Chapter 12

Waves and Sound

Most of the information about our physical surroundings comes to us through our senses of hearing and sight. In both cases we obtain information about objects without being in physical contact with them. The information is transmitted to us in the first case by sound, in the second case by light. Although sound and light are very different phenomena, they are both waves. A wave can be defined as a disturbance that carries energy from one place to another without a transfer of mass. The energy carried by the waves stimulates our sensory mechanisms.

In this chapter, we will first explain briefly the nature of sound and then review some general properties of wave motion applicable to both sound and light. Using this background we will examine the process of hearing and some other biological aspects of sound. Light will be discussed in Chapter 15.

12.1 Properties of Sound

Sound is a mechanical wave produced by vibrating bodies. For example, when an object such as a tuning fork or the human vocal cords is set into vibrational motion, the surrounding air molecules are disturbed and are forced to follow the motion of the vibrating body. The vibrating molecules in turn transfer their motion to adjacent molecules causing the vibrational disturbance to propagate away from the source. When the air vibrations reach the ear, they cause the eardrum to vibrate; this produces nerve impulses that are interpreted by the brain.

All matter transmits sound to some extent, but a material medium is needed between the source and the receiver to propagate sound. This is demonstrated by the well-known experiment of the bell in the jar. When the bell is set in motion, its sound is clearly audible. As the air is evacuated from the jar, the sound of the bell diminishes and finally the bell becomes inaudible.

The propagating disturbance in the sound-conducting medium is in the form of alternate compressions and rarefactions of the medium, which are initially caused by the vibrating sound source. These compressions and rarefactions are simply deviations in the density of the medium from the average value. In a gas, the variations in density are equivalent to pressure changes.

Two important characteristics of sound are *intensity*, which is determined by the magnitude of compression and rarefaction in the propagating medium, and *frequency*, which is determined by how often the compressions and rarefactions take place. Frequency is measured in cycles per second, which is designated by the unit *hertz* after the scientist Heinrich Hertz. The symbol for this unit is Hz. (1 Hz = 1 cycle per second.)

The vibrational motion of objects can be highly complex (see Fig. 12.1), resulting in a complicated sound pattern. Still, it is useful to analyze the properties of sound in terms of simple sinusoidal vibrations such as would be set up by a vibrating tuning fork (see Fig. 12.2). The type of simple sound

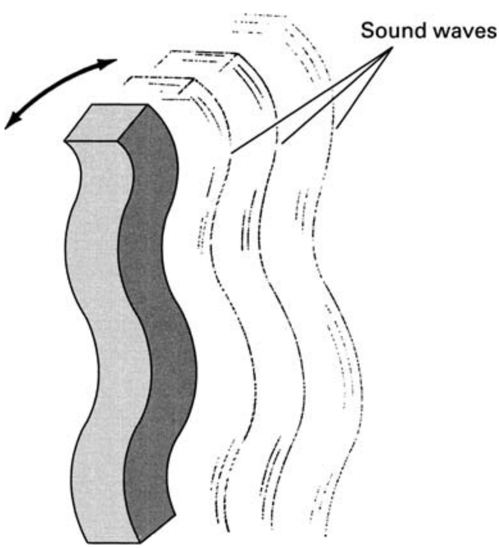

FIGURE 12.1 ► A complex vibrational pattern.

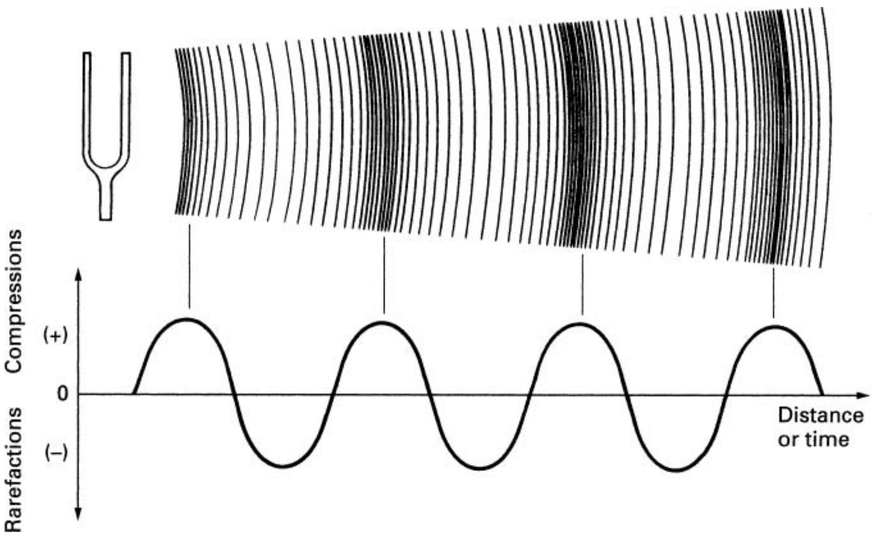

FIGURE 12.2 ► Sinusoidal sound wave produced by a vibrating tuning fork.

pattern shown in Fig. 12.2 is called a *pure tone*. When a pure tone propagates through air, the pressure variations due to the compressions and rarefactions are sinusoidal in form.

