24.3 Sound

How do we know that sound is a wave? First, it has both frequency and wavelength. We also know sound is a wave because it does all the things other waves do. Sound can be reflected, refracted, and absorbed. Sound also shows diffraction and interference. Resonance occurs with sound waves and is especially important for understanding how musical instruments work.

VOCABULARY

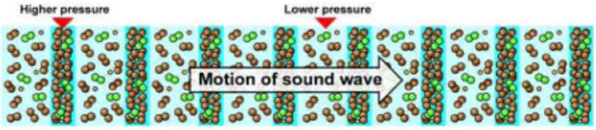
sound - a traveling oscillation of atoms or pressure.

Sound is a traveling oscillation of atoms

What is sound? Depending on the material, **sound** is a traveling oscillation of atoms or pressure. Since these oscillations are in the same direction as the sound travels, sound is a longitudinal wave.

Sound in solids and liquids In solids and liquids, sound involves oscillations of neighboring atoms. If you push one atom, it pushes its neighbor, and so on. The pushes among atoms cause them to oscillate back and forth like tiny beads on springs. The oscillation spreads through the connections between atoms to make a sound wave.

Sound in air and gases In air and gases, atoms are spread out and interact by colliding with one another. Sound travels in air and gases as a traveling oscillation of pressure. A layer of high pressure pushes on the next group of atoms and causes those atoms to squeeze together. Then, the pattern repeats.



Looking at a sound wave Figure 24.18 illustrates what a sound wave might look like if you could see the atoms (the effect of sound on air molecules is exaggerated). Sound from a stereo reaches your ears when the surface of a speaker moves back and forth at the same frequencies as the sound waves being produced. If you touch the surface of a speaker, you can "feel" the sound as vibrations. These vibrations create a traveling sound wave of alternating high and low pressure.

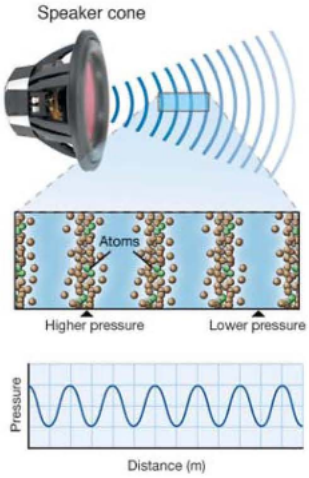


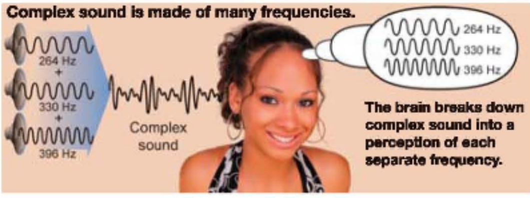
Figure 24.18: *This is what a sound wave might look like if you could see the atoms. The effect of sound on air molecules is exaggerated.*

Frequency and pitch

Frequency and pressure change The frequency of sound indicates how fast air pressure oscillates back and forth. The purr of a cat, for example, might have a frequency of 50 hertz. This means the air pressure alternates 50 times per second. The frequency of a fire truck siren might be 3,000 hertz. This corresponds to 3,000 vibrations per second in the pressure of the air.

Frequency and pitch Your ears are very sensitive to the frequency of sound. The **pitch** of a sound is how you hear and interpret its frequency. A low-frequency sound has a low pitch, like the rumble of a big truck or a bass guitar. A high-frequency sound has a high pitch, like the scream of a whistle or siren. Animals might hear a wider range of frequencies, or higher or lower frequencies than humans.

Most sound has more than one frequency Almost all the sounds you hear contain many frequencies at the same time. In fact, the sound of the human voice contains thousands of different frequencies—all at once (see the image below). Because voices have different mixtures of frequencies, you can identify one person's voice from another. Figure 24.19 shows the frequency spectrum for three people saying *hello*. A frequency spectrum shows loudness on the y-axis and frequency on the x-axis. What differences do you see among the graphs?



