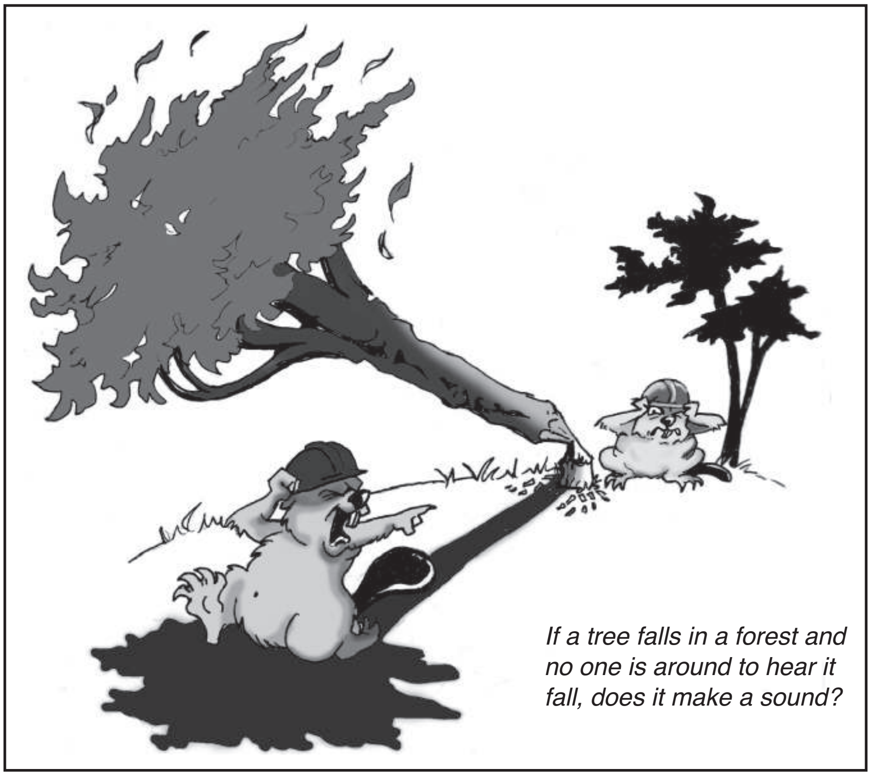
3

Sound Waves



If a tree falls in a forest and no one is around to hear it fall, does it make a sound?

"Mr. Watson—come here—I want to see you."
The first audible words spoken over the telephone.

—Alexander Graham Bell, Scottish Inventor of the telephone and audiometer, among many other inventions (1847–1922)

Does a tree falling in the forest create a sound if no one is around to hear it fall? We shall leave that oft-debated question to the philosophy classes; however, as speech-language pathologists, we will define sound as a pressure wave that is audible to the human ear with normal auditory sensitivity. The nature of that pressure wave, its production and perception, is the heart of the content of this textbook and, indeed, the heart of clinical speech-language pathology. And so the sound wave bears closer examination.

3.1 Vibration

What is vibration? At its most simple, **vibration** (**oscillation**) is a back-and-forth motion. Pretend you have a small ball attached to a spring suspended from a bar. The ball has a certain mass (a measure of the quantity of its matter), and we refer to this setup as a mass-spring system. Initially, the ball will stretch the spring to a point where it will sit quietly at rest, suspended on the spring. The ball-spring system is then said to be at **equilibrium**. When not disturbed by an outside force, the ball will maintain this rest position. We know this fact because Newton's first law of motion tells us so. If the spring is distorted by some agent pulling it downward and then releasing it, the mass and spring will immediately recoil upward. Why? Because Newton's third law of motion tells us that a force will act upon the system equally and opposite to the initial downward distortion. The potential energy that is built up in the system by the downward pull will be released as kinetic energy in the upward movement. The force that causes the mass-spring system to be restored to its prior, undistorted position is called a **restorative force**. The initial force that caused the mass-spring system to move from its position of equilibrium can be referred to as a **displacement force**. When the system is undisturbed at rest, it is at equilibrium, which means that the net restoring forces acting upon it are zero. The greater the displacement force, the greater proportionately the restorative force. Stretch the spring a little and the force that acts to restore the mass to equilibrium is small. Displace the spring a great deal, and the restorative force is large. (Displace the mass too much and the spring breaks—a special situation we will ignore.)

Now we know that if the mass is displaced by pulling on the spring, it will not simply move back to its initial rest position and stop. If an object is distorted and then released, elastic restorative forces accelerate the mass upward toward its equilibrium position (Figure 3–2). As the mass approaches equilibrium, the net restoring force decreases, and eventually when the mass reaches equilibrium, the net restoring force is zero. But why does the mass not stop at that point? Why does it maintain its upward trajectory? Inertial forces cause the mass to continue moving upward. Remember that inertia is the tendency of an object to resist change in movement. And we know that the momentum of an object is a product of its mass and acceleration. Thus, inertia causes the mass to overshoot the equilibrium position and continue moving upward. As the mass continues to overshoot equilibrium (that is, the negative displacement is increasing), the restorative force increases. The increasing restorative force acts to slow the upward movement of the mass—the restorative force acts to decelerate the mass. Finally, it stops at its topmost point and is pulled back toward equilibrium. However, the inertia of the displaced mass causes it to overshoot the rest position and distort in the opposite direction. Again, elastic restorative forces cause the mass to return to its original position. And again, the inertia of this second displacement causes the object to overshoot the rest position and distort in the initial direction. This cycle of vibration continues to repeat itself. However, frictional forces (forces that oppose movement) will cause the vibration to lose energy with each cycle, unless an outside force provides energy, and eventually the mass will stay in its rest position (Figure 3–3).

3.2 The Nature of Waves

Speech is composed of sound waves, which is why we spend so much time studying waves.

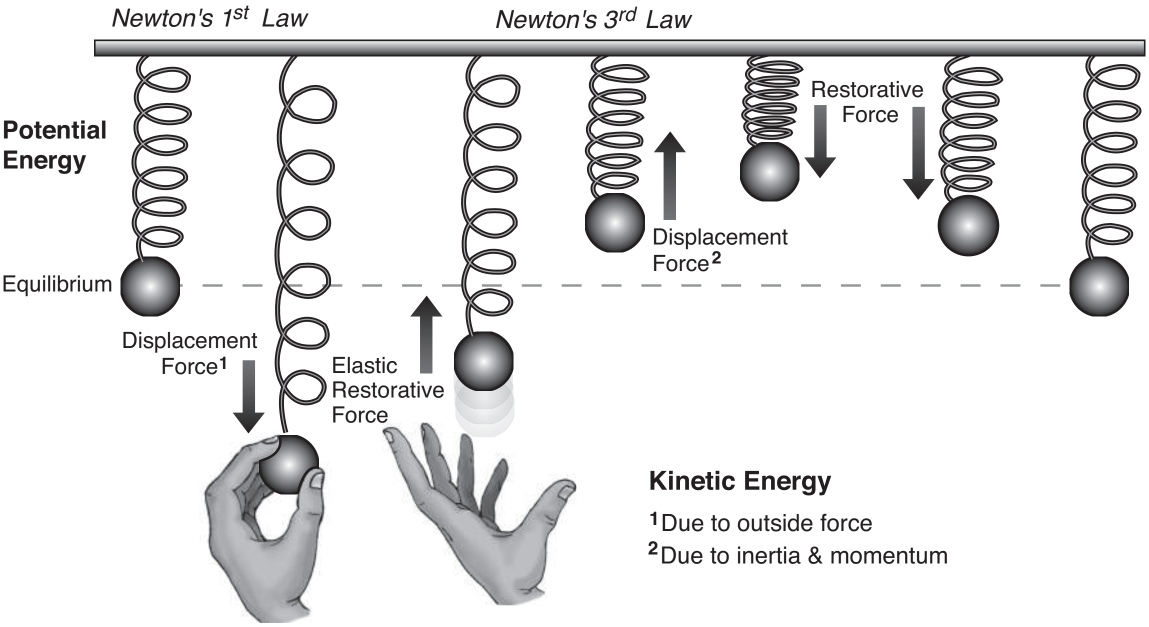


Figure 3–2. A description of vibration.

