15 Sound

KEY IDEA

Sound is a longitudinal wave that travels through a solid, liquid, or gaseous medium.

PHYSICS AROUND US . . . The Concert

Imagine yourself at a rock concert. As the house lights dim and the laser show starts, the first loud chords reach your ears. You notice several different instruments—guitars, drums, and synthesizers, not to mention the human voice—each contributing its distinctive part to the overall dynamic sound.

Or perhaps your tastes run more to symphonic music. A classical orchestra features an even greater variety of instruments, from the fat seven-foot-tall double basses to the slender piccolo, which measures less than 1 foot in length.

In diverse cultures across the globe, human inventiveness has led to an astonishingly rich array of string, wind, and percussion instruments, each with its own characteristic sound. What exactly is sound, and how can musical instruments produce such a range of sounds that are pleasing to our ears?

PROPERTIES OF SOUND

As we have seen in Chapter 14, sound is a longitudinal wave that travels through a medium such as air, water, or rock. When you talk, for example, your vocal cords vibrate in the surrounding air. This vibration produces a series of slightly higher and slightly lower air pressures, which move through the space surrounding you. Thus, sound is a longitudinal pressure wave. When a higher-pressure part of the wave strikes your friend's eardrum, the eardrum is pushed in. When a lower-pressure part of the wave strikes the eardrum, it moves back out. From this motion of the eardrum, your friend can detect the information transmitted by your sound wave.

In Figure 15-1*a* we show a snapshot of what that sound wave looks like after it has left your mouth. The dots represent molecules of air, and you can see that in some places these particles are packed together more tightly, while in others they are scattered more thinly. It is these successive regions of compression and rarefaction that travel through the air and make up the sound wave. If we take another snapshot a moment after this one (Figure 15-1*b*), we see that the whole pattern has moved outward, with the amount of movement determined by the speed of the wave.

You can make an analogy between the sound wave shown in Figure 15-1 and the ripples on water we analyzed in Chapter 14 by graphing the pressure versus distance along the wave's line of motion. In this case, we get a graph such as the one shown in Figure 15-2*a*. The high pressures correspond to the regions where air molecules are packed more tightly together, and low pressures correspond to regions where they are scattered more thinly. This graph looks just like a cross-sectional view of a ripple on the water. It even behaves like a ripple in that, if you make a pressure-versus-distance graph for the second pattern (Figure 15-1*b*), it will look like the graph of Figure 15-2*b*. In other words, the pressure graph associated with the sound wave moves along just as if it were a wave on water.

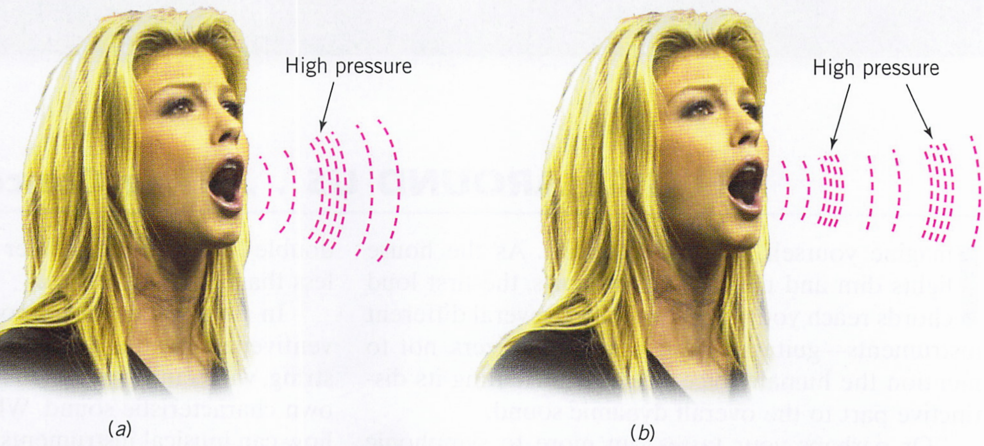


FIGURE 15-1. (*a*) Your voice creates a distinctive pattern of compressions and rarefactions in air. (*b*) As you speak, the sound waves move away from your mouth.

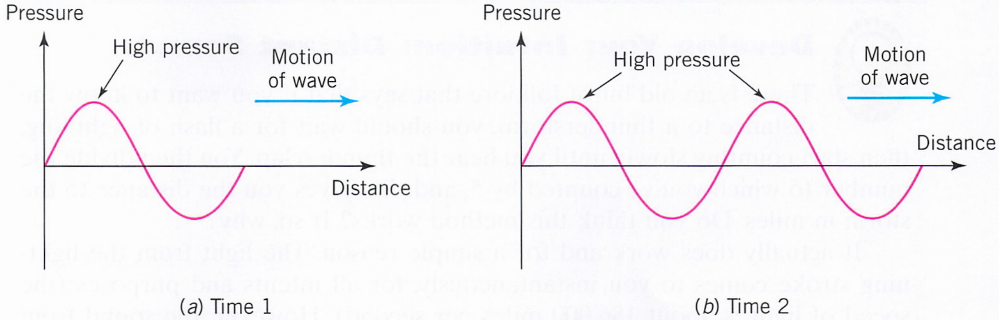


FIGURE 15-2. (*a*) The sound of your voice can be plotted on a graph as a distinctive pattern of air pressure. (*b*) As you speak, the pattern moves through the air.

The Speed of Sound

The speed of sound in air varies with the temperature of the air. At 0°C, the speed of sound is 331 m/s, while at 20°C (close to normal room temperature), the speed is a bit faster—about 344 m/s. This temperature effect on the speed of sound has an intriguing consequence. Have you ever noticed how much easier it is to hear distant voices and other sounds at night? During the daytime, upper levels of the air are generally cooler than those near the ground, so during the day sound waves tend to bend upward because the upper air levels slow them down (Figure 15-3*a*). At night, just the opposite effect occurs: sound waves tend to stay closer to the ground, and sound seems to travel farther (Figure 15-3*b*). This bending of sound waves is an example of a more general phenomenon known as *refraction,* which we will study in more detail in Chapter 20.

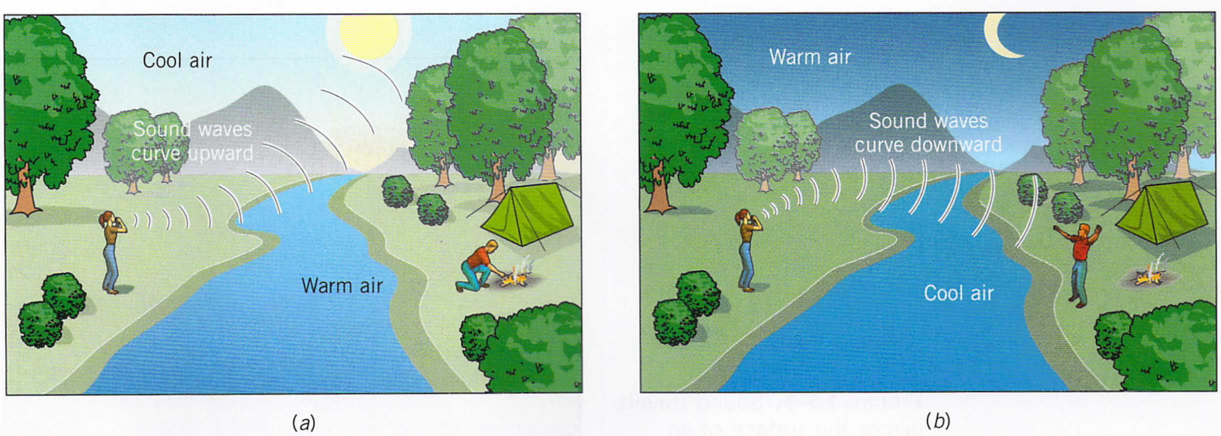


FIGURE 15-3. Sound waves bend when passing through layers of air at different temperatures. (*a*) During the daytime, upper layers of air are cooler, so sound waves tend to bend upward. (*b*) At night, upper layers of air tend to be warmer, so sound waves bend downward. That's why it's often easier to hear sounds from a distance at night.

Develop Your Intuition: Distant Sounds

There is an old bit of folklore that says that if you want to know the distance to a thunderstorm, you should wait for a flash of lightning, then start counting slowly until you hear the thunderclap. You then divide the number to which you've counted by 5, and that gives you the distance to the storm in miles. Do you think this method works? If so, why?