The frequency range of sound waves Anything that vibrates creates sound waves, as long as there is contact with other atoms. However, not all "sounds" can be heard. Humans can hear in the range from 20 to 20,000 Hz. Bats can hear high-frequency sounds from 2,000 to 110,000 Hz, and elephants hear lower-frequency sounds from 16 to 12,000 Hz.

VOCABULARY

pitch - the perception of high or low that you hear at different frequencies of sound.

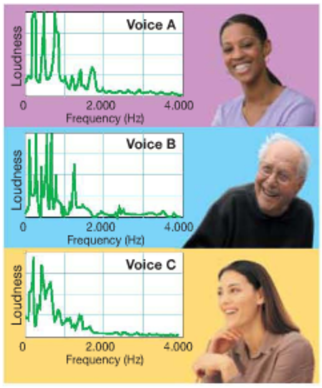


Figure 24.19: *The frequencies in three people's voices as they say the word* hello. *Each person's voice is made up of a mixture of frequencies.*

Intensity and loudness of sound

Decibels The unit for the intensity, or strength, of a sound is the **decibel (dB)**. We can measure sound intensity with scientific instruments just like we can measure mass with a balance. The decibel scale (shown below) is convenient to use because most sounds fall between 0 and 100. The amplitude of a sound increases 10 times for every 20-decibel increase (Figure 24.20).

0 dB	Threshold of human hearing; quietest sound we can hear
10–15 dB	A quiet whisper 1 meter away
30–40 dB	Background sound level in a house
45–55 dB	The noise level in an average restaurant
65 dB	Ordinary conversation 1 meter away
70 dB	City traffic
90 dB	A jackhammer cutting up the street 3 meters away
100 dB	MP3 player turned to its maximum volume
110 dB	The front row of a rock concert
120 dB	The threshold of physical pain from loudness

Loudness When you experience a loud sound, you experience the effects of its intensity *and* frequency. An *equal loudness curve* compares how loud you hear sounds of different frequencies (Figure 24.21). As you can see, the human ear responds differently to high and low frequencies. This curve shows that for you to hear low-frequency sounds (below 100 Hz) the same as sounds from 100 to 1,000 Hz, the decibel value needs to be higher for the low-frequency sound. Notice that the numbers are not evenly spread out on the *x*-axis of this graph. This type of spacing is called a *logarithmic scale*. You read the graph in the same way that you would read an evenly spaced graph.

Acoustics *Acoustics* is the science and technology of sound. Knowledge of acoustics is used to design facilities like libraries, recording studios, and concert halls. A design might address how to reduce sound intensity and/or whether sound needs to be absorbed, amplified, or even prevented from entering a room.

VOCABULARY

decibel - a unit of measure for the intensity or strength of a sound.

Comparing Decibels and Amplitude

Decibels (dB)	Amplitude
0	1
20	10
40	100
60	1,000
80	10,000
100	100,000
120	1,000,000

Figure 24.20: *The decibel scale measures amplitude (loudness).*

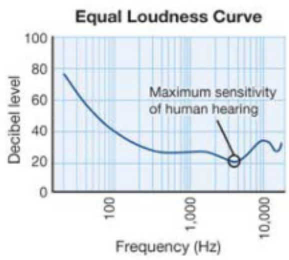


Figure 24.21: *All points on an equal loudness curve have the same loudness.*

The speed of sound

Sound is slower than light You might have noticed that the sound of thunder often comes many seconds after you see lightning. Lightning is what creates thunder, so they really happen at the same time. You hear a delay because sound travels much slower than light. The speed of sound is about 1,200 km/h (745 mph). Light travels at 300,000 km/s (186,000 mi/s).

Subsonic and supersonic Objects that move faster than sound are called **supersonic**. If you were on the ground watching a supersonic plane fly toward you, there would be silence (Figure 24.22). The sound would be *behind* the plane, and reach your ears after the plane had passed over you. Some military jets fly at supersonic speeds. Passenger jets are *subsonic* because they travel at speeds from 600 to 800 km/h.

