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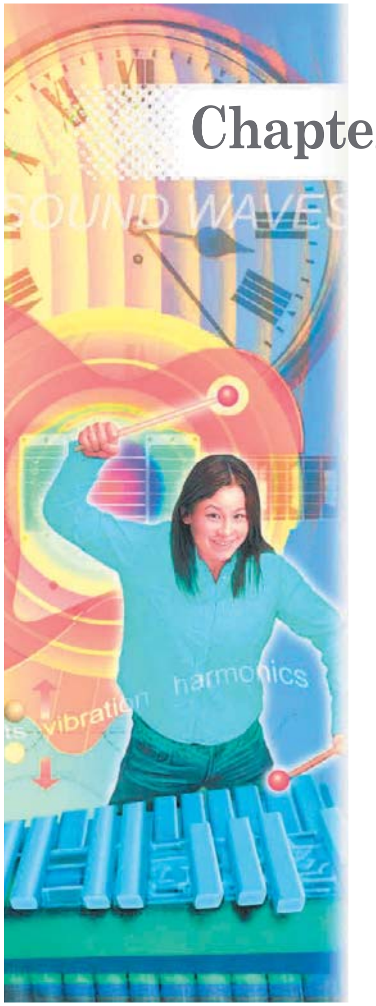

Chapter 21

Sound

Humans were making musical instruments to produce sounds 20,000 years before the wheel and axle were invented! Among instrument builders, perhaps Antonio Stradivari is the most famous. Between 1667 and 1730 Stradivari built violins in the small town of Cremona, Italy. A violin's sound is rich and complex because vibrations of its wooden parts create a unique blend of frequencies.

Stradivari worked tirelessly trying different woods and different varnishes, searching for the perfect sound. Over time he developed a secret formula for varnish, and special ways to carve and treat the all-important vibrating parts of the violin. In the 300 years since Stradivari, no one has figured out how he did it. Today, a Stradivarius violin is the most highly prized of all musical instruments. Its rich sound has never been duplicated.

Key Questions

- ✓ How do atoms make sound happen?
- ✓ Why is your voice unique?
- ✓ How do beats keep you in tune?

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21.1 Properties of Sound

Like other waves, sound has the properties of frequency, wavelength, amplitude, and speed. Because sound is such a big part of human 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.

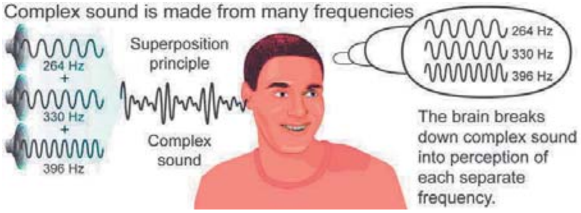
The frequency of sound

Frequency and pitch

Sound is a wave, and like all waves it has a frequency. 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. The range of frequencies humans can hear varies from about 20 hertz to 20,000 hertz.

Most sound has more than one frequency

Most sound that you hear contains many frequencies. In Chapter 20 we talked about the *superposition principle*. Complex sound is created by the superposition of many frequencies. In fact, the sound of the human voice contains thousands of different frequencies — all at once. (Figure 21.1).



The frequency spectrum

Why is it easy to recognize one person's voice from another, even when people are saying the same word? The reason is that voices have different mixtures of frequencies. A *frequency spectrum* is a graph showing the different frequencies present in a sound. Loudness is on the vertical axis and frequency is on the horizontal axis. Figure 21.1 shows the frequencies of the voices for three individuals saying "hello."

Vocabulary

pitch, decibels, acoustics, subsonic, supersonic, shock wave, Doppler effect

Objectives

- ✓ Explain how pitch, loudness, and speed are related to waves.
- ✓ Explain the Doppler effect.
- ✓ Describe how sound is created and recorded.

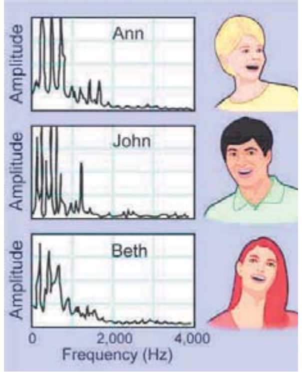


Figure 21.1: *The frequencies in three people's voices as they say the word "hello."*

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. Almost no one (except scientists) uses amplitude to measure loudness. Instead we use the decibel scale (Figure 21.2). Most sounds fall between zero and 100 on the decibel scale, making it a very convenient number to understand and use.

Table 21.1: ***Common sounds and their loudness in decibels***

0 dB	The threshold of human hearing; the 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; louder sounds than 90 dB cause hearing damage
100 dB	Walkman turned to its maximum volume
110 dB	The front row of a rock concert
120 dB	The threshold of physical pain from loudness

The sensitivity of the ear How loud you hear a sound depends on both the amplitude of the sound wave and the response of your ear. The human ear is most sensitive to frequencies of sound between 500 and 5,000 Hz. It is no surprise that these are same the frequencies in voices! An *equal loudness curve* compares how loud you hear sounds of different frequencies (Figure 21.3). 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. Almost no one can hear sound above 20,000 Hz no matter how large the amplitude is.

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.

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 21.2: *The decibel scale is a measure of the amplitude of sound waves. We use the decibel scale because our ears can hear a wide range of amplitudes. Every increase of 20 decibels (dB) means the sound wave has 10 times greater amplitude and it sounds about twice as loud.*

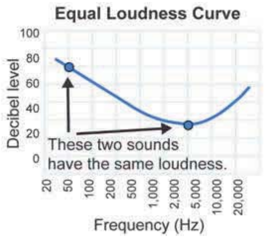


Figure 21.3: *All points on an equal loudness curve have the same loudness.*

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The speed of sound

Sound moves about 340 meters per second

You have likely noticed that you hear thunder many seconds after you see lightning. Lighting is what creates thunder so they occur at the same time. You hear a delay because sound travels much slower than light. The speed of sound in air is 343 meters per second (660 miles per hour) at one atmosphere of pressure and room temperature. The speed varies some with temperature and pressure.