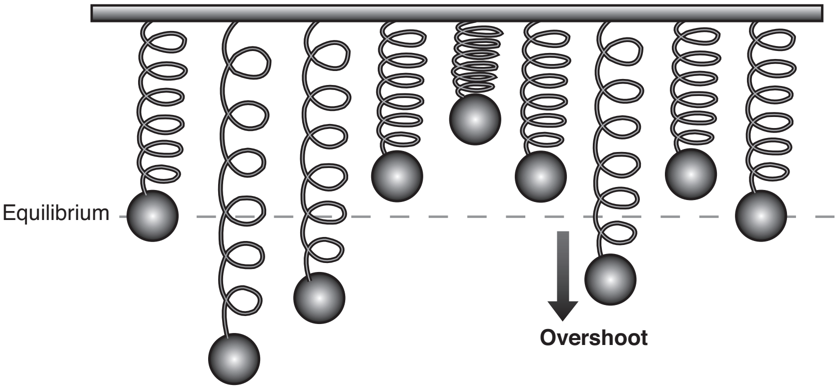


Figure 3–3. Frictional forces will cause the vibration to lose energy with each cycle, unless an outside force provides energy, and eventually the mass will stay in its rest position.

Waves are all around us, more ubiquitous probably than most people realize. Waves are composed of vibrations that move energy from Point A to Point B without actually moving an object or material from A to B. How is this so?

Waves are created by a disturbance. A wave is a disturbance that travels through a medium, transporting energy from one location to another. The medium is the material through which the wave passes; it is that which carries or transports the wave. Throwing a stone into a pond causes waves. The stone (and the force with which it has been thrown) is the disturbance, and the medium that transports the disturbance is water. The medium is simply a series of interconnected particles that interact with one another. The particles of the water wave are the water molecules. Say hello to your friend and your friend hears you because of the sound wave you produced. Your vocal folds created the disturbance (much more about that later). The medium that transports the disturbance is air. The particles of air that interact with one another to carry the energy of your "hello" to your friend are the air molecules. In old-time western movies, the cowboy would put his ear against the railroad track to feel for vibrations alerting him that a train was approaching. The train creates a disturbance and the metal railroad track is the medium. The molecules of metal are the particles that interact with one another, and the resulting vibrations through the train track are felt by the cowboy. The examples of waves in the pond, the air, and the train track are all examples of **mechanical waves**, which require a medium to transport energy from one point to another. Energy transfer of mechanical waves cannot occur in a vacuum. (Other waves, such as light and electromagnetic waves, are not mechanical, but they are generally not considered for study in speech-language pathology.)

Pulse Waves

The simplest wave is a **pulse wave**, in which a single disturbance travels through a medium. Set up a row of dominoes, standing on end and not touching at a distance less than their height. Knock over the first one. The first domino will knock over the next one, and this disturbance will travel down the row of dominoes in a single pulse wave. Hold a jump rope at one end and have your friend hold the other end. Abruptly raise your hand up and down once. This disturbance causes the rope at your end to move up and down. The single upward and downward movement travels along the rope to your friend in a single pulse wave. Think of a line of cars driving along a road. Pretend each car is driving at a steady 30 mph. A bit of road is broken, requiring the cars to slow down. Thus, each car decelerates as it nears the broken area and then accelerates back to 30 mph after passing over the broken road. When viewed from a traffic helicopter above, the disturbance of the broken road causes a pulse wave of momentary slowing down. The stone thrown into the pond sends out a single pulse wave in all directions. A single clap of the hands transmits a pulse sound wave. Speech contains many examples of pulsed sounds, such as the phonemes /t/ and /k/, or the tongue click contained in certain African languages. We will explore the characteristics of pulse speech sound waves in detail in a later chapter.

Longitudinal Pressure Waves

Unlike a pulse, most waves are characterized by repeated disturbances over some period of time. **Sound waves** consist of a series of pressure disturbances. Consider a vibrating tuning fork (Figure 3–4). When the tuning fork is struck with a mallet, the tines vibrate back and forth (Figure 3–5). As they vibrate, the tines push on the air particles surrounding them. The forward motion of the tines pushes the air molecules forward. Let us pretend that we can see the individual air particles moving. Examining a single air molecule, the force of the tine moving forward causes Particle A to collide with Particle B. This collision causes Particle A to be pushed back into its rest position (an equal and opposite force, remember) while displacing Particle B forward, which in turn collides with Particle C. Due to momentum, however, Particle A overshoots rest position and moves farther away from Particle B. The collisions of air molecules result in regions of increased density and air pressure called **compressions**. The restorative force and momentum cause the air particles to separate, resulting in regions of decreased density and air pressure, called **rarefactions**. The alternating compressions and rarefactions of air molecules are the

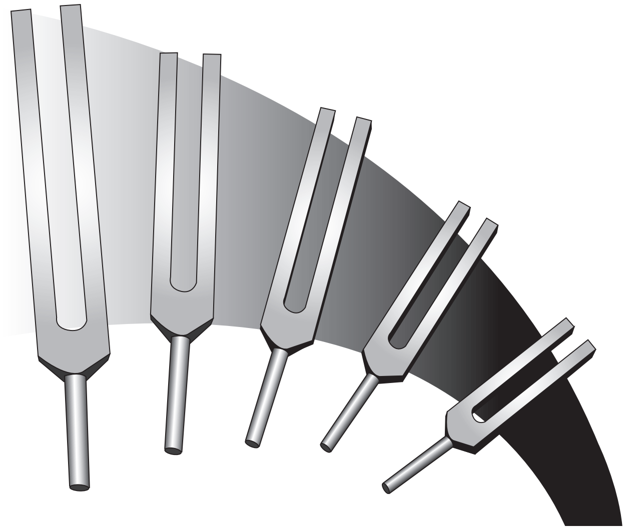


Figure 3–4. Tuning forks of different sizes.

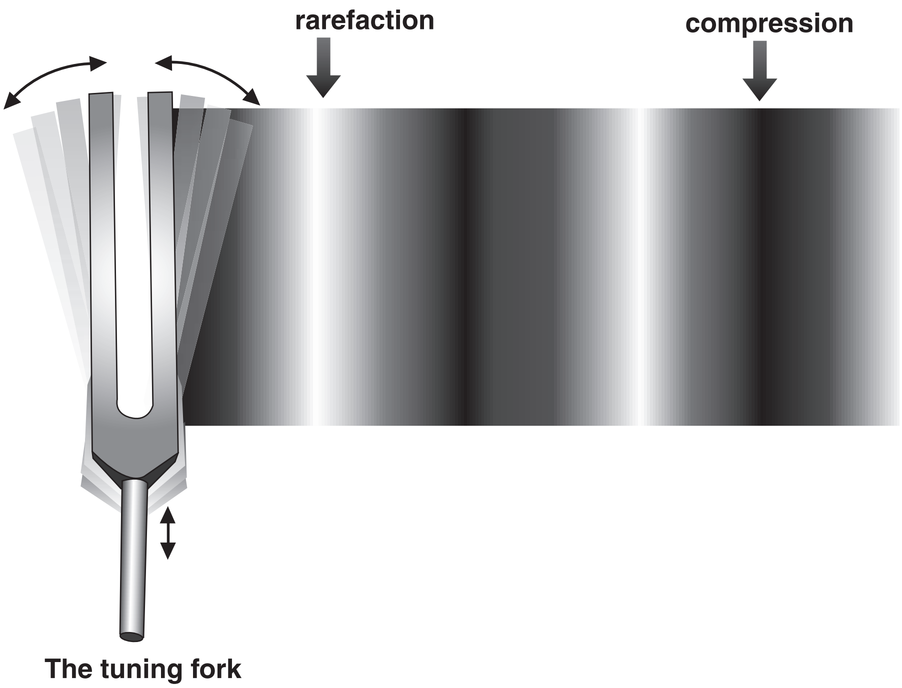


Figure 3–5. Compressions and rarefactions of air molecules resulting from the vibrating tines of a tuning fork.

