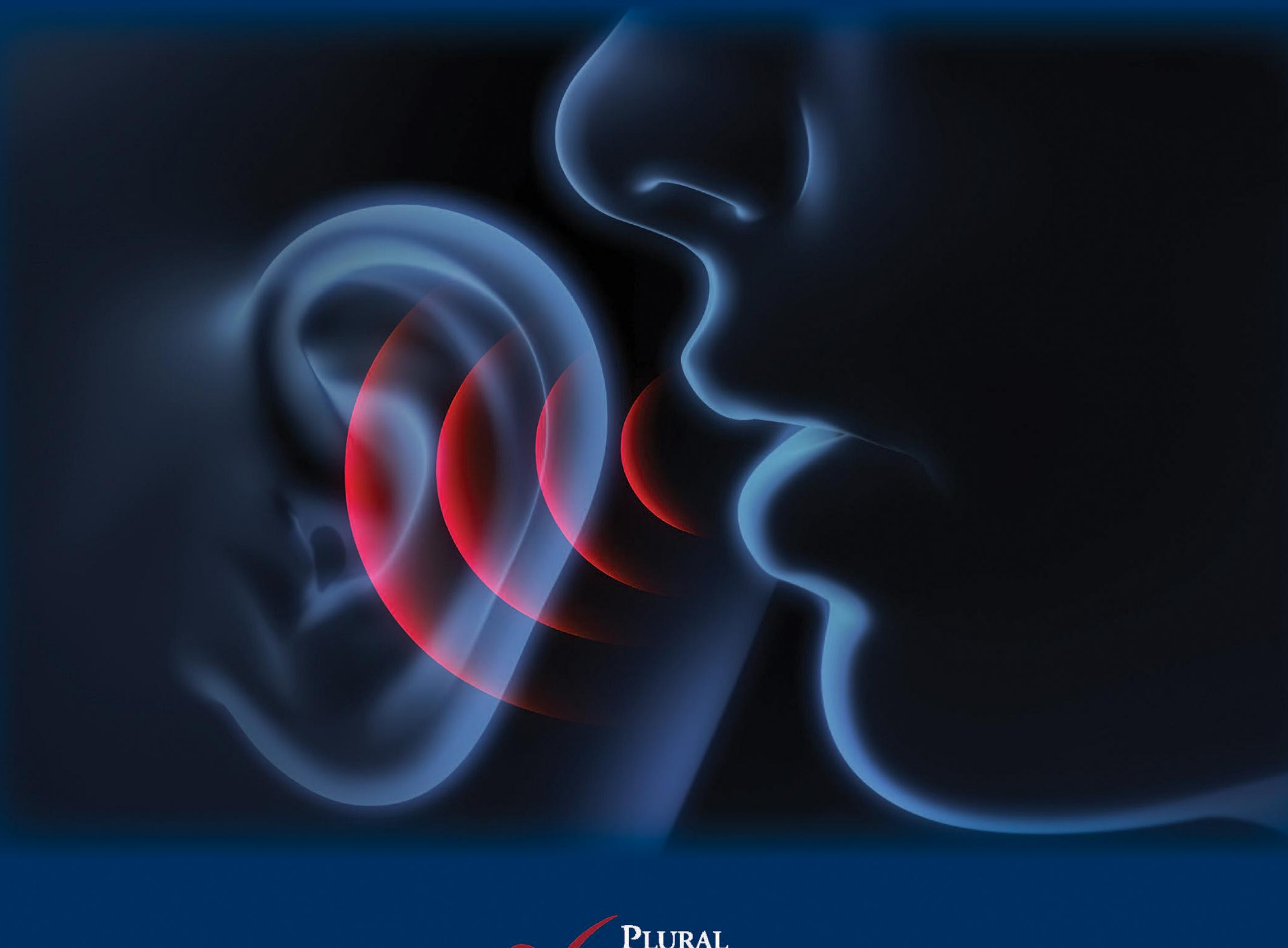
HEARING SCIENCE FUNDAMENTALS

SECOND EDITION

Norman J. Lass
Jeremy J. Donai



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PREFACE

Hearing Science Fundamentals, Second Edition, addresses basic concepts in hearing science in an understandable manner to facilitate the learning of technical material by both undergraduate and graduate students. The book contains numerous student-friendly features, including the following:

- learning objectives and key terms at the beginning of each chapter to prepare the student for learning the chapter contents;
- audio examples illustrating concepts within each chapter;
- recorded review lectures of each chapter to enhance learning;
- more than 150 anatomical and line illustrations to help in understanding important technical concepts;
- *Vocabulary Checkpoints* throughout the text to reinforce learning of critical terms;
- *Clinical Notes* throughout the text to address potential clinical applications of the contents of each chapter;
- *Q & A* boxes to reinforce important information presented in the text;
- study questions at the end of each chapter for review of chapter contents;
- suggested readings at the end of each chapter for further clarification and study of the technical contents of each chapter;
- a Glossary of important terms used throughout the text (terms included in the glossary are in **boldface** type the first time they appear in the text) to enhance the learning process for students; and
- a PluralPlus companion website containing a question test bank, a sample course syllabus, an image collection of figures from the text for instructors and animations, practice test questions, and anatomy labeling exercises for students.

These features make ***Hearing Science Fundamentals, Second Edition***, useful not only to students in facilitating the learning process but also to instructors for the purposes of explaining technical concepts; providing a source of questions and illustrations for quizzes, exams, and in-class learning exercises; and assigning additional readings on selected topics.

This new edition contains four sections divided into 17 chapters. The first section, ***Acoustics***, includes three chapters. ***Basic Acoustics*** introduces students to important concepts associated with sound, including conditions necessary to create sound, properties of vibrating systems, sinusoidal (i.e., simple harmonic) motion, sine curves and their spatial (i.e., amplitude and wavelength) as well as temporal (i.e., period, frequency, phase, and velocity) features, and characteristics of complex sounds. Also included is a discussion of sound propagation and interference as well as the phenomenon of resonance, specifically cavity (i.e., acoustical) resonance involving the tube model, which has direct relevance to hearing because of its analogy to the human external auditory meatus. Finally, this chapter addresses the concept of the decibel. An understanding of these topics will assist the reader in applying basic concepts in acoustics to an understanding of the hearing process.

The second chapter, ***Review of Speech Acoustics***, provides a concise review of the acoustic structure of the speech signal as well as information regarding speech production. An understanding of these concepts will assist the reader in understanding and applying concepts in future chapters regarding the psychoacoustic processing of auditory information.

The third chapter, ***Digital Signal Processing (DSP)***, provides an entry-level overview of DSP with applications to the hearing sciences. Given the widespread use of DSP in speech- and hearing-related fields, this chapter will enhance the breadth of the reader's knowledge for future study.

The second section of the book, ***Structure and Function***, contains three chapters intended to teach students basic anatomy and physiology of the auditory mechanism. ***Anatomy and Physiology of the Conductive Auditory Mechanism*** describes the structures involved in conducting vibrational sound energy from outside the head through the outer ear (i.e., auricle and external auditory meatus), tympanic membrane, and middle ear (i.e., ossicular chain) to the inner ear. Also included is a detailed description of the nonacoustic functions of the conductive mechanism (the role of ceruminous and sebaceous glands and the curvature of the ear canal in protecting the tympanic membrane) as well as its acoustic function, including the resonance of the external auditory canal and the conversion of acoustic energy from the auricle and external auditory meatus to mechanical energy at the tympanic membrane and through the ossicular chain of the middle ear. The transformer action function of the middle ear is discussed, including the condensation effect, lever action of the malleus and incus, and curved membrane buckling mechanism of the tympanic membrane. In addition, the function of the auditory (i.e., eustachian) tube and the two middle ear muscles (tensor tympani and stapedius) are presented.

Anatomy and Physiology of the Sensory Auditory Mechanism is concerned with the auditory portion of the inner ear contained in the cochlea, a very complex structure with much still unknown about its function. All information that is necessary to understand speech, interpret sounds indicating danger to the organism, or appreciate music must be coded in this tiny structure of approximately 35 mm in length. The anatomical structure of the cochlea is described in detail, including its three canals and the organ of Corti, which resides in one of the canals. In addition, the outer and inner hair cells of the organ of Corti and their function are addressed. The function of the cochlea is very complex and not fully understood. Mechanical, electrochemical, and active processes contribute to the conversion from mechanical movement of parts of the conductive mechanism (i.e., tympanic membrane and ossicular chain) to the neural code that allows us to detect and interpret acoustic aspects of our environment. The mechanical properties and active processes involved in the sensory mechanism, as well as cochlear electrophysiology and single-cell electrical activity, are described in detail.

A comprehensive description of the anatomical structure and physiological function of the central auditory mechanism is presented in ***Anatomy and Physiology of the Central Auditory Mechanism***, including the afferent and efferent central auditory pathways. The central auditory system is much more than a conduit from the cochlea to the brain. While actions like the startle reflex, acoustic reflex, and localization responses are initiated at levels that are peripheral to the cerebral cortex, complex analysis of speech, music, and multisensory construction of our environment take place within the cortex. Thus, complexity of function usually increases from the VIIIth nerve to the cerebral cortex. In addition to information flow from the cochlea to higher centers, there is also neural energy flow, much of which is inhibitory or suppressive, from higher centers to lower areas, including the cochlea and efferent system. While the function of the central auditory system is not completely understood, much is learned from instances in which its function is impaired, such as from cerebrovascular accidents, head trauma, and (central) auditory processing disorders.

