12. Discuss and interpret graphs related to the psychoacoustic (perceptual) properties of loudness, pitch, temporal integration, and localization.

We live in a world of sounds, some of which are meaningful and some of which are just part of our noisy environment. We often take for granted the remarkable ability of the auditory system to extract meaningful sounds from the less meaningful so that we can sense danger, localize the source of a sound, communicate, learn, and even be entertained. Even when asleep we learn to tune out familiar sounds, but may wake up at an unfamiliar sound. At a noisy party, you can focus on a conversation with one person while ignoring the background conversations, but readily become aware when someone calls your name from across the room or your favorite song begins. When you listen to an orchestra or band you may find yourself listening to the whole song or picking out the various instruments. Our ability to hear in our everyday world requires the auditory system to process complex sounds from our environment. The process of hearing involves the generation of sounds, their travels and interactions within the environment, physiological processing by the ear, neural processing in the nervous system, and psychological/cognitive processing by the brain. The sounds we hear have basic physical properties that are processed by the auditory system into meaningful information.

Acoustics is the study of the physical properties of sounds in the environment, how they travel through air, and how they are affected by objects in their environment. As you will see in this chapter, any simple vibration can be uniquely described by its frequency, amplitude, and starting phase. Complex vibrations can be described as combinations of simple vibrations. However, not all sounds generated in the environment are audible and the audible range may be different across species; for example, dogs and cats are more responsive to higher pitched sounds than are humans. The human ear is capable of hearing a wide range of frequencies over an extensive range of amplitudes. But how does frequency relate to our perception of pitch? How does amplitude relate to our perception of loudness? How do we compare the loudness of sounds across frequencies? How do we use our two ears to localize the source of sounds? These types of questions come under the area of *psychoacoustics*, which is the study of how we perceive sound. The psychoacoustic aspects of sound covered in this chapter include some basic perceptions of pitch, loudness, temporal integration, and localization. After reading this chapter, perhaps you will be able to answer the age-old philosophical question that goes something like, "If a tree falls in the woods and there are no living creatures around, does it make a sound?"

The definitions and terminology reviewed in this chapter are necessary to be able to better understand topics that are covered in the following chapters, including the physiology of the auditory system, the clinical procedures used to evaluate hearing loss, and the function of hearing aids. A thorough understanding of acoustics requires knowledge of some mathematical concepts and formulas; however, in this introductory text, only the basic concepts are presented and every attempt is made to keep the mathematics to a minimum. The interested reader is referred to other textbooks (Gelfand, 2009; Mullin, Gerace, Mestre, & Velleman, 2003; Speaks, 2017; Villchur, 2000) for a more thorough treatment of acoustics and psychoacoustics.

SIMPLE VIBRATIONS AND SOUND TRANSMISSION

Sounds are produced because of an object being set into vibration. Some familiar examples include vibrations of tuning forks, guitar strings, other musical instruments, stereo speakers, engines, thunder, and the vocal cords while speaking. Almost any object can be made to vibrate, but some objects vibrate more easily than other objects depending on their mass and elasticity. Although most sounds in our environment are complex vibrations, we begin by looking at very simple vibrations called *pure tones*. Pure tones are used by audiologists as part of the basic hearing evaluation. In addition, an understanding of pure tones is useful because all complex vibrations can be described as combinations of different pure tones, which was mathematically proven by a man named Fourier. Today, we have electronic instruments that can perform *fast Fourier transforms (FFTs)* to determine the different pure tones that comprise any complex vibration.

