9.3 Sound

Like other waves, sound has frequency, wavelength, amplitude, and speed. Because sound is part of your daily experience, you already know its properties—but by different names. You may never hear anyone complain about *amplitude*, but you have heard about sound being too *loud*. The loudness of sound comes from the amplitude of a sound wave.

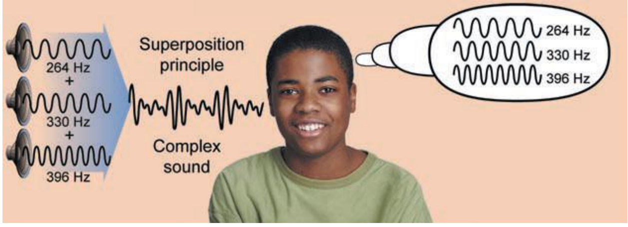
The frequency of sound

Frequency and pitch

Your ear is 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. Humans can generally hear frequencies between 20 Hz and 20,000 Hz. Animals may hear both higher and lower frequencies.

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. (Figure 9.18).



The frequency spectrum

Why is it easy to recognize one person's voice from another's, even when both are saying the same word? The reason is that people have different mixtures of frequencies in their voices. A *frequency spectrum* shows loudness on the vertical axis and frequency on the horizontal axis. Figure 9.18 shows the frequency spectrum for three people saying "hello." Can you see any difference between the graphs?

The loudness of sound

The decibel scale

The loudness of sound is measured in **decibels** (dB). Loudness is determined mostly by the amplitude of a sound wave. However, almost no one (except scientists) uses amplitude to measure loudness. Instead, we use the decibel scale (Figure 9.19). Most sounds fall between 0 and 100 on the decibel scale, making it a very convenient number to understand and use.

The sensitivity of the ear

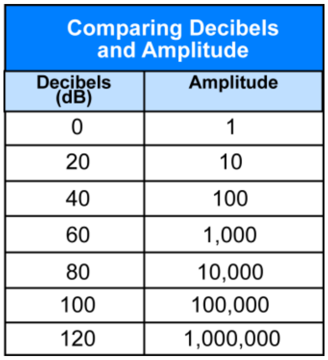
How loud you *hear* a sound depends on both amplitude and frequency. The human ear is most sensitive to frequencies between 500 and 5,000 Hz. It is no surprise that these are the same the frequencies found in voices! An *equal loudness curve* compares how loud you hear sounds of different frequencies (Figure 9.20). Sounds near 2,000 Hz seem louder than sounds of other frequencies, even at the same decibel level. According to this curve, a 40 dB sound at 2,000 Hz sounds just as loud as an 80 dB sound at 50 Hz.

Acoustics

Acoustics is the science and technology of sound. Knowledge of acoustics is important in many situations. For example, reducing the loudness of sound is important in designing libraries so that sounds are absorbed to maintain quiet. Recording studios are designed to prevent sound from the outside from mixing with the sound inside.

Table 9.1: Common sounds and their loudness in decibels

0 dB	Threshold of human hearing; quietest sound we can hear
10–15 dB	A quiet whisper 3 feet away
30–40 dB	Background sound level at a house
45–55 dB	The noise level in an average restaurant
65 dB	Ordinary conversation 3 feet away
70 dB	City traffic
90 dB	A jackhammer cutting up the street 10 feet 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



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 9.19: *The decibel scale measures amplitude (loudness).*

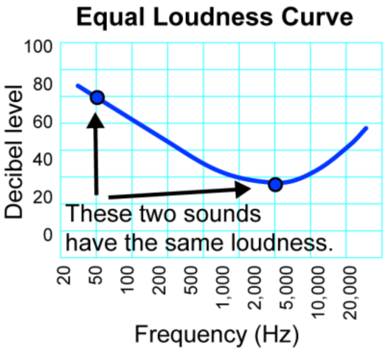


Figure 9.20: *All points on an equal loudness curve have the same loudness*

The speed of sound

Sound moves about 340 meters per second

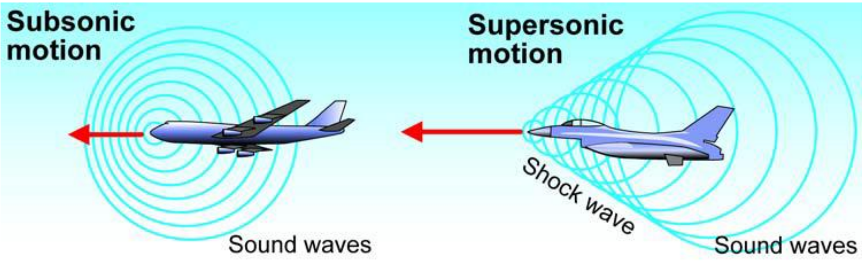
You have may have noticed the sound of thunder often comes many seconds after you see lightning. Lighting is what creates thunder so they really happen at the same time. You hear a delay because sound travels much slower than light. The speed of sound in normal air is 343 meters per second (660 miles per hour).