Sound in liquids and solids Sound travels through most liquids and solids faster than through air (Figure 24.23). Sound travels about 5 times faster in water and about 18 times faster in steel. Why? Recall that a pendulum keeps moving through its cycle because the force of gravity continually pulls it back to an equilibrium position. For a pendulum, gravity is the *restoring force*. Sound also depends on restoring forces. The forces holding steel atoms together are much stronger than the forces between the molecules in air. Stronger restoring forces increase the speed of sound.

Sound speed depends on temperature and pressure In air, the energy of a sound wave is carried by the motion of atoms. Therefore, anything that affects the motion of atoms affects the speed of sound. For example, molecules move more slowly in cold air, and the speed of sound decreases. At 0°C, the speed of sound is 330 m/s, but at 21°C, the speed of sound is 344 m/s. Also, when pressure increases, atoms become more crowded and the speed of sound increases because collisions between atoms increase. If the pressure decreases, the speed of sound decreases.

Sound speed and molecular weight Lighter atoms and molecules (those with lower molecular weights) move faster than heavier ones at the same temperature. The speed of sound is higher in helium gas because helium atoms are lighter (and faster) than either the oxygen (O_2) or nitrogen (N_2) molecules that make up air.

VOCABULARY

supersonic - a term to describe speeds faster than the speed of sound.

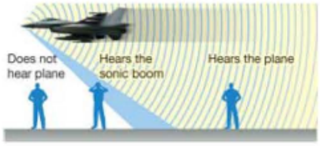


Figure 24.22: *The boundary between hearing and not hearing the plane is the "shock wave." The person in the middle hears a sonic boom as the shock wave passes over him.*

Material	Sound Speed (m/s)
Air	330
Helium	965
Water	1,530
Wood (average)	2,000
Gold	3,240
Steel	5,940

Figure 24.23: *The speed of sound in various materials (helium and air at 0°C and 1 atmospheric pressure).*

The wavelength of sound

Range of wavelengths of sound

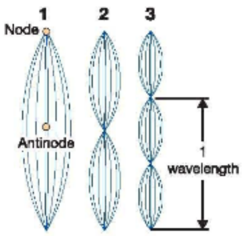
The wavelengths of sound in air can be compared to the size of everyday objects (Table 24.1). As with other waves, the wavelength of a sound is inversely related to its frequency (Figure 24.24). A low-frequency, 20-hertz sound has a wavelength the size of a large classroom. At the upper range of hearing, a 20,000-hertz sound has a wavelength about the width of a finger.

Table 24.1: Frequency and Wavelength for Some Typical Sounds

Frequency (Hz)	Wavelength	Typical Source
20	17 m	rumble of thunder
100	3.4 m	bass guitar
500	68 cm (27")	average male voice
1,000	34 cm (13")	female soprano voice
2,000	17 cm (6.7")	fire truck siren
5,000	6.8 cm (2.7")	highest note on a piano
10,000	3.4 cm (1.3")	whine of a jet turbine
20,000	1.7 cm (0.67")	highest-pitched sound you can hear

Standing waves

A wave that is confined in a space is called a **standing wave**. It is possible to make standing waves of almost any type, including sound, water, and even light. You can experiment with standing waves using a vibrating string. Vibrating strings create sound on a guitar or piano. Like all oscillators, a string has natural frequencies. The lowest natural frequency is called the **fundamental**. A vibrating string also has other natural frequencies called **harmonics**.



The diagram at the right shows the first three harmonics. You can find the harmonic number by counting the number of "bumps," or places of greatest amplitude. The first harmonic has one bump, the second has two, the third has three, and so on. The place of highest amplitude on a string is the *antinode*. The place where the string does not move is called a *node*.

VOCABULARY

standing wave - a wave that is confined in a space.

fundamental - the lowest natural frequency of an oscillator.

harmonic - one of the many natural frequencies of an oscillator.