Tuning Forks

A tuning fork is a deceptively simple instrument in which two tines (prongs) form a U-shape (see Figure 3–5). The tuning fork is deceptive because it is made of elastic steel that is designed to vibrate at a single frequency, producing a pure tone (see section on Pure and Complex Tones later in this chapter). The tuning fork was invented in 1711 by John Shore, the trumpet player to the British court of George I (born in 1660, became king in 1714, and died in 1727). Tuning forks are commonly used to tune musical instruments because they produce a "pure" vibration (more about that soon). One "plays" a tuning fork by striking it gently against a hard surface. The resulting sound pressure wave is generally of low amplitude, yielding a soft sound (we discuss soon the relationship of amplitude and sound). Therefore, tuning forks often are heard most easily by being struck and then being placed on a solid surface that resonates (more on that later in the chapter) with greater amplitude. You can see in Figure 3–4 that tuning forks are made in different lengths. The length of the tines determines the frequency at which the tuning fork will vibrate. We will learn about the relationship of length and frequency in the Resonance and Standing Wave Patterns sections and in our discussion of vocal fold vibration in Chapter 5.

traveling sound wave. Because the sound wave is composed of a repeating pattern of regions of high pressure and low pressure moving through a medium, a sound wave is sometimes referred to as a pressure wave.

Sound pressure waves are longitudinal waves. In **longitudinal waves**, the particles of the medium move parallel to the direction of the wave (see Transverse Waves in this chapter for more information about different types of waves). Said another way, particle motion is parallel to wave motion. As the sound wave moves from the speaker's lips to the listener's ears, the particles of air vibrate backward and forward parallel to the direction in which the wave energy is transported. Regardless of the source (vocal folds, clapping hands, tuning fork), sound is always a longitudinal wave. The distinguishing feature of a longitudinal wave is that the particles of the medium move in a direction parallel to the direction of energy transport.

3.3 Transfer of Energy in Waves

Sound waves are mechanisms of energy transfer. Energy can be carried by the particles or by the wave itself. Suppose that you have a row of dominoes that are lined up, each standing on end very close to the next but not touching. If you tap the first domino so that it falls over onto the second domino, that domino will in turn fall onto the third domino, which will knock over the fourth domino. This will continue until all the dominoes have been knocked over. In this example, the energy has been transferred from your finger tap to the final domino. The falling pattern of the dominos was a wave of movement of each individual particle (domino). The individual particles did not move forward from beginning to end with the wave; they only moved slightly in place (falling over). The wave, however, traveled from the first to the last domino. (Hence, the term "domino effect" to describe a cascade of events that starts with a single initial event.) The motion of the wave was not the same as the motion of the individual particles. In contrast, let's say that you take the first domino and throw it at another domino. In this case, the kinetic energy of the thrown domino is imparted directly to the next domino. The thrown domino travels in an arc but it is not a wave motion. The particle, not the wave, carries the energy to another particle. (See Figure 3–6 for examples of the methods of energy transfer just discussed.)

Think back to the displacement of air molecules as the result of the vibrating tuning fork. As the first particle is displaced, it pushes on the second particle, which displaces that second particle from its equilibrium position. As the second particle is displaced, it in turn displaces the third particle, and so on. In this way, the

Figure 3–6. Transfer of energy can be represented by (**A**) throwing the object or (**B**) collision of a series of objects—a wave.

disturbance itself is traveling through the particles. But the particles themselves do not travel beyond their own area of disturbance. Think of the particles as being interconnected by springs, like a child's Slinky toy (Figures 3–7 and 3–8). The springs transmit the displacement from one particle to the next. Any point on the coiled toy moves back and forth a small distance, but the disturbance itself is transmitted along the length of the entire toy.

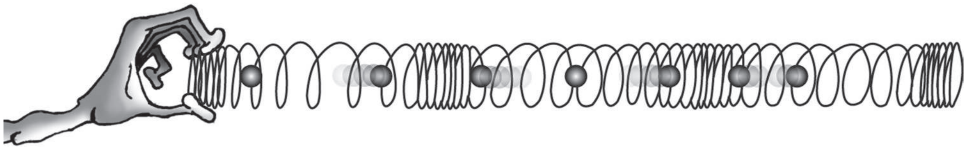


Figure 3–7. Particle movement in a longitudinal pressure wave is represented by balls attached to the individual coils of a child's Slinky toy. The energy is transmitted in a wave from one vibrating (back and forth) particle to the next.

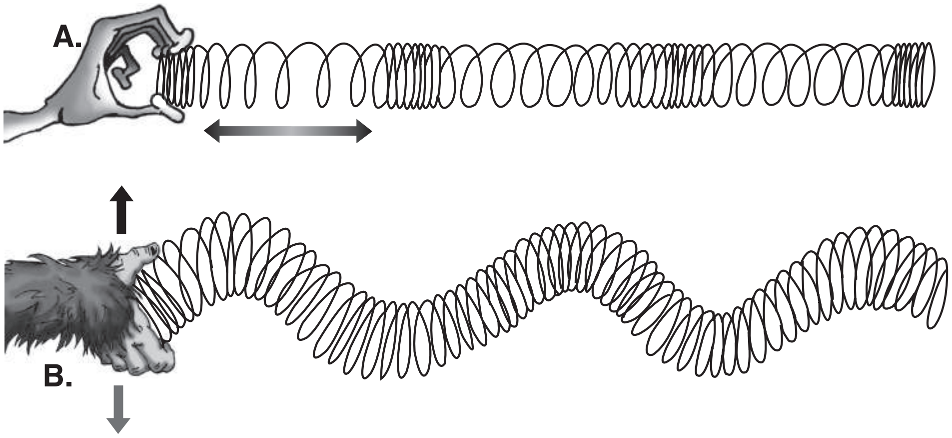


Figure 3–8. A. A longitudinal wave is represented by the horizontal motion of individual coils of a child's Slinky toy, which are parallel to the horizontal motion of the wave along the entire length of the toy. **B.** A transverse wave is represented by the vertical motion of the individual coils, which is perpendicular to the horizontal motion of the wave along the entire length of the toy.

Transverse Waves

One of the most common types of waves that can be visualized easily is the ocean wave, or the ripples in water created by throwing a stone into a pond. Be careful, however, not to get confused. Although there are similarities between these types of waves and sound waves, their properties are different. Ocean waves and pond ripples are examples of a combination of longitudinal and transverse waves. In a longitudinal wave, the vibration of the medium is parallel to the motion of the wave, such as the wave created with the Slinky toy in Figure 3–8A. In the motion of transverse waves, the vibration is perpendicular to the motion of the wave. In a transverse wave, instead of compressions, there are high points (crests), and in place of rarefactions, there are low points (troughs) (Figure 3–8B).

Transverse waves typically occur in more rigid mediums. For example, in our earlier example of a pulse wave traveling along a jump rope, the single upward and downward movement of the vibration is an example of a transverse wave. Gravity helps the particles in a transverse wave return to equilibrium. Transverse waves cannot exist by themselves in a fluid because the molecules would simply slip by one another rather than being pushed upward or downward. However, water waves are a combination of transverse and longitudinal waves. The transverse characteristic (crests and troughs) dominates visually, but the individual water molecules follow an elliptical path, therefore combining motions that are both perpendicular and parallel to the motion of the wave. Sound waves do not have crests and troughs.