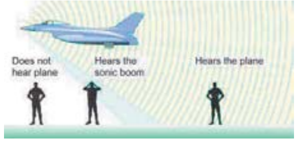


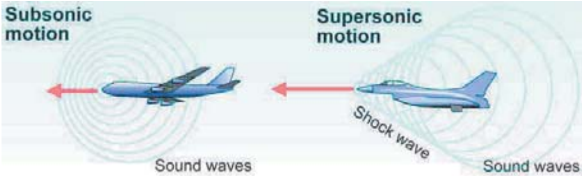
Figure 21.4: *If a supersonic jet flew overhead, you would not hear the sound until the plane was far beyond you. The boundary between sound and silence is called a "shock wave." It is almost as if all the sound were compressed into a thin layer of air. The person in the middle hears a sonic boom as the shock wave passes over him. Because the sonic boom can shatter windows, planes are not allowed to fly over cities at supersonic speeds.*

Subsonic and supersonic

Objects that move slower than sound are called **subsonic**. A passenger jet is subsonic because its speed ranges from 400 to 500 miles per hour. Objects that move faster than sound are called **supersonic**. Some military jets fly at supersonic speeds. If you were on the ground watching a supersonic plane fly toward you, there would be silence (Figure 21.4). The sound would be *behind* the plane, racing to catch up.

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 wave fronts pile up. 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*.



Sound in liquids and solids

The speed of sound in liquid and solid materials is usually faster than in air (Figure 21.5). Compared to air, sound travels about five times faster in water, and about 18 times faster in steel. This is because sound is really a travelling oscillation of the atoms in a material. Like other oscillations, sound depends on restoring forces and inertia, only on an atomic scale. The forces holding steel atoms together in a solid are much stronger than the forces between molecules in air. Stronger restoring forces raise the speed of sound.

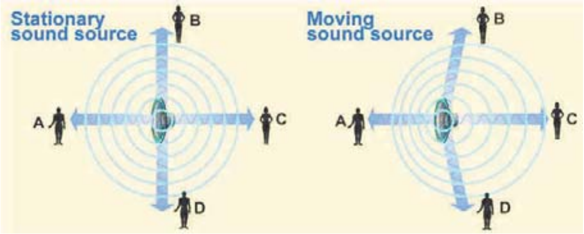
Material	Sound speed (m/sec)
Air	330
Helium	965
Water	1530
Wood (average)	2000
Gold	3240
Steel	5940

Figure 21.5: *The speed of sound in various materials (helium and air at 0°C and 1 atmospheric pressure).*

The Doppler effect

Definition of the Doppler effect

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



The cause of the Doppler effect

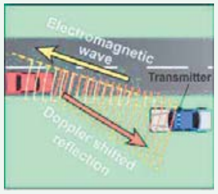
The Doppler effect occurs because an observer hears the frequency at which wave fronts arrive at his or her ears. Observer (A) in the graphic above hears a higher frequency. This is because the object's motion causes the crests in front to be closer together. The opposite is true behind a moving object,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

Demonstrating the Doppler effect

You can hear the Doppler effect when you hear the siren of a fire engine coming toward you and then move past you. You can observe the Doppler effect if someone whirls a small battery-powered beeper around his head on a string. The frequency shifts up and down with each rotation according to whether the beeper is moving toward you or away from you.

Doppler radar

The Doppler effect also happens with reflected waves, including microwaves. With Doppler radar, a transmitter sends a pulse of microwaves. The microwaves reflect from a moving object, such as a car. The frequency of the reflected wave is increased if the car is moving toward the source and decreases if the car is moving away.



The difference in frequency between the reflected and transmitted wave is called the Doppler shift. Because Doppler shift is proportional to speed, Doppler radar is a way to measure speed accurately at a distance. Doppler radar is used to enforce speed limits, to measure the speed of wind in storms, and in many other applications where speed needs to be measured from a distance.

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Recording sound

The importance of recorded sound A hundred years ago the only way to hear music was to be within hearing range of the musicians as they played. The recording of sound was a breakthrough in technology that changed human experience.

The microphone To record a sound you must store the pattern of vibrations in a way that can be replayed and be true to the original sound. A common way to record sound starts with a microphone. A microphone transforms a sound wave into an electrical signal with the same pattern of vibration (top of Figure 21.6).

Analog to digital conversion In modern digital recording, a sensitive circuit called an "analog to digital converter" measures the electrical signal 44,100 times per second. Each measurement consists of a number between zero and 65,536 corresponding to the amplitude of the signal. One second of compact-disc-quality sound is a list of 44,100 numbers. The numbers are recorded as data on the disc.

Playback of recorded sound To play the sound back, the string of numbers on the CD is read by a laser and converted into electrical signals again by a second circuit. This circuit is a digital to analog converter, and it reverses the process of the first circuit. The playback circuit converts the string of numbers back into an electrical signal. The electrical signal is amplified until it is powerful enough to move the coil in a speaker and reproduce the sound (bottom of Figure 21.6).

Stereo sound Most of the music you listen to has been recorded in stereo. A stereo recording is actually two recordings, one to be played from the right speaker, the other from the left. Stereo sound feels almost "live" because it creates slight differences in phase between sound reaching your left and right ears.

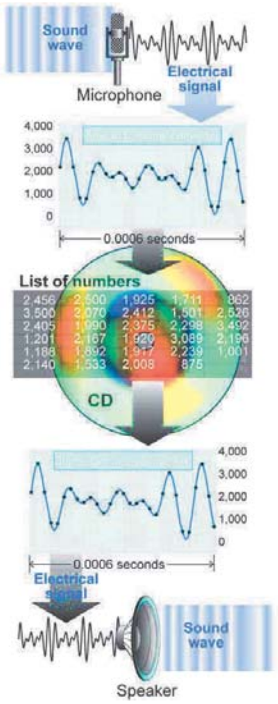


Figure 21.6: *The process of digital sound reproduction.*

21.1 Section Review

1. What is the relationship between pitch and frequency?
2. Do two sound waves that seem equally loud always have the same amplitude? Explain.
3. How do the amplitudes of a 120-decibel sound and a 100-decibel sound compare?
4. Would a car driving at 800 mph be supersonic or subsonic?
5. A paramedic in an ambulance does not experience the Doppler effect of the siren. Why?
6. How many numbers are involved in generating one minute of stereo sound on a CD?

21.2 Sound Waves

You can see the water move in a water wave, but sound waves are invisible. Sound is a wave because 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 interference and diffraction. Resonance occurs with sound waves and is especially important in how instruments work.

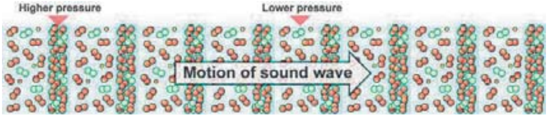
What is oscillating in a sound wave?

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 masses on springs. The oscillation spreads through the connections between atoms to make a sound wave.

Sound in air and gases

In air the situation is different. Air molecules are spread far apart and interact by colliding with each other. The pressure is higher where atoms are close together and lower where they are farther apart. 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 molecules are compressed in 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. The oscillations we call sound waves cover a wide range of frequencies. Humans can hear only the narrow 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.