The third section of the book, ***Psychoacoustics***, contains eight chapters concerned with how sound is perceived via the auditory pathway. In ***Normal Hearing,*** several aspects of auditory sensitivity are addressed, including the frequency, intensity, and duration of the auditory stimulus, mode of stimulus presentation, psychophysical methods, and listener characteristics such as preparatory set and age. The concept of normal hearing is discussed and it is concluded that hearing sensitivity is dynamic, with the quantification of threshold partially dependent on the operational definition of the examiner. Clinical assessment of auditory sensitivity, the primary cues (i.e., intensity and time) associated with localization of sound sources, and hearing by bone conduction are also addressed. It is concluded that the processes involved in normal hearing are not simple. The role assumed by the auditory and other sensory systems is very complex, and the complexity and subtlety of their interaction is usually taken for granted as long as it functions as intended.

Binaural Processing builds upon concepts in the previous chapter and provides additional details regarding how the human auditory system effectively navigates the auditory scene. Specific examples of processes and mechanisms used to effectively listen in noise are provided.

The chapter on ***Masking*** addresses the concept of masking, a process in which the threshold of one sound (the signal) is raised by the simultaneous presentation of another sound (the masker). It involves the introduction of a sound (the masker) to an ear in order to preclude a person from hearing another sound (the signal) in the same ear. This chapter includes the masking of tones by other tones, masking as a function of noise level, the concept and importance of the critical band in masking, wideband noise as a masker of pure tones, temporal (i.e., forward and backward) masking, and masking level difference. Also discussed is masking in clinical audiology, including the concepts of cross-hearing, cross-skull attenuation, crossover, speech (or pink) noise, and effective masking.

Temporal Processing describes how the human auditory system processes sound over time. It defines the processes of temporal resolution and temporal integration and provides examples of each concept. It also introduces concepts related to temporal processing tests used in the evaluation of (central) auditory processing disorders.

Loudness and Pitch addresses the measurement of these subjective perceptions of the objective physical attributes of intensity and frequency, respectively. It is concluded that both loudness and pitch are very complex psychophysical phenomena. While it is possible to scale both loudness (in phons and sones) and pitch (in mels) with very high intrasubject consistency, there are components of each that are not fully understood. Neither loudness nor pitch vary directly with their physical counterparts of intensity and frequency, respectively, while each is influenced primarily by those physical properties.

The ***Differential Sensitivity*** chapter is concerned with how much of a change in a physical parameter of an auditory signal must be made before it is noticed by a listener. This minimum change that is necessary for the signal to be detected is called a *just noticeable difference* (jnd) or *difference limen*. The Fechner/Weber law is discussed and some findings pertaining to difference thresholds for the acoustic parameters of intensity, frequency, and time are presented. The general principle that the magnitude of change necessary for detection of a signal increases with the magnitude of the standard (i.e., fixed) stimulus applies over a broad range of stimulus parameters in all sensory systems.

Signal Detection Theory describes how factors, including attention and listener response criteria, influence the perception of signals, particularly in the auditory domain. Issues related to conservative and liberal response criteria and the effects on audiological testing are discussed in detail.

The last chapter in this section, ***Auditory Perception and Hearing***

Impairment, is intended to provide the student with information to aid in understanding how hearing impairment influences the perception of auditory information. This chapter naturally follows materials on the normal processing of information through the auditory channel. The material contained in this chapter provides an excellent introduction for graduate-level psychoacoustics courses and future study in this area.

The fourth section of the book, ***Pathologies of the Auditory Mechanisms,*** contains three chapters. ***Pathologies of the Conductive Auditory Mechanism*** describes common auditory pathologies affecting the outer and middle ear; ***Pathologies of the Sensory Auditory Mechanism*** describes common auditory pathologies of the inner ear, including the organ of Corti and the semicircular canals; and ***Pathologies of the Central Auditory Mechanism*** discusses pathologies of the central auditory system. Multiple disorders from each portion of the auditory system are described in detail. These chapters are intended to provide an introduction to auditory pathologies to support future coursework in audiology and related fields.

The authors have brought a combined 60+ years of higher-education teaching experience and understanding of the learning process to the writing of this book, which is the result of their compilation of material from journal articles, papers presented at professional meetings, books, and chapters in books used in their classes. In addition, Dr. Jeremy Donai has brought his extensive clinical experience to a discussion throughout the entire text of important clinical applications of hearing science concepts discussed in this volume. It is the authors' intention that the contents of this volume will result in the reader's understanding of important basic concepts and current unresolved issues in hearing science that will facilitate a deeper, more thorough appreciation for the complex processes involved in audition.

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Dr. Donai would like to thank all of his professors and mentors who have inspired him to pursue various academic endeavors. In particular, he would like to offer his sincere gratitude to his PhD advisor and friend, Dr. Dwayne Paschall, for his mentorship and insistence that he strive for excellence in all areas of his academic career. He would also like recognize and thank his family for their support throughout his career. To Addison and Jeremy, thank you for being great kids and being patient and understanding when he had to work long hours. His wish is that you live a life full of joy and success. To all the students with which he has worked over the years, thank you for the time and effort. He is not successful without your talents and efforts. Lastly, Dr. Donai would like to thank Dr. Norman Lass for inviting him to collaborate on this most recent edition of the text. Six years after their initial discussion, they finally made it happen.

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SECTION I

Acoustics

BASIC ACOUSTICS

KEY TERMS

absorption
amplitude
aperiodicity
audiometric zero (0 dB HL)
bandwidth
clinical audiometer
complex sounds
compression (condensation)
cycle
damping
decibel (dB)
elasticity
fast Fourier transform (FFT)
feedback
Fourier analysis
frequency
frequency response curve
(resonance curve)
fundamental frequency
harmonics
hearing threshold level (HTL)
impedance
inertia
J. B. Fourier
logarithm
mass
molecules
noise
peak amplitude
peak-to-peak amplitude
period
periodicity
phase
phase inversion
physicists' zero
pitch
pure tone
rarefaction
reflection
resistance

- resonant frequency (natural frequency)
- rest position
- reverberation
- reverberation time
- root mean square (rms)
- sinusoidal motion (simple harmonic motion)
- sound
- sounding board resonance (sounding board effect)
- sound pressure level (SPL)
- spectral envelope
- spectrum
- spring-mass model
- stiffness
- transduction
- velocity
- waveform
- wavelength
- wideband noise

LEARNING OBJECTIVES

After studying this chapter, the student will be able to do the following:

- Define sound and identify the elements necessary for the production of sound.
- Describe the motion of a sine wave.
- Discuss spatial and temporal concepts associated with sine waves.
- Describe the relationship between frequency/period and frequency/wavelength.
- Discuss the difference between simple and complex sounds and provide examples.
- Differentiate periodicity and aperiodicity in sounds.
- Define fundamental frequency and harmonics of complex sounds.
- Define harmonics in terms of energy distribution on a discrete (line) spectrum.
- Identify the three components of impedance and explain how each affects energy transfer.
- Calculate the resonant frequencies of an inanimate tube system.
- Discuss the importance of the decibel, how it is computed, and how it is used in describing the energy of sound.

Discuss the following concepts:

- frequency response curve
- undampened resonators
- damped resonators
- bandwidth
- audiometric zero

This chapter addresses basic concepts associated with sound. Its purpose is to help the reader gain insight into basic acoustics, which can then be applied to an understanding of the processing of auditory signals, both simple (e.g., pure tones) and complex (e.g., speech sounds, music).

Aspects of sound presented here include basic parameters, spatial and temporal aspects, spectral and pressure measurements, and sound propagation and conduction. This chapter is not intended to be a comprehensive review of acoustics, but rather an introduction to those aspects of sound that are most important in understanding the coupling of our external acoustic environment to our perceptual mechanism through the auditory system.

SOUND

Sound can be defined as a condition of disturbance of particles in a medium. Three components are necessary for the production of sound: (a) an energy source, (b) a body capable of vibration, and (c) a transmitting medium. The propagating medium of most relevance for humans is air. If a portion of air could be observed microscopically, it would be found to consist of billions of air particles called **molecules**. A further discovery would be that these molecules are consistently spaced with respect to one another.

The properties common to the medium of air and other media used for the transmission of sound waves are mass, elasticity, and inertia. **Mass** is any form of matter (solid, liquid, gas). The particles in a medium such as air consist of mass. If a medium has **elasticity**, it is able to resist permanent distortion to its original shape or the distribution of its molecules. Thus, it possesses the property of springiness, or a propensity to return to its original position when the forces of displacement are removed. This elasticity resulting in springiness is also referred to as stiffness. Because air is not observable, it is difficult to think of it as having a shape that can be distorted. A visual aid useful for an understanding of these concepts is the **spring-mass model** shown in Figure 1–1.

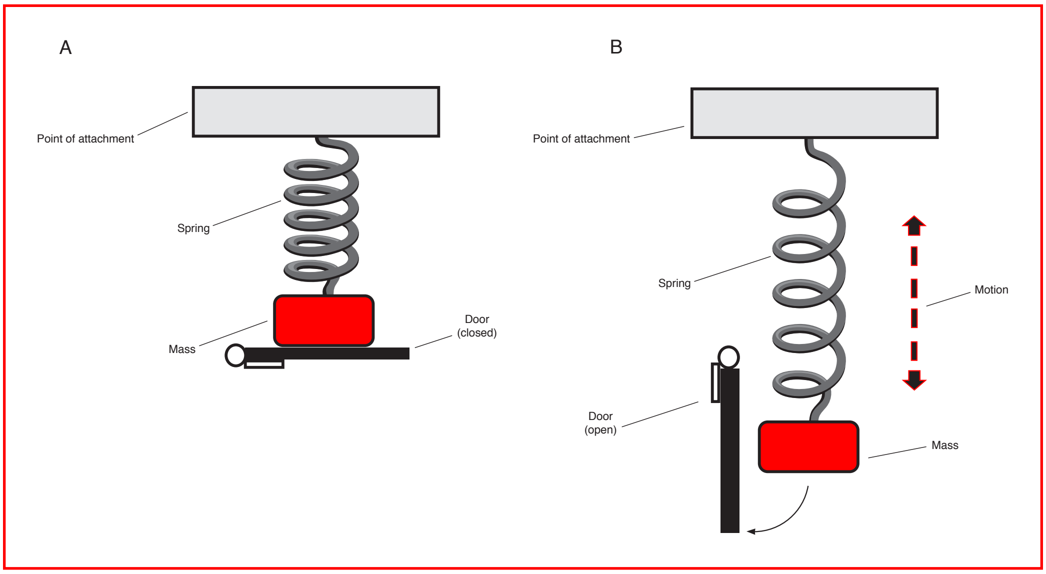

FIGURE 1–1. Schematic of the spring-mass model.