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 9.21). The sound would be *behind* the plane, racing to catch up. Some military jets fly at supersonic speeds. Passenger jets are *subsonic* because they travel at speeds from 400 to 500 miles per hour.

Sonic booms

A supersonic jet “squishes” the sound waves that are created as its nose cuts through the air. A cone-shaped *shock wave* forms where the waves “pile up” ahead of the plane. In front of the shock wave there is total silence. Behind the shock wave you can hear the noise from the plane. Right at the shock wave the amplitude changes abruptly, causing a very loud sound called a *sonic boom*.



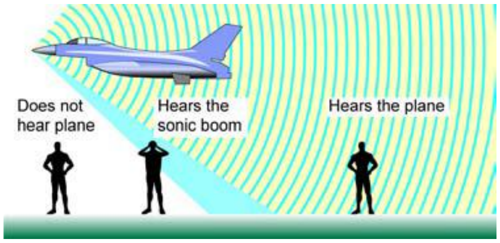


Figure 9.21: *If a supersonic jet flew overhead, you would not hear the sound until the plane was far beyond you. The boundary between sound and silence is the "shock wave." The person in the middle hears a sonic boom as the shock wave passes over him. Because the sonic boom can shatter windows, planes are not allowed to fly over cities at supersonic speeds*

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

Figure 9.22: *The speed of sound in various materials (helium and air at 0°C and 1 atmospheric pressure).*

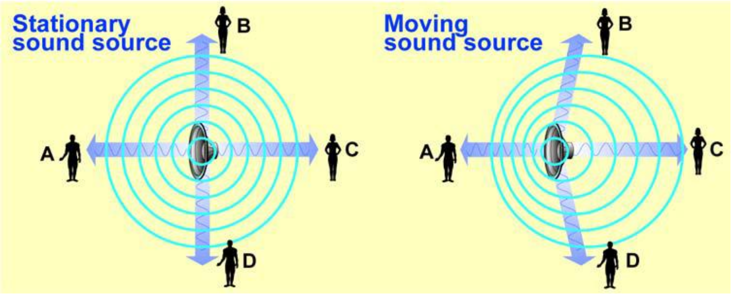
Sound in liquids and solids

Sound travels through most liquids and solids faster than through air (Figure 9.22). Sound travels about five times faster in water, and about 18 times faster in steel. This is because sound is a traveling oscillation. Like other oscillations, sound depends on restoring forces. The forces holding steel atoms together are much stronger than the forces between the molecules in air. Stronger restoring forces raise the speed of sound.

The Doppler Effect

The Doppler effect is caused by motion

If an object making sound is not moving, listeners on all sides will hear the same frequency. When the object is moving, the frequency will *not* be the same to all listeners. People moving with the object or to the side hear the frequency as if the object were at rest. People in front hear a higher frequency. People behind hear a lower frequency. The shift in frequency caused by motion is called the **Doppler effect**. The Doppler effect occurs at speeds *below* the speed of sound.



The cause of the Doppler effect

The Doppler effect occurs because an observer hears the frequency at which wave crests arrive at his or her ears. Observer (A) in the graphic above hears a higher frequency. This is because the object's motion causes the crests in front to be closer together. The opposite is true behind a moving object, where the wave crests are farther apart. Observer (C) in back hears a lower frequency because the motion of the object makes more space between successive wave crests. The greater the speed of the object, the larger the difference in frequency between the front and back positions.

Hearing the Doppler effect

You hear the Doppler effect when you hear a police or fire siren coming toward you, then going away from you. The frequency shifts up when the siren is moving toward you. The frequency shifts down when the siren is moving away from you.

What is a sound wave?