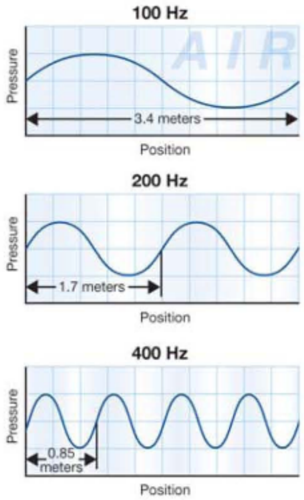


Figure 24.24: *The frequency and wavelength of sound are inversely related. When the frequency goes up, the wavelength goes down proportionally.*

How we hear sound

The cochlea The cochlea provides us with our ability to interpret sound—in other words, our sense of hearing. However, the cochlea is in the inner ear (Figure 24.25). Sound has to reach the cochlea by first entering the ear canal, where it encounters the eardrum. Here, the sound waves cause the eardrum to vibrate. Then, three delicate bones of the inner ear transmit these vibrations to the side of the cochlea. In turn, fluid in the spiral channel of the cochlea vibrates and creates waves. Nerves along the channel have tiny hairs that shake when the fluid vibrates. Near the entrance, the channel is relatively large, so the nerves respond to longer-wavelength, lower-frequency sound. The nerves at the small end of the channel respond to shorter-wavelength, higher-frequency sound.

The semicircular canals As you know, the function of our ears is hearing. But did you know that your ears also provide you with your sense of balance? Near the cochlea in the inner ear are three semicircular canals. Like the cochlea, each canal contains fluid. The movement of this fluid in the canals indicates how the body is moving (left–right, up–down, or forward–backward).

Human hearing In general, the combination of the eardrum, bones, and the cochlea limit the range of human hearing from 20 hertz to 20,000 hertz. However, hearing varies greatly among different people, and it changes with age. Some people can hear sounds above 15,000 Hz and other people can't. On average, people gradually lose high-frequency hearing with age. Most adults cannot hear frequencies above 15,000 hertz, while children can often hear to 20,000 hertz.

Hearing can be damaged by loud noise Hearing is affected by exposure to loud or high-frequency noise. Listening to loud sounds for a long time can cause the hairs on the nerves in the cochlea to weaken or break off, causing permanent damage. Therefore, it is important to always protect your ears by keeping the volume of noise at a low or reasonable level. It is also important to wear ear protection if you have to stay in a loud place. In concerts, many musicians wear earplugs onstage to protect their hearing.

Earplug

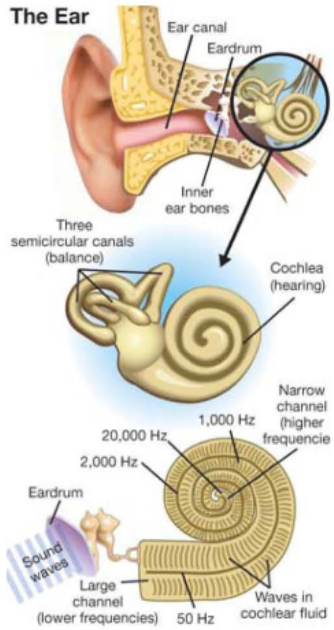
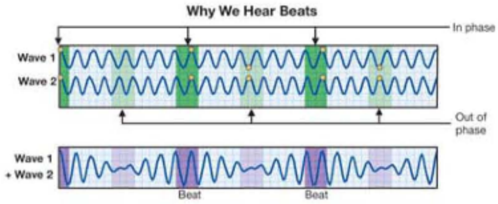


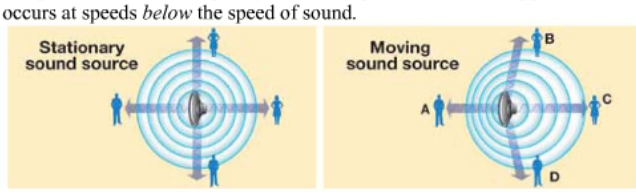
Figure 24.25: *The structure of the inner ear. When the eardrum vibrates, three small bones transmit the vibrations to the cochlea. The vibrations make waves inside the cochlea, which shake hairs attached to nerves in the spiral. Each part of the spiral is sensitive to a different frequency.*

Beats and the Doppler effect

Beats When two frequencies of sound are not exactly equal in value, the loudness of the total sound seems to oscillate, creating a **beat** The *superposition principle* states that sound waves occurring at the same time combine to make a complex wave. The sound (amplitude) of this wave is louder than either wave separately when the waves are *in phase* due to constructive interference. When the waves are *out of phase,* the sound is quieter due to destructive interference. We hear the alternation in amplitude as beats.