In Figure 1–1, the initial portion (A) depicts a weight attached to a spring on a trapdoor. The spring is attached to a solid suspension system. Note that the spring is in a neutral position, neither extended nor compressed. The second portion (B) shows the effects of opening the trapdoor, at which point the force of gravity moves the weight downward until the elasticity of the spring overcomes the effect of gravitational force on the mass. The movement then changes to an upward motion. This up-and-down motion will continue until the resistance of the air results in the cessation of motion. This phenomenon can be readily demonstrated by attaching a small weight to a rubber band. Using gravity as the force, drop the weight and observe the elasticity of the rubber band and the mass of the weight interact in an up-and-down motion.

Vocabulary Checkpoint

Elasticity: Ability of an object or material to resume its original shape (i.e., resist permanent distortion) after being stretched or compressed.

If we vary the size of the weight and the elasticity of the rubber band, we can observe the difference in movement related to the various combinations. The molecules (mass) in air behave as if they had springs attached to them (springiness = elasticity), allowing them to be moved from and returned to their original rest position. Because of inertia, however, they do not stop. **Inertia** is a property common to all matter: A body in motion tends to remain in motion, whereas a body at rest tends to remain at rest unless acted on by an external force. Because the molecules are in motion as they move toward their rest position, they will not stop at this position, but rather will continue to move beyond it.

An energy source is used to activate a vibrator of some kind; the energy source required often depends on the vibrator itself. A vibrator such as a tuning fork needs to be struck against a hard surface to be activated. Drum heads need to be hit with a stick or mallet to cause disturbances in the medium. If air is forced between tightly constricted lips, a buzzing sound can be made, which is used as a sound source for trumpet and tuba players. Air is also the primary propagating medium for speech production.

A vibrating body will not remain in motion indefinitely because of another basic physical property: **resistance**. Whereas mass and stiffness store energy within a system, resistance dissipates energy. This dissipation occurs primarily by transduction (conversion) into thermal energy. In a mechanical system, mass, stiffness, and resistance constitute **impedance**, which represents overall opposition to energy transfer. The dissipation of vibratory energy is referred to as damping.

Pressure is a force distributed over a particular area and is defined by the following formula: $p = F/A$. In discussing pressure, historically both the applied force and the area over which it was distributed were noted; that is, dyne/cm^2, with the dyne being a measure of force and square centimeters (cm^2) a measure of area. Currently, pressure is measured in units of pascals (Pa), in honor of Blaise Pascal, a 17th-century mathematician. For example, 0.0002 dyne/cm^2 is equal to 20 micropascals (μPa).

Thus, when variations in pressure from current atmospheric pressure occur with a frequency of occurrence that is detectable by the auditory system, a sound is produced. For this to happen, it is necessary to have something cause pressure to vary, usually an object capable of vibrating, some source of energy to cause this object to vibrate, and some medium to transport the pressure variations caused by the vibrating object to our ears.

Sinusoidal Motion

Describing sound in such a way as to visualize it is not a straightforward process because of the abstract nature of the concept of sound. One way is by discussing the simplest type of sound wave motion that can occur in a medium. This simple wave motion is called **sinusoidal motion** (or **simple harmonic motion**). Sinusoidal motion is a disturbance in a medium that occurs when devices such as tuning forks and clock pendulums are activated and undergo simple "to and fro" motion. An additional example is the motion seen when viewing someone on a swing. Figure 1–2 illustrates sinusoidal motion as it is being traced from movements of a clock pendulum.

If a sheet of paper could be pulled underneath the back-and-forth movements (i.e., oscillations) of a swinging pendulum with a pen attached to the bottom of the pendulum, the picture of a sine wave would emerge on the

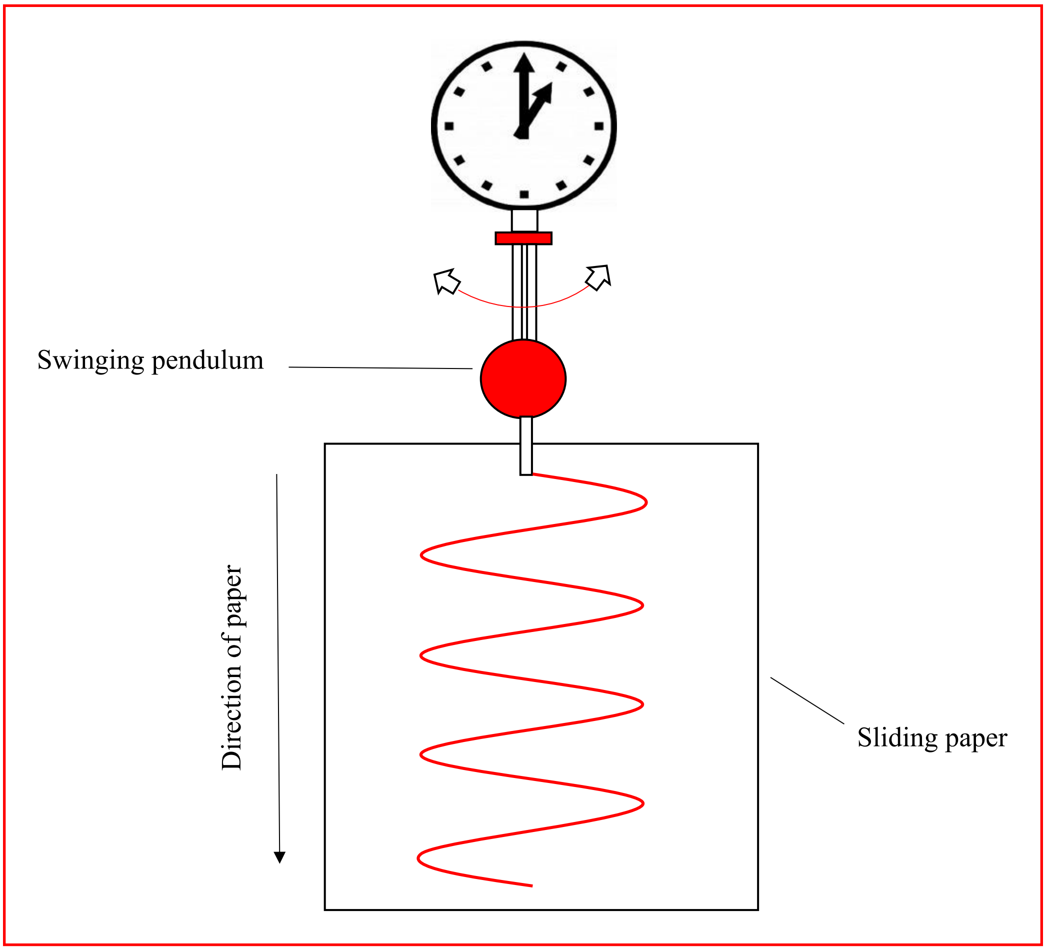

FIGURE 1–2. Example of sinusoidal motion.

paper. The pendulum would begin its movement from a point of rest, move in one direction to a point of maximum displacement, return to its point of rest, go through its point of rest to a maximum displacement in the opposite direction, and then again return to its rest position. The result is a sine wave tracing, which is a graph displaying two basic properties of motion: time and displacement.

The sound that is generated from vibrators that produce sinusoidal movement is often designated as a **pure tone**, a sound that has almost all of its energy located at one frequency. Pure tones are rarely heard in everyday situations; most of the sound that we routinely hear in our environment are complex in that their energy is concentrated at more than a single frequency.

When sinusoidal wave motion disturbs the particles of the medium, they react in a predictable way (Figure 1–3). As the pendulum or tuning fork tine begins to move from rest to maximum

Clinical Note

As a result of simple harmonic motion, tuning forks create signals containing energy concentrated at one frequency and have a long history in diagnostic audiology. Prior to the advent of the (i.e., equipment currently used to evaluate hearing), tuning forks were used to determine the type of hearing loss. Two common tuning fork tests are called the Rinne and the Weber and are described in Huizing (1973).

displacement in one direction, the particles in the medium are pushed closer toward each other; they are said to be in a state of **compression** (or **condensation**). Maximum compression takes place at the point of maximum excursion of the vibrating pendulum or tuning fork tine. As the pendulum or tuning fork tine begins to move in the opposite direction, the particles attempt to return to their original positions because of elasticity, but they overshoot that position because of inertia before coming to rest again. This overshoot, where the particles are spread apart more than they normally would be, is called a state of **rarefaction** (or expansion). These two concepts are shown in Figure 1–3.