How we know sound is a wave

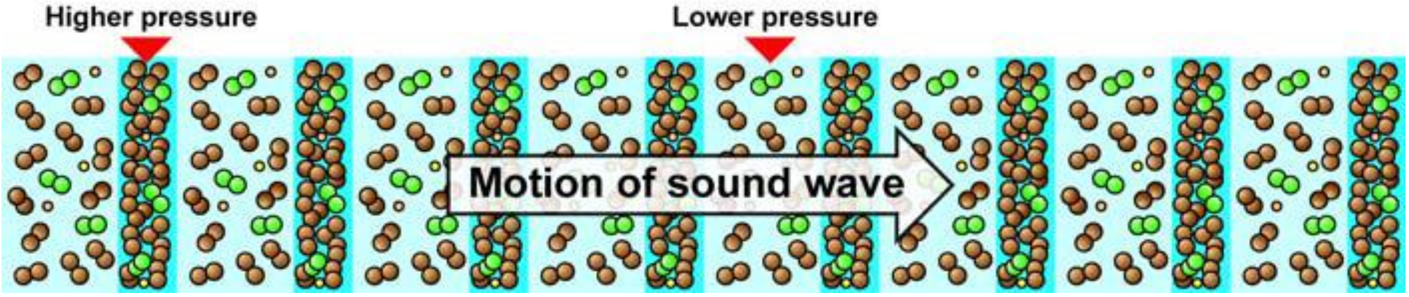
You can see the water move in a water wave, but sound waves are invisible. We know sound is a wave because it does all the things other waves do. Sound can be reflected, refracted, and absorbed. Sound also shows interference and diffraction. What is really oscillating in a sound wave?

Sound in solids and liquids

Sound is a traveling oscillation of atoms. If you push on one atom, it pushes on its neighbor. That atom pushes on the next atom, and so on. The push causes atoms to oscillate back and forth like tiny beads on springs. The oscillation spreads through the connections between atoms to make a sound wave. This is how sound moves through liquids and solids.

Sound in air and gases

In air the situation is different. Air molecules are spread far apart and interact by colliding with each other (Figure 9.23). The pressure is highest where atoms are close together and lowest where they are farthest apart (Figure 9.24). Imagine pushing the molecules on the left side of the picture below. Your push squeezes atoms together creating a layer of higher pressure. That layer pushes on the next layer, which pushes on the next layer, and so on. The result is a traveling oscillation in pressure, which is a sound wave. Sound is a *longitudinal* wave because the oscillations are along the same direction the wave travels.



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 only the range between 20 Hz and 20,000 Hz. Bats can hear high frequency sounds between 40,000 and 100,000 Hz and whales hear very low frequency sounds that are lower than 10 Hz.

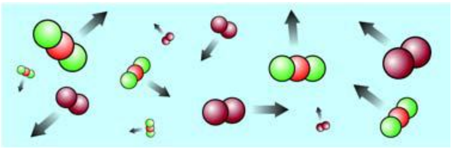


Figure 9.23: *Air is made of molecules in constant random motion, bumping off each other and the walls of their container.*

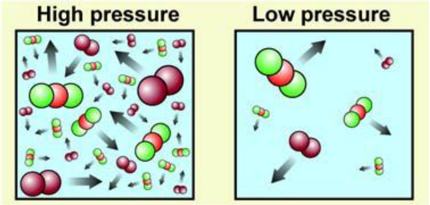


Figure 9.24: *At the same temperature, high pressure means more molecules per unit volume. Low pressure means fewer molecules per unit volume.*

The wavelength of sound

Range of wavelengths of sound

The wavelength of sound in air is similar to the size of everyday objects. The table below gives some examples. As with other waves, the wavelength of a sound is inversely related to its frequency (Figure 9.25). 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 your finger.

Table 9.2: Frequency and wavelength for some typical sounds

Frequency (Hz)	Wavelength (λ)	Typical Source
20	17m	Rumble of thunder
100	3.4m	Bass guitar
500	70cm	Average male voice
1,000	34cm	Female soprano voice
2,000	17cm	Fire truck siren
5,000	7cm	Highest note on a piano
10,000	3.4cm	Whine of a jet turbine
20,000	1.7cm	Highest pitched sound you can hear

Wavelengths of sounds are important

Although we usually think about different sounds in terms of frequency, wavelength is also important. Suppose you wanted to make a sound of a certain wavelength (or frequency). You often need to have a vibrating object that is similar in size to the wavelength of that sound. That is why instruments like French horns have valves. A French horn makes sound by vibrating the air trapped in a long coiled tube. Short tubes only fit short wavelengths and make higher frequency sounds. Long tubes fit longer wavelengths and make lower frequency sounds (Figure 9.26). Opening and closing the valves on a French horn allows the player to add and subtract different length tubes, changing the frequency of the sound.