Vocabulary

reverberation, Fourier's theorem

Objectives

- ✓ Learn how sound is made and know the factors that affect the speed of sound.
- ✓ Know that the speed of sound changes in different materials.
- ✓ The importance of the wavelength of sound.
- ✓ Describe sound interactions.
- ✓ Compare the superposition principle and Fourier's theorem.

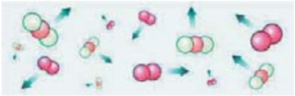


Figure 21.7: *Air is made of molecules in constant random motion, bumping off each other and the walls of their container.*

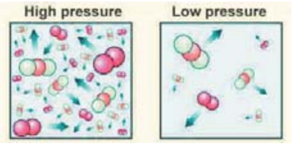


Figure 21.8: *At the same temperature, high pressure means more molecules per unit volume. Low pressure means fewer molecules per unit volume.*

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Sound and air pressure

Speakers If you touch the surface of a speaker, you can easily feel the vibration that creates a sound wave. Figure 21.9 shows a magnified illustration of a speaker, a sound wave, and the oscillation of pressure. When music is playing, the surface of the speaker moves back and forth at the same frequencies as the sound waves. The back and forth motion of the speaker creates a traveling sound wave of alternating high and low pressure.

Air pressure You can feel the pressure in a soda bottle, so why can't you feel the pressure from a sound wave? You can! But you need your ears. Your skin is not nearly sensitive enough to detect sound waves. The change in air pressure created by a sound wave is incredibly small. An 80 dB sound, equivalent to a loud stereo, changes the air pressure by only 1 part in a million.

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 may be 3,000 hertz. This corresponds to 3,000 vibrations per second (3,000 Hz) in the pressure of the air.

Sound speed depends on temperature In air, the energy of a sound wave is carried by moving molecules bumping into each other. Anything that affects the motion of molecules also affects the speed of sound. When the air gets cold, the molecules move more slowly and the speed of sound decreases. For example, at 0°C, the speed of sound is 330 meters per second, but at 21°C, the speed of sound is 344 meters per second.

Sound speed and pressure If the pressure of air goes up, molecules become more crowded. The speed of sound increases4 because the atoms collide with each other more often. If the pressure goes down, the speed of sound decreases. This affects airplanes. At high altitudes, both the pressure and temperature go down. A plane that is subsonic at low altitudes may become supersonic at higher altitudes.

Sound speed and molecular weight Remember, temperature measures the average kinetic energy of molecules. Lighter molecules go faster than heavier molecules at the same temperature. The speed of sound is higher in helium gas because helium atoms are lighter (and faster) than either oxygen (O_2) or nitrogen (N_2) molecules that make up air. That is why you sound funny when you talk after inhaling helium gas.

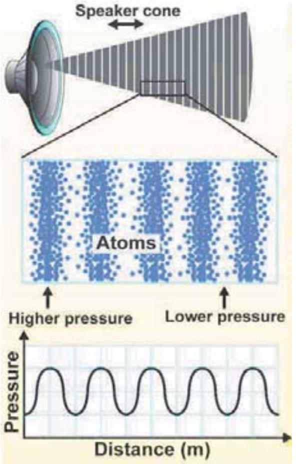


Figure 21.9: *What a sound wave might look like if you could see the atoms. The effect is greatly exaggerated to show the variation.*

The wavelength of sound

Range of wavelengths of sound

The wavelength of sound in air is comparable to the size of everyday objects. The chart below gives some typical frequencies and wavelengths for sound in air. As with other waves, the wavelength of a sound is inversely related to its frequency (Figure 21.10). 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.

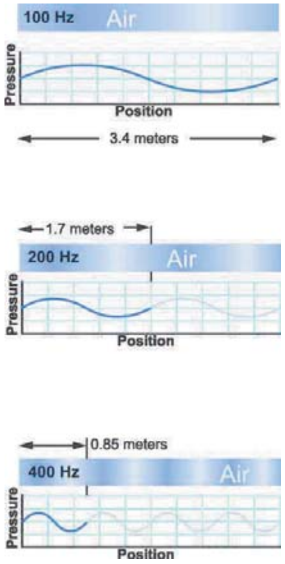
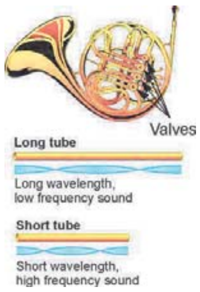


Figure 21.10: *The frequency and wavelength of sound are inversely related. When the frequency goes up, the wavelength goes down proportionally.*

Table 21.2: ***Frequency and wavelength for some typical sounds***

Frequency (Hz)	Wavelength	Typical source
20	17 meters	rumble of thunder
100	3.4 meters	bass guitar
500	70 cm (27”)	average male voice
1,000	34 cm (13”)	female soprano voice
2,000	17 cm (6.7”)	fire truck siren
5,000	7 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

Wavelengths of sounds are important



Although we usually think about different sounds in terms of frequency, the wavelength can also be important. If you want to make sound of a certain wavelength, you often need to have a vibrating object that is similar in size to the wavelength. That is why instruments like a French horn 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 high frequency sound. Long tubes fit longer wavelengths and make lower frequency sounds. 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.

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Interaction between sound waves and boundaries

Interactions of sound and materials

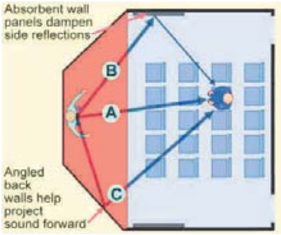
Like other waves, sound waves can be reflected by hard surfaces and refracted as they pass from one material to another. Diffraction causes sound waves to spread out through small openings. Carpet and soft materials can absorb sound waves. Figure 21.11 shows examples of sound interactions.

Reverberation

In a good concert hall, the reflected sound and direct sound from the musicians together create a multiple echo called **reverberation**. The right amount of reverberation makes the sound seem livelier and richer. Too much reverberation and the sound gets muddy from too many reflections. Concert hall designers choose the shape and surface of the walls and ceiling to provide the best reverberation. Some concert halls have movable panels that can be raised or lowered from the ceiling to help shape the sound.

Constructing a good concert hall

Direct sound (**A**) reaches the listener along with reflected sound (**B**, **C**) from the walls. The shape of the room and the surfaces of its walls must be designed and constructed so that there is some reflected sound, but not too much.