The Doppler effect is caused by motion The **Doppler effect** is a shift in the frequency of an oscillation caused by motion of the source of the oscillation. If a stationary object is producing sound, listeners on all sides will hear the same frequency (see diagram below). When the object is in motion, the frequency will *not* be the same for all listeners. People moving with the object hear the frequency as if the object were at rest. To the side (positions B and D) a slightly higher frequency is heard as it approaches, and then a slightly lower frequency as it passes. A higher frequency is heard at position A as the approaching sound waves are compressed. A lower frequency is heard at position C. The Doppler effect occurs at speeds *below* the speed of sound.



VOCABULARY

beat - the oscillation between two sounds that are close in frequency.

Doppler effect - an increase or decrease in frequency caused by the motion of the source of an oscillation (such as sound).

SCIENCE FACT

Bats and Beats

Bats use *echolocation* to navigate and find insects for food. Like a "sonic flashlight," the bat's voice "shines" ultrasound waves into the night. The sound occurs as "chirps," short bursts of sound that rise in frequency. When the sound reflects off an insect, the bat's ears receive the echo. Since the frequency of the chirp is always changing, the echo comes back with a slightly different frequency. The difference between the echo and the chirp makes beats that the bat can hear. The beat frequency is proportional to how far the insect is from the bat. A bat can even determine where the insect is by comparing the echo it hears in its left ear with what it hears in its right ear.

24.3 Section Review

1. What is the relationship between pitch and frequency?
2. If you looked at the frequency spectrums of two friends saying the word *dog*, would they look the same or different? Explain your answer.
3. What two variables affect how loudly you hear sound?
4. How do the amplitudes of a 120-decibel sound and a 100-decibel sound compare?
5. Would an object moving at 750 km/h be supersonic or subsonic?
6. Would an object moving at 100 mph be supersonic or subsonic? Use the conversion factor 1 mile = 1.6 kilometers.
7. Why does sound travel faster through water than through air?
8. The first five harmonics for a vibrating string are shown in Figure 24.26.
   a. For each harmonic, identify the number of wavelengths represented.
   b. For each harmonic, identify the number of nodes and antinodes that are present (include the ends of the string in your count).
   c. Which of the five harmonics has the highest natural frequency?
   d. Make a drawing that shows what the 6th harmonic would look like.
9. If two sound waves have exactly the same frequency, will you hear beats? Why or why not?
10. How does the cochlea allow us to hear both low-frequency and high-frequency sound?
11. If you were talking to an elderly person who was having trouble hearing you, would it be better to talk in a deeper voice (low-frequency sound) or a higher voice (high-frequency sound)?
12. A paramedic in an ambulance does not experience the Doppler effect of the siren. Why?
13. You hear an ambulance in your neighborhood that is traveling a few blocks from where you are. The pitch of the siren seems to be getting lower and lower. Is the ambulance traveling toward you or away from you? How do you know?
14. What happens when two sound waves are out of phase?

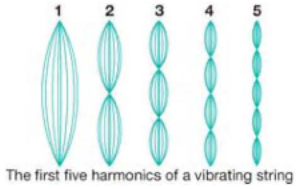


Figure 24.26: *Question 8.*

TECHNOLOGY

Doppler Radar

Doppler radar is a way to measure the speed of a moving object at a distance. A transmitter sends a pulse of microwaves. The waves reflect from a moving object, such as a car. The frequency of the reflected wave is increased if the car is moving toward the oncoming microwaves and decreased if the car is moving away. The difference in frequency between the reflected and transmitted wave is proportional to the speed.

Do research to find out how Doppler radar is used in weather forecasting.