car} = \frac{(\text{speed of light}) \times (\text{change in frequency})}{\text{frequency of radar}}$$

Suppose a radar unit has a frequency of 10^{10} Hz.

a. What are the speeds of cars that cause frequency shifts of 100 Hz? 300 Hz? 700 Hz? 1000 Hz? (The interstate speed limit equivalent is about 25 m/s.)

b. When the radar unit is moving, the speed of the car is actually the relative speed between the car and the radar unit. Would the frequency shifts in part (a) increase or decrease if the car were traveling east and the radar unit were traveling west? Explain.

c. When moving radar is used, two frequency shifts are measured. One frequency shift is measured from radar waves reflected from the moving car. A second frequency shift is measured from radar waves reflected from the road. Suppose that the car and radar unit are moving in opposite directions. The frequency shift measured from radar waves reflected from the moving car is 750 Hz and the shift reflected from the road is 500 Hz. What is the speed of the car relative to the radar unit? The speed of the radar unit relative to the road?

d. Use the equations for relative velocities in Chapter 3 to determine if the driver of the car deserves to be cited for speeding.

C12. Singing in the shower has long been known to change the sound of one's voice compared to singing in an auditorium.

a. What range of frequencies would you expect to be enhanced by resonances in the shower room?

b. In terms of energy output, why is it particularly useful to enhance these frequencies?

D. Activities

D1. If you can borrow an oscilloscope, look at the waves produced by your voice or music.

D2. The next time you are in the bathroom, sing a scale. Can you identify the resonant frequencies of the bathroom?

D3. Visit a stereo store and learn how the designers of the store considered resonances in designing the speaker demonstration room.

D4. The next time you close your window to keep out your neighbor's loud music, place your hand on the wall or window. Can you feel it vibrate?

D5. Tune your radio to a distant station. Change the antenna length until you find the best reception. Is this length different for FM and AM reception?

D6. Investigate different brands of microwave ovens. Ask a salesperson to explain how the ovens avoid standing waves (usually called hot spots) and how they keep the energy inside the oven. Listen to the sales pitch carefully. Then evaluate the salesperson's knowledge of physics.