Interference can also affect sound quality

Reverberation also causes interference of sound waves. When two waves interfere, the total can be louder or softer than either wave alone. The diagram above shows a musician and an audience of one person. The sound reflected from the walls interferes as it reaches the listener. If the distances are just right, one reflected wave might be out of phase with the other. The result is that the sound is quieter at that spot. An acoustic engineer would call it a *dead spot* in the hall. Dead spots are areas where destructive interference causes some of the sound to cancel with its own reflections. It is also possible to make very loud spots where sound interferes constructively. The best concert halls are designed to minimize both dead spots and loud spots.

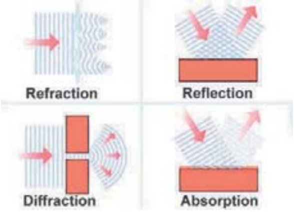
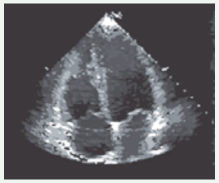


Figure 21.11: *Sound displays all the properties of waves in its interactions with materials and boundaries.*

Ultrasound



Ultrasound is sound that has high frequency, often 100,000 hertz or more. We cannot hear ultrasound, but it can pass through the human body easily. Medical ultrasound instruments use the refraction and reflection of sound waves inside the body to create images. Doctors often take ultrasound pictures of the human body. The ultrasound image pictured above is a heart.

Standing waves and resonance

Resonance of sound

Spaces enclosed by boundaries can create *resonance* with sound waves. Almost all musical instruments use resonance to make musical sounds. A panpipe is a good example of resonance in an instrument. A panpipe is a simple instrument made of many tubes of different lengths (Figure 21.12). One end of each tube is closed and the other end is open. Blowing across the open end of a tube creates a standing wave inside the tube. The frequency of the standing wave is the frequency of sound given off by the pipe. Longer pipes create longer wavelength standing waves and make lower frequencies of sound. Shorter pipes create shorter wavelength standing waves and therefore make higher frequencies of sound.

Standing wave patterns

The closed end of a pipe is a closed boundary. A closed boundary makes a node in the standing wave. The open end of a pipe is an open boundary to a standing wave in the pipe. An open boundary makes an antinode in the standing wave. Figure 21.12 shows a standing wave that has a node at the closed end and an antinode at the open end. The wavelength of the fundamental is four times the length of the pipe. The pipe resonates to a certain sound when its length is one-fourth the wavelength of the sound.

Designing a musical instrument

Suppose you wish to make a pipe that makes a sound with a frequency of 660 hertz (the note E). Using the relationship between frequency and wavelength, the required wavelength is (343 m/sec) ÷ (660 Hz) = 0.52 meters. The length of pipe needs to be one-fourth of the wavelength to make a resonance in the fundamental mode. One-quarter of 52 centimeters is 13 centimeters. If you make a thin pipe that is 13 centimeters long with one closed end, it will have a natural frequency of approximately 660 hertz. This is the principle on which musical instruments are designed. Sounds of different frequencies are made by standing waves. The length of a vibrating system can be chosen so that it resonates at the frequency you want to hear.

Wave speed = *Frequency* x *Wavelength*

Wave speed ÷ *Frequency* = **Wavelength**

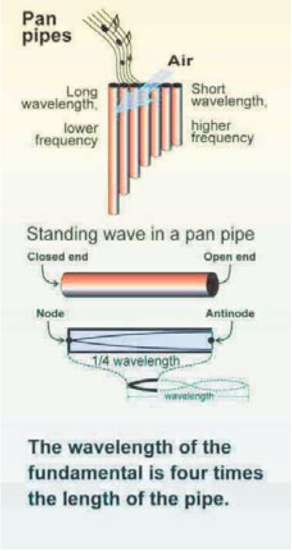


Figure 21.12: *A panpipe is made from tubes of different length. The diagram shows the fundamental for a standing wave of sound in a panpipe.*

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Fourier’s theorem

How are multiple frequencies of sound created?

To make a single frequency of sound, a speaker vibrates back and forth in a simple pattern with a single wavelength and frequency. However, almost all the sound you hear is a combination of frequencies. What kind of motion should a speaker use to create multiple frequencies of sound at the same time, as there is in music or speech?

Fourier’s theorem

The answer involves **Fourier’s theorem**. Fourier’s theorem says a wave of any shape can be made by adding up single frequency waves. Remember that the superposition principle states that many single waves add up to one complex wave. Fourier’s theorem works from the other direction. A complex wave can be made from a sum of single frequency waves, each with its own frequency, amplitude, and phase.

An example

Figure 21.13 shows a “square wave” with a frequency of 100 Hz. A square wave does not have a single frequency, but instead contains many frequencies. In agreement with Fourier’s theorem a pretty good reproduction of the square wave can be made by adding five waves of different frequencies and amplitudes. To produce multiple frequencies, a speaker vibrates back and forth with a complex motion. If a speaker were to vibrate back and forth with sudden jerks, like the square wave, it would create sound of all the frequencies it takes to make the square wave!

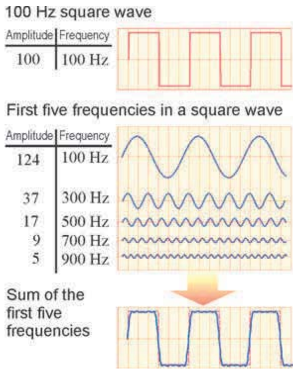

Figure 21.13: *Making a square wave by adding up five single-frequency waves.*

21.2 Section Review

1. How could you increase the air pressure inside a bag containing a group of air molecules?
2. Is sound a longitudinal or transverse wave?
3. 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?
4. In which situation does sound travel faster: (a) outside on a winter day, or (b) outside on a summer day?
5. Would a full concert hall have different reverberation from an empty hall? Explain.
6. The superposition principle states: wave A + wave B = wave C. Write an equation like this for Fourier’s theorem.

21.3 Sound, Perception, and Music

Sound is everywhere in our environment. We use sound to communicate and we listen to sound for information about what is going on around us. Our ears and brain are constantly receiving and processing sound. In this section you will learn about how we *hear* a sound wave and how the ear and brain construct meaning from sound. This section will also introduce some of the science behind music. Musical sound is a rich language of rhythm and frequency, developed over thousands of years of human culture.

The perception and interpretation of sound

Constructing meaning from patterns

As you read this paragraph, you subconsciously recognize individual letters. However, the *meaning* of the paragraph is not in the letters themselves. The meaning is in the *patterns* of how the letters make words and the words make sentences. The brain does a similar thing with sound. A single frequency of sound is like one letter. It does not have much meaning. The meaning in sound comes from patterns of many frequencies changing together.