If we were to take a "snapshot" of the sound at a given instant in time, we would see pressure variations in space, which are also sinusoidal. (Such pictures can actually be obtained with special techniques.) In such a picture the distance between the nearest equal points on the sound wave is called the *wavelength* λ.

The speed of the sound wave v depends on the material that propagates the sound. In air at 20°C, the speed of sound is about 3.3×10^4 cm/sec, and in water it is about 1.4×10^5 cm/sec. In general, the relationship between frequency, wavelength, and the speed of propagation is given by the following equation:

$$v = \lambda f \tag{12.1}$$

This relationship between frequency, wavelength, and speed is true for all types of wave motions.

The pressure variations due to the propagating sound are superimposed on the ambient air pressure. Thus, the total pressure in the path of a sinusoidal sound wave is of the form

$$P = P_a + P_o \sin 2\pi f t \tag{12.2}$$

where P_a is the ambient air pressure (which at sea level at 0°C is $1.01 \times 10^5\,\text{Pa} = 1.01 \times 10^6\,\text{dyn/cm}^2$), P_o is the maximum pressure change due to the sound wave, and f is the frequency of the sound. The amount of energy transmitted by a sinusoidal sound wave per unit time through each unit area perpendicular to the direction of sound propagation is called the *intensity* I and is given by

$$I = \frac{P_o^2}{2\rho v} \tag{12.3}$$

Here ρ is the density of the medium, and v is the speed of sound propagation.

12.2 Some Properties of Waves

All waves, including sound and light, exhibit the phenomena of reflection, refraction, interference, and diffraction. These phenomena, which play an important role in both hearing and seeing, are described in detail in most basic physics texts (see [12-8]). Here we will review them only briefly.

12.2.1 Reflection and Refraction

When a wave enters one medium from another, part of the wave is reflected at the interface, and part of it enters the medium. If the interface between the two media is smooth on the scale of the wavelength (i.e., the irregularities of the interface surface are smaller than λ), the reflection is specular (mirrorlike). If the surface has irregularities that are larger than the wavelength, the reflection is diffuse. An example of diffuse reflection is light reflected from paper.

If the wave is incident on the interface at an oblique angle, the direction of propagation of the transmitted wave in the new medium is changed (see Fig. 12.3). This phenomenon is called *refraction*. The angle of reflection is always equal to the angle of incidence, but the angle of the refracted wave is, in general, a function of the properties of the two media. The fraction of the energy transmitted from one medium to another depends again on the properties of the media and on the angle of incidence. For a sound wave incident perpendicular to the interface, the ratio of transmitted to incident intensity is given by

$$\frac{I_t}{I_i} = \frac{4\rho_1 v_1 \rho_2 v_2}{(\rho_1 v_1 + \rho_2 v_2)^2} \tag{12.4}$$

where the subscripted quantities are the velocity and density in the two media. The solution of Eq. 12.4 shows that when sound traveling in air is incident

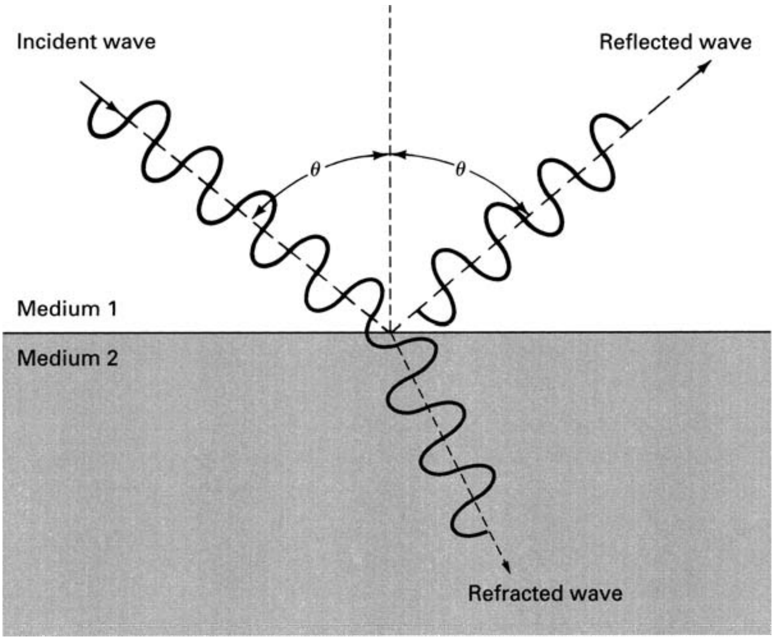

FIGURE 12.3 ► Illustration of reflection and refraction. (θ is the angle of incidence.)

perpendicular to a water surface, only about 0.1% of the sound energy enters the water; 99.9% is reflected. The fraction of sound energy entering the water is even smaller when the angle of incidence is oblique. Water is thus an efficient barrier to sound.

12.2.2 Interference

When two (or more) waves travel simultaneously in the same medium, the total disturbance in the medium is at each point the vectorial sum of the individual disturbances produced by each wave. This phenomenon is called *interference*. For example, if two waves are in phase, they add so that the wave disturbance at each point in space is increased. This is called *constructive interference* (see Fig. 12.4a). If two waves are out of phase by 180°, the wave disturbance in the propagating medium is reduced. This is called *destructive interference* (Fig. 12.4b). If the magnitudes of two out-of-phase waves are the same, the wave disturbance is completely canceled (Fig. 12.4c).