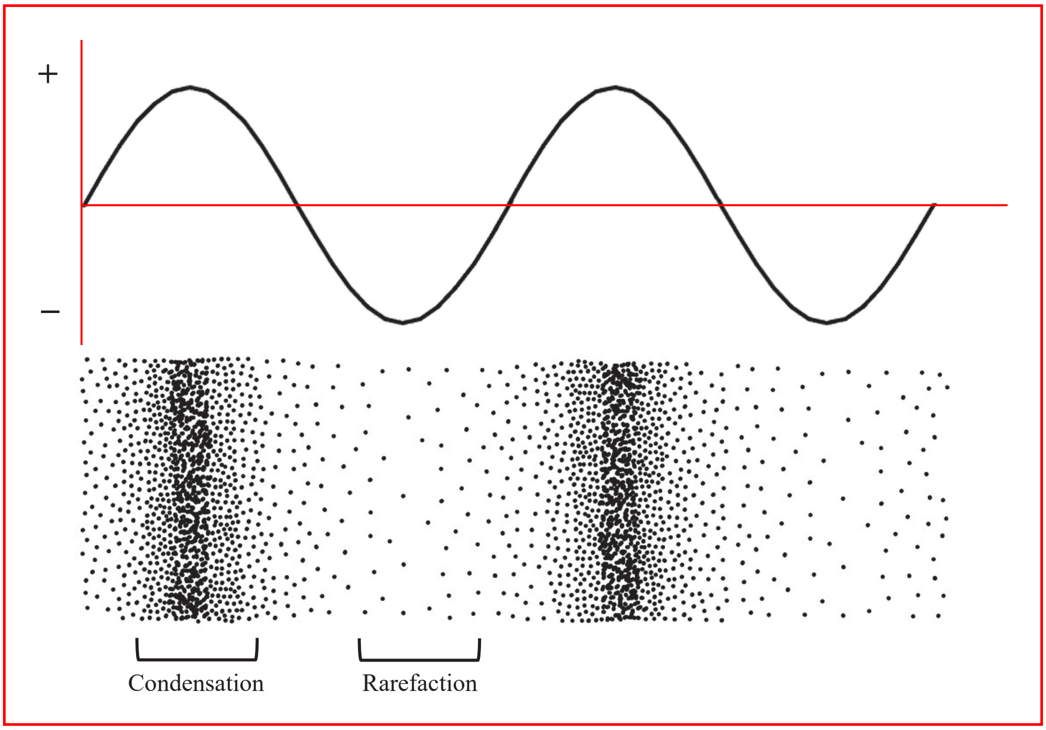

FIGURE 1–3. Condensation and rarefaction.

These condensations and rarefactions are the actual sound disturbances that travel through the medium from the sound source. It should be noted that the particles (molecules) themselves are not moving through the medium. The particles near an environmental noise during sound production will move around their points of origins (rest positions), but once the sound disturbance has traveled away from the point of origin, those particles will return to their rest positions. Thus, the disturbance will have moved away from the noise source, but not the individual particles in the medium; they will simply be displaced temporarily from their rest position.

The sine wave tracing can provide a spatial or temporal picture of particle disturbances in the medium. As a spatial picture, the sine wave tracing indicates the relative positions of the particles in the medium at a single instant in time. As a temporal picture, it can be used to study the movement of a single particle over time as it changes its location around its rest position. Each view of the sine wave tracing has a set of terms associated with it.

J. B. Fourier, a French mathematician who lived in the early 19th century, showed that any complex periodic sound wave disturbance (i.e., sound with more than one frequency) can be mathematically broken down into its individual sine wave (e.g., pure tone or sinusoidal) components, which vary in frequency, amplitude, and phase relations with respect to one another. This mathematical analysis of complex signals into their sinusoidal components is called **Fourier analysis**, or its more efficient derivative, the **fast Fourier transform (FFT)**. Thus, when we look at a pure tone, we are studying the most basic element of sound.

Clinical Note

The FFT is a foundational technique used by a host of professions, including speech and hearing scientists, audiologists, speech pathologists, and engineers. As previously described, the FFT takes information from the time domain (i.e., waveform) and transforms it into the frequency domain (i.e., spectrum). For speech and hearing professionals, the FFT is used in clinical and research settings to decompose signals, such as speech or music, into their individual frequency components. Because of its foundational nature, the FFT will be discussed throughout this text. For a historical overview, please refer to Heideman, Johnson, and Burrus (1984).

SPATIAL CONCEPTS

Amplitude

Amplitude refers to the maximum displacement of the particles of a medium. It is related perceptually to the magnitude (i.e., loudness) of the sound.

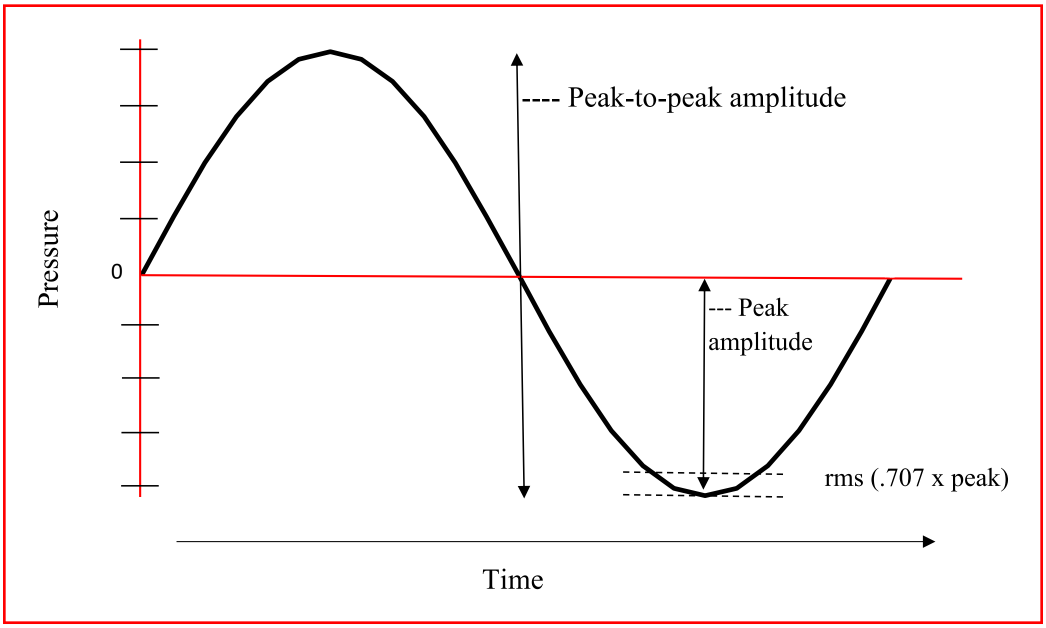

FIGURE 1–4. Examples of peak, peak-to-peak, and root mean square (rms) amplitude.

Amplitude indicates the energy (i.e., intensity) of a sound; it is usually measured from the baseline (i.e., point of rest) to the point of maximum displacement on the waveform (Figure 1–4). This linear measurement is called **peak amplitude** measurement.

The distance between the baseline and the point of maximum displacement is related to the movement of the swinging pendulum or tuning fork tine as it moves from rest to maximum excursion in one direction. In other words, amplitude is related to the point of maximum displacement of a particular vibrating object. In the case of the spring-mass model, it represents maximum excursion of the mass from its rest position (Fig. 1–5). Note that the maximum displacement occurs at the peaks of the sine wave (points 2 and 4) in Figure 1–5.

In some instances, amplitude measurements are made on the sine wave tracing from the point of maximum displacement in one direction to the point of maximum displacement in the other direction, instead of from baseline to the point of maximum displacement in one direction. This linear measurement is called **peak-to-peak amplitude** measurement (see Figure 1–4). It is important to indicate whether the amplitude being reported is in peak or peak-to-peak measurements.

Measurement of amplitude of sound pressure is often a **root mean square (rms)** value, which is mathematically the square root of the average of all instantaneous variations of pressure squared within the sine wave (additional details provided in Chapter 2). This value, in a sinusoid, is equivalent to 0.707 times the peak value and

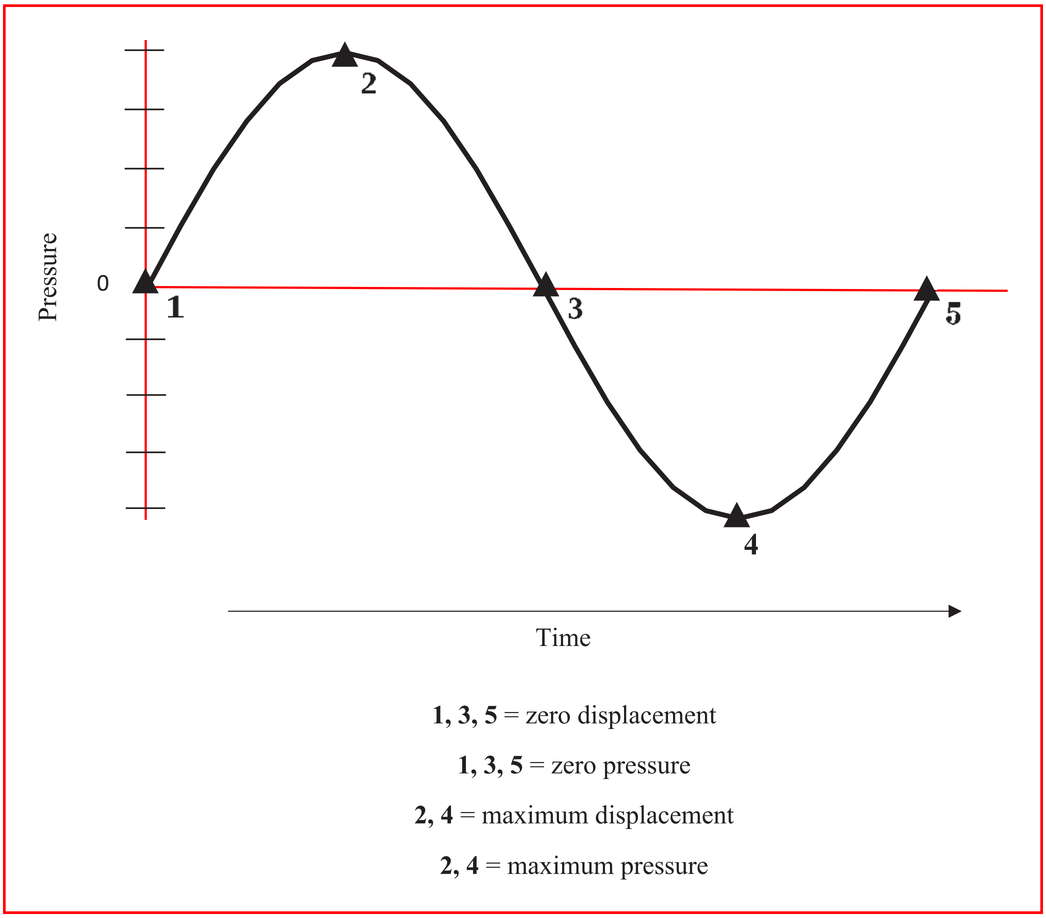

FIGURE 1–5. Particle displacement and pressure.

represents the average sound pressure variations within the sinusoid (see Figure 1–4). Amplitude is related to the measurement of intensity at rms, which can be expressed in *sound pressure level (SPL)* or power. The decibel (dB) is the most common unit used to express sound intensity when amplitude is being measured in sound pressure or power (see later discussion).