The ear hears many frequencies at once

When you hear a sound, the nerves in your ear respond to more than 15,000 different frequencies at the same time. This is like having an alphabet with 15,000 letters! The brain interprets all 15,000 different frequency signals from the ear and creates a "sonic image" of the sound. The meaning in different sounds is derived from the patterns in how the different frequencies get louder and softer.

Complex sound waves

Imagine listening to live music with a singer and a band. Your ears can easily distinguish the voice from the instruments. How does this occur? The microphone records a single "wave form" of how pressure varies with time. The recorded wave form is very complex, but it contains all the sound from the music and voice (Figure 21.14).

How the brain finds meaning

You ear is a living application of Fourier's theorem. The ear separates the sound into different frequencies. Your brain has learned to recognize certain patterns of how each frequency changes over time. One pattern might be a word. Another might be a musical note. Inside your brain is a "dictionary" that associates a meaning with a pattern of frequency the same way an ordinary dictionary associates a meaning from a pattern of letters (a word).

Vocabulary

frequency spectrum, sonogram, cochlea, rhythm, musical scale, note, octave, beat, consonance, dissonance

Objectives

- ✓ Describe how the meaning of sound is related to frequency and time.
- ✓ Learn how we hear sound.
- ✓ Describe the musical scale, consonance, dissonance, and beats in terms of sound waves.
- ✓ Learn about the role of harmonics in how instruments sound.

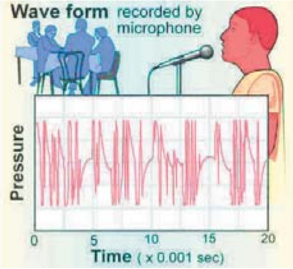

Figure 21.14: *The recorded wave form from 0.02 seconds of music.*

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The frequency spectrum and sonogram

Frequency spectrum

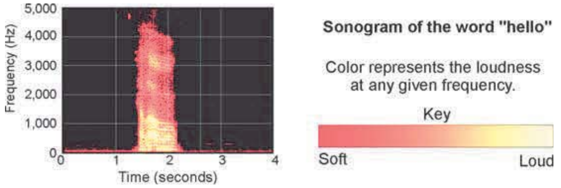
A **frequency spectrum** is a graph showing the different frequencies present in a sound. The vertical axis tells you the loudness and the horizontal axis tells you the frequency. Sound containing many frequencies has a wave form that is jagged and complicated. The wave form in the Figure 21.15 is from an acoustic guitar playing the note E. The frequency spectrum shows that the complex sound of the guitar is made from many frequencies, ranging up to 10,000 Hz and beyond.

Wave form and spectrum change with time

Both the wave form and the spectrum change as the sound changes. The wave form and spectrum represent only a single moment of the sound. Since meaning comes from patterns of changing frequencies, we need another graph that can show three variables at once: frequency, amplitude, and time.

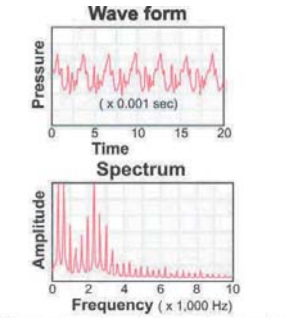
Sonograms

A **sonogram** shows how loud sound is at different frequencies over a period of time (Figure 21.16). The sonogram below is for a male voice saying "hello." The word lasts from 0.1 seconds to about 0.6 seconds. You can see lots of sound below 1,500 hertz and two bands of sound near 2,350 and 3,300 hertz. Every person's sonogram is different, even for the same word.



Reading a sonogram

A sonogram shows frequency on the vertical axis and time on the horizontal axis. The loudness is shown by different colors. The sonogram above shows the word "hello" lasting from 1.4 to 2.2 seconds. You can see that there are many frequencies almost filling up the space between 0 and 5,000 Hz. Figure 21.16 shows a simpler sonogram to help you learn to read this complex graph. Which bar represents a loud sound of 100 Hz lasting from 1 to 3 seconds (A, B, C, or D)?



The *spectrum* shows the frequencies that make up a complex wave form.

Figure 21.15: *Each peak in the spectrum represents the frequency and amplitude of a wave that makes up the wave form.*

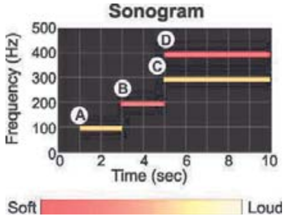


Figure 21.16: *A sonogram shows how the loudness of different frequencies of sound changes with time.*

How we hear sound

Hearing sound We get our sense of hearing from the **cochlea**, a tiny fluid-filled organ in the inner ear (Figure 21.17). The inner ear has two important functions: providing our sense of hearing and our sense of balance. The three semicircular canals near the cochlea are also filled with fluid. Fluid moving in each of the three canals tells the brain whether the body is moving left-right, up-down, or forward-backward.

How the cochlea works The perception 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. 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 range of human hearing is between 20 hertz and 20,000 hertz (or 20 kilohertz, abbreviated kHz). The combination of the eardrum, bones, and the cochlea all contribute to the limited range of hearing. You could not hear a sound at 50,000 hertz (50 kHz), even at a loudness of 100 decibels. Animals such as cats and dogs can hear much higher frequencies because of the design of their outer ears and the more sensitive structures in their inner ears.

Hearing ability changes with time Hearing varies greatly with people and changes with age. Some people can hear higher-frequency sounds and other people cannot. 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 nerve signals that carry sensation of sound to the brain are created by tiny hairs that shake when the fluid in the cochlea is vibrated. 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 reasonable and wearing ear protection if you have to stay in a loud place. In concerts, many musicians wear earplugs to protect their hearing.

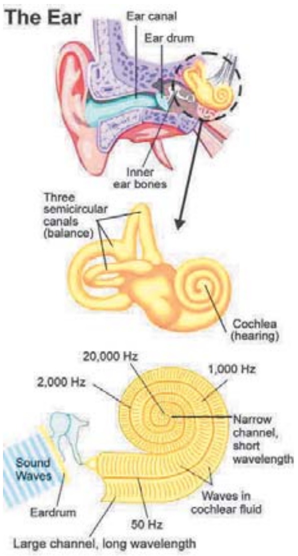


Figure 21.17: *The structure of the inner ear. When the eardrum vibrates, three small bones transmit the vibration to the cochlea. The vibrations make waves inside the cochlea, which vibrates nerves in the spiral. Each part of the spiral is sensitive to a different frequency.*

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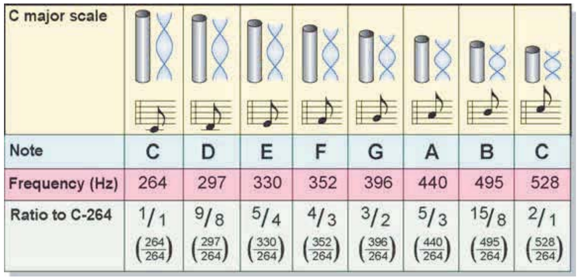
Music

Pitch The *pitch* of a sound is how high or low we hear its frequency. A higher frequency sound is heard as a higher pitch. However, because pitch depends on the human ear and brain. The way we hear a sound can be affected by the sounds we heard before and after.