A special type of interference is produced by two waves of the same frequency and magnitude traveling in opposite directions. The resultant wave

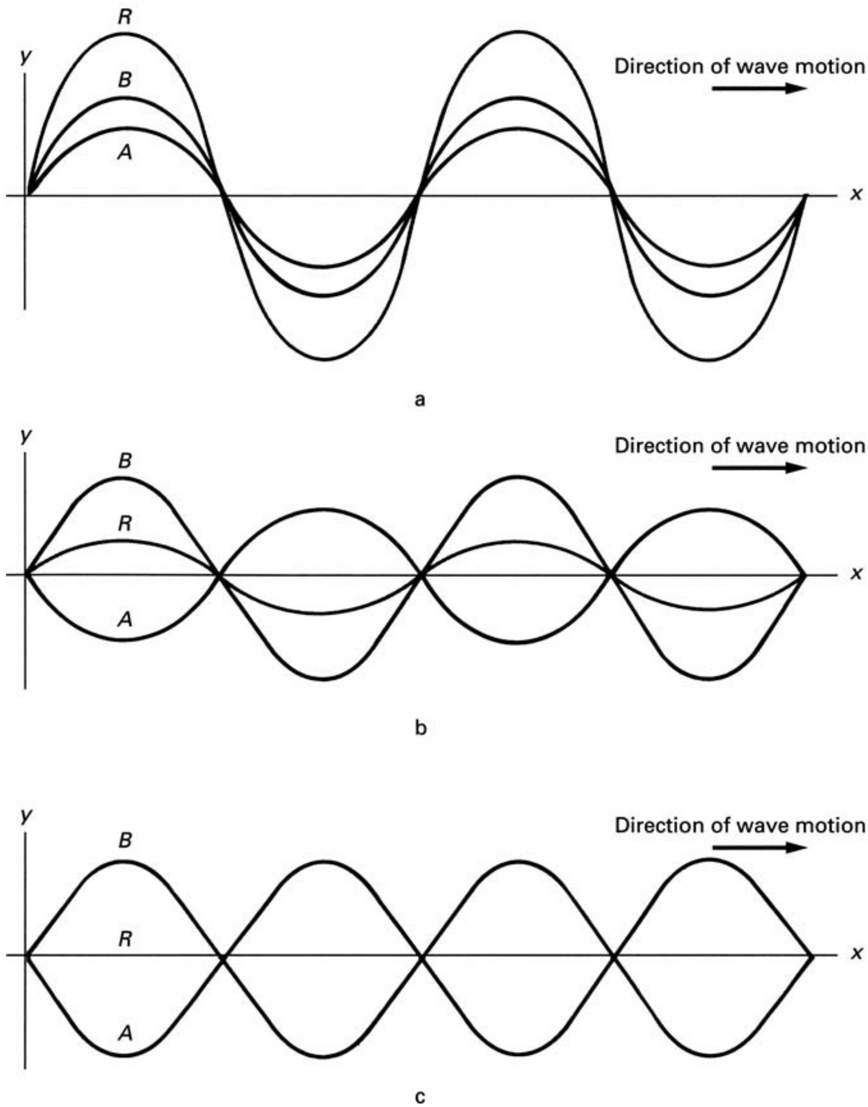

FIGURE 12.4 ► (a) Constructive interference. (b, c) Destructive interference. *R* is the resultant of the interference of the two waves *A* and *B*.

pattern is stationary in space and is called a *standing wave*. Such standing sound waves are formed in hollow pipes such as the flute. It can be shown that, in a given structure, standing waves can exist only at specific frequencies, which are called *resonant frequencies*.

12.2.3 Diffraction

Waves have a tendency to spread as they propagate through a medium. As a result, when a wave encounters an obstacle, it spreads into the region behind the obstacle. This phenomenon is called *diffraction*. The amount of diffraction depends on the wavelength: The longer the wavelength, the greater is the spreading of the wave. Significant diffraction into the region behind the obstacle occurs only if the size of the obstacle is smaller than the wavelength. For example, a person sitting behind a pillar in an auditorium hears the performer because the long wavelength sound waves spread behind the pillar. But the view of the performance is obstructed because the wavelength of light is much smaller than the pillar, and, therefore, the light does not diffract into the region behind the pillar.

Objects that are smaller than the wavelength do not produce a significant reflection. This too is due to diffraction. The wave simply diffracts around the small obstacle, much as flowing water spreads around a small stick.

Both light waves and sound waves can be focused with curved reflectors and lenses. There is, however, a limit to the size of the focused spot. It can be shown that the diameter of the focused spot cannot be smaller than about $\lambda/2$. These properties of waves have important consequences in the process of hearing and seeing.

12.3 Hearing and the Ear

The sensation of hearing is produced by the response of the nerves in the ear to pressure variations in the sound wave. The nerves in the ear are not the only ones that respond to pressure, as most of the skin contains nerves that are pressure-sensitive. However, the ear is much more sensitive to pressure variations than any other part of the body.