Sound waves are longitudinal, with parallel compressions and rarefactions of molecules. Note, however, that our previous discussion of energy transfer applies to both transverse and longitudinal waves. An individual point in the transverse wave moves up and down but not forward. An individual point in the longitudinal wave moves forward and backward around a central point, but it does not travel forward down the length of the toy. A fun example of a transverse wave is the stadium wave performed by the fans (Figure 3–9). Each individual stands up and sweeps his hands up over his head and then brings his arms down as he sits down. When this activity is performed by each person sequentially, the visual effect is a giant wave sweeping around the stadium. Each person rises and falls, as in a crest and a trough, but everyone remains in the same position relative to the entire stadium. The movement of the individual "particles" is not the same as the movement of the wave. Could you change the stadium wave to a longitudinal wave, like a sound wave? Sure. Instead of standing up and sitting down, an individual could lean quickly to the right to bonk into the next person (compression), then sit back erect (rarefaction) as the next person moves quickly to the right. Such a longitudinal stadium wave probably would not look as impressive from the air, however!

Figure 3–9. A stadium wave is an example of a transverse wave.

Study Questions

1. Define vibration and equilibrium. What is a synonym for vibration?
2. Explain a cycle of vibration, accounting for displacement and restorative forces, and equilibrium.
3. What is a mechanical wave? A pulse wave?
4. Describe the mechanics of a longitudinal pressure wave, including the phenomena of compressions and rarefactions.
5. What are two different ways by which energy can be transferred in a wave? How is energy transferred in a sound wave?

3.4 Visualizing a Sound Wave

In our example of simple vibration of the mass-spring system, we noted a repetition of a pattern: the repeated upward compression and downward extension of the mass and spring. If we ignore frictional forces, we could say that this upward and downward oscillation continues unchanged through each cycle of vibration. This movement is an example of **simple harmonic motion**, also called projected uniform circular motion. Figure 3–10 shows a waveform of simple harmonic motion. A waveform is a graphic representation of the change of some phenomenon (a vibration in this case) as a function of time. The waveform of simple harmonic motion is a projection of circular motion at constant speed onto one axis in a plane. Figure 3–10 is the projection of the arc of the upward and downward movement of the mass-spring unit drawn onto the white background. If we could scroll the white background forward at a steady rate, we would see that the projection of the uniform up and down movement is circular; hence, the name uniform circular motion. By convention, a waveform is drawn with time on the *x*-axis oriented horizontally (Figure 3–11). This representation of uniform circular motion is also called a **sinusoidal wave**, or **sine wave** for short, because circular motion can be represented mathematically by the sine and cosine of an angle.

Just as we represent uniform circular motion as a waveform, we can display a sound wave graphically by representing the areas of high pressure (compressed air molecules) and low pressure (rarefied air molecules) with the upward and downward curves of the waveform (Figure 3–12). The horizontal *x*-axis represents time going forward, and the vertical *y*-axis represents the amplitude of the pressure.

3.5 Properties of Sound Waves

We describe the objects around us by their distinguishing characteristics—size, weight, color, shape, for example. We can also describe sound waves by their distinguishing characteristics.

Frequency

The **frequency** of a sound wave is the rate at which the particles vibrate back and forth each second. It answers the question of how often the air molecules vibrate or, said another way, how often the pattern of compressions and rarefactions repeats itself. The unit of measurement for frequency is the hertz, using the symbol Hz (note that no period is used after the symbol). In case you are wondering, the measurement unit is named after Heinrich Rudolf Hertz (1857–1894), who was the first to transmit and receive radio waves. Before the unit of measurement was designated the hertz, frequency was measured in cycles per second, which is equivalent to hertz. One cycle is equal to one complete repetition of a pattern. In our sound pressure wave, one cycle represents one unit of alternating compression and rarefaction of air molecules. It is important to note that, for purposes of calculating the frequency, the beginning point of the cycle can be designated anywhere on the waveform if the end

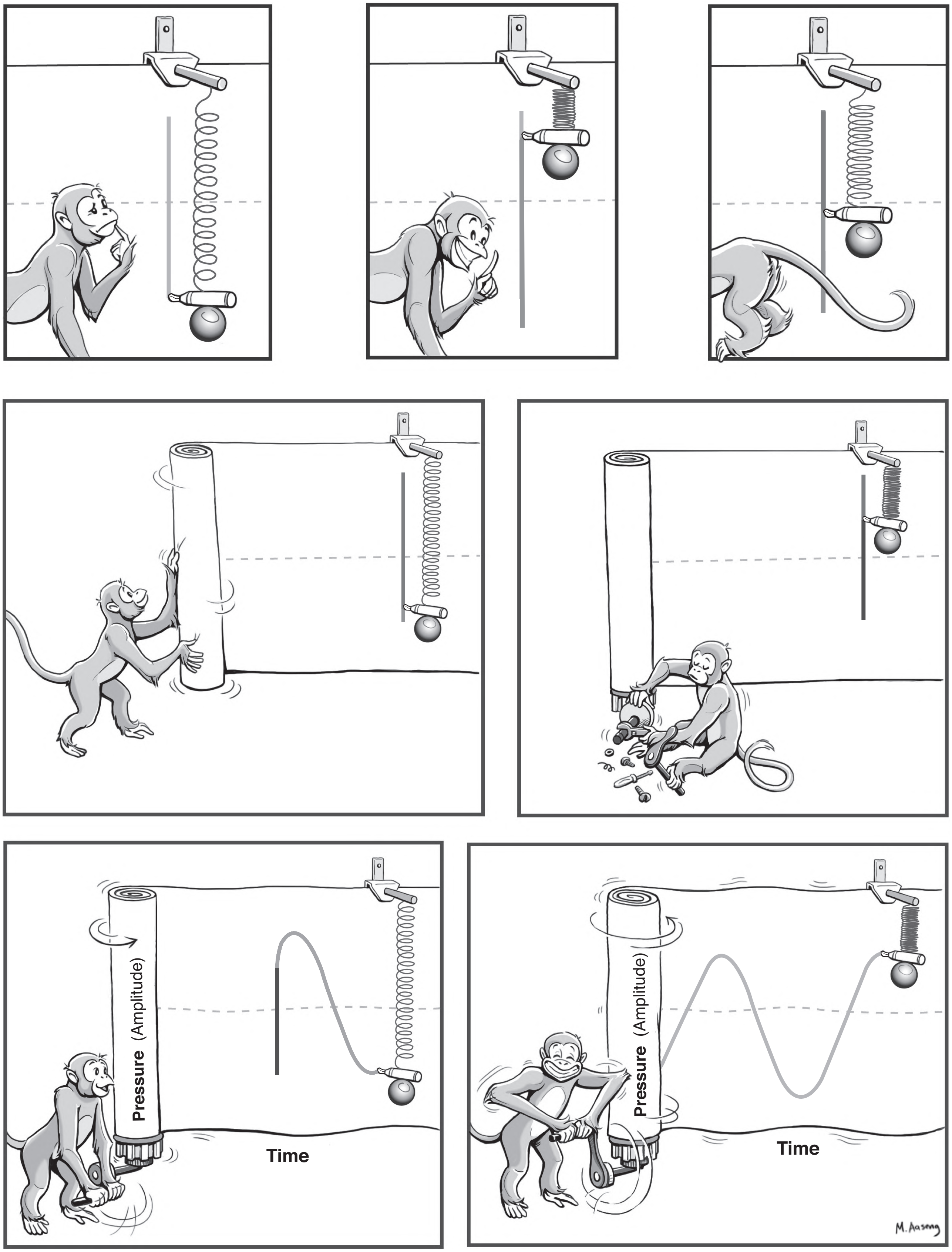


Figure 3–10. Uniform circular motion represents oscillatory motion at a constant rate and path over time.