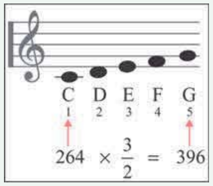
Rhythm **Rhythm** is a regular time pattern in a sound. Here is a rhythm you can 'play' on your desk: TAP-TAP-tap-tap-TAP-TAP-tap-tap. Play 'TAP' louder than you play 'tap.' Rhythm can be made with sound and silence or with different pitches. People respond naturally to rhythm. Cultures are distinguished by their music and the special rhythms used in music.

The musical scale Music is a combination of sound and rhythm that we find pleasant. Styles of music are vastly different but all music is created from carefully chosen frequencies of sound. Most of the music you listen to is created from a pattern of frequencies called a **musical scale**. Each frequency in the scale is called a **note**. The range between any frequency and twice that frequency is called an **octave** (see sidebar). Notes that are an octave apart in frequency share the same name. Within the octave there are eight primary notes in the Western musical scale. Each of the eight is related to the first note in the scale by a ratio of frequencies (see sidebar). The scale that starts on the note C (264 Hz) is show in the diagram below.



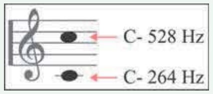
C major scale								
Note	C	D	E	F	G	A	B	C
Frequency (Hz)	264	297	330	352	396	440	495	528
Ratio to C-264	$1/1$ $\left(\frac{264}{264}\right)$	$9/8$ $\left(\frac{297}{264}\right)$	$5/4$ $\left(\frac{330}{264}\right)$	$4/3$ $\left(\frac{352}{264}\right)$	$3/2$ $\left(\frac{396}{264}\right)$	$5/3$ $\left(\frac{440}{264}\right)$	$15/8$ $\left(\frac{495}{264}\right)$	$2/1$ $\left(\frac{528}{264}\right)$

Notes on a musical scale



The notes on a musical scale are related to the first note by ratios of frequency. For example, the fifth note has a frequency 3/2 times the frequency of the first note. If the first note is C-264 Hz, then the fifth note has a frequency of 1.5 times 264, or G-396 Hz.

Octaves



Two notes are an octave apart when the frequency of one note is double the frequency of the other. Notes that are an octave apart are given the same name because they sound similar to the ear. For example, the note C has a frequency of 264 Hz. Frequencies of 132 Hz and 528 Hz are also named "C" because they are an octave apart from C-264 Hz.

Consonance, dissonance, and beats

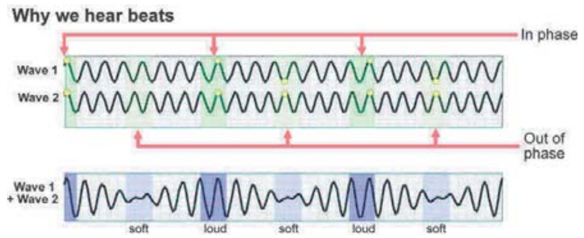
Harmony

Harmony is the study of how sounds work together to create effects desired by the composer. From experience, you know that music can have a profound effect on people's moods. For example, the tense, dramatic soundtrack of a horror movie is a vital part of the audience's experience. Harmony is based on the frequency relationships of the musical scale.

Beats

The frequencies in the musical scale are specifically chosen to reduce the occurrence of a sound effect called *beats*. When two frequencies of sound are close but not exactly equal, the loudness of the total sound seems to oscillate or **beat**. At one moment the two waves are in phase and the total sound is louder than either wave separately. A moment later the waves are out of phase and they cancel each other out, making the sound quieter. The rapid alternation in amplitude is what we hear as beats. The sidebar at right describe how bats use beats to locate insects. Beats are also useful for determining if an instrument is out of tune (see sidebar next page).

Adding two waves with different frequency


Why we hear beats

Consonance and dissonance

When we hear more than one frequency of sound and the combination sounds good, we call it **consonance**. When the combination sounds bad or unsettling, we call it **dissonance**. Consonance and dissonance are related to beats. When frequencies are far enough apart that there are no beats, we get consonance. When frequencies are too close together, we hear beats that are the cause of dissonance. Dissonance is often used to create tension or drama. Consonance can be used to create feelings of balance and comfort.

Echolocation and beats

Bats navigate at night using ultrasound waves instead of light. A bat's voice is like a "sonic flashlight" shining a beam of sound. A bat emits short bursts of sound that rise in frequency and are called "chirps." 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 the left ear with what it hears in the right ear.

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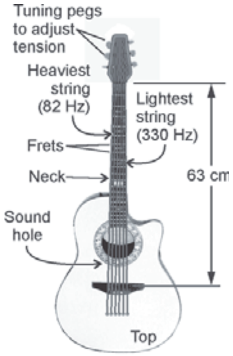
Voices and instruments

Voices The human voice is a complex sound that starts in the larynx, a small structure at the top of your windpipe. The term *vocal cords* is a little misleading because the sound-producing structures are not really cords but are folds of expandable tissue that extend across a hollow chamber known as the larynx. The sound that starts in the larynx is changed by passing through openings in the throat and mouth (Figure 21.18). Different sounds are made by changing both the vibrations in the larynx and the shape of the openings.

The guitar



The guitar has become a central instrument in popular music. Guitars come in many types but share the common feature of making sound from vibrating strings. A standard guitar has six strings that are stretched along the neck. The strings have different weights and therefore different natural frequencies.

The heaviest string has a natural frequency of 82 Hz and the lightest a frequency of 330 Hz. Each string is stretched by a tension force of about 125 newtons (28 pounds). The combined force from six strings on a folk guitar is more than the weight of a person (750 N or 170 lbs). The guitar is tuned by changing the tension in each string. Tightening a string raises its natural frequency and loosening lowers it.