Figure 12.5 is a drawing of the human ear. (The ear construction of other terrestrial vertebrates is similar.) For the purposes of description, the ear is usually divided into three main sections: the outer ear, the middle ear, and the inner ear. The sensory cells that convert sound to nerve impulses are located in the liquid-filled inner ear.

The main purpose of the outer and middle ears is to conduct the sound into the inner ear.

The outer ear is composed of an external flap called the *pinna* and the ear canal, which is terminated by the *tympanic membrane* (eardrum). In many animals the pinna is large and can be rotated toward the source of the sound; this helps the animal to locate the source of sound. However, in humans the pinna is fixed and so small that it does not seem to contribute significantly to the hearing process.

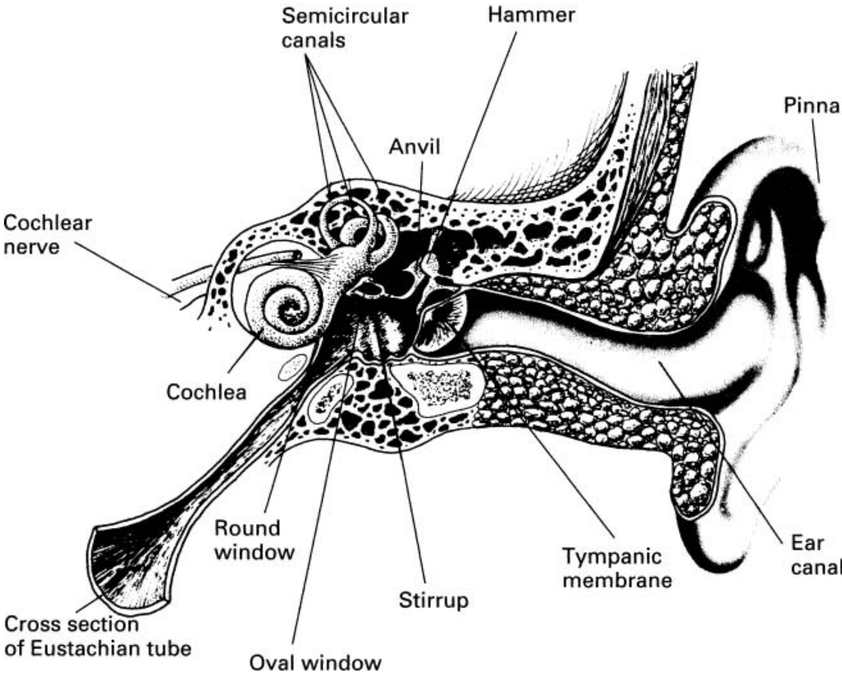

FIGURE 12.5 ► A semidiagrammatic drawing of the ear with various structures cut away and simplified to show the basic relationships more clearly. The middle ear muscles have been omitted.

The ear canal of an average adult is about 0.75 cm in diameter and 2.5 cm long, a configuration that is resonant for sound waves at frequencies around 3000 Hz. This accounts in part for the high sensitivity of the ear to sound waves in this frequency range.

For an animal to perceive sound, the sound has to be coupled from air to the sensory cells that are in the fluid environment of the inner ear. We showed earlier that direct coupling of sound waves into a fluid is inefficient because most of the sound energy is reflected at the interface. The middle ear provides an efficient conduction path for the sound waves from air into the fluid of the inner ear.

The middle ear is an air-filled cavity that contains a linkage of three bones called *ossicles* that connect the eardrum to the inner ear. The three bones are called the *hammer*, the *anvil*, and the *stirrup*. The hammer is attached to the inner surface of the eardrum, and the stirrup is connected to the oval window, which is a membrane-covered opening in the inner ear.

When sound waves produce vibrations in the eardrum, the vibrations are transmitted by the ossicles to the oval window, which in turn sets up pressure variations in the fluid of the inner ear. The ossicles are connected to the walls of the middle ear by muscles that also act as a volume control. If the sound is excessively loud, these muscles as well as the muscles around the eardrum stiffen and reduce the transmission of sound to the inner ear.

The middle ear serves yet another purpose. It isolates the inner ear from the disturbances produced by movements of the head, chewing, and the internal vibrations produced by the person's own voice. To be sure, some of the vibrations of the vocal cords are transmitted through the bones into the inner ear, but the sound is greatly attenuated. We hear ourselves talk mostly by the sound reaching our eardrums from the outside. This can be illustrated by talking with the ears plugged.

The *Eustachian tube* connects the middle ear to the upper part of the throat. Air seeps in through this tube to maintain the middle ear at atmospheric pressure. The movement of air through the Eustachian tube is aided by swallowing. A rapid change in the external air pressure such as may occur during an airplane flight causes a pressure imbalance on the two sides of the eardrum. The resulting force on the eardrum produces a painful sensation that lasts until the pressure in the middle ear is adjusted to the external pressure. The pain is especially severe and prolonged if the Eustachian tube is blocked by swelling or infection.