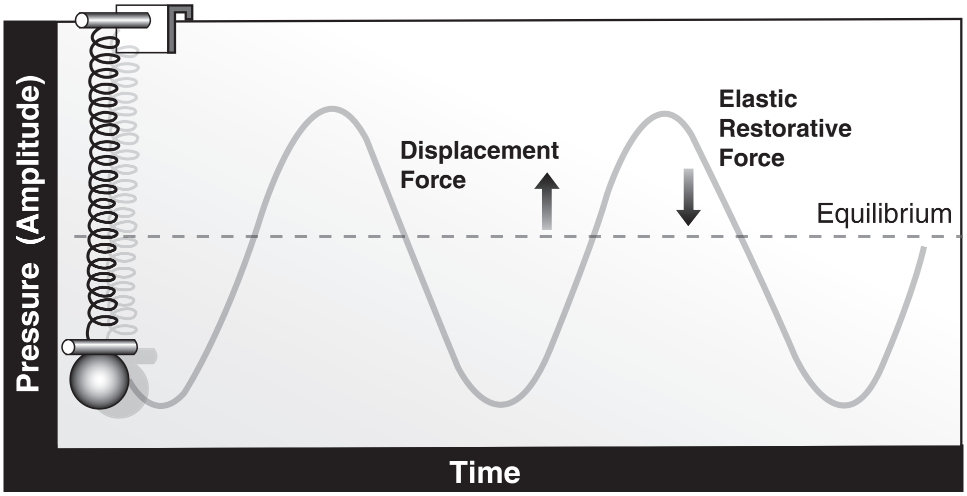


Figure 3–11. A waveform of uniform circular motion (simple harmonic motion) with time on the *x*-axis and change in amplitude of the motion on the *y*-axis.

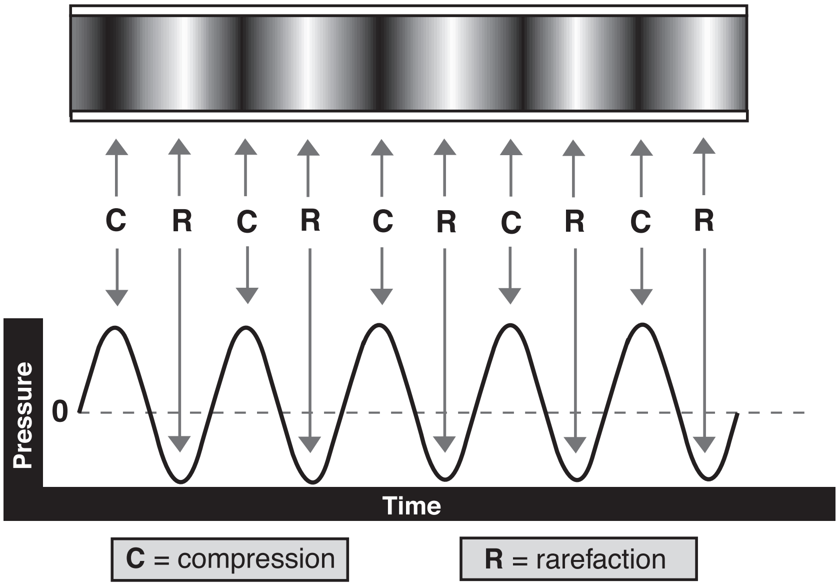


Figure 3–12. The waveform is a graphic display that represents the alternating compressions and rarefactions of air molecules that make up the longitudinal sound pressure wave.

point of the cycle follows after one complete pattern repetition. The point in the cycle at which the waveform begins is referred to as the **phase**. Phase is not critical for calculation of frequency, but it shall become relevant later in our discussion of resonance.

If a wave is composed of particles that vibrate 100 times every second, then we say that its frequency is 100 Hz. It is important to know that each particle in the medium vibrates at the same frequency. This makes sense if we consider for a moment how the particles are set into motion. In the simplest example, a single particle is disturbed by some mechanical force. This disturbance causes it to collide with its neighbor, which in turn causes the second particle to collide with its neighbor. Each collision sets off the vibration of another particle and also causes the particle before it to move back toward rest position. Because each particle is composed of the same matter, each particle vibrates in the same way, so all particles are moving (vibrating) at the same frequency. Everywhere the motion is at the same rate. The rate at which the source of the sound vibrates is the rate of the vibration of the sound wave. If the first particle is set into motion at a rate of vibration of 210 Hz (210 cycles of alternating compressions and rarefactions per second), then every other particle in the wave is set into vibration at 210 Hz. (See Table 3–1 for some interesting facts about frequencies.) Specifically, each cycle, or repeating pattern, is composed of 210 alternating rarefactions and compressions of air molecules.

In Figure 3–13, two waveforms are displayed, one corresponding to a low frequency

Table 3–1. Amusing Frequency Statistics

Frequency	Description
10 Hz	Typical car engine (equivalent to 600 revolutions per minute)
50 Hz	European standard alternating current (AC)
60 Hz	American electrical AC
100 Hz	Typical car engine "redlining" (equivalent to 6,000 rpm)
261.6 Hz	Musical tone C4: middle "C" on the piano
440 Hz	Musical tone A4 (A above middle C): "concert pitch"
740 kHz	The clock speed of the Intel 4004, in the mid-1970s, the very first commercial microprocessor
3–73 GHz	The clock speed of the 2005 Pentium 4 microprocessor
30–300 MHz	(Electromagnetic waves) TV broadcast signals
88–108 MHz	(Electromagnetic wave) FM radio broadcast signals

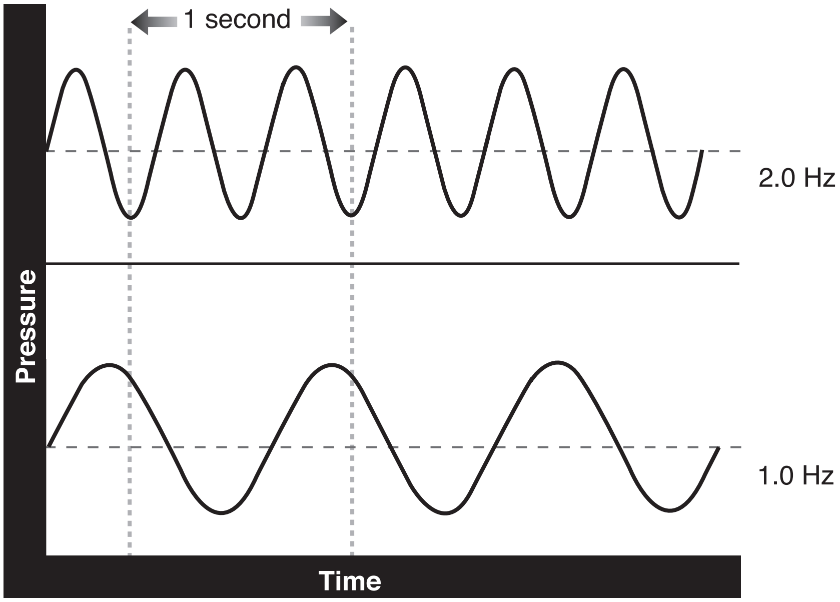


Figure 3–13. Two sine waves of different frequencies.

and the other to a higher frequency. Both plots represent one second of each wave. Note that in the higher frequency wave, the fluctuations in sound pressure occur closer together, or more rapidly, than in the lower frequency wave. In the same amount of time (1 second), there are more compressions and rarefactions of air molecules in the higher-frequency wave than in the lower-frequency wave.

Period

If we look at the waveforms in Figures 3–14 and 3–15, we see the change in pressure as a function of time (that is, the wave's frequency). But what if we want to measure how long it takes to go through just one cycle of compression and rarefaction? The time between successive points of low or high pressure is called the **period** and is the reciprocal of the frequency. This means that a sound wave with a high frequency will have a small period, and a sound wave with a low frequency will have a large period. Think about it: The longer the duration of the period, the more time it takes to complete one cycle of compression and rarefaction, so there are fewer cycles per second. The frequency is lower. The shorter the duration of the period, the less time it takes to complete once cycle, so the higher the number of cycles per second, or the higher the frequency.