> **Vocabulary Checkpoint**
>
> Rarefaction: Spreading apart or reduction in density of molecules in a medium (also referred to as expansion).

Wavelength (λ)

Wavelength (λ) is a linear measurement that refers to the distance that a sound wave disturbance can travel during one complete cycle of vibration.

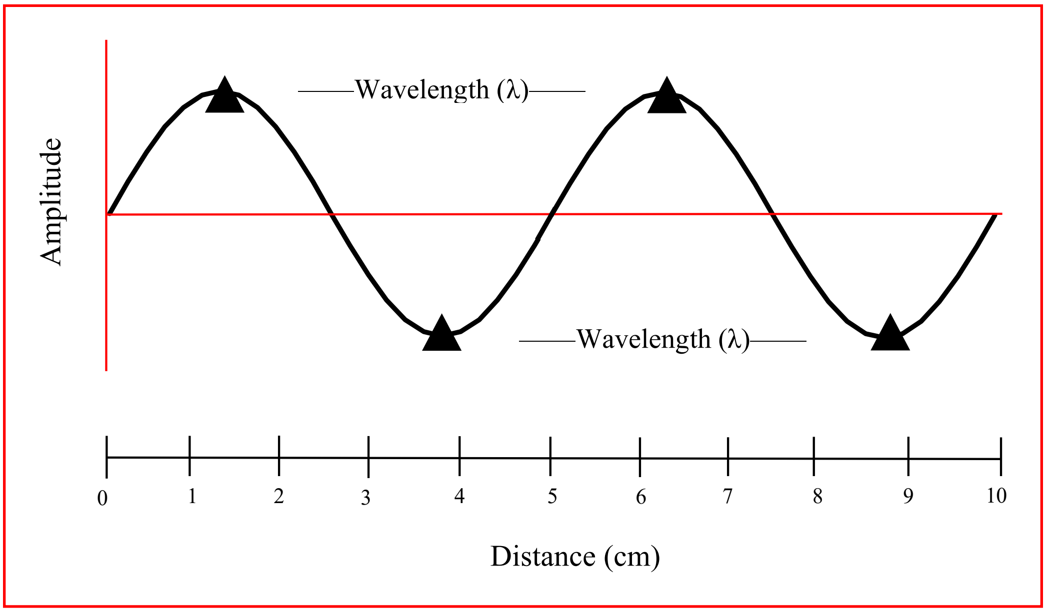

FIGURE 1–6. Wavelength (λ).

More specifically, wavelength can be defined as the distance between points of identical phase in two adjacent cycles of a wave (Figure 1–6). Wavelength can be expressed in feet, meters, or centimeters and, as discussed later, is inversely related to the frequency of the sound being produced. Phase is described in the following section.

TEMPORAL CONCEPTS

Cycle

Cycle is a time concept referring to movement of a vibrating object from rest position to maximum displacement in one direction, back to rest, to maximum displacement in the opposite direction, and back to rest again. Figure 1–7 shows two cycles of the sine wave.

Period

Period is the time (usually expressed in milliseconds; 1 msec is 1/1000 of a second) that it takes for a vibrating object to complete one complete cycle of vibration (Figure 1–8). The period of the sine curve in Figure 1–8 is 2 msec because it took that amount of time to complete one cycle of vibration.

Frequency

Frequency is the number of complete cycles that occur during a certain time period, usually 1 second. Frequency is expressed in cycles per second (cps) or hertz (Hz) (in honor of Heinrich Hertz,

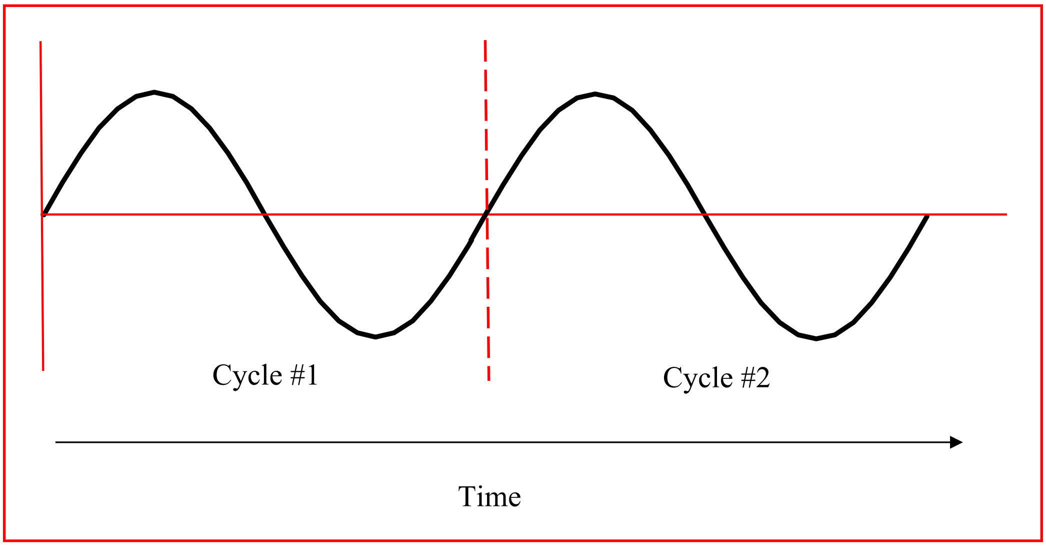

FIGURE 1–7. Cycles of a sine wave.

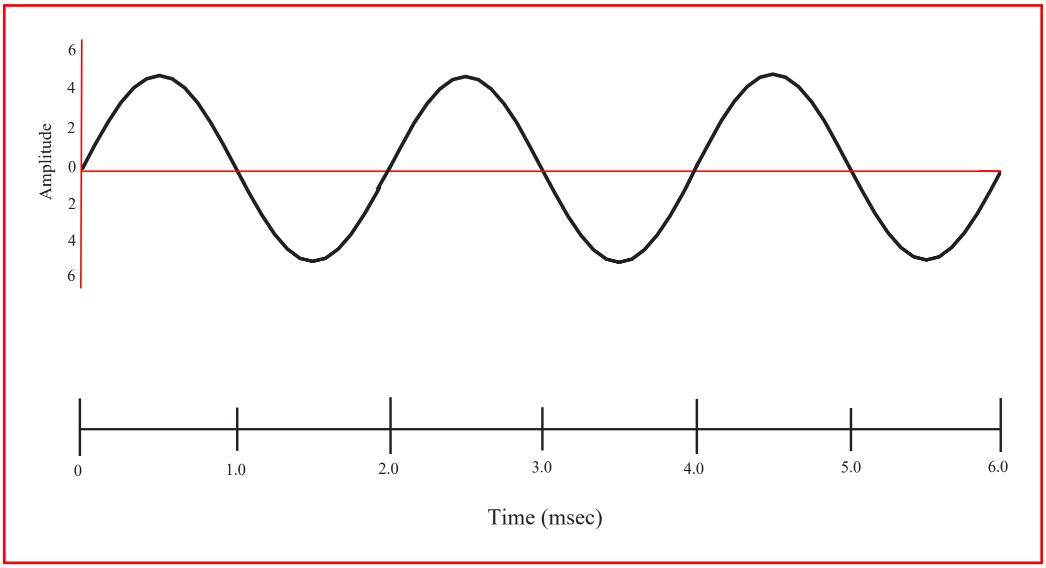

FIGURE 1–8. Period of a 500 Hz sine wave.

the first person to demonstrate electromagnetic waves) or, more often, in kilohertz (1 kHz = 1000 Hz). In Figure 1–9 the sine curve has one complete cycle of vibration (indicated by the dashed line) in 1 msec; therefore, its frequency is 1000 cps (or Hz) (1/0.001 = 1000). That is, one cycle in 1 msec (1/1000 of a second) results in a period of 0.001 sec. If the swinging pendulum or tuning