It actually does work and for a simple reason. The light from the lightning stroke comes to you instantaneously, for all intents and purposes (the speed of light is about 186,000 miles per second). However, the sound from the thunderclap (created when air rushes back into the partial vacuum created by the lightning) travels much more slowly and arrives much later. If you count slowly ("one one-thousand, two one-thousand, three one-thousand . . ."), you have estimated the number of seconds it took the sound from the storm to reach you. Sound travels at about 1000 feet per second, and there are about 5000 feet in a mile (5280, to be exact). Thus, dividing by 5 gives you an estimate of how many 5000-foot lengths (i.e., how many miles) the sound traveled before it reached you.

Note that to apply this method using the metric system, just divide the number of seconds by 3 to get the approximate distance in kilometers (1 km ~ 3250 feet).

Echoes

EXAMPLE 15-1

Have you ever visited an echo lake? You can find them all across North America, from Maine to California. Imagine standing on the shore, shouting "Hello!" and hearing the distinct echo from the far shore exactly 4 seconds later. What is the distance L across the lake?

REASONING AND SOLUTION: An echo is a sound wave that travels across a distance, bounces off some surface, and comes back to your ears. At an echo lake,

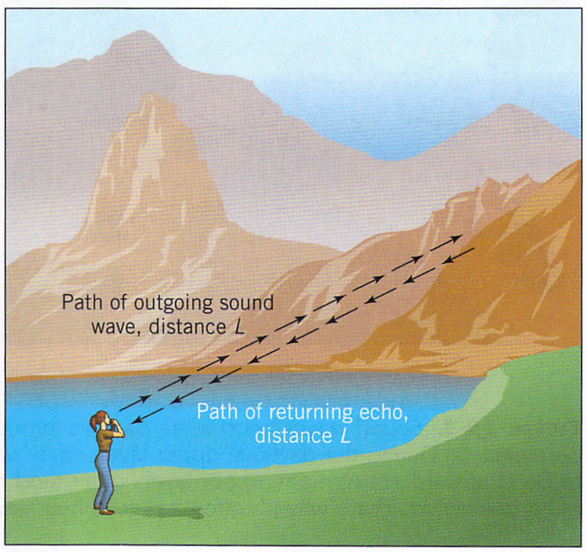


FIGURE 15-4. Sound travels across the surface of an echo lake, bounces off the far side, and comes back to its source. The distance across the lake can be measured by the time it takes for the echo to return.

the sound must travel across the lake and back, for a total distance of $2L$ (Figure 15-4). Recall the equation for distance in terms of speed and time:

$$\text{Distance (m)} = \text{Speed (m/s)} \times \text{Time (s)}$$

In this problem,

$$\begin{aligned} 2L &= 340 \text{ m/s} \times 4 \text{ s} \\ &= 1360 \text{ m} \end{aligned}$$

Therefore,

$$L = 1360/2 \text{ m} = 680 \text{ m}$$

In this way you can determine that the echo lake is about 2000 feet across just by standing on the shore and shouting. ●

The Nature of Sound Waves

Think about your many everyday experiences with sound. From your own observations, you can recognize some important attributes of sound:

1. **Sound travels in media other than air.** Have you ever been in a city and heard the sound of a subway deep beneath your feet? Or have you ever heard recordings of whale songs? These experiences should convince you that sound travels in media other than air—through water and solid materials, for example. How else could you hear your neighbor's stereo through the dorm walls? In general, air is a rather poor conductor of sound, and sound waves travel much faster and farther in water and in rock than they do in air.

2. **There are ways of generating sound waves other than using vocal cords.** Think about all the many ways that you can produce a sound. You can clap your hands, pluck a guitar string, set off a firecracker, or sand a piece of wood. Indeed, any event that causes a compression–rarefaction process in a medium can generate a sound wave. A hammer hitting a nail, for example, makes a sound because it compresses air around it (in this case, the hammer produces a sound pulse rather than a continuous wave). In a stereo system, a flexible diaphragm (often made of paper) in the speaker moves back and forth in response to electrical signals and thus causes increases and decreases in the air pressure in front of the speaker, similar to the sound wave caused by your vocal cords.

3. **Sound waves have all the properties of waves discussed in Chapter 14.** Unlike waves on the surface of water, sound waves are invisible. Nevertheless, they exhibit the full range of wavelike properties. As we have seen, sound waves have speed (about 340 m/s in air), and they have frequency and amplitude, as we describe in more detail later. Sound waves beautifully illustrate the Doppler effect, as you've experienced whenever a fast-moving vehicle whizzes by. (Indeed, as we mention in Chapter 14, the Doppler effect was first investigated using sound waves.) Finally, as we shall see, sound waves exhibit interference—a fact that is critical in the design of auditoriums.

Hearing and the Human Ear

The human ear, shown in Figure 15-5, is a complex organ that allows us to detect sound waves. To accomplish this feat, the ear senses the rapid changes in air pressure associated with sound and transmits these changes to the brain. First, as noted earlier, the membrane we call the eardrum vibrates in response to the pressure of the incoming sound wave. This vibration, in turn, is transmitted through a series of small bones to another membrane located on the cochlea, a coiled tube in the inner ear. The vibrations of this second membrane cause, in their turn, vibrations in the fluid inside the cochlea. The inside of the cochlea is formed in such a way that sounds of different frequencies have maximum effect at different places, stimulating different hair cells lining the walls of the cochlea. The movements of these hairs stimulate auditory nerves, which carry to the brain the signals you interpret as sound.

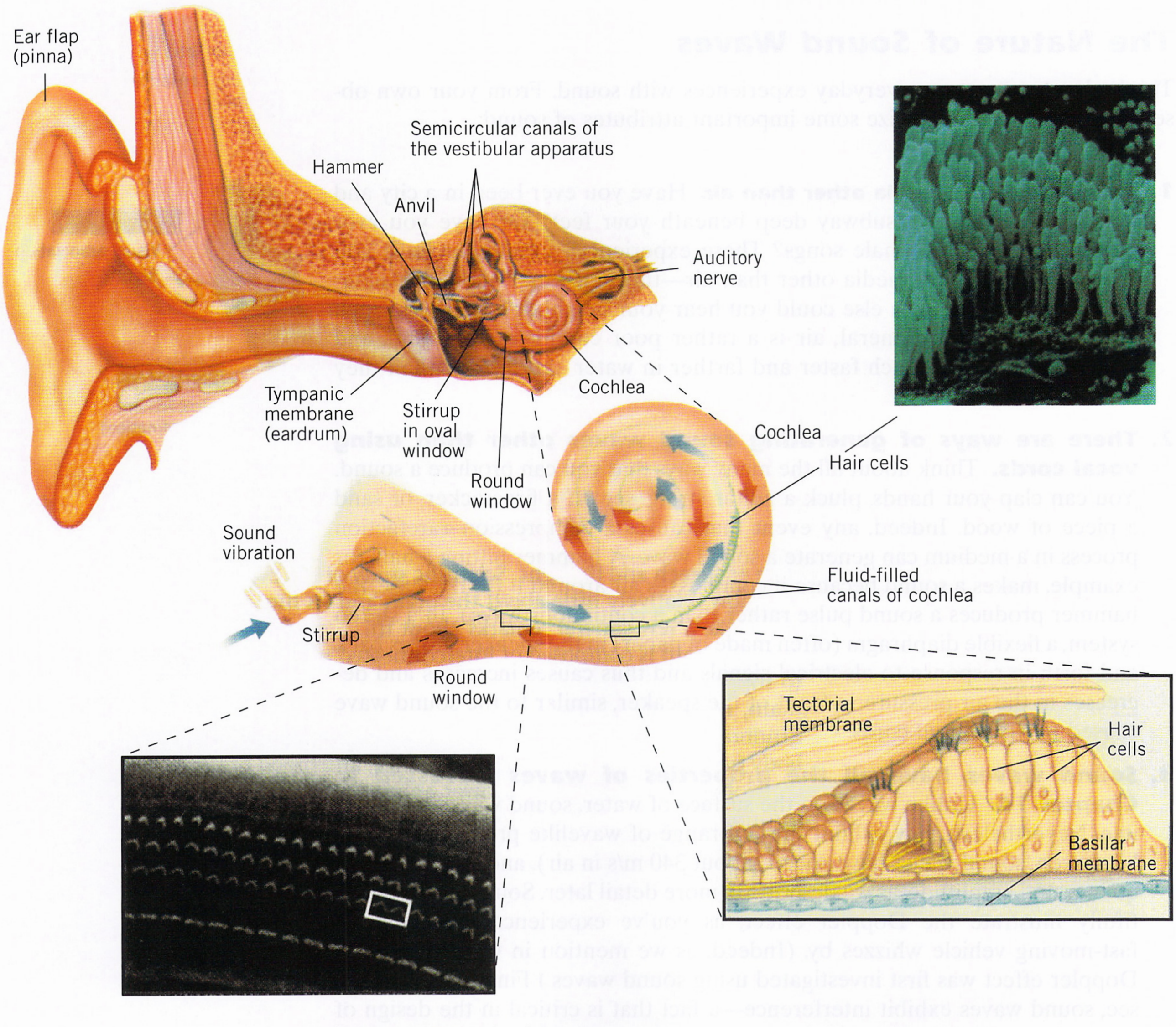


FIGURE 15-5. The human ear is a marvelously sensitive instrument.