Period (t) = 1/frequency
Frequency = 1/t

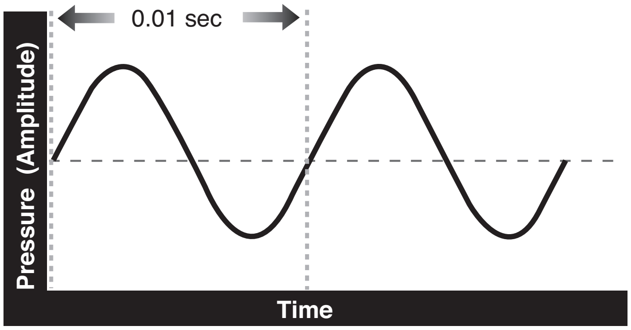


Figure 3–14. The time between a successive alternating compression and rarefaction is called the period.

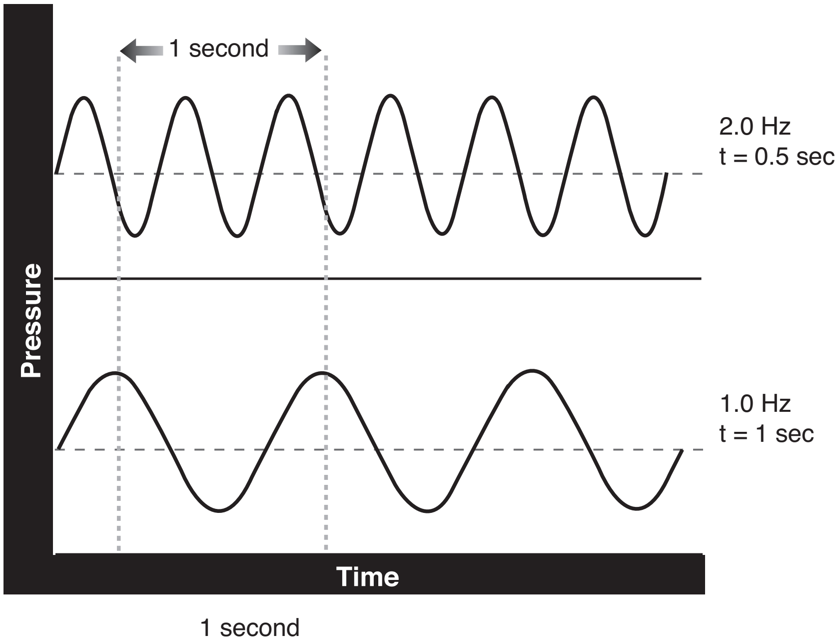


Figure 3–15. The period (*t*) is the reciprocal of the frequency. The longer the period, the lower the frequency. The shorter the period, the higher the frequency.

Relationship of Frequency and Period Defined

In words: The longer the period, the lower the frequency. The shorter the period, the higher the frequency.

The equations using words: Period = 1/frequency and Frequency = 1/period.

The equation using symbols: $t = 1/f$ and $f = 1/t$.

Study Questions

6. Without referring to Figures 3–11 and 3–12, can you draw a waveform that represents simple harmonic motion? Label the *x*- and *y*-axes. Draw and label the line of equilibrium. Indicate a point of compression and one of rarefaction. Where does the displacement force occur? The elastic restorative force?
7. Define frequency and period and explain the relationship between the two measures.
8. Calculate the period of a 220-Hz sound wave to the nearest tenth.
9. Calculate the frequency of a sound wave with a period of 6.5 ms. (*Hint*: 6.5 ms = .0065 s)

Intensity

Every sound wave has a characteristic amount of energy. What do we mean by this? When we talk about a sound pressure wave, we can think of the energy in that wave as a measure of its power. Remember that the pressure wave is initiated by a disturbance—let's say a guitar string that is vibrating back and forth. It disturbs the air molecules immediately adjacent to it, a disturbance that then causes those particles to disturb the next adjacent molecules, and so on. The disturbance, which carries energy, travels from one air molecule to the next. The amount of energy, or power, that is transferred from one particle to the next depends on the **amplitude** of vibrations of the guitar string. If the guitar string is plucked strongly (more work is done to displace the string from its position of equilibrium, or rest), then the string vibrates with wider amplitude. The wider the amplitude of vibration, the greater the displacement of the string; the greater the displacement of the adjacent air particles from rest position, the more power is imparted.

Intensity is the power per unit area and is expressed in units of measurement called watts (W). By convention, the area of measurement is the square meter (m^2), and so intensity is expressed as W/m^2. In Figure 3–16, we see that the power of the sound wave is represented by its amplitude. The greater the power of the sound wave, the greater its amplitude. Although amplitude of the sound pressure wave and its power or intensity are directly related, the intensity increases more rapidly than does the amplitude. In fact, intensity or power increases as the square of the amplitude of the sound pressure. For example, for a doubling of amplitude, the increase of intensity will be quadrupled (2^2). When the amplitude is increased by a factor of 6, the intensity will be increased by a factor of 36 (6^2).

The inverse is also true; when the amplitude is halved, the intensity is decreased by four times. This information becomes important for classrooms, as the students sitting in the back row hear the instructor at a much lower intensity than the students sitting in the front row. If a student sitting in the back row has hearing loss, the instructor may not be heard, especially if the amplitude of noise surrounding the student is greater than the amplitude of the instructor's voice. As the sound pressure wave is carried through a medium, its intensity diminishes with increasing distance from the source. This decrease is due to the outward propagation of the sound wave, spreading out over a progressively larger surface area. As energy is always conserved in nature, and the area through which the sound wave propagates increases, the power must decrease. (Remember, the power is measured on a per-area basis.) This relationship between intensity and distance from the source is called the inverse square relationship (Figure 3–17). That is, the intensity varies inversely with the distance from the source. Remember that the inverse relationship means that as one quantity increases, the other quantity decreases. The **inverse square relationship** means that whatever factor by which the distance is increased, the intensity is decreased by a factor equal to the square of the distance change factor. For example, if the distance from the source is increased by a factor of 2 (doubled), the intensity is reduced by a factor of 4 (quartered), because the square of 2 is 4.

Unlike frequency, we do not measure the absolute value of intensity of sound. Rather, we measure intensity as the relative power of one sound to another. The relative measurement of intensity is not unlike identifying height as tall or short; these descriptors imply that an individual is tall or short relative to other individuals. Speech intensity is measured in decibels of sound pressure level (dB SPL). Let's take a moment to explore this measure.

Figure 3–16. The peak-to-peak height of the pressure wave represents its power. Although the amplitude of the sound pressure wave and its power or intensity are directly related, the intensity increases more rapidly than does the amplitude.

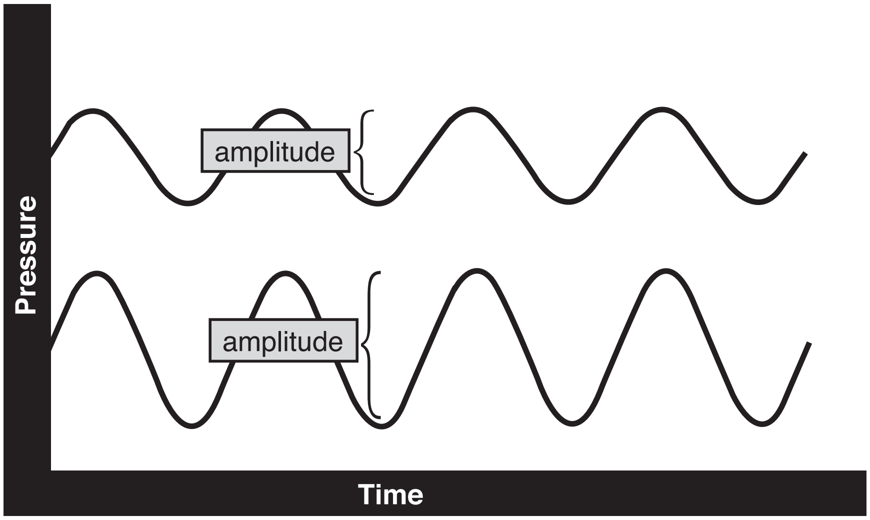
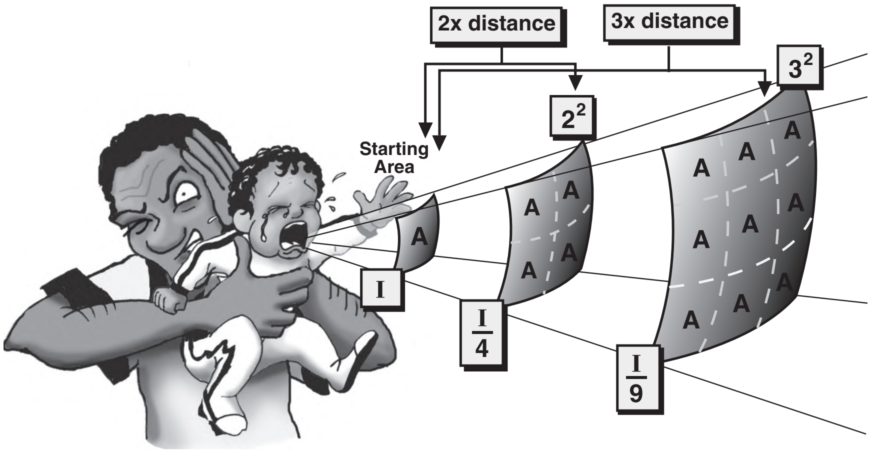