The conversion of sound waves into nerve impulses occurs in the *cochlea*, which is located in the inner ear. The cochlea is a spiral cavity shaped like a snail shell. The wide end of the cochlea, which contains the oval and the round windows, has an area of about $4\,\text{mm}^2$. The cochlea is formed into a spiral with about $2\frac{3}{4}$ turns. If the cochlea were uncoiled, its length would be about 35 mm.

Inside the cochlea there are three parallel ducts; these are shown in the highly simplified drawing of the uncoiled cochlea in Fig. 12.6. All three ducts are filled with a fluid. The vestibular and tympanic canals are joined at the apex of the cochlea by a narrow opening called the *helicotrema*. The cochlear duct is isolated from the two canals by membranes. One of these membranes, called the *basilar membrane*, supports the auditory nerves.

The vibrations of the oval window set up a sound wave in the fluid filling the vestibular canal. The sound wave, which travels along the vestibular canal and through the helicotrema into the tympanic canal, produces vibrations in the basilar membrane which stimulate the auditory nerves to transmit electrical pulses to the brain (see Chapter 13). The excess energy in the sound wave is dissipated by the motion of the round window at the end of the tympanic canal.

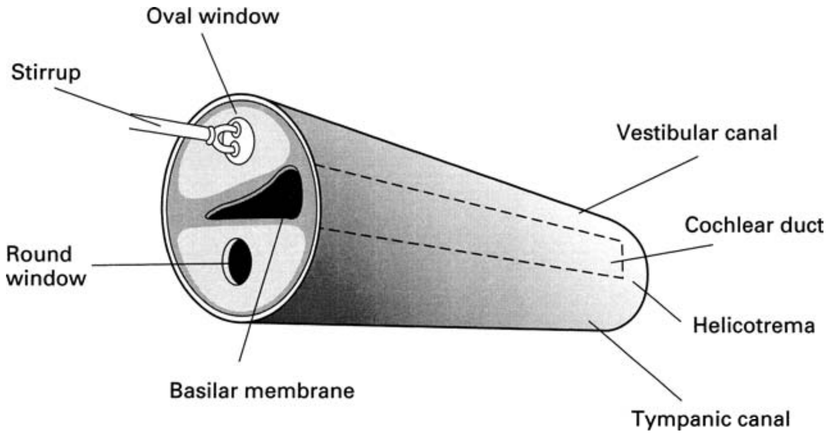

FIGURE 12.6 ► An uncoiled view of the cochlea.

12.3.1 Performance of the Ear

The nerve impulses evoke in the brain the subjective sensation of sound. *Loudness, pitch*, and *quality* are some of the terms we use to describe the sounds we hear. It is a great challenge for physiologists to relate these subjective responses with the physical properties of sound such as intensity and frequency. Some of these relationships are now well understood; others are still subjects for research.

In most cases, the sound wave patterns produced by instruments and voices are highly complex. Each sound has its own characteristic pattern. It would be impossible to evaluate the effect of sound waves on the human auditory system if the response to each sound pattern had to be analyzed separately. Fortunately the problem is not that complicated. About 150 years ago, J. B. J. Fourier, a French mathematician, showed that complex wave shapes can be analyzed into simple sinusoidal waves of different frequencies. In other words, a complex wave pattern can be constructed by adding together a sufficient number of sinusoidal waves at appropriate frequencies and amplitudes. Therefore, if we know the response of the ear to sinusoidal waves over a broad range of frequencies, we can evaluate the response of the ear to a wave pattern of any complexity.

An analysis of a wave shape into its sinusoidal components is shown in Fig. 12.7. The lowest frequency in the wave form is called the *fundamental*, and the higher frequencies are called *harmonics*. Figure 12.8, shows the sound pattern for a specific note played by various instruments. It is the harmonic content of the sound that differentiates one sound source from another.

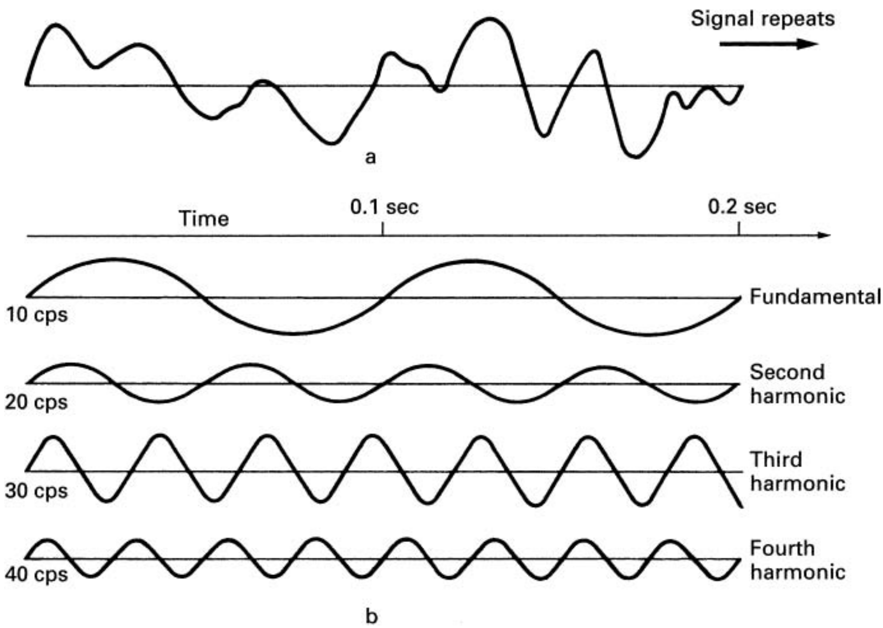

FIGURE 12.7 ► The analysis of a complex wave shape (a), into its sine components (b). The point-by-point addition of the fundamental frequency sine wave and the harmonic frequency sine waves yields the wave shape shown in (a).