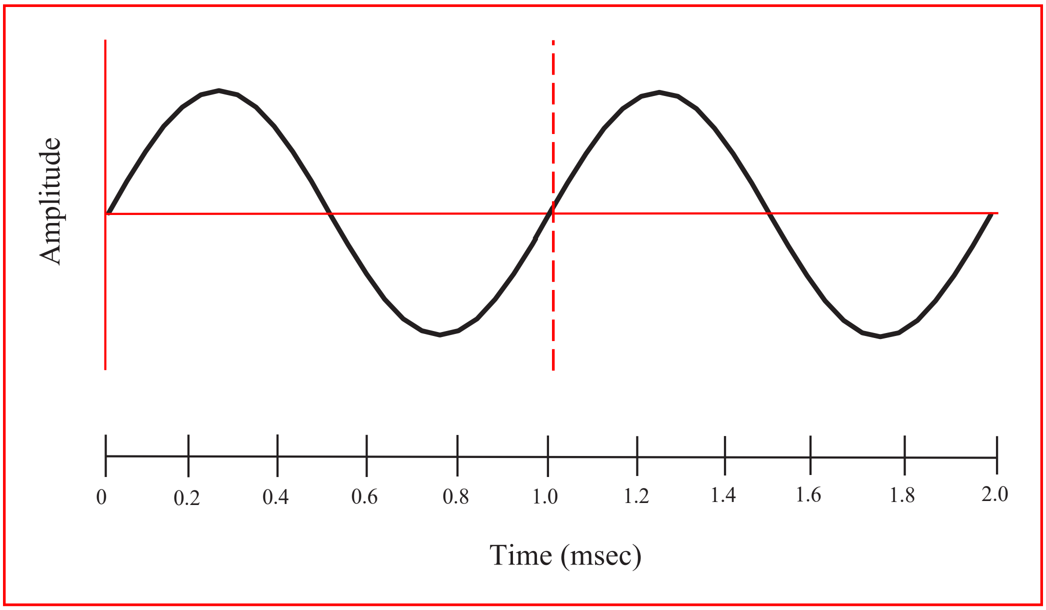

FIGURE 1–9. Frequency of a sine wave.

fork tine or mass of a spring-mass model completes 100 cycles in 1 second, then its frequency of vibration is 100 cps (Hz) and its period is 10 msec (1/100 = 0.01 second × 1000 = 10 msec).

The **pitch** (perception of low to high) of a signal is the perceptual correlate of frequency. For example, a 100 Hz pure tone would be perceived as being lower in pitch than a 250 Hz pure tone. As is also the case for loudness, pitch determination requires human perceptual judgements of sound. Concepts related to loudness and pitch perception are discussed in Chapter 11.

Phase

Phase represents the point in the cycle at which the vibrating object is located at a given instant in time. If we transpose the two portions of the sine wave so that the top and bottom portions join, forming a circle or ellipse, it becomes evident that any portion of that figure can be defined in degrees of a circle. The result of this notation is shown in Figure 1–10. Two sinusoids are in phase when their wave disturbances crest and trough at the same time (Figure 1–10A) and out of phase when they do not (Figure 1–10B). Given this description, the exact relationship of any sine waves may be defined as a certain number of degrees out of phase with each other. For example, Figure 1–10B shows two sine waves that are 180 degrees out of phase.

Velocity

Velocity is the speed of sound through a transmitting medium. The average speed of a sound in the medium of air

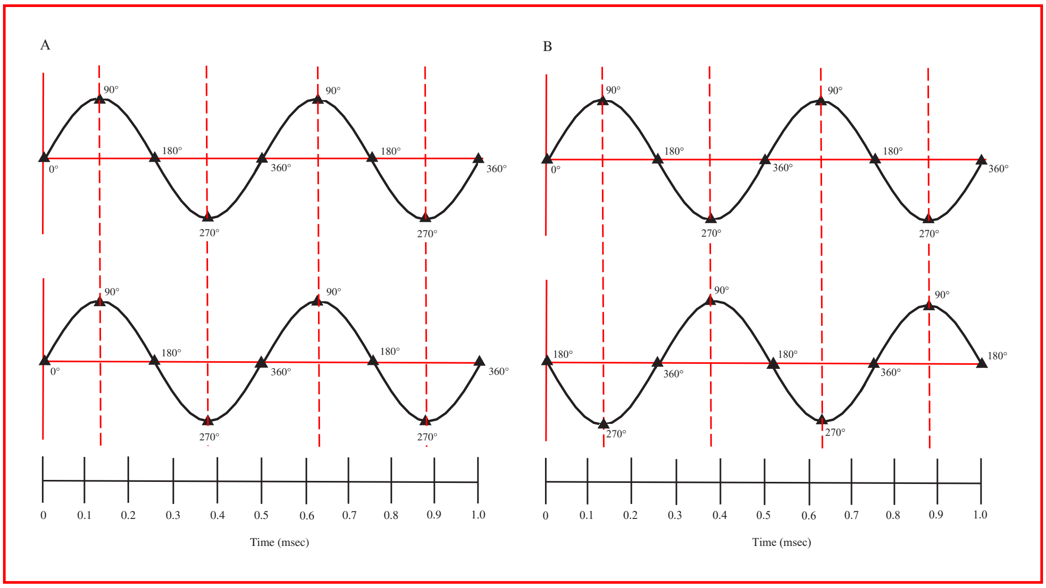

FIGURE 1–10. Sine waves in phase (A). Sine waves 180 degrees out of phase (B).

Clinical Note

Prior to the advent and refinement of digital signal processing (DSP) hearing aids, many patients reported experiencing feedback, or whistling, created by their hearing aids. is caused by amplified sound escaping the ear canal and being reprocessed by the microphone. It is similar to when someone with a microphone stands too close to a speaker, which creates that awful squeal (we've all heard it and know how terrible it sounds). Within the last decade or so, hearing aids have been equipped with a feature known as feedback suppression. While there are many ways to reduce feedback, one popular technique is commonly referred to as or phase cancellation. When the hearing aid detects feedback, a signal of the same frequency that is 180 degrees out of phase with the feedback signal is used to create a cancellation effect and reduce feedback. Prior to the advent of this technology, feedback was reduced using techniques that had negative effects on the audibility of many speech sounds. Phase inversion has reduced the prevalence of feedback and maintained adequate audibility for recognizing the speech signal.

Question: Why do sound waves travel faster through the medium of steel than through the medium of air?

Answer: Although the density of steel (a solid) is greater than that of air (a gas), the elasticity of steel is also greater than that of air, and elasticity is the primary factor in determining the velocity of sound waves.

is approximately 1,100 feet per second, or 340 meters per second, or 34,000 centimeters per second. Different sources will vary slightly with regard to these figures because there are some differences in the speed of sound in air, and velocity is measured at different heights above sea level and at different temperatures. The speed of sound in air is relatively constant because of the elastic and inertial properties of a given medium. Water has different elastic and inertial properties than air, and consequently the speed of sound is faster in water than in air.

Frequency/Period Relationship

An inverse relationship (e.g., as one increases, the other decreases) exists between period and frequency. This reciprocal relationship is expressed in the following formula:

Vocabulary Checkpoint

Phase: Point in the cycle at which the vibrating object is located at a given instant in time.

$$\text{Frequency} = 1/\text{Period}$$

If the frequency of a particular sound wave is 1000 Hz, its period would be 0.001 second (period = 1/1000 second). Because period is the time needed for the completion of one cycle of vibration, as a frequency is increased (more cycles per second), period will be reduced (less time for the completion of any one cycle). Thus, as frequency is increased, period decreases proportionally (Figure 1–11). For example, a pure tone of 250 Hz will have a longer period (1/250 or 4 msec or 0.004 sec) than one of 1000 Hz (1/1000 or 1 msec or 0.001 sec).

Frequency/Wavelength Relationship

An inverse relationship exists between the time concept of frequency and the spatial concept of wavelength. As frequency is increased, wavelength becomes shorter, and as frequency is decreased, wavelength becomes longer. Because the number of cycles is increased within the same unit of time, each cycle will take less time and cover a shorter distance (see Figure 1–11). It is an established fact in environmental

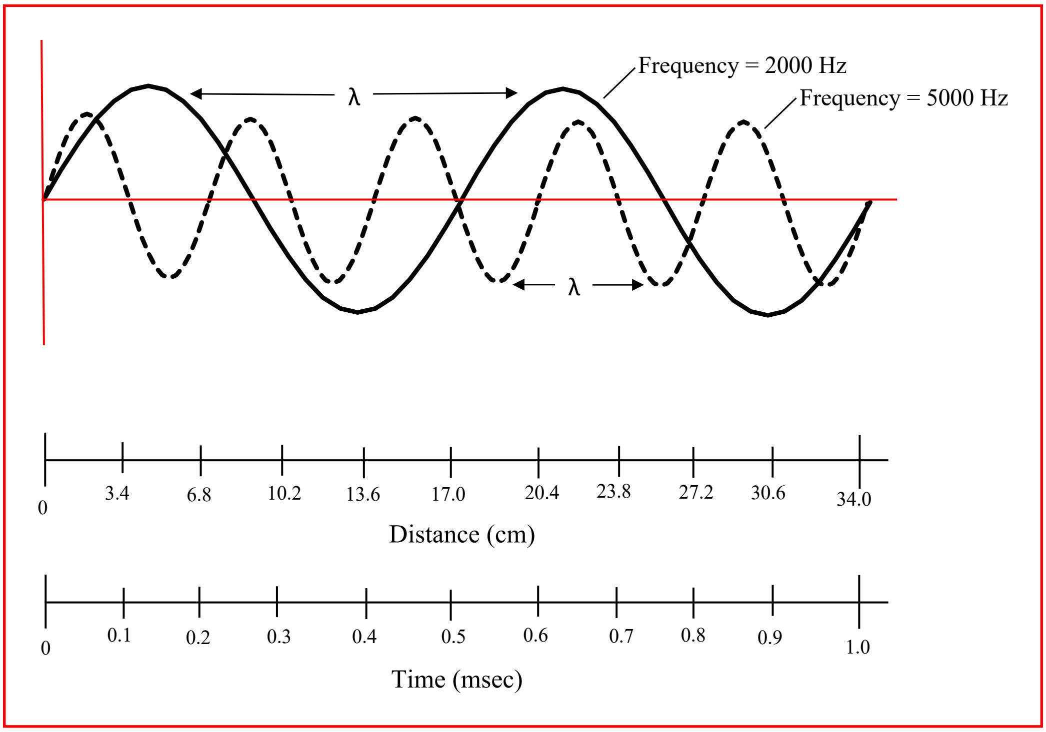

FIGURE 1–11. Reciprocal relationship between frequency and period and frequency and wavelength.

acoustics that lower frequencies are more difficult to absorb than higher frequencies because of their longer wavelengths. A frequency of 100 Hz, for example, has a wavelength of approximately 11 feet, whereas a frequency of 10,000 Hz has a wavelength of only approximately 1.2 inches. The 10,000-Hz tone could be absorbed by acoustical ceiling tile that is only a few inches thick. However, the 100-Hz frequency would require an unusually thick wall or some other type of acoustical treatment for it to be completely absorbed.