Figure 3–17. The inverse square relationship means that whatever factor by which the distance is increased, the intensity is decreased by a factor equal to the square of the distance change factor.



Hearing Thresholds

The faintest detectable sound is called the threshold of human hearing. The average person with normal hearing sensitivity can detect a sound that has an intensity of 1×10^{-12} W/m^2. This level corresponds to a pressure wave in which the compressions of air particles have only 0.3 billionths of an atmosphere pressure greater than the surrounding air. It also means that the air particles are displaced by only a billionth of a centimeter. The loudest sound that can be detected without damaging the structures of the ear is more intense than one billion times the threshold of hearing!

Table 3–2. Hearing Thresholds

Frequency Range	Animal
20 Hz–20 kHz	Human beings
50 Hz–45 kHz	Dogs
100 Hz–65 kHz	Cats
1 kHz–100 kHz	Bats
1 kHz–150 kHz	Dolphins
200 Hz–90 kHz	Rats
5 Hz–10 kHz	Elephants

The range of intensities that can be detected by the human ear is very large (see Hearing Thresholds above and Table 3–2). Therefore, the scale commonly used to measure intensity is based upon multiples of 10. Such scales are called **logarithmic scales** and allow us to manage large ranges of numbers more easily. A well-known logarithmic scale is the scale used to measure earthquake magnitude. An earthquake of magnitude 5 releases 10 times as much energy as a quake of magnitude 4. (By the way, the earthquake is a pressure wave, not unlike sound waves. However, the frequency of earthquake pressure waves is on the order of 1 Hz, well below the threshold of hearing. Therefore, seismologists, rather than acousticians, "listen" to earthquakes!) The logarithmic scale used to measure intensity is the decibel (dB) scale. A **decibel** is one-tenth of a Bel, a unit named after the Scottish American scientist Alexander Graham Bell (1847–1922), inventor of the telephone. (We shall bump into the Bell family again in Chapter 7, where we will find that his father also had some interest in speech production.) The decibel unit describes the relative intensity of a sound wave. The threshold of hearing at 1000 Hz (1×10^{12} W/m^2 or equivalently, 20 μPa) is assigned a sound level of 0 dB. A sound wave that is 10 times as intense (1×10^{11} W/m^2) is assigned a sound level of 10 dB. A sound wave that is 100 (10 × 10) times as intense (1×10^{10} W/m^2) as the threshold of hearing corresponds to 20 dB. A sound wave that is 1,000 (10 × 10 × 10) times as intense as the threshold of hearing corresponds to 30 dB. A 50-dB sound wave would have an intensity that is (10 × 10 × 10 × 10 × 10) times as intense (1×10^{7} W/m^2) as the threshold of hearing. You can quickly see that using a logarithmic scale allows us to talk about sound intensity more easily than the nonlogarithmic notation of watts/m^2. (See Table 3–3 for relative intensity levels of common events.)

Intensity of speech, then, is a ratio of acoustic powers expressed in logarithms. Because we said that speech creates a pressure wave in air, we measure intensity of speech in units of dB sound pressure level (dB SPL). The sound pressure level (SPL) is the difference in decibels (dB) between a pressure of interest and the standard reference pressure of 0.0002 dyne per square centimeter, or more currently but equivalently under the newer MKS measurement system, 1×10^{12} W/m^2 (or its equivalent, 20 μPa). To compare the relative intensities of two sounds, the following formula is used:

$$\text{dB SPL} = 20 \log_{10} (P_m/P_r)$$

Table 3–3. Relative Intensity Levels

Sound Source	Decibels	Energy Relative to Threshold	Physical Sensation
	0	1	Threshold of hearing
Quiet breathing	10	10	Just audible
Voiced whisper	30	1,000	
Soft speech	40	10,000	
Typical conversation	60	1 million	
Normal street traffic	70	10 million	
Screaming baby	90	1 billion	Threshold for endangering hearing
Power leaf blowers	100	10 billion	
Loud music concert	120	1 trillion	Threshold of pain
Construction jackhammer	130	10 trillion	
Jet taking off nearby	150	1 quadrillion	Threshold over which total deafness may occur

in which P_m is the sound you want to measure and P_r is the reference sound (the one you use for comparison). We can calculate the intensity in dB SPL of a certain sound if we know how much greater its sound pressure wave is compared to the reference pressure. For example, we are told that a very soft whisper is produced with 10 times as much sound pressure as a sound produced at hearing threshold (barely audible). In other words, P_m/P_r is equal to 10. The log of 10 equals 1 (that is, $10^1 = 1 \times 10$) and $20 \times 1 = 20$. Therefore, we would say that the very soft whisper is produced at 20 dB SPL.

$$P_m/P_r = 10$$

$$\text{dB SPL} = 20 \log_{10} (10)$$

$$\text{dB SPL} = 20 \times 1 = 20$$

We also can compute in the opposite direction and calculate the relationship of one sound pressure to the other if we know both intensity levels. For example, we are told that the intensity of a moderately soft conversation is produced at 60 dB SPL.

$$60 \text{ dB SPL } 20 \log_{10} (P_m/P_r)$$

Substitute X for $\log_{10} (P_m/P_r)$ to get
$60 \text{ dB SPL} = 20X$

Now solve for X by dividing each side by 20:
$60/20 = 20/20X$

$$X = 3 = \log_{10} (P_m/P_r), \text{ so}$$
$$\log_{10} 3 = 10 \times 10 \times 10 = 10^3 = 1{,}000$$

We learned that a sound wave that is 1,000 (= 10 × 10 ×10) times as intense as the threshold of hearing corresponds to 30 dB (in units of power, W/m^2). Since power = pressure × pressure, for every 10-fold increase in intensity (in units of power), there is a 20-fold increase in intensity (in units of dB SPL). Therefore, speech that is 1,000 times as intense as the threshold of hearing is equal to 60 dB SPL.

Another important concept to know about decibels is how to interpret values of different decibels relative to each other. Using the equation

$$\text{dB SPL} = 20 \log_{10} (P_m/P_r)$$

and if $P_m/P_r = 2$ (i.e., measured pressure = 2× the reference pressure)

we can determine that $\log_{10} 2 = 0.3$ (that is, $10^{0.3} = 2$)

$$20 \times 0.3 = 6 \text{ dB SPL}$$

A 6-dB increase is equivalent to a doubling of sound pressure, and conversely, a 6-dB decrease is equivalent to a halving of sound pressure.