For a given note played by the various instruments shown in Fig. 12.8, the fundamental frequency is the same but the harmonic content of the wave is different for each instrument.

12.3.2 Frequency and Pitch

The human ear is capable of detecting sound at frequencies between about 20 and 20,000 Hz. Within this frequency range, however, the response of the ear is not uniform. The ear is most sensitive to frequencies between 200 and 4000 Hz, and its response decreases toward both higher and lower frequencies. There are wide variations in the frequency response of individuals. Some people cannot hear sounds above 8000 Hz, whereas a few people can hear sounds above 20,000 Hz. Furthermore, the hearing of most people deteriorates with age.

The sensation of pitch is related to the frequency of the sound. The pitch increases with frequency. Thus, the frequency of middle C is 256 Hz, and the

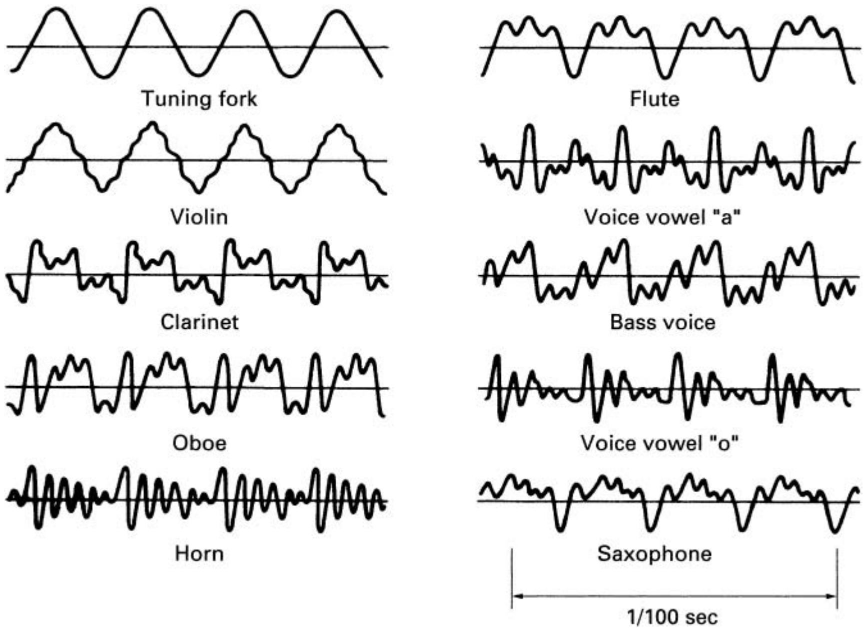

FIGURE 12.8 ► Wave forms of sound from different musical instruments sounding the same note.

frequency of the A above is 440 Hz. There is, however, no simple mathematical relationship between pitch and frequency.

12.3.3 Intensity and Loudness

The ear responds to an enormous range of intensities. At 3000 Hz, the lowest intensity that the human ear can detect is about 10^{-16} W/cm^2. The loudest tolerable sound has an intensity of about 10^{-4} W/cm^2. These two extremes of the intensity range are called the *threshold of hearing* and the *threshold of pain*, respectively. Sound intensities above the threshold of pain may cause permanent damage to the eardrum and the ossicles.

The ear does not respond linearly to sound intensity; that is, a sound which is a million times more powerful than another does not evoke a million times higher sensation of loudness. The response of the ear to intensity is closer to being logarithmic than linear.

Because of the nonlinear response of the ear and the large range of intensities involved in the process of hearing, it is convenient to express sound intensity on a logarithmic scale. On this scale, the sound intensity is measured relative to a reference level of 10^{-16} W/cm^2 (which is approximately the

TABLE 12.1 ► Sound Levels Due to Various Sources (representative values)

Source of sound	Sound level (dB)	Sound level (W/cm^2)
Threshold of pain	120	10^{-4}
Riveter	90	10^{-7}
Busy street traffic	70	10^{-9}
Ordinary conversation	60	10^{-10}
Quiet automobile	50	10^{-11}
Quiet radio at home	40	10^{-12}
Average whisper	20	10^{-14}
Rustle of leaves	10	10^{-15}
Threshold of hearing	0	10^{-16}

lowest audible sound intensity). The logarithmic intensity is measured in units of decibel (dB) and is defined as

$$\text{Logarithmic intensity} = 10 \log \frac{\text{Sound intensity in W/cm}^2}{10^{-16}\,\text{W/cm}^2} \qquad (12.5)$$

Thus, for example, the logarithmic intensity of a sound wave with a power of 10^{-12} W/cm^2 is

$$\text{Logarithmic intensity} = 10 \log \frac{10^{-12}}{10^{-16}} = 40\,\text{dB}$$

Intensities of some common sounds are listed in Table 12.1.