The relationship between frequency and wavelength can be expressed in the following formulas:

$$\lambda = v/f$$
$$f = v / \lambda$$

where f = frequency, λ = wavelength, and v = velocity (a constant; refers to the speed of sound).

In Example 1, if the unit of measurement for velocity is feet per second, the wavelength is expressed in feet. If the unit of measurement is meters per second, the wavelength is expressed in meters. It is important to note that the answer is not expressed in feet or meters per second, but in feet or meters. Wavelength is a linear measurement of the distance covered by a sound wave disturbance during one cycle of its vibration.

Example 1

If the frequency of vibration for a particular sound wave disturbance is 100 Hz, the wavelength for that frequency would be 11 feet, or 3.4 meters, or 34,000 centimeters (wavelength = velocity/frequency; 1,100 feet per sec/100 Hz = 11 feet; or 340 meters per sec/100 Hz = 3.4 meters; or 34,000 cm per sec/100 Hz = 340 cm).

Example 2

If the wavelength for a particular sound wave disturbance is 1.1 feet, or 0.34 meters, the frequency for that sound wave disturbance would be 1000 Hz (frequency = velocity/wavelength: 1,100 feet per sec/1.1 feet = 1000 Hz; or 340 meters per sec/0.34 meters = 1000 Hz).

SOUND PROPAGATION AND INTERFERENCE

Once a sound wave strikes an object, three things can happen to it (Figure 1–12). First, the sound can simply continue as though the object were not there. The intervening object does nothing to impede the magnitude of the sounds as it moves outward from the sound source. In this case an object (e.g., a wall) has been struck but the sound disturbance keeps going as though the object did not exist. Second, the sound energy being emitted can be absorbed (through a process known as **absorption**) by the object that has been struck.

If the object is a wall with absorptive properties, the sound energy enters the structure, is converted to thermal energy (heat), and is then dissipated. Third, when sound strikes an object, it can bounce off the object. When sound bounces off a wall, it is said to be reflected (known as **reflection**). If the reflections are multiple or continuous to the point where they actually prolong the existence of the sound within a confined space, they are referred to as **reverberations**, the prolongation of a sound through multiple or continuous reflections. Reverberations are measured using a metric known as **reverberation time (T_{60})**, which is defined as the amount of time required for a sound to decay by 60 dB in a closed space. This measurement is commonly used in concert halls and classrooms to evaluate the suitability of the acoustic environment.

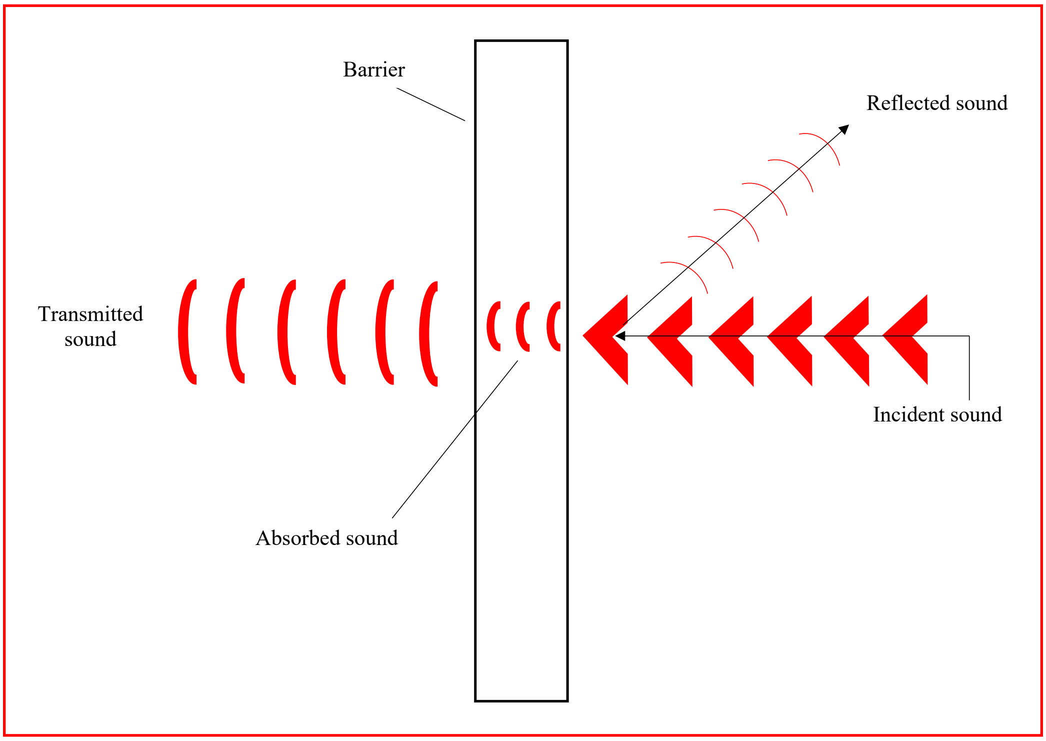

FIGURE 1–12. Effects of sound waves striking an object.

COMPLEX SOUNDS

Thus far, our discussion of basic acoustics has centered on simple sound disturbances. When sounds of varying frequency and intensity interact, the result may be displayed in a graph. An example of this graph appears in Figure 1–13A, which shows the interaction of two pure tones of different frequency. These sinusoidal disturbances have been shown graphically on an amplitude-by-time display known as a **waveform** (Figure 1–13A). Another method for displaying sound is to graph it in terms of amplitude as a function of frequency. When amplitude is plotted as a function of frequency, the resulting graph is referred to as a **spectrum** (Figure 1–13B).

The vertical length of the single line is equal to the amplitude of the pure tone that has been graphed. A spectrum shows amplitude as a function of frequency at a single instant in time and has the advantage of allowing frequency to be read directly from the display. A waveform has the advantage of showing amplitude changes over time, but frequency would need to be calculated. The spectrum provides few advantages over the waveform display when viewing pure tones because all the energy is concentrated at a single frequency. However, when viewing complex sounds, in which there

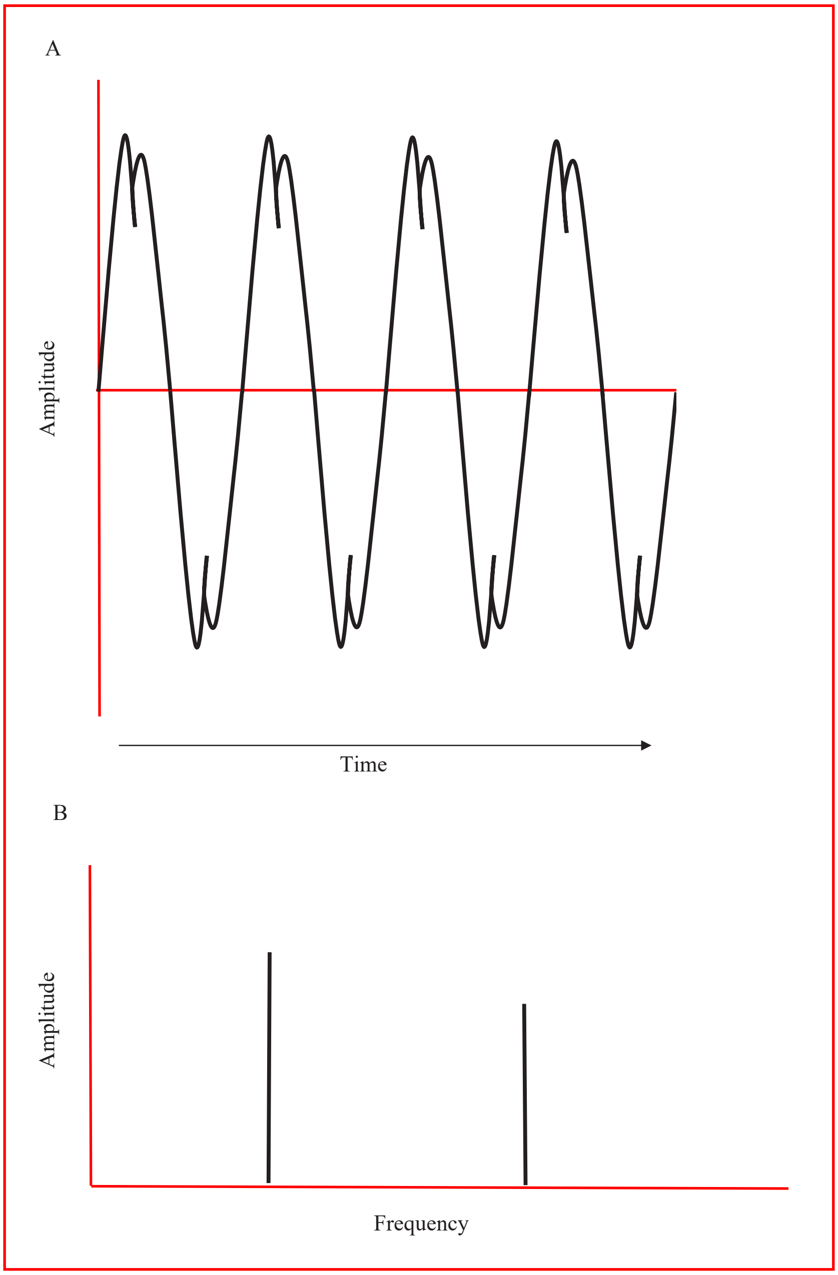

FIGURE 1–13. Complex periodic waveform (A). Line spectrum of complex signal (B).