Wavelength

Wavelength is the distance traveled by one cycle of vibration (one cycle of alternating compression and rarefaction of air molecules). The symbol for wavelength is the Greek letter lambda (λ). In Figure 3–18, it is evident that the wavelength and period (and, therefore, frequency) are related. Wavelength refers to cycle distance, and frequency and period refer to aspects of cycle time. Wavelength also depends upon the speed of sound. The speed of sound traveling through the atmosphere is, in turn, dependent mainly on altitude (density of air molecules) and temperature (speed of movement of the molecules) (more on the speed of sound below). The standard reference is 59°F at sea level, at which the velocity of sound is 340 meters/s (761 mph). Therefore, the wavelength of a sound wave is calculated as the speed of sound divided by the frequency of the wave.

As an example, let's say that a man says "hi" at a steady frequency of 120 Hz. (The frequency is common for men, as we shall learn in Chapter 4, but saying "hi" at a steady frequency is unlikely, as we shall learn in Chapter 7!) Let us also assume that a woman produces the same greeting but at a steady frequency of 220 Hz (a common frequency at which women speak). Using the standard reference for the speed of sound, the sound wave of the man's greeting has a wavelength of 2.8 m/s, whereas the sound wave of the woman's greeting has a wavelength of approximately 1.6 m/s. From the equation for wavelength and these examples, we can see that frequency and wavelength are inversely related. (Recall that an inverse relationship simply means that as one quantity is increased, the other will decrease.) Higher-frequency sounds correspond to shorter wavelengths, and lower-frequency sounds correspond to longer wavelengths.

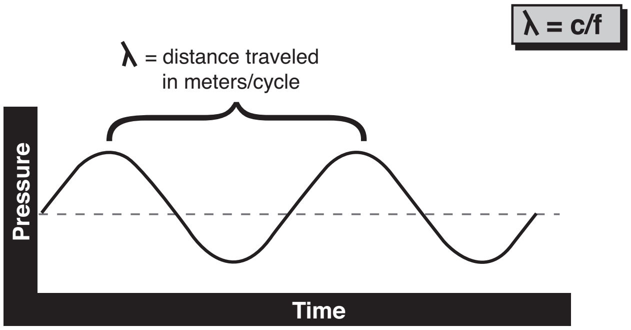


Figure 3–18. Wavelength is the distance traveled by one cycle of vibration (one cycle of alternating compressions and rarefactions of air molecules).

Wavelength Defined

In words: An inverse relationship exists between wavelength and frequency.

The equation using words: Wavelengths (in m) = velocity of sound (in m/s) / frequency (in Hz)

The equation using symbols: $\lambda = c/f$ where λ is the symbol for wavelength and c is the symbol for the velocity of sound.

Speed of Sound

The speed of sound refers to the rate at which the pressure disturbance is transmitted from one particle to the next. Do not confuse speed and frequency and wavelength. Frequency of a sound wave refers to the number of cycles of compressions and rarefactions per second and answers the question “how often?” Wavelength is the distance traveled per cycle of compression and rarefaction and answers the question “how far?” Speed, however, characterizes the distance per unit of time. The speed of a sound wave is the distance that a compression or rarefaction travels per second, so speed answers the question “how fast?” Speed is usually expressed as distance divided by time. The unit of measurement is meters/second (m/s). We know that a car traveling down the road will cover more distance the faster it goes. Similarly, the faster a sound wave travels, the more distance it will cover per unit of time.

The speed of a sound wave is determined by the properties of the medium through which it travels. The greater the density of a mass, the greater the inertia and the slower the interaction between neighboring molecules. Hence, all other things being equal, sound travels faster through less dense material. Air is three times as dense as helium, and so sound waves travel three times as fast through helium as through the normal atmosphere (see Donald Duck in Chapter 7). However, another important characteristic that determines the speed of a sound wave is the state of the medium (solid, liquid, gas). Solid materials generally have the strongest bond between molecules of the three states, followed by liquids, with gases having the weakest bonds. The strong bonds allow the particles to interact with one another more easily than weaker bonds. For this reason, sound waves travel faster in solids than in liquids, and they travel faster in liquids than in gases. Therefore, even though inertial factors would seem to favor gases, the strong bonds between molecules of certain solids outweigh the inertia.

The temperature and pressure of the air also influence the speed of sound. The pressure influences the density of the air, because greater pressure results in increased density of particles. The temperature influences the strength of the interaction between the particles. At a given air pressure, the higher temperature causes the interactions between particles to become more elastic. That is, the particles are more easily separated. The medium therefore has less resistance to being deformed (changing shape). When the temperature is 68°F at sea level pressure, sound travels at 343 meters/second (equal to 750 mph).

Sometimes, speed of sound is referred to as the velocity of sound. Velocity is speed in a given direction. Sound pressure waves, however, generally radiate outward in all directions, and therefore, for our purposes, we use speed and velocity equivalently in this specific instance.

In summary, the speed of a sound wave is not dependent upon its frequency or wavelength. (Remember the inverse relationship of frequency and wavelength: As one quantity increases, the other quantity must decrease.) The speed of a sound wave can be altered only by the properties of the medium through which it travels.

Study Questions

10. Define intensity. How are pressure and amplitude of vibration related to intensity?
11. What is meant by the inverse square relationship?
12. How do we measure intensity? Why is a logarithmic scale used? (*Hint*: How much energy is in an extremely loud sound compared to one that is just barely perceptible to us?)
13. Define wavelength.
14. What factors can influence the speed of a sound wave? What properties of sound waves do not affect the speed?

Turn Down the Music!

The wavelength of a sound wave and the material through which it travels affect us daily. Have you ever sat next to someone listening to music through headphones? Chances are, if the music was turned up sufficiently loudly or the earpieces were sitting loosely, you could hear the bass but little else. Low-frequency, long-wavelength sounds spread out more than do high-frequency, short-wavelength sound pressure waves. The longer wavelengths bend around objects and propagate through solids more easily, whereas the short-wavelength sounds are highly directive and do not escape easily around and through objects. We shall learn in later chapters that the frequencies of speech sounds are generally high frequency. Therefore, the low bass sounds escape the music lover's earphones more easily than do the higher-frequency sounds of speech as well as other musical instruments such as the flute.

Why Do Sounds Travel Farther at Night?

It is easier to hear faraway sounds in the evening than in the daytime. This effect is due to air temperature and a phenomenon called *refraction*. In general, during the daytime, the air nearer to the ground is warmer than the air higher up away from the ground. The sound wave travels more easily in the warmer temperatures and gets slowed down by the cooler temperatures. This difference in velocity causes refraction, a bending upward of the sound waves toward the slower moving, cooler air. At night, the opposite occurs. The sound waves bend downward toward the cooler air along the ground. Thus, the sounds waves appear to be traveling farther, as they stay closer to the ground across a greater distance.

3.6 The Perception of Sound Waves

Our *perception* of the frequency of a sound is not equal to the measured frequency of the pressure wave, nor is our perception of its intensity equivalent to the measured intensity of the wave. Each perceptual construct depends on how well our brain analyzes sounds for frequency and intensity. **Pitch** is the perceptual correlate of frequency and **loudness** is the perceptual correlate of intensity. Pitch and loudness are subjective human judgments based upon a complex interplay of factors. While our perception of pitch is based strongly on the frequency of the sound wave, it is also influenced by the intensity of the sound. Similarly, our perception of loudness, although based primarily on intensity, is also strongly influenced by the frequency. **Psychophysics** is the study of the relationship between the physical properties of a stimulus and our subjective experience of the stimulus. The German experimental psychologist Gustav Fechner (1801–1887), a pioneer in experimental psychology, is credited with noting that the relationship between stimulus intensity and perception of the strength of the stimulus is nonlinear. In other words, the perception of the sound increases as the logarithm of the stimulus. So, to perceive a series of sounds as increasing in loudness with equal increments, the actual intensity of the sounds would have to increase logarithmically. (This information has been recognized since the 1800s. The logarithmic scale corresponds well to perceived intensity differences in the human ear. The human ear is designed to perceive the middle frequencies comprising speech with much less intensity than is needed for very high or