The vibrating sound source sets up sound waves that travel, called *propagation* (*propagate*), through some elastic medium, such as air, water, and most solids. Propagation of sound through air occurs because of the back and forth movement of air molecules around their position of equilibrium in response to the back and forth vibration of an object. The air molecules closest to the vibrating object move back and forth first. Because of the inertial and elastic properties of the air molecules, the air molecules only move within a localized region, but as they push against adjacent air molecules the process repeats itself, which causes the *pressure* variations to propagate through the medium. When the vibrating object moves outward, the air molecules are pushed together causing an increase in the density of air molecules (more molecules per volume), called *condensation*, and this corresponds to an increase in sound pressure. When the vibrating object moves in the opposite direction, there is a decrease in the density of air molecules, called *rarefaction*, and this corresponds to a decrease in sound pressure. Figure 3–1 illustrates how these increases and decreases in the density of air molecules occur in response to a simple vibrating object such as a *tuning fork*. When the vibration repeats itself over and over, as depicted in Figure 3–1, there are continuing cycles of condensation and rarefaction that produce a continuous sound that can be measured at different points in the surrounding area. In Figure 3–1, you can see the areas in which the air molecules are more densely packed (condensations) and where the air molecules are less densely packed (rarefactions). The condensations and rarefactions reflect a repetitive pattern of increasing and decreasing air pressure. For unobstructed sound waves in air, the air molecules move outward in a spherical direction and the actual size of the air pressure peak (amplitude) diminishes with distance because of friction, as well as because the pressure is being radiated in an increasing spherical pattern. At some distance from the source, the pressure will no longer be measurable because the energy is spread out over a large enough spherical area. The actual

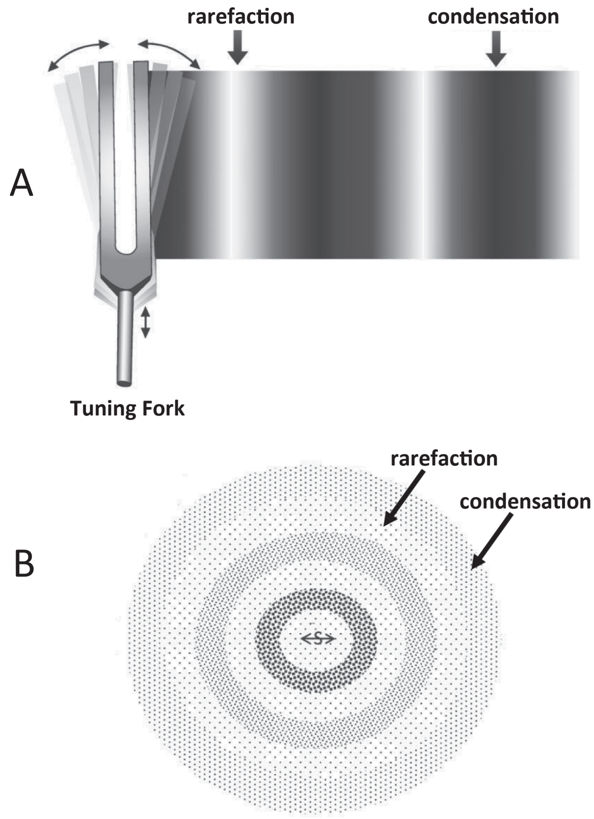

FIGURE 3–1. A and B. Illustration showing propagation of air molecules to a vibrating sound source. **A.** Tuning fork vibration producing alternating areas of increased density of air molecules (condensation) and decreased density of air molecules (rarefaction) that are propagated across the air from its source. **B.** Sound waves as they propagated spherically away from the sound source with alternating condensation and rarefaction phases. As the distance from the sound source increases, the force is distributed over a wider area.

amplitude of a sound at any point in space obviously depends on the original intensity level of the sound, that is, louder sounds will travel greater distances than softer sounds.