Each string can make many notes A typical guitar string is 63 centimeters long. To make different notes, the vibrating length of each string can be shortened by holding it down against one of many metal bars across the neck called frets (Figure 21.19). The frequency goes up as the vibrating length of the string gets shorter. A guitar with 20 frets and six strings can play 126 different notes, some of which are duplicates.

Figure 21.18: *The human voice is created by a combination of vibrating folds of skin in the larynx and the resonant shapes of the throat and mouth.*

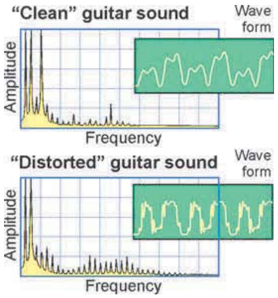


Figure 21.19: *Wave forms from "clean" and "distorted" guitar sounds. Notice that both sounds have the same fundamental frequency but the distorted sound has more high- frequency harmonic content.*

Harmonics and the sound of instruments

The same note can sound different

The same note sounds different when played on different instruments. As an example, suppose you listen to the note C-264 Hz played on a guitar and the same C-264 Hz played on a piano. A musician would recognize both notes as being C because they have the same frequency and pitch. But the guitar sounds like a guitar and the piano sounds like a piano. If the frequency of the note is the same, what gives each instrument its characteristic sound?

Instruments make mixtures of frequencies

The answer is that the sound from an instrument is not a single pure frequency. The most important frequency is still the fundamental note (C-264 Hz, for example). The variation comes from the *harmonics*. Remember, harmonics are frequencies that are multiples of the fundamental note. We have already learned that a string can vibrate at many harmonics. The same is true for all instruments. A single C note from a grand piano might include 20 or more different harmonics.

Recipes for sound

A good analogy is that every instrument has its own *recipe* for the frequency content of its sound. Another word for recipe in this context is *timbre*. In Figure 21.20 you can see how the mix of harmonics for a guitar compares to the mix for a piano when both instruments play the note C. This graphic illustrates that the timbre of a guitar is different from that of a piano.

21.3 Section Review

1. Explain how the cochlea allows us to hear both low-frequency and high-frequency sound.
2. What is the range of frequencies for human hearing?
3. 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)?
4. What is the difference between the pitch of a sound and its frequency?
5. If two sound waves are in phase, do you hear beats? Why or why not?
6. A musician in a group plays a "wrong" note. Would this note disrupt the harmony or the rhythm of the song they are playing? Explain your answer.
7. Why does an A played on a violin sound different from the same note played on a guitar?

Beat frequency

An "A" tuning fork produces vibrations for the note A at 440 hertz. Let's say the A string on a guitar is out of tune and its natural frequency is 445 hertz. This means that when you play the string and listen to the tuning fork, you will hear a beat frequency of 5 beats per second or 5 hertz! The beat frequency becomes zero, when the string is tuned to a natural frequency of 440 hertz.

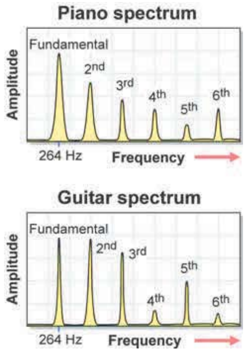


Figure 21.20: *The sound of the note C played on a piano and on a guitar. Notice that the fundamental frequencies are the same but the harmonics have different amplitudes.*

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Sound Spaces

Loud and quiet places

In the study of acoustics, the science of sound, the focus is usually on enclosed spaces. Your living room or bedroom at home is an enclosed space, but so is your school cafeteria or auditorium. Physicists who specialize in acoustics study how sound acts in these spaces.

Think about the sound you hear in a school cafeteria or gymnasium versus the school library. From experience, you know that a cafeteria and gym are often loud places, and libraries are quiet. Now, think about the design of these spaces and the types of materials used in them. What comes to mind?

Most libraries and auditoriums have carpet on the floors. The walls and ceilings of these spaces may also have special materials that absorb sound. Of course, the sound in a library or auditorium is also controlled by rules and what types of events are happening.People study quietly in libraries and may listen to speeches or music in an auditorium.

In contrast, cafeteria’s tend to be large spaces with tile floors and bare ceilings. Such flooring is easier to clean, but also provides a surface that reflects sound. The floor of a gymnasium is good for bouncing basketballs and for bouncing sound. When sound is reflected rather than absorbed by a surface the space tends to be noisy rather than quiet.

Sound review

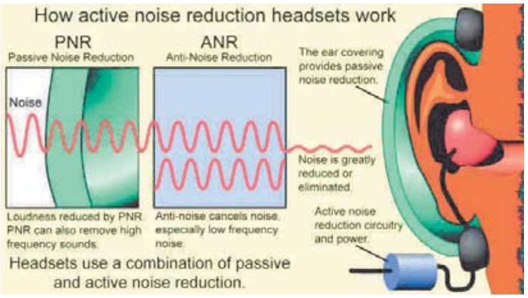
As you know, sound travels through a medium (solid, liquid, or gas) until the energy is absorbed by the medium. As sound travels the medium compresses and releases; in air, sound is characterized by waves of increasing and decreasing air pressure. The time that it takes for sound to be absorbed is called reverberation time. The sound waves move through a room and reflect off surfaces that they contact. The time varies depending upon many variables including the strength of the initial sound, the absorption rate of the walls of the room, and the size of the room. A *live room* is one whose materials have a low absorption rate and therefore a long reverberation time. Live rooms include gymnasiums and cafeterias where sounds easily reflect off walls, last a long time, even while many news sounds are made. A library or auditorium is an example of a *dead room*. In such rooms, the absorption rate of the materials is much higher. The reverberation time is decreased causing the space to be quieter.

Passive versus active noise reduction

In a library, passive noise reduction (PNR) is used to help make this enclosed space quiet. Carpet or heavy curtains or even ear plug are examples of passive noise reduction items. These materials absorb sound.

Another way to reduce sound is by active noise reduction (ANR). ANR technology tries to eliminate rather than absorb sound that is unwanted. Specially designed headphones are one part of the growing technology of ANR. There are three basic parts of ANR in a headphone: a microphone, processing electronics, and a speaker. These parts, which must all fit into the ear piece of the headphones, work together to cancel unwanted sound waves.

With carefully designed ANR, the microphone very near the ear canal continually detects noise. The frequency and amplitude profile of the noise is detected. The processing electronics create another noise that is just the opposite of the original. This new noise—or anti-noise—is sent into the ear canal by the speaker and cancels the offending sound.