Humans use sound to communicate, as do many other animals. But some animals have refined the use of sound to a much higher level. In 1793, the Italian physiologist Lazzaro Spallanzani did some experiments that established that bats use sound to locate their prey. First Spallanzani blinded some of the bats that lived in the cathedral tower in Pavia and then turned them loose. Weeks later, those bats had fresh insects in their stomachs, proving that they did not need sight to locate food. Similar experiments with bats that were deafened, however, showed that they could neither fly nor locate insects.

Today, we understand that bats navigate by emitting high-pitched sound waves—frequencies as high as 150,000 Hz, which is much higher than can be heard by humans. They then listen for the echo of those waves bouncing off other objects. By measuring the time it takes for a pulse of sound waves to go out, be reflected, and come back, the bat can determine the distance to surrounding objects, particularly the flying insects that constitute its diet (Figure 15-6). This process is called *echolocation*. Typically, a bat can detect the presence of an insect up to 10 meters away. In addition, the bat can use the Doppler effect to tell whether the target is moving, detecting the slight difference in frequency in an echo from an insect moving away from the bat (slightly lower frequency) or moving toward it (slightly higher frequency).

By contrast, some animals (elephants, for example) routinely use sound waves that are at the lowest range of human hearing, in the 20–40 Hz range, to communicate with one another over long distances. For example, humans

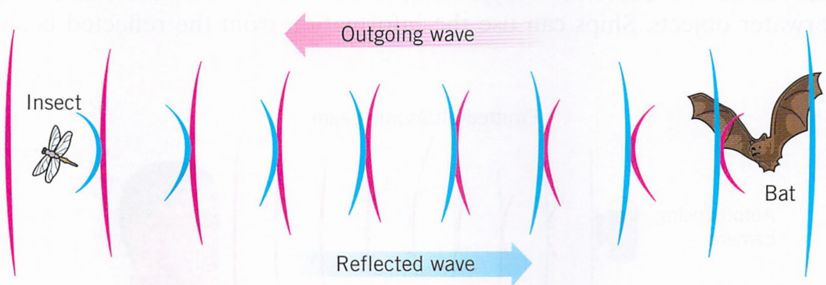


FIGURE 15-6. A bat emits a sound wave, which reflects off its target. By sensing the time it takes the sound to go out and back, the bat can tell how far away the target is.

experience the mating call of the female elephant more as a vibration than as sound, but the call attracts bull elephants from many miles away.

Whales, dolphins, and porpoises use echolocation as a navigation tool in the ocean, much as bats do in air. Sometimes, however, the sounds they emit are in the audible range for humans. Perhaps the most famous sophisticated uses of sound by animals are the songs of the humpback whales, which have been used in many commercial recordings. The function of these distinctively haunting songs remains a mystery. It appears, however, that all humpback whales in a wide area of ocean (the southern Atlantic, for example) sing similar songs, although some individual whales may leave out parts. Furthermore, the songs seem to change year by year, and whales in a given area are likely to change their songs together. We certainly have a lot to learn about how animals use sounds to communicate.

Connection

Applications of Ultrasound

We've mentioned that a bat emits sound waves with frequencies as high as 150,000 Hz. Sound waves with such high frequencies, above the 20,000-Hz limit of human hearing, are often called ultrasound. To see why such high-frequency sound waves can be very useful, think again about the bat searching for prey. Bats hunt insects, which are pretty small objects. To locate such a small object with a sound wave, you need a wave with a very small wavelength; a wave with a large wavelength would not reflect but would just keep going past the tiny insect. But sound waves with small wavelengths must have high frequencies since sound travels at a constant speed in air and speed equals wavelength times frequency. In other words, the advantage of ultrasonic frequencies is that they can reflect off very small objects.

Ultrasound is used in many different modern devices. For example, cameras with automatic range finders use beams of ultrasound to determine the distance to the object they are aimed at and set the camera's focus appropriately (Figure 15-7). Probably the most well-known application of ultrasound is in medical diagnosis. Pulses of sound at ultrasonic frequencies can travel through the body and partially reflect from every boundary between surfaces within the body. The reflections can be put together to form an image of organs within the body, such as the heart or a fetus, without any invasive surgery (Figure 15-8).

Ultrasonic frequencies are also used in sonar, which is a word derived from the phrase "sound navigation ranging." Sonar equipment sends out beams of ultrasound (about 20,000 to 100,000 Hz) under water, which are reflected from underwater objects. Ships can use the information from the reflected beams to

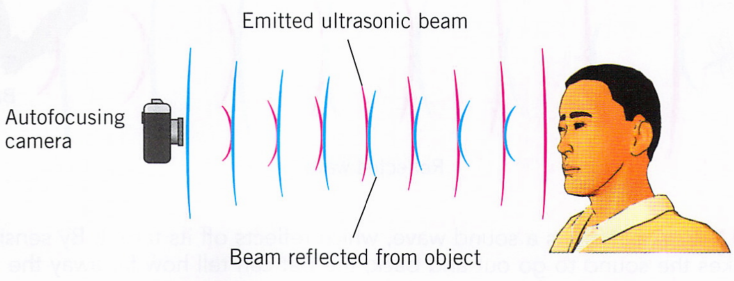
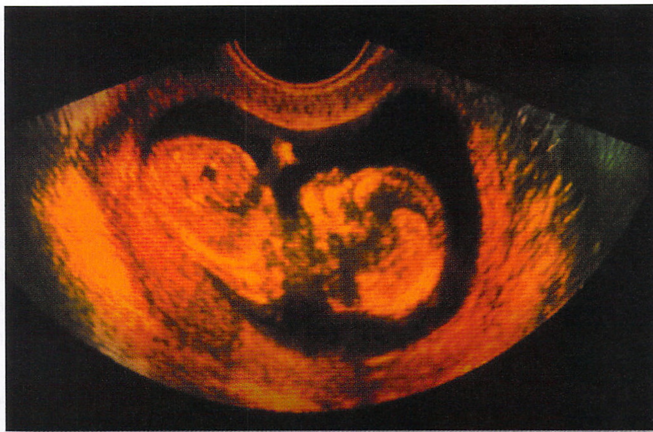


FIGURE 15-7. An autofocusing camera emits a pulse of ultrasound and measures the time for the echo to return.

(a)



(b)

FIGURE 15-8. (a) The ultrasound emitter is placed on a pregnant woman's abdomen. (b) An image of the fetus is produced.

navigate around shallow reefs or detect sunken vessels, submarines, or even schools of fish. The physics involved is much the same as in echolocation: determining the location of objects by the use of sound instead of light.

INTENSITY AND FREQUENCY

The two attributes of sound that are most obvious to us in our everyday experience are its intensity (loudness) and its frequency (pitch). Both of these characteristics are related to physical properties of the sound wave.

Intensity and Loudness

Sound *intensity* is a measure of the energy of a sound wave and is a quantitative term that refers to a specific physical measurement: the energy carried by a wave through an area per unit of time. The intensity varies as the square of the wave's amplitude. Thus, the greater the difference in pressure between the regions of compression and rarefaction of the sound wave, the higher is its intensity. Intensity is closely related to the more subjective word **loudness,** which refers to how the sound is perceived by us. For example, a sound that seems loud and out of place in a quiet room may be almost unnoticeable when it's heard on a busy street corner, even though it has the same intensity.

The intensity of a sound is usually expressed in a unit called the **decibel (dB),** which is actually $\frac{1}{10}$ of a unit called the "bel," a unit named after the American scientist Alexander Graham Bell, who invented the telephone. (Remember from Chapter 2 that the prefix deci- means $\frac{1}{10}$.) For reasons of convenience, and because of long historical precedent, scientists and engineers use the decibel instead of the bel.