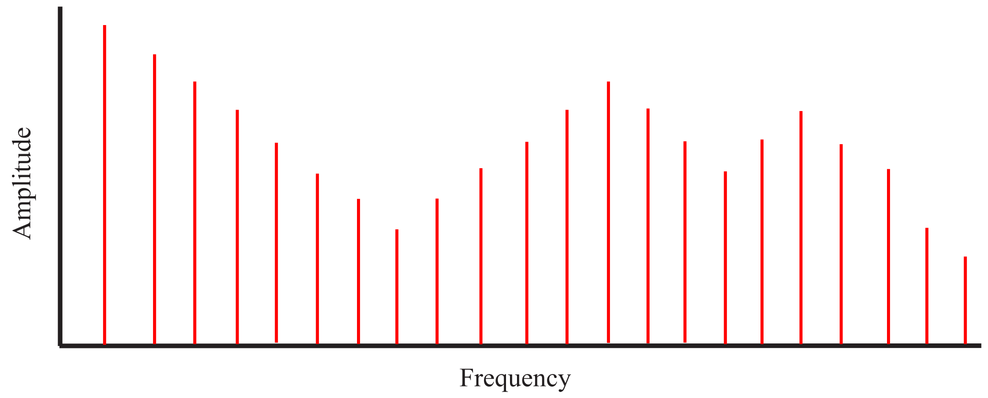

FIGURE 1–14. Spectrum of the vowel /i/.

is energy at more than one frequency, the sound spectrum becomes more valuable.

Complex sounds differ from simple sounds in that they have energy distributed at more than one frequency. A single tuning fork generates a sound with energy concentrated at one frequency. If two tuning forks of different frequencies were activated simultaneously, the sound generated would consist of two frequencies and would therefore be considered complex in nature. The resultant waveform would no longer show smooth curves like that of the sine wave, and the spectrum would have two vertical lines, each line representing the frequency of vibration of one of the tuning forks vibrating simultaneously with the other (see Figure 1–13B). Speech sounds, like the vowels of English, are complex in that they have energy distributed at numerous frequencies involved. Figure 1–14 shows the sound spectrum for the vowel /i/ as in beet. Note the number of vertical lines representing energy contained at various frequencies.

Vocabulary Checkpoint

Spectrum: Graph displaying amplitude (y-axis) plotted as a function of frequency (x-axis).

PERIODICITY VERSUS APERIODICITY

A periodic sound disturbance is one in which the wave shape repeats itself as a function of time; that is, the wave shape is said to have **periodicity** (see Figure 1–13A). A pure tone that provides simple harmonic motion is, by definition, periodic, as is the swing of a pendulum or tuning fork tine. The pure tone has a clearly defined frequency because of the cyclical (i.e., periodic) behavior of the vibrator generating it.

An aperiodic sound disturbance is one in which the wave shape does not repeat itself as a function of time and therefore is said to have **aperiodicity**. Static on the radio and a sudden explosion are examples of an aperiodic sound disturbance. When these sounds are heard, they are usually perceived as **noise** because they lack any cyclical or repetitive vibrations. Another, and perhaps more practical, definition of noise is an unwanted sound; no matter how periodic your roommate's music is when you are studying, it may well fit within this psychological definition of noise.

Spectral displays of complex periodic and complex aperiodic sounds reveal the major differences between them. For complex periodic waves, the frequency of each component is a whole-number multiple of the component with the lowest frequency, referred to as the **fundamental frequency** (Figure 1–15). The first bar (i.e., the bar showing the lowest frequency) is the fundamental frequency, and the energy bars above it are whole-number multiples of the fundamental frequency, called **harmonics**. If the lowest bar of energy has a frequency of 200 Hz, the second energy bar would have a frequency of 400 Hz, the third would have a frequency of 600 Hz, and so on. The heights of the energy bars for the various frequencies in this spectrum refer to the relative amplitude for each pure tone making up this complex periodic sound. In this spectrum the pure-tone component with the highest concentration of energy (i.e., the greatest amplitude) is the fundamental; the component pure tone comprising this complex signal with the lowest frequency.

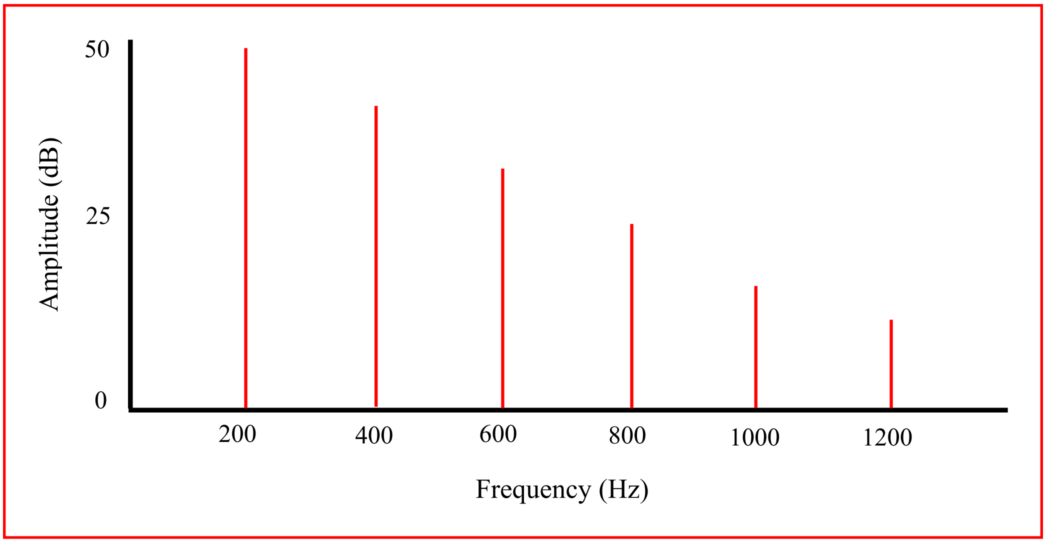

FIGURE 1–15. Spectrum showing fundamental frequency (200 Hz) and harmonics.

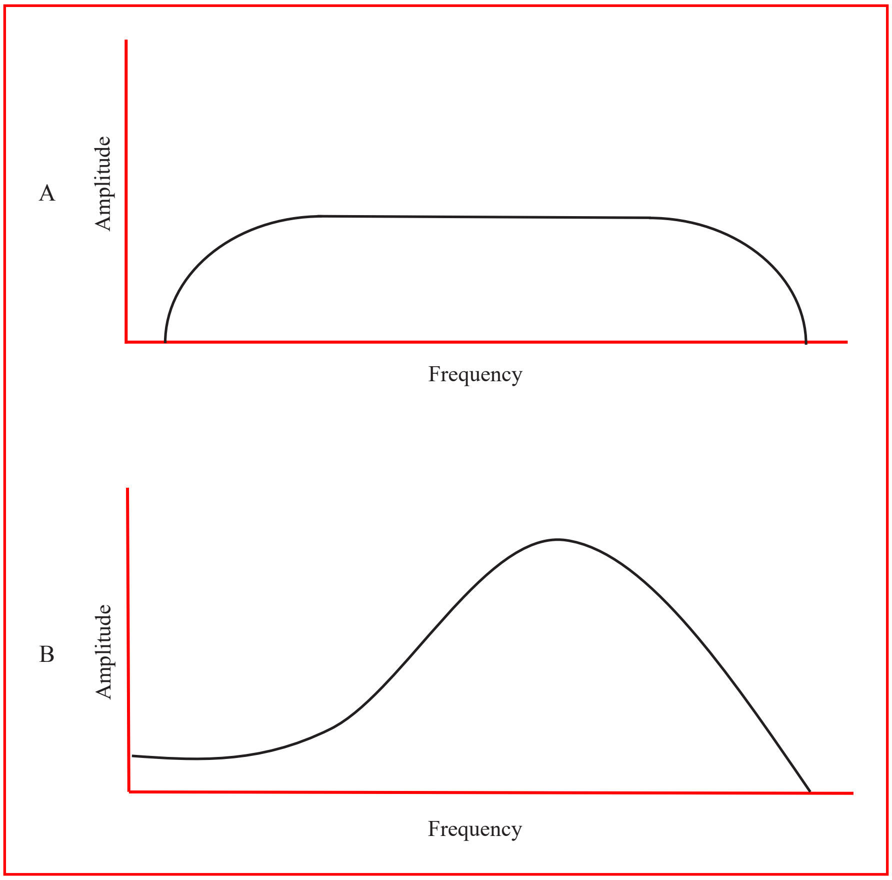

FIGURE 1–16. Spectral envelope for white noise (A). Spectral envelope for /s/ sound (B).

For complex aperiodic sounds, there is no fundamental frequency or harmonics because the disturbances produced do not set up any cyclical or repetitious behavior. Instead, energy is distributed throughout the sound spectrum at a particular instant in time. Figure 1–16A shows the spectrum for **wideband noise**, which sounds like a prolonged "sh" sound. White noise has energy distributed evenly throughout the spectrum and is therefore effective for masking other sounds. Instead of having discrete lines representing concentrations of energy or energy bars like those for complex periodic sound spectra, a graph or display called a **spectral envelope** is used to show the

Vocabulary Checkpoint

Aperiodicity: Property of a sound