To effectively address noise, scientists have learned that passive and active noise reduction are effective in different ways. ANR seems to work more efficiently with low frequency sounds while PNR is more efficient absorbing the higher frequencies. For example, studies have shown that the noise produced by propellers in airplanes is in the low frequency range. Therefore, specialized ANR headphones work well for airplane pilots. Extra soundproofing for passive noise reduction, although it would lessen high frequency noise, would add too much weight to a plane to be practical.

ANR technology is also available for headphones used with CD or MP3 players. These headphones are safe to wear because they only cancel the lower frequencies of sound, and not speech or warning sirens. Presently, ANR technology is being tested to lower the noise from the cooling fans inside electronic devices like your computer, tailpipes of cars, or inside the cabin of the car. As ANR technology grows, new uses for ANR will be discovered. Can you think of a new use for ANR technology?

Questions:

1. What is the difference between a live room and a dead room in terms of sound?
2. If you wanted to create a recording studio for recording a new CD for your band, what would you do? You may want to do research on the Internet to find out the design features of recording studios.
3. Compare and contrast passive and active noise reduction.
4. Does active noise reduction work using constructive or destructive interference?

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Chapter 21 Review

Understanding Vocabulary

Select the correct term to complete the sentences.

Doppler effect
consonance
reverberation
Fourier's theorem
acoustics
musical scales
sonogram
pitch
shock wave
supersonic
decibels
cochlea
beat
dissonance

Section 21.1

1. The loudness of a sound wave is measured in ____.
2. The science and technology of sound is known as ____.
3. The ____ of a sound is how high or low we hear its frequency.
4. A ____ jet travels faster than sound.
5. The shift in sound frequency caused by a moving sound source is called the ____.
6. A sonic boom is caused by the pressure change across a(n) ____.

Section 21.2

7. Reflected sound waves added to direct sound create a multiple echo called ____.
8. ____ states that a wave form is the sum of single frequent waves.

Section 21.3

9. The ____ is the tiny fluid filled organ in the inner ear that provides our sense of hearing.
10. Most music is based on patterns of frequencies called ____.
11. When two frequencies of sound are close, but not exactly the same, the loudness of the sound seems to oscillate or ____.
12. A combination of sound frequencies that sound good is called ____.
13. A combination of unsettling-sounding frequencies is called ____.
14. A special kind of graph that shows how loud sound is at different frequencies is called a(n) ____.

Reviewing Concepts

Section 21.1

1. Imagine you are cruising in outer space in a spaceship when you notice an asteroid hurtling towards your ship. You fire a missile and score a direct hit. The asteroid explodes into a billion pieces. Would you hear the explosion? Explain your answer.
2. How do we recognize people's voices?
3. What does the decibel scale measure, and what scale does it use?
4. If a fire engine moves toward you, does the pitch of its siren increase or decrease?
5. How fast does an airplane need to be traveling to create a sonic boom? Is this speed supersonic or subsonic?
6. How is stereo sound recorded and why does it sound "live"?

Section 21.2

7. Explain how sound is caused at the molecular level. Sketch what a sound wave would look like at the molecular level.
8. What type of waves are sound waves?
9. How does pressure work as a restoring force to create a sound wave?
10. Which of the following sounds has the shortest wavelength?
    a. The rumble of thunder at 20 Hz
    b. A base guitar at 100 Hz
    c. A fire truck siren at 2,000 Hz
    d. The highest note on a piano at 5,000 Hz
11. If the temperature of a material increased, how would the speed of sound through this material be affected? Why?
12. In which space would it be easier to hear a musician and why—outdoors or in your classroom?

Section 21.3

13. What is the difference between a wave form graph and a sound spectrum graph for a complex sound? Which graph best illustrates the harmonic motion of sound. Which graph best illustrates which frequencies are the loudest in a complex sound?

14. Some musicians wear earplugs when playing in concerts. What happens when the inner ear is exposed to very loud noises?
15. Which part of the ear vibrates in response to sound in the ear canal?
16. How are the pitch and frequency of a sound related?
17. What gives different instruments their characteristic sound? For example, why does a note played on a piano sound different from the same note played on a guitar?
18. How are beats created?
19. Why can't you hear a dog whistle at 25,000 Hz, but your dog can?

Solving Problems

Section 21.1

1. The sound of ordinary conversation 3 feet away is 65 decibels and the sound in a restaurant is 45 decibels.
    a. To our ears, how much louder is the ordinary conversation than the restaurant?
    b. How much larger is the amplitude of the sound waves in ordinary conversation than in the restaurant?
2. The Doppler effect is used by astronomers to determine if stars are moving away from or toward Earth. Red light has a lower frequency than blue light. If light from a star is shifted to the red does that mean the star is moving toward or away from Earth?

Section 21.2

3. The speed of sound through air is approximately 340 m/sec. What is the wavelength of a sound wave with a frequency of 680 Hz?
4. The range of human hearing is between 20 Hz and 20,000 Hz. If the speed of sound is 340 m/sec, what is the longest wavelength you can hear? What is the shortest?
5. Suppose you stand in front of a wall that is 170 meters away. If you yell, how long does it take for the echo to get back to you if the speed of sound is 340 m/sec?
6. What is the fundamental frequency for an organ pipe that is one meter long? The pipe has one end that is open and another end that is closed. Use a wave speed of 340 m/sec.

Section 21.3

7. If middle C on a piano has a frequency of 264 Hz, what is the frequency of the C one octave higher? One octave lower?
8. Describe what you hear when a musical note at 440 Hz is played at the same time as another note at 443 Hz.

Applying Your Knowledge

Section 21.1

1. Some people have perfect pitch. Research in your library or on the Internet what it means to have perfect pitch. What are the pros and cons of having perfect pitch?

Section 21.2

2. Why is hanging heavy curtains a good way to decrease sound in a room? Use the terms *absorption* and *amplitude* in your answer.
3. Compare the superposition principle to Fourier's theorem.

Section 21.3

4. Compare the active noise reduction to traditional hearing protection, such as ear muffs or ear plugs.
5. At what level does sound become unsafe? What are some ways you can protect your hearing? Suggest three places where you might need to use hearing protection.
6. Harmonic synthesizers can mimic almost any sound and allow you to play it as music on a keyboard. A synthesizer can sound like a flute, a bell, or a piano. In a short paragraph, describe how the synthesizer is able to play the same keyboard notes with such different sounds.
7. The human voice is a complex sound that is created by a combination of vibrating folds of skin in the larynx and the resonant shapes of the throat and mouth. Humans can hear sounds at frequencies of 20 to 20,000 Hz. Research the range of human voice frequencies. How do the voice ranges compare to the hearing ranges?