The decibel unit describes the relative intensity delivered by the sound wave. An incoming sound intensity of 10^{-12} watts per square meter—a sound that is

TABLE 15-1 Decibel Ratings

Total deafness may occur	>160 dB
Jet plane taking off nearby	150 dB
Jackhammer	130 dB
Threshold of pain	120 dB
Rock concert; siren	110 dB
Harmful ranges for humans	>90 dB
Food blender; screaming baby	90 dB
Busy street traffic	70 dB
Normal conversation	60 dB
Buzzing mosquito	40 dB
Average whisper	30 dB
Pin dropped on a hard surface	20 dB
Rustling leaves	10 dB
Softest sound a human can hear	0 dB

barely audible to the human ear—is called 0 on this scale. A sound with 10 times that intensity is 10 dB, a sound with 100 (10^2) times that energy is 20 dB, a sound with 1000 (10^3) times that intensity is 30 dB, and so on. In Table 15-1 we give some familiar sounds and their decibel ratings.

This measure of sound intensity is an example of what physicists call a logarithmic scale. Each increase by a factor of 10 in the intensity associated with the sound wave results in an increase of 1 in the bel scale (and thus an increase of 10 in the decibel scale). While this convention might seem strange at first, there are many other examples of logarithmic scales in science. Earthquake energies, for example, are measured in a scale in which an earthquake of magnitude 5 releases 10 times as much energy as an earthquake of magnitude 4 and 100 times the energy of an earthquake of magnitude 3. The brightness of stars is also recorded as a logarithmic magnitude. And on a more fanciful level, the "warp drive" on ships in the *Star Trek* series also measures the speed of the ship on a logarithmic scale. In all these cases, a small range of numbers expresses a much larger range of magnitudes, which is the main advantage of a logarithmic scale.

Frequency and Pitch

Pitch, in contrast to loudness, is related to the frequency of a sound wave. The higher the frequency, the higher the pitch of the sound seems to be. Human hearing is typically sensitive to sounds in the frequency range from about 20 to 20,000 Hz, while some animals can sense sounds as low as 15 Hz (dogs) or as high as 150,000 Hz (bats).

It is useful to note that the speed of sound in air is essentially the same for all wavelengths. We can relate the frequency and wavelength of sound by the familiar equation

$$\text{Speed} = \text{Frequency} \times \text{Wavelength}$$

This equation tells us that the higher the frequency of a wave is, the shorter its wavelength, while the lower the frequency of a wave is, the longer the wavelength. Because of this relationship, we can say that

High-frequency sounds correspond to short wavelengths, and low-frequency sounds correspond to long wavelengths.

You can observe the consequences of this relationship between pitch and wavelength in the higher-pitched sounds emitted by smaller musical instruments or animals. For example, think about the shrill yapping of a Chihuahua versus the throaty growl of a Great Dane.

INTERFERENCE OF SOUND WAVES

Like all other waves, sound waves from two different sources interfere with one another when they come together. One interesting example of this phenomenon involves interference of sound waves in an auditorium. Occasionally, an auditorium is built in such a way that almost no sound can be heard in certain seats (so-called dead spots), while other seats receive unusually intense sound. This unfortunate situation results when two waves—for example, one directly from the stage and one bouncing off the ceiling or wall—arrive at those seats in just such a way as to cause significant destructive or constructive interference. One of the main goals of acoustical design of auditoriums, a field that relies on complex computer modeling of sound interference patterns, is to avoid such problems.

Davies Symphony Hall in San Francisco. This concert hall underwent a major renovation to improve its acoustics. Note the many sound baffles on the ceiling, hanging from the ceiling, and on the side walls.

The next time you're in a modern auditorium, take a look around. You will probably see large blocks of brightly colored fabric that look like wall and ceiling decorations. These structures, called "sound baffles," are placed carefully by acoustic engineers to absorb sound at crucial spots in the room, thereby preventing a sound wave that would normally be reflected from traveling farther and causing the kind of destructive interference just described. When a new auditorium is built, there is often a period of "tuning" while devices like this are moved around and adjusted for optimal performance.

Two concert halls that are famous for their excellent acoustical properties are the symphony halls in Boston, Massachusetts, and Vienna, Austria. Both of these halls were built in the nineteenth century, before architects were familiar with sound baffles and other devices for adjusting interference of sound waves. However, the decorative tastes of the time led the builders of these halls to include many statuettes and ornate wall decorations around the outer walls of the hall. These surfaces break up the sound waves just as effectively as modern techniques do, helping to produce a clear rich sound without dead spots.

Beats

Another interesting phenomenon occurs when two sound waves of almost the same frequency interfere with one another. As shown in Figure 15-9, if the two waves start out interfering destructively with one another, then with each cycle

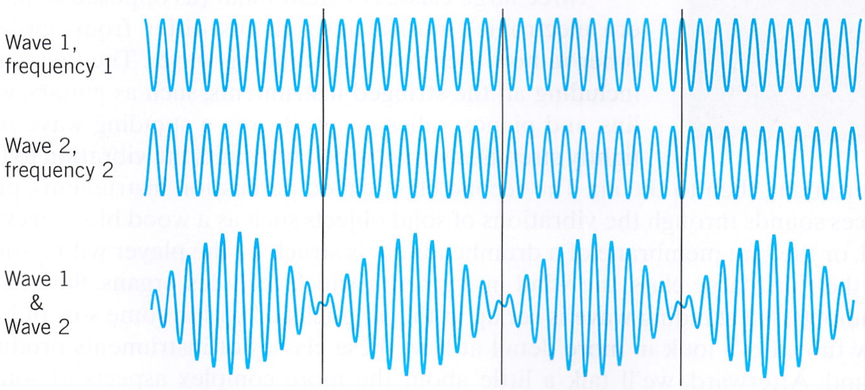


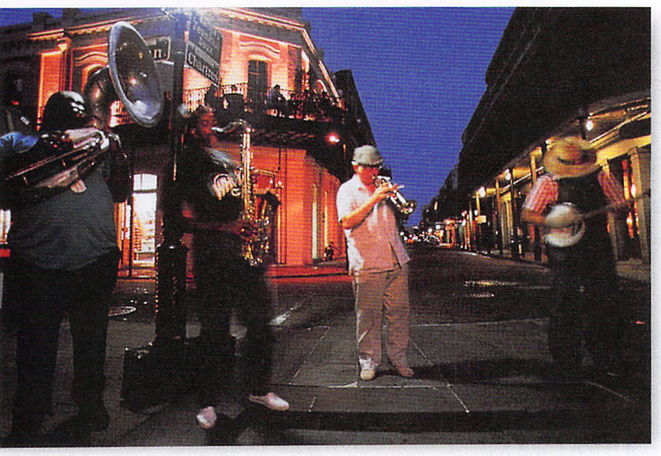
FIGURE 15-9. The origin of beat patterns. When two pitches of nearly the same frequency interfere, you hear a sequence of beats.

the crest of one arrives a little bit later than the crest of the other. Eventually the two waves begin to interfere constructively. But this constructive interference doesn't last either, because the falling behind of the crest continues until we recover the initial destructive interference. In this cycle, from one destructive interference to the next, one more crest of the higher-frequency wave has arrived at the listening point than the number of crests from the lower-frequency wave.

The result of this situation is that you hear a slow, pulsing sound when the two waves interfere. These pulses, called *beats,* result from the successive increases and decreases of intensity in the combined wave. When two frequencies combine to produce beats, the beat frequency equals the higher frequency minus the lower. Symphony musicians learn to avoid beats by adjusting the pitch of their instruments to play in tune.

THE SOUND OF MUSIC

Music, whether pop, jazz, or classical, consists of a pleasing succession of pitches. Any pitch (i.e., frequency) is possible, but musical pitches are usually selected from a specific sequence called a *scale.* In Western music, for example, the "well-tempered" scale consists of a sequence of pitches, each of which is the twelfth root of 2, or about 1.06, times the frequency of the next lower note. This relationship is derived from a 12-note scale; the thirteenth note has twice the frequency of the first note and thus sounds an *octave* higher. Look carefully at a piano keyboard and you'll see a 12-note pattern of white and black keys repeated over several octaves. Other cultures, such as Japan and India, use different musical scales, which can sound quite unusual to Western listeners.



Different-sized instruments in a New Orleans jazz ensemble play in different ranges. The large tuba on the left plays low notes, while the smaller trumpet at the center plays in a higher range.

Musical Instruments

The production of sound involves setting up a wave in the air. A wave pulse can be created by a single event such as clapping your hands or snapping your fingers. However, to set up a continuous sound, such as that produced by a musical instrument or a human voice, it is necessary to set up a standing wave that produces many pulses of the sound wave.

Three large classes of traditional (as opposed to modern electronic) musical instruments differ from one another in how they produce standing waves. The first class, including all the stringed instruments, such as guitars, violins, and pianos, relies on producing a standing wave in a tightly stretched string, which transmits the vibration to the instrument, then to the air. The second class, called percussion instruments, produces sounds through the vibrations of solid objects such as a wood block, a cymbal, or the taut membrane of a drumhead that is struck by the player with a stick. In the third large class, the wind instruments, which includes organs, flutes, and trumpets, the standing wave is set up in the air enclosed within some sort of hollow tube. Let's look in more detail at how these classes of instruments produce sound. Afterward, we'll talk a little about the more complex aspects of sound that make one instrument sound different from another.