Sound propagation can also be influenced by how the waves are reflected or interfered with by objects or walls. Much of our real-world listening situations are in closed environments, whereby much of the sound energy does not penetrate the walls but instead bounces off or is absorbed by the walls. The angle at which a sound will bounce off a wall is similar to a ball bouncing off a wall. The angle of reflection will depend on the angle of incidence relative to the perpendicular. This becomes even more complicated when the encountered object is curved (convex or concave), or in a room with four walls, where the sound may bounce back and forth among the walls. How sound waves might interact with an object in its environment is also important. Some sounds will bounce off an object, whereas other sounds easily go around the object, and depends primarily on the sound's wavelength (see section on wavelength). As you will learn in the following sections, there are also areas in which the condensation phase of a wave meets up with another wave's rarefaction phase, resulting in wave cancellation (where no sound is present). In addition, materials have certain absorption characteristics that come into play in determining how sounds act in the real world. Understanding acoustics in these types of environments is especially important when designing theater or music venues (something acoustic engineers are trained to do, but it is well beyond the scope of this textbook).

Another characteristic of sound waves is the speed or velocity with which they are propagated through the medium. Sound travels faster in water and most solids than it does in air. The *speed of sound* in air is about 343 m/s or 1126 feet/s,[1] which is much slower than the 186,282 miles per second that light travels. You probably use this knowledge, maybe unknowingly, when you estimate how many miles away you are from a storm by counting the seconds between seeing the lightning (seen instantaneously) and hearing the thunder (heard later). Your estimate of how far away the storm is will be more accurate if you divide the number of counted seconds by five to take into account that the speed of sound is about one-fifth of a mile per second.

When the increases and decreases in pressure occur in the direction of the vibrating object, as for sound waves, the sound is called a *longitudinal wave*. The process of localized back and forth movement of air molecules results in the propagation of a longitudinal sound wave through the air, more precisely in a spherical pattern. When this sound wave reaches the ear, the corresponding condensations and rarefactions in air pressure cause the tympanic membrane to move in and out, thus beginning the process of hearing. You will see in the next chapter how vibrations are received by the ear and how the ear transforms the incoming vibrations into auditory information. Before that, however, we need to turn our attention to understanding the basic physical parameters of sound, frequency, amplitude, and starting phase.

FREQUENCY

Pure tones are characterized by regular repetitive movements. Imagine holding a pencil in your hand and moving it up and down on a piece of paper at a consistent height and speed. As you are moving your hand up and down, begin to move the paper from right to left; you should see a pattern that looks something like those shown in Figure 3–2. The actual separation of the peaks that are produced will depend on the speed at which you move the paper (the slower the paper, the closer the peaks). To be able to quantify the pattern of vibratory movement, the motion is displayed as a function of time along the *x*-axis. The *y*-axis represents a measure of magnitude or amplitude of the vibrations (e.g., how far up and down you moved your hand). When the pattern of movement is displayed with amplitude as a function of time, it is called a *time-domain waveform* or simply a *waveform*.

[1]The speed of sound in air is dependent upon both the temperature and the density. The value used in this textbook is an approximation for 68°F. The speed of sound in air slows down as temperature decreases, for example, it is about 341 m/s or 1086 feet/s at 32°F.