At one time, it was believed that the ear responded logarithmically to sound intensity. Referring to Table 12.1, a logarithmic response would imply that, for example, a busy street sounds only six times louder than the rustle of leaves even though the power of the street sounds is a million times greater. Although it has been shown that the intensity response of the ear is not exactly logarithmic, the assumption of a logarithmic response still provides a useful guide for assessing the sensation of loudness produced by sounds at different intensities (see Exercises 12-1 and 12-2).

The sensitivity of the ear is remarkable. At the threshold of hearing, in the range of 2000–3000 Hz, the ear can detect a sound intensity of 10^{-16} W/cm^2. This corresponds to a pressure variation in the sound wave of only about 2.9×10^{-4} dyn/cm^2 (see Exercise 12-3). Compare this to the background atmospheric pressure, which is 1.013×10^6 dyn/cm^2. This sensitivity appears even more remarkable when we realize that the random pressure variations in air due to the thermal motion of molecules are about 0.5×10^{-4} dyn/cm^2. Thus, the sensitivity of the ear is close to the ultimate limit at which it would begin to detect the noise fluctuations in the air. The displacement of the molecules corresponding to the power at the threshold of hearing is less than the size of the molecules themselves.

The sensitivity of the ear is partly due to the mechanical construction of the ear, which amplifies the sound pressure. Most of the mechanical amplification is produced by the middle ear. The area of the eardrum is about 30 times larger than the oval window. Therefore, the pressure on the oval window is increased by the same factor (see Exercise 12-4). Furthermore, the ossicles act as a lever with a mechanical advantage of about 2. Finally, in the frequency range around 3000 Hz, there is an increase in the pressure at the eardrum due to the resonance of the ear canal. In this frequency range, the pressure is increased by another factor of 2. Thus, the total mechanical amplification of the sound pressure in the 3000-Hz range is about $2 \times 30 \times 2 = 120$. Because the intensity is proportional to pressure squared (see Eq. 12.3), the intensity at the oval window is amplified by a factor of about 14,400.

The process of hearing cannot be fully explained by the mechanical construction of the ear. The brain itself plays an important role in our perception of sound. For example, the brain can effectively filter out ambient noise and allow us to separate meaningful sounds from a relatively loud background din. (This feature of the brain permits us to have a private conversation in the midst of a loud party.) The brain can also completely suppress sounds that appear to be meaningless. Thus, we may lose awareness of a sound even though it still produces vibrations in our ear. The exact mechanism of interaction between the brain and the sensory organs is not yet fully understood.

12.4 Bats and Echoes

The human auditory organs are very highly developed; yet, there are animals that can hear even better than we can. Notable among these animals are the bats. They emit high-frequency sound waves and detect the reflected sounds (echoes) from surrounding objects. Their sense of hearing is so acute that they can obtain information from echoes which is in many ways as detailed as the information we can obtain with our sense of sight. The many different species of bats utilize echoes in various ways. The *Vespertilionidae* family of bats emit short chirps as they fly. The chirps last about 3×10^{-3} sec (3 msec) with a time interval between chirps of about 70 msec. Each chirp starts at a frequency of about 100×10^3 Hz and falls to about 30×10^3 Hz at the end. (The ears of bats, of course, respond to these high frequencies.) The silent interval between chirps allows the bat to detect the weak echo without interference from the primary chirp. Presumably the interval between the chirp and the return echo allows the bat to determine its distance from the object. It is also possible that differences in the frequency content of the chirp and the echo allow the bat to estimate the size of the object (see Exercise 12-5). With a spacing between chirps of 70 msec, an echo from an object as far as 11.5 m can be detected before the next chirp (see Exercise 12-6). As the bat comes closer to the object (such as an obstacle or an insect), both the duration of and the spacing between chirps decrease, allowing the bat to localize the object more accurately. In the final approach to the object, the duration of the chirps is only about 0.3 msec, and the spacing between them is about 5 msec.

Experiments have shown that with echo location bats can avoid wire obstacles with diameters down to about 0.1 mm, but they fail to avoid finer wires. This is in accord with our discussion of wave diffraction (see Exercise 12-7). Other animals, such as porpoises, whales, and some birds, also use echoes to locate objects, but they are not able to do so as well as bats.

12.5 Sounds Produced by Animals

Animals can make sounds in various ways. Some insects produce sounds by rubbing their wings together. The rattlesnake produces its characteristic sound by shaking its tail. In most animals, however, sound production is associated with the respiratory mechanism. In humans, the *vocal cords* are the primary source of sound. These are two reeds, shaped like lips, attached to the upper part of the trachea. During normal breathing the cords are wide open. To produce a sound the edges of the cords are brought together. Air from the lungs passes through the space between the edges and sets the cords into vibration. The frequency of the sounds is determined by the tension on the vocal cords. The fundamental frequency of the average voice is about 140 Hz for males and about 230 Hz for females. The sound produced by the vocal cords is substantially modified as it travels through the passages of the mouth and throat. The tongue also plays an important role in the final sound. Many voice sounds are produced outside the vocal cords (for example, the consonant *s*). The sounds in a whispering talk are also produced outside the vocal cords.