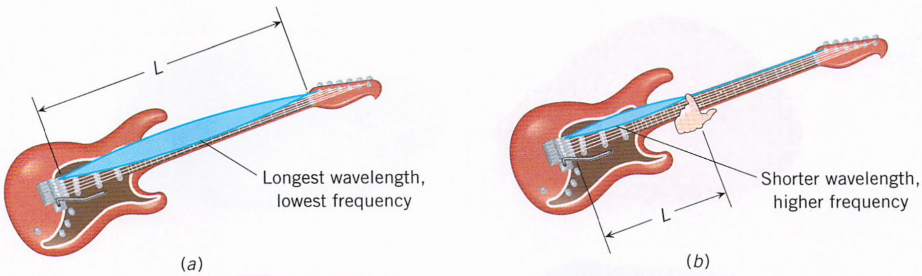
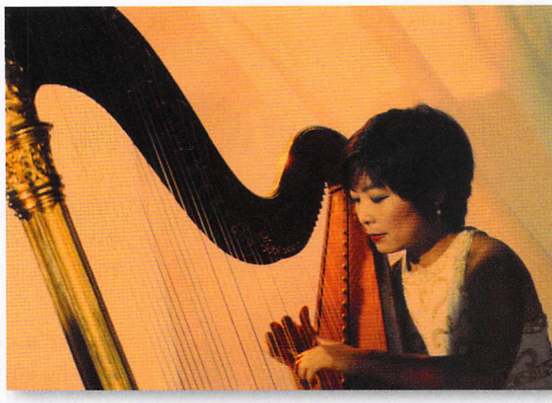


FIGURE 15-10. (*a*) An open guitar string vibrates at its lowest possible pitch. (*b*) A guitar player varies the pitch of her instrument by shortening the string with her fingers.

Stringed Instruments Think about what happens when you pluck a guitar string. Your finger pulls the stretched string to the side and lets it go. The string is then free to vibrate from side to side at its natural vibration frequencies. The lowest-pitched sound (corresponding to the longest wavelength and lowest vibration frequency) that can exist on the guitar string is shown in Figure 15-10*a*. This is the sort of standing wave pattern we discussed in Chapter 14. This vibration frequency produces the musical pitch of the note that we hear. The plucked string produces a sound by vibrating the instrument which in turn creates pressure waves in the air—traveling sound waves that match the frequency of the standing wave. These sound waves, in turn, travel at the speed of sound in air and come to your ear, allowing you to hear the plucked string.

Musicians who play stringed instruments can change the pitch of a stretched string in several ways. The frequency of the longest wave on a stretched string depends on three factors: the mass of the string, how tightly the string is stretched, and the length of the string. You can see all three of these factors come into play on a guitar or violin. First, the lower-pitched strings are always thicker and thus more massive compared to the higher-pitched strings. Then, to tune each string, musicians turn pegs on their instruments to tighten or loosen the strings. Finally, the musician's fingers press the strings down against the fingerboard to change the effective length of each string, producing the desired musical patterns of notes.



The strings of a harp are fixed in length; the performer produces different notes by plucking different strings.

Pianos and harps employ a different strategy to change notes. Each of dozens of strings is pretuned to a specific pitch (88 different pitches in the modern piano, for example). Each pitch is sounded by striking a different piano key or by plucking a different string on the harp. The musician cannot change the effective length of a piano or harp string; the pattern of notes is created by the sequence of different strings that are struck.

Percussion Instruments Perhaps the earliest forms of music were made by rhythmically striking objects that produce a pleasing sound. Percussion instruments, including all manner of drums, gongs, bells, and rattles, rely on the natural vibration frequencies of solid objects. Once struck, these objects vibrate at a characteristic set of frequencies, producing their characteristic sounds. Many instruments in the percussionist's vast arsenal of instruments, including ratchets, chimes, cymbals, and wood blocks, produce a single distinctive sound. In addition, a variety of mallet instruments, including xylophones, marimbas, and

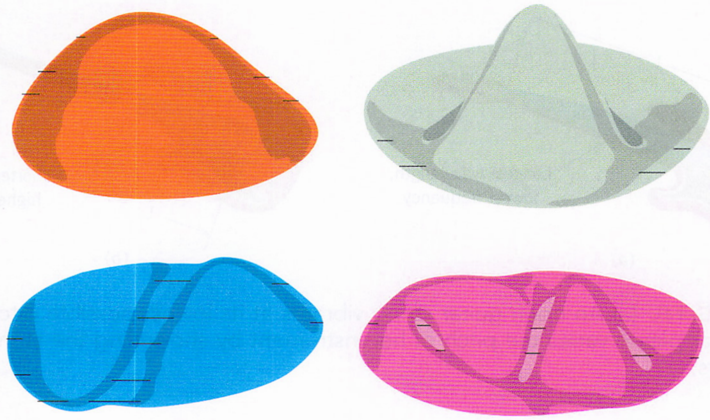


FIGURE 15-11. Drumheads vibrate with several different two-dimensional harmonics, which are analogous to those of a vibrating string. These four computer images show such vibrations with vertical exaggeration.

vibraphones, have a keyboard-like arrangement of dozens of individual wood or metal blocks, each sounding a specific pitch when struck.

Other percussion instruments can be tuned—for example, by changing the tautness of a drumhead. Next time you go to a symphony concert, watch as the timpanist carefully tunes the large copper drums. A drum (as well as a speaker in a stereo system) works in essentially the same way as a guitar string, except that in these cases a vibration is set up in a stretched membrane—a two-dimensional object, in contrast to a string, which has only one dimension (Figure 15-11).

Wind Instruments The third important class of traditional musical instruments, the wind instruments, rely on producing standing waves of a fixed pitch in an enclosed column of air. Wind instruments have existed since prehistoric times and now include a bewildering variety of forms, including all sorts of instruments that you blow into (saxophones, trumpets, flutes, oboes), as well as such mechanical instruments as pipe organs and even automobile horns. In order to understand how wind instruments work, it's important to distinguish the very different behavior of tubes with ends that are open versus those that are closed.

1. **At a closed end** Sound is a longitudinal wave, so the air molecules move in the same direction as the wave. Since the molecules can't move into the solid wall that closes the tube, the wave amplitude must be zero at the wall. In the language of Chapter 14, there must be a node in the standing wave at a closed end.
2. **At an open end** The sound wave must be at maximum amplitude at the open end of the tube—an antinode.

With this background, we can identify two different configurations for wind instruments. First, there are instruments (such as the clarinet or oboe) that are open at one end (the bell) and closed at the other (the mouthpiece), with a sound wave as shown in Figure 15-12*a*. In this case, there is a node at one end and an antinode at the other end, so the longest possible standing wave is of wavelength $4L$ (since only $\frac{1}{4}$ of a wavelength fits in the tube). Second, there are instruments (such as the flute and some organ pipes) in which the tube is open at both ends, as shown in Figure 15-12*b*. Here there are antinodes at both ends and the longest

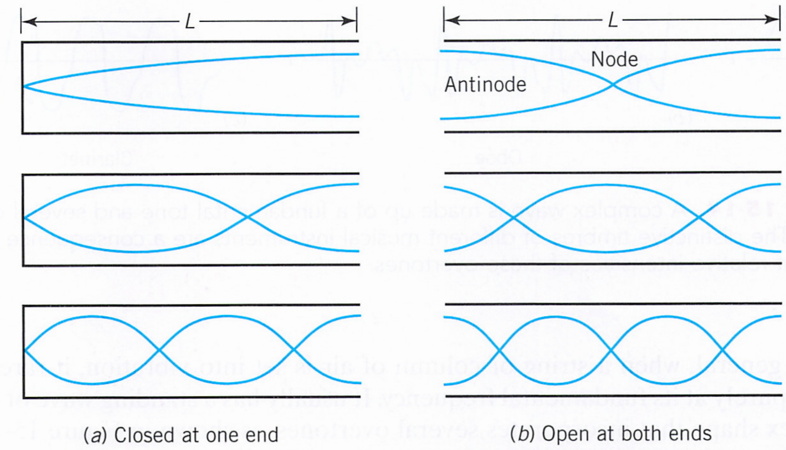


FIGURE 15-12. Wind instruments produce sound when a column of air vibrates in a tube. The two varieties of wind instruments rely on (*a*) a tube that is closed at one end or (*b*) a tube that is open at both ends.

standing wavelength is $2L$ (since only $\frac{1}{2}$ of a wavelength fits in the tube). Note that you could have a tube that is closed at both ends, but then the sound would have no way to leave the tube and could not be heard—rather an unfortunate situation for a musical instrument.