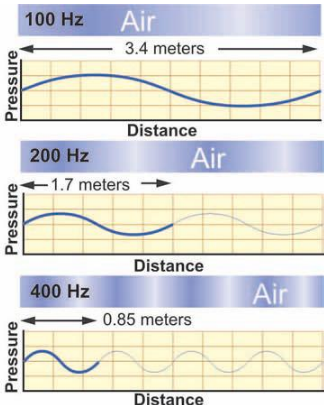


Figure 9.25: *When the frequency of sound goes up, the wavelength goes down proportionally.*

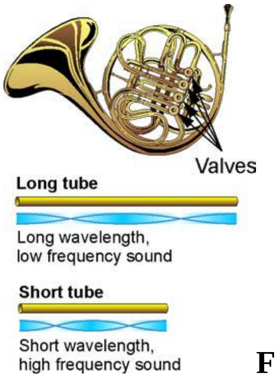


Figure 9.26: *Musical instruments use the wavelength of a sound to control its frequency*

How we hear sound

The inner ear

The inner ear has two important functions—providing our sense of hearing and our sense of balance (Figure 9.27). The sense of balance comes from the three semicircular canals. Fluid moving in each of the three canals tells the brain whether the body is moving left-right, updown, or forward-backward.

How the cochlea works

The “hearing” of sound starts with the eardrum. The eardrum vibrates in response to sound waves in the ear canal. The three delicate bones of the inner ear transmit the vibration of the eardrum to the side of the cochlea. We get our sense of hearing from the *cochlea*. Fluid in the spiral of the cochlea vibrates and creates waves that travel up the spiral. The spiral channel starts out large and gets narrower near the end. The nerves near the beginning see a relatively large channel and respond to longer-wavelength, lower frequency sound. The nerves at the small end of the channel respond to shorter-wavelength, higher-frequency sound.

The range of human hearing

The combination of the eardrum, bones, and the cochlea limit the range of human hearing to between 20 hertz and 20,000 hertz. Animals, such as cats and dogs can hear much higher frequencies because their ears have evolved slightly differently.

Hearing ability changes with time

Hearing varies greatly with people and 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. The nerves in the cochlea have tiny hairs that shake when the fluid in the cochlea vibrates. Listening to loud sounds for a long time can cause the hairs to weaken or break off. It is smart to protect your ears by keeping the volume of noise reasonable and wearing ear protection if you have to stay in a loud place. In concerts, many musicians wear earplugs on-stage to protect their hearing!

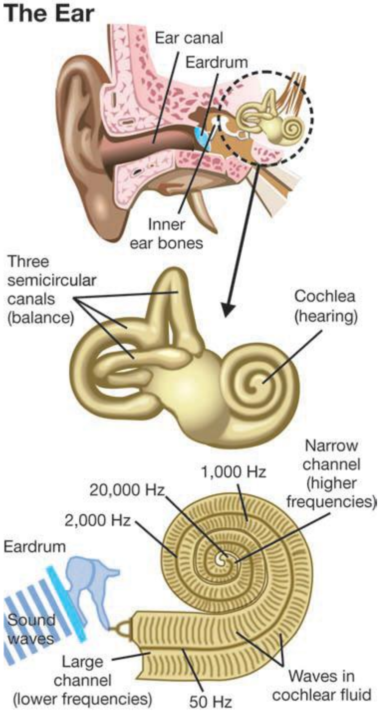


Figure 9.27: *The structure of the inner ear. When the eardrum vibrates, three small bones transmit the vibrations to the cochlea. The vibrations make waves inside the cochlea, which vibrates nerves in the spiral. Each part of the spiral is sensitive to a different frequency.*

9.3 Section Review

1. What is the relationship between pitch and frequency?

2. The sound that you hear around you usually
a. occurs one frequency at a time
b. contains many frequencies at the same time

3. If one sound wave has twice the amplitude of another, the first sound is:
a. louder
b. softer
c. higher pitched
d. lower pitched

4. Do two sound waves that seem equally loud always have the same amplitude? Explain.

5. Would a car driving at 800 mph be supersonic or subsonic?

6. A paramedic in an ambulance does not experience the Doppler effect of the siren. Why?

7. How could you increase the air pressure inside a bag containing a group of air molecules?

8. Is sound a longitudinal or transverse wave?

9. A 200-hertz sound has a wavelength about equal to the height of an adult. Would a sound with a wavelength equal to the height of a 2-year-old child have a higher or lower frequency than 200 Hz?

10.Explain how the cochlea allows us to hear both low-frequency and high-frequency sound.

11.What is the range of frequencies for human hearing?