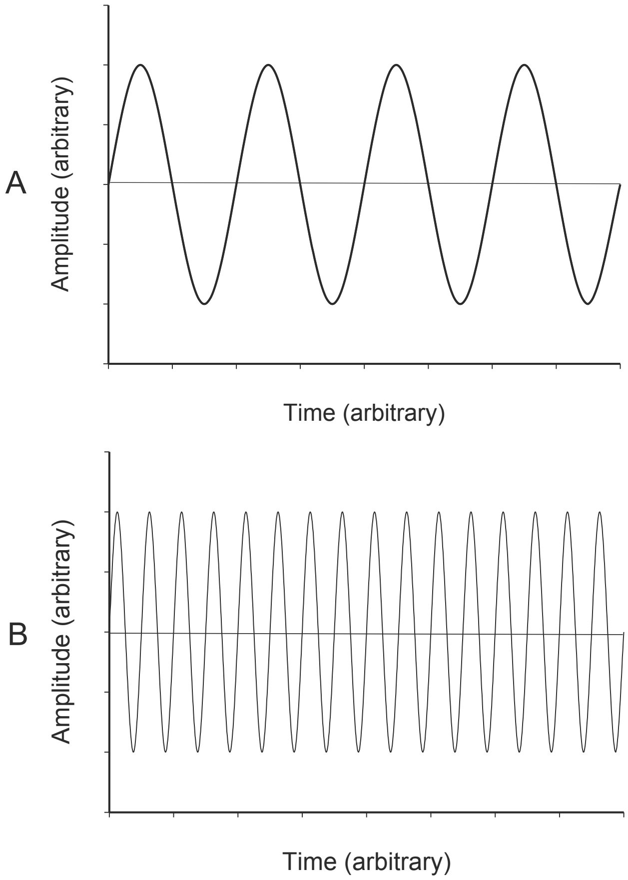

FIGURE 3–2. A and B. Representations of two different pure-tone vibration patterns as a function of time in arbitrary units. The vibration in (**A**) is slower than the vibration in (**B**) even though the time scales are equal.

A *cycle* of vibration describes the pattern of movement as the object goes through its full range of motion one time. In other words, one cycle represents the movement of an object from its starting point to its maximum peak, then to its negative peak, then back to its starting point. Figure 3–3 shows one cycle of a pure tone.

Most vibrations repeat themselves; therefore, pure tones are usually described by how many cycles occur in 1 second (s), called *frequency* of vibration. However, instead of using cycles per second as the unit of measure for frequency, the term *hertz (Hz)* is used to mean the same thing. For example, a vibration that repeats itself 100 cycles in 1 s is called a 100 Hz pure tone. Conversely, a 100 Hz pure tone would complete 100 cycles in 1 s. An 8000 Hz pure tone completes 8000 cycles in 1 second. The *frequency range of audibility for humans* is from 20 to 20,000 Hz.

Figure 3–4 shows some examples of different frequencies as they would appear on paper when graphed with a 1 s time scale. As you can notice, it is difficult to visually count the number of cycles as the frequency increases, and counting would be extremely difficult for much of the audible frequency range if graphed using a 1 s time scale. However, another way to graphically represent the different frequencies of pure tones is to change the time scale along the *x*-axis. In other words, only a few cycles (or even a single cycle) are plotted over a specified time scale. The actual frequency is calculated from knowing how long it takes to complete one cycle, called the *period* of the vibration. Figure 3–5 shows some examples of how the period is related to frequency. In Figure 3–5A, you can see that the time it takes to complete the one cycle is equal to 0.01 s (one hundredth of a second), which means it would be able to complete 100 cycles in 1.0 s (100 Hz). In Figure 3–5B, the time it takes to complete the one cycle is 0.001 s, which means this vibration would be able to complete 1000 cycles in 1 s (1000 Hz). In Figure 3–5C, the time it takes to complete the

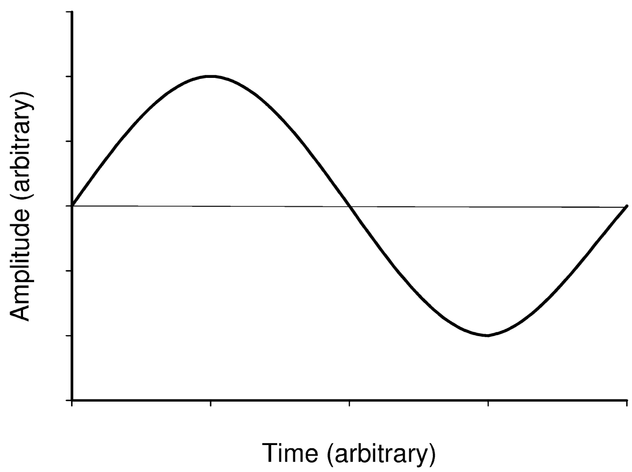

FIGURE 3–3. Time domain waveform showing one cycle of vibration. The vibration moves from its starting point to its maximum peak (amplitude), then to its negative peak, then back to its starting point as a function of time.