All modern wind instruments have the ability to change pitches by changing the length of the air column, and most of them employ one of three common mechanisms to do so. The trombone employs a long slide that changes the entire length of the instrument. Other brass instruments, including trumpets and horns, have valves that add or subtract fixed lengths of tubing. And all woodwind instruments, including flutes, saxophones, clarinets, and oboes, feature tubes lined with numerous keys and holes; opening and closing these holes also alters the effective length of the tube.

Fundamentals, Overtones, and Harmonics

A wave of a single frequency would be a rather unusual and haunting sound. Most of the sounds we hear are much more complex than that. To understand how complex sounds are generated, let's go back to the example of the vibrating guitar string. Think for a moment of all of the standing waves that could fit on the string, some of which are shown in Figure 15-13. In addition to the wave of wavelength $2L$ (a wave that is called the *fundamental,* or first **harmonic**), waves of wavelength L, $\frac{2}{3}L$, $\frac{1}{2}L$, and so on can also fit on the string. Each of these higher harmonics or **overtones,** were it acting alone, would produce a specific frequency, corresponding to a specific pitch, with shorter and shorter wavelengths corresponding to higher and higher pitches.

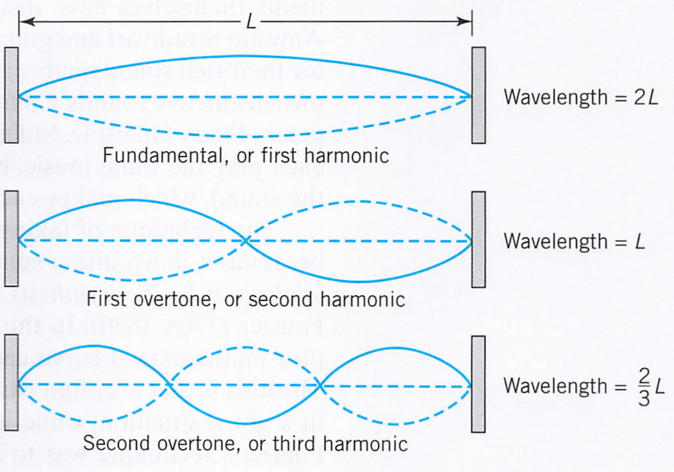


FIGURE 15-13. The first three harmonics of a vibrating string.

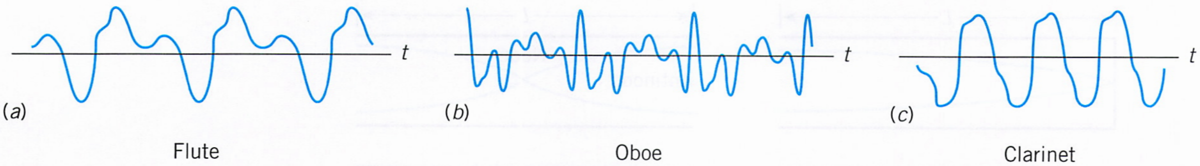


FIGURE 15-14. A complex wave is made up of a fundamental tone and several overtones. The distinctive timbres of different musical instruments are a consequence of different relative intensities of these overtones.

In general, when a string or column of air is set into vibration, it rarely vibrates purely at its fundamental frequency. It usually has a standing wave of more complex shape that incorporates several overtones, as shown in Figure 15-14. In this case, physicists think of the actual shape of the string as being built up by combining standing waves of the various harmonics, using the standard techniques of wave interference we discuss in Chapter 14. For example, in Figure 15-15*a* we show three waves—the first three harmonics. In this example, the amplitudes of the second and third harmonics are $\frac{1}{2}$ and $\frac{1}{3}$ of the fundamental, respectively, but in principle they could be as large (or as small) as we liked. If we add these three waves together, we get the complex wave shown in Figure 15-15*b*. Thus, by adding together only three of the possible waves that can fit on the string, we can create a complex wave that looks like none of the three. If we keep adding overtones, we can build up any shape on the string that we want. This process, in turn, means that when we pluck the string, the resulting sound wave is a complex mix of several harmonics.

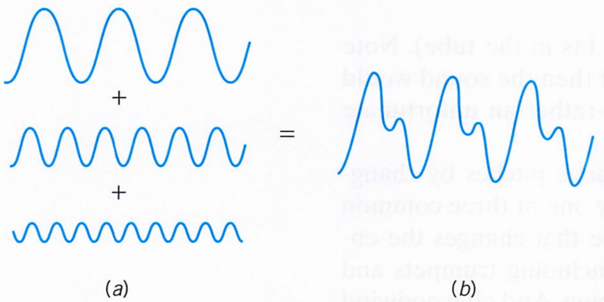


FIGURE 15-15. Adding waves. (*a*) The first three harmonics. (*b*) The combination of these waves into a complex sound wave.

Have you ever wondered why a guitar sounds so different from a flute or piano, even when they play the same melody? The complex mix of fundamental and overtones, which musicians call the quality or *timbre* of the sound, is what distinguishes the many different musical instruments. In some cases, the instruments themselves have distinctive timbres. Violins by the great Italian master Antonio Stradivari and guitars by the American firm of Gibson are highly prized for their rich sound quality. By the same token, different musicians produce their own distinctive sounds. Compare the very different timbres of the great jazz trumpeters Dizzy Gillespie, Miles Davis, and Wynton Marsalis, for example. They can each play the same music, but each has a slightly different mix of overtones in the sound, which makes each player sound slightly different.

The technique of taking a complex shape, such as the wave on a string, and breaking it down into a sum of simple, single-frequency waves, is called *Fourier analysis* or *Fourier synthesis,* after the French mathematician Jean Baptiste Joseph Fourier (1768–1830). In the early nineteenth century, he showed that any complex mathematical curve can be broken down into a sum of simple harmonics. The idea is that it's often easy to analyze the behavior of a single-frequency wave in a given situation, while it's quite difficult to deal with more complex waves. Fourier's technique was to solve the problem for a simple wave and then add the solutions together to the get the solution for the more complex shapes. Scientists quickly adopted his technique to analyze all sorts of situations, from heat flow in engines to the way that a skyscraper sways in the wind. This is also the

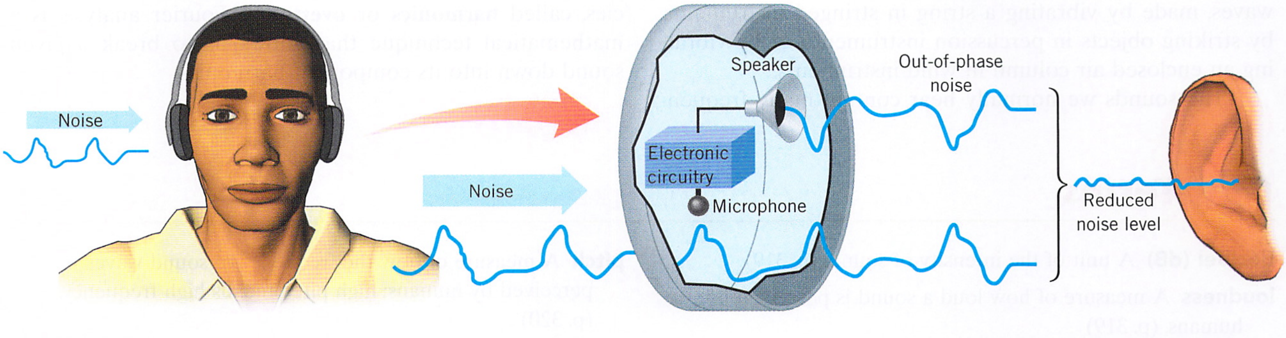


FIGURE 15-16. Noise-canceling headphones break down an incoming sound pattern into simple wave components and then generate new wave components that are out of phase with the incoming ones. The resulting sound is greatly reduced.

basis for noise-reducing headphones (Figure 15-16), which break down incoming noise into simpler wave components. They then generate new waves that are exactly opposite to the original sound pattern, causing destructive interference and effective cancellation of the noise.

THINKING MORE ABOUT

Sound: Acoustic Versus Electronic Instruments

Electronic musical instruments, such as the familiar synthesizer, rely on wave generators to build up musical sounds by adding together many waves of different frequencies—a process that is closely related to Fourier analysis. Almost any sound, from a bass drum to a guitar to the human voice, can be duplicated by this technology. Synthesized music is remarkable for its range of effects, its versatility, and its amplified power.