12.6 Acoustic Traps

Electronically generated sounds that mimic those of animals and insects are increasingly being used as lures to trap the creatures. Electronic fishing lures are now commercially available. One such device mimics the distress call of a mackerel and attracts marlin and other larger fish to the fishhook.

To obtain baseline data on bat populations, often the bats have to be captured and examined. In one such study, the social call of a rare Bechstein's bat that inhabits the woodlands of southeast England was synthesized luring the bats into the net. (The bats were released after examination.)

The Mediterranean fruit fly commonly called medfly is a pest that infests fruits and other crops causing on the order of $1 billion damage worldwide. At present, spraying of pesticides is the most common way of controlling the medfly. An environmentally more friendly way of controlling the pest has been sought for many years. Sound traps under development may provide a viable alternative. The male medfly produces with its wings a vibration at a fundamental frequency of about 350 Hz accompanied by complex harmonics. The female medflys are attracted to this courtship call and can be lured into a trap.

12.7 Clinical Uses of Sound

The most familiar clinical use of sound is in the analysis of body sounds with a stethoscope. This instrument consists of a small bell-shaped cavity attached to a hollow flexible tube. The bell is placed on the skin over the source of the body sound (such as the heart or lungs). The sound is then conducted by the pipe to the ears of the examiner who evaluates the functioning of the organ. A modified version of the stethoscope consists of two bells that are placed on different parts of the body. The sound picked up by one bell is conducted to one ear, and the sound from the other bell is conducted to the other ear. The two sounds are then compared. With this device, it is possible, for example, to listen simultaneously to the heartbeats of the fetus and of the pregnant mother.

12.8 Ultrasonic Waves

With special electronically driven crystals, it is possible to produce mechanical waves at very high frequencies, up to millions of cycles per second. These waves, which are simply the extension of sound to high frequencies, are called *ultrasonic waves.* Because of their short wavelength, ultrasonic waves can be focused onto small areas and can be imaged much as visible light (see Exercise 12-8).

Ultrasonic waves penetrate tissue and are scattered and absorbed within it. Using specialized techniques called *ultrasound imaging*, it is possible to form visible images of ultrasonic reflections and absorptions. Therefore, structures within living organisms can be examined with ultrasound, as with X-rays. Ultrasonic examinations are safer than X-rays and often can provide as much information. In some cases, such as in the examination of a fetus and the heart, ultrasonic methods can show motion, which is very useful in such displays.

The frequency of sound detected by an observer depends on the relative motion between the source and the observer. This phenomenon is called the *Doppler effect.* It can be shown (see Exercise 12-9) that if the observer is stationary and the source is in motion, the frequency of the sound f' detected by the observer is given by

$$f' = f\frac{v}{v \mp v_s} \tag{12.6}$$

where f is the frequency in the absence of motion, v is the speed of sound, and v_s is the speed of the source. The minus sign in the denominator is to be used when the source is approaching the observer, and the plus sign when the source is receding.

Using the Doppler effect, it is possible to measure motions within a body. One device for obtaining such measurements is the *ultrasonic flow meter*, which produces ultrasonic waves that are scattered by blood cells flowing in the blood vessels. The frequency of the scattered sound is altered by the Doppler effect. The velocity of blood flow is obtained by comparing the incident frequency with the frequency of the scattered ultrasound.

Within the tissue, the mechanical energy in the ultrasonic wave is converted to heat. With a sufficient amount of ultrasonic energy, it is possible to heat selected parts of a patient's body more efficiently and evenly than can be done with conventional heat lamps. This type of treatment, called *diathermy*, is used to relieve pain and promote the healing of injuries. It is actually possible to destroy tissue with very high-intensity ultrasound. Ultrasound is now routinely used to destroy kidney and gall stones (lithotripsy).

► EXERCISES ►

12-1. The intensity of a sound produced by a point source decreases as the square of the distance from the source. Consider a riveter as a point source of sound and assume that the intensities listed in Table 12.1 are measured at a distance 1 m away from the source. What is the maximum distance at which the riveter is still audible? (Neglect losses due to energy absorption in the air.)

12-2. Referring to Table 12.1, approximately how much louder does busy street traffic sound than a quiet radio?

12-3. Calculate the pressure variation corresponding to a sound intensity of 10^{-16} W/cm^2. (The density of air at 0°C and 1 atm pressure is 1.29×10^{-3} g/cm^3; for the speed of sound use the value 3.3×10^4 cm/sec.)

12-4. Explain why the relative sizes of the eardrum and the oval window result in pressure magnification in the inner ear.

12-5. Explain how a bat might use the differences in the frequency content of its chirp and echo to estimate the size of an object.

12-6. With a 70-msec space between chirps, what is the farthest distance at which a bat can detect an object?

12-7. In terms of diffraction theory, discuss the limitations on the size of the object that a bat can detect with its echo location.

12-8. Estimate the lower limit on the size of objects that can be detected with ultrasound at a frequency of 2×10^6 Hz.

12-9. With the help of a basic physics textbook, explain the Doppler effect and derive Eq. 12.6.