Nevertheless, many musicians find greater satisfaction in traditional acoustic instruments, where the player has a more direct role in producing the good vibrations. After all, a violinist sweeps her bow across the strings to set the strings into vibration, a trumpet player takes a deep breath and buzzes his lips to produce a clear high note, and a percussionist strikes the cymbals and drums to make their dramatic sounds. Musicians can feel as well as hear the vibrations of these instruments; they can control the musical sound directly by the actions of their bodies. Many musicians crave this intimate physical feedback.

Should the difference between electronic and acoustic music matter? If a synthesizer can duplicate exactly the radiant tone of a Stradivarius violin or the rhythmic intensity of a rocker's set of drums, should the musician care about how the sound is produced? Should the audience?

Summary

Sound waves are longitudinal waves that travel through media such as air and water. The wave consists of alternate regions of high and low pressure in the medium. Sound is used by many animals for communication, navigation, and locating prey.

The intensity or **loudness** of a sound, measured in units of watts per square meter or **decibels** respectively, depends on the square of the amplitude of the wave. The **pitch** depends on the frequency, with higher frequencies corresponding to higher pitches. Sound waves exhibit interference, a fact that is important in the science of acoustics.

Musical sounds are normally produced by standing waves, made by vibrating a string in stringed instruments, by striking objects in percussion instruments, or by vibrating an enclosed air column in wind instruments.

The sounds we normally hear contain many frequencies, called **harmonics** or **overtones.** Fourier analysis is a mathematical technique that allows us to break a given sound down into its component harmonics.

Key Terms

decibel (dB) A unit of the intensity of sound. (p. 319)

loudness A measure of how loud a sound is perceived by humans. (p. 319)

overtones (harmonics) A series of oscillations in which the frequency of each oscillation is a integral multiple of the fundamental frequency. (p. 325)

pitch A measure of how the frequency of sound waves is perceived by humans; high pitch means high frequency. (p. 320)

Review

1. Why is sound considered a longitudinal wave?
2. How does the compression and rarefaction of molecules result in sound?
3. What is the speed of a sound wave? How and why does this vary with temperature?
4. How can you tell the distance you are from a thunderstorm simply from seeing the flash of lightning and hearing the sound of the thunder? Explain.
5. What is an echo? How can it be used to tell the distance across an echo lake?
6. Can sound travel in media other than air? If so, what other media and how does this occur?
7. What are some of the other ways sound can be generated other than through the use of your vocal cords?
8. What wave properties does sound have? Explain.
9. How does the human ear sense the rapid changes in air pressure associated with sound?
10. How do bats locate their prey? What methods have been used to demonstrate this?
11. Give examples of how animals other than bats use sound.
12. What is meant by the intensity of a sound? How does it differ from loudness? What wave property is responsible for this?
13. What is the unit of relative loudness and who was it named after? What is the intensity in watts per square meter of a decibel value of zero?
14. What does it mean to say that the decibel system is a logarithmic system? What are some other examples of logarithmic scales used in science?
15. Do short sound wavelengths correspond to high or low frequencies? Long wavelengths?
16. At the extremes of human hearing, what strange qualities does sound perception take on?
17. How can destructive wave interference affect sound in a poorly designed auditorium? Explain exactly how this can occur.
18. How are good modern auditoriums designed so as to avoid problems with interference? Give an example.
19. What are beats and how do musicians avoid them?
20. What is a musical scale? An octave?
21. To get continuous sound out of a voice or instrument, why do you need to set up a standing wave?
22. What are the three main classes of traditional musical instruments, and how does each produce sound?
23. What three factors does the frequency of a stretched string depend on?
24. How do percussion instruments make use of the natural vibration frequencies of solid objects to produce their sounds? How do percussionists tune their instruments?
25. How do wind instruments work? Why must there be a wave node at the end of a closed-tube instrument? Why must there be an antinode at the end of an open-tube instrument?
26. How do musicians physically change the length of the air columns in their instruments and thus change the standing wave generated? How do brass instruments and woodwinds each do this?
27. What is a harmonic, or overtone? How is it produced and why is it desirable?
28. What is the timbre of a sound?
29. What is Fourier analysis and how is it used to analyze sound?
30. How does an electronic musical instrument differ from a traditional acoustic instrument?

Questions

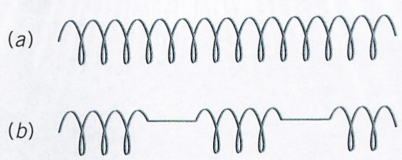
1. In what ways are sound waves similar to water waves? How are they different?

2. If a tree falls in a forest, what kinds of waves are created? Where did the energy that produced those waves come from?

3. If an atomic bomb were detonated on the surface of the Moon, how long would it be until we heard the explosion here on Earth?

4. Runners line up side by side at the starting line of a road race. About how long would the starting line have to be for there to be a one-second delay between the sound of the starting gun reaching the closest runner and the farthest runner from the gun? Are roads usually this wide?

5. A longitudinal wave in a Slinky is a nice representation of a sound wave. Suppose a Slinky is cut into pieces and those pieces are connected by rigid rods, as shown in the figure. If the mass of the rods were the same as the mass of the missing links, how would the speed of the waves in this new Slinky compare to those in the original one? Explain your answer.



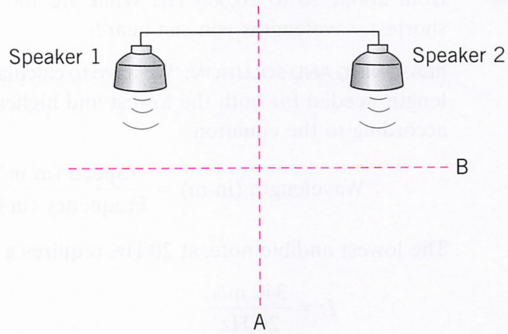
6. Why do you think that sound moves faster in water or rock than in air? What might be happening at a molecular level that accounts for this?

7. Do you think that sound travels slower or faster at very high altitudes than at sea level? Or does elevation make absolutely no difference in the speed of a sound wave? How would sound travel in outer space?

8. Why do you think that sound travels faster in warmer temperatures? Why does the elasticity or "springiness" of air increase with higher temperature?

9. What physical features make an echo lake produce echoes? What other types of spaces produce echoes?

10. Two stereo speakers are plugged into the same jack and emit pure 500-Hz tones. The speakers are separated by a distance of a few meters (see figure). As you walk along line A, describe what you hear. As you walk along line B, you hear alternating loud and soft sounds. Explain why this happens. What would change if you doubled the frequency and then walked along line B again?



11. Two speakers are plugged into the same jack and emit a pure tone of 1000 Hz. You walk along a line connecting them (see figure). When you are between them, the loudness of the sound fluctuates up and down. When you are not between the speakers and are walking away from them, the loudness does not fluctuate but gradually decreases. Explain the difference.

12. A guitar and a flute are in tune with each other. Explain how a change in temperature could affect this happy situation.

13. A pure tone with frequency 500 Hz is played through two stereo speakers plugged into the same jack. As you walk around the room, you notice that the loudness of the sound alternates from loud to soft repeatedly. What is happening? Would anything be different if a 1000-Hz sound wave were used instead?

14. For most vibrating systems, the amplitude of vibrations does not affect the frequency as long as the amplitude is not too high. Explain why this fact makes the construction and use of musical instruments possible.

15. When a tuning fork of frequency 256 Hz vibrates alongside a piano string, beats are heard. The string is tightened slightly and the beats go away. Was the original frequency of the string greater or less than 256 Hz? Explain.

16. Lower-pitched strings on guitars and pianos often have copper wire wound around them. This wire does not make the string stronger or change the tension of the string. What purpose does this extra wire serve?

Problem-Solving Examples

EXAMPLE 15-2 The Limits of Human Hearing

The normal human ear can hear sounds at frequencies from about 20 to 20,000 Hz. What are the longest and shortest wavelengths you can hear?

REASONING AND SOLUTION: We have to calculate the wavelength needed for both the lowest and highest frequency, according to the equation

$$\text{Wavelength (in m)} = \frac{\text{Speed (in m/s)}}{\text{Frequency (in Hz)}}$$

The lowest audible note, at 20 Hz, requires a wavelength

$$L = \frac{340 \text{ m/s}}{20 \text{ Hz}}$$

$$= 17 \text{ meters (about 50 feet long)}$$

Similarly, the highest audible note, at 20,000 Hz, is produced by a wavelength

$$L = \frac{340 \text{ m/s}}{20{,}000 \text{ Hz}}$$

$$= 0.017 \text{ meters (about two-thirds of an inch)}$$

At these extremes of human hearing, sounds take on a strange quality. The highest-frequency notes have a shrill, piercing quality, while at the lowest frequencies we don't so much hear the notes as feel them as a kind of low rumble. Listen carefully to your surroundings to see if you can identify everyday sources of these highest and lowest pitches. ●

EXAMPLE 15-3 The Limits of Human Hearing Revisited

Of all the traditional musical instruments, a large pipe organ has the widest range of pitches. Given that the human ear can hear sounds at frequencies from about 20 to 20,000 Hz, what are the longest or shortest open-ended organ pipes you are likely to see? (Treat organ pipes as columns of air open at both ends.)

REASONING AND SOLUTION: In Example 15-2, we have seen that these two frequencies correspond to wavelengths of 17 m (about 50 feet) and 0.017 m (about $\frac{2}{3}$ inch), respectively. Open organ pipes producing these notes need to be about half these wavelengths—approximately 8.5 and 0.009 meters, respectively. Most large pipe organs have pipes ranging from about 8 meters to less than 0.05 meter in length. Next time you have the chance, visit a church or auditorium with a large pipe organ and look at the variety of pipes. Not only are there many different lengths, but there are also many distinctive shapes, each sounding like a different instrument. ●

A mighty pipe organ.

Problems

1. Rank the following media from slowest to fastest in terms of the speed with which a sound wave travels through them: air at 40°C, steel, air at 0°C, water.

2. Rosa and Jon were asked by their physical science teacher to determine the speed of sound. While walking to their dormitories after class, Jon clapped his hands, which Rosa and Jon heard a moment later as an echo. The echo bounced off a building that was 300 ft away. They knew that they could not measure the brief time for a single clap to return, so they had a brilliant idea. Jon clapped and then started to clap as soon as he heard the echo, and he then continued this synchronized clapping so that Rosa could measure the frequency. Rosa counted 56 of Jon's claps in one-half minute.
   a. What is the frequency of Jon's clapping?
   b. What is the speed of sound as determined by Rosa and Jon?
   c. How does this speed compare with the speed of sound at room temperature (about 340 m/s)?

3. Rosa and Jon decided to test their results, so they walked an additional 100 ft away from the wall. Using their calculated sound speed in Problem 2, answer the following.
   a. Predict their new clapping frequency. Will it be greater than, equal to, or less than the frequency determined in Problem 2?
   b. What is the new time between successive claps?
   c. How many claps will Jon have to make in one-half minute?

4. Upon seeing a flash of lightning, Giselle counts 7 seconds until she hears the rumble of thunder. Assuming that the flash travels to her instantaneously, use the estimation method given on page 314 to determine how far away the lightning struck. If the temperature was 20°C, what was the distance using the known speed of sound at that temperature? How does this distance compare to the estimated values?

5. Anna was on vacation and came across an echo lake. Wanting to know how far she had to swim to get across the lake to the other side, she yelled across "Hello!" Assume that the temperature is 20°C and the speed of sound is 344 m/s.
   a. If 5 seconds later she heard her own echo, estimate the distance in feet, miles, and meters across the lake.
   b. If she had heard the echo in 3 seconds, what would the distance be?

6. **A.** Assume that the speed of a sound wave produced by an elephant at 20°C is 344 m/s and the frequency is around 25 Hz.
   a. What is the wavelength of this wave?
   b. Can you tell the amplitude or the intensity/loudness of the sound from this information? Why?
   c. Do you expect the wavelength of sound to be shorter or longer for higher-frequency sounds? Why?
   d. Consider the compression and rarefaction pattern of a sound wave and identify each of the following terms in the context of the elephant's sound wave: wavelength, frequency, and amplitude.

6. **B.** Repeat the calculations in part a for a high-frequency sound of 150,000 Hz that might be produced by a bat in order to confirm your answer in part c. Would a human hear this sound?

7. Use the data in Table 15-1 for the following problem. The decibel system is a logarithmic scale that measures the intensity of a sound relative to a 0-decibel level that corresponds to a sound wave with intensity 10^{-12} watts/m^2.
   a. How many times more intense is a food blender than a normal conversation? Than a pin dropped on a soft surface?
   b. Compare the intensity of sound of a jet at takeoff to that of an average loud rock concert.
   c. How much more intense is the sound of a jet compared to a normal conversation? Compared to a sound with a decibel value of zero?

8. A dog can hear sounds in the range from 15 to 50,000 Hz. What are the wavelengths that correspond to these sounds at 20°C?

9. Draw two sound waves together on the same graph. First draw the cases of destructive and constructive interference when the waves have the same frequency. Also, draw a case in which the waves have different frequencies. Is the interference constructive, destructive, or a mix of the two in this case?

10. If the length of a flute open at both ends is 0.4 m, what is the longest possible wavelength that could be produced by this instrument?

11. Calculate the fundamental frequency of a 4-meter organ pipe that is open at both ends. Calculate the same frequency for a pipe that is open at one end and closed at one end. Assume that the temperature is 20°C and the speed of sound is 344 m/s.

12. A stringed instrument has a maximum string length of 0.3 m and is tuned so that a wave travels along the string at 120 m/s.
   a. What is the string's fundamental frequency at this length and wave speed?
   b. What are some of the overtones or harmonics associated with this fundamental frequency?
   c. Is each of the fundamental waves and its overtones a standing wave?
   d. Do overtones enrich a sound or take away from it? What role does wave interference play in producing the final sound you hear? Explain your answer.

Investigations

1. Whales communicate over distances of thousands of miles. Investigate how they do this. What kind of wave is used? What is its speed? Its frequency? Its wavelength? Listen to a recording of humpback whale sounds.

2. Go to several local and campus concert halls and rate the quality of the acoustics for each one you are able to visit. What characteristics do the halls with good acoustics share? What are some of the obvious design additions that improve the sound? Do some initial research into the design of these structures before going so you know what to pay attention to in terms of design.

3. How do submarines use sound and sonar to navigate and to detect other ships? Research the history and development of these sound detection and sound suppression technologies. Evaluate the progress made so far, and find out if scientists see any further improvements on the horizon.

4. Go to a church with a pipe organ and listen to a concert, and if possible take a closer look at the pipes. How many are there and what shapes and sizes do they come in? Are they open- or close-ended? Interpret the sounds in terms of what you learned in this chapter. Which pipes produce high-pitched sounds and which ones low-pitched sounds? How is the volume or intensity controlled?

5. A symphony concert is a good place to hear a variety of sounds. Watch how the musicians tune their instruments before they play. What does each player do? Why is it effective?

6. Investigate the wave generators used in the production of electronic music. How do they do this, and what is the actual physical generator of sound?

7. Go to your local stereo store and compare stereo systems. What are the differences in sound from different systems? Do systems in the same price range always sound the same? If not, how are they different and why is this the case? Similarly, what is different in terms of sound generation in some of the cheaper versus the high-end systems?

8. How does a hearing aid work? What site(s) in the ear does it target?

9. How does a car muffler work? Find out just how it suppresses engine sound. What decibel levels are heard with and without it?

10. Pick up a guitar sometime and, as you play around with it, note how the thickness of the string affects the sound as you play or pluck away. Also note how the length of the string affects the sound as you hit different frets by pressing down the string at different places. Try adjusting the tuning by changing the tightness of the strings and note how a tighter versus a looser string changes the sound. Would changing the actual composition of the strings make a difference?

11. What types of animals use sound to communicate? What are some organisms that do not use sound to communicate? What might be some of the evolutionary advantages and disadvantages of using sound?

12. What are the types of instruments that were available to "primitive" or premodern cultures? How do they compare to modern instruments?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://asa.aip.org/sound.html** Interesting sounds from the Acoustical Society of America.
2. **http://www.silcom.com/~aludwig/musicand.htm** An equation-free description of the physics of sound, with animations.
3. **http://www.phy.ntnu.edu.tw/java/sound/sound.html** A visible/audible Java applet that demonstrates Fourier synthesis.
4. **http://hyperphysics.phy-astr.gsu.edu/hbase/sound/soucon.html#c1** The physics of sound concept maps.
5. **http://www.earaces.com/anatomy.htm#Cross%20Section%20Of%20Ear** The anatomy of the human ear.
6. **http://www.phys.unsw.edu.au/PHYSICS_!/SPEECH_HELIUM/speech.html** The physics of human speech.
7. **http://www.geocities.com/Vienna/3941/index.html** Essays on physics of brass wind instruments, concentrating on the trumpet.
8. **http://www.kettering.edu/%7Edrussell/Demos.html** An extensive collection of acoustics and vibrations animations.
9. **http://www.harmony-central.com/Guitar/harmonics.html** The physics of guitar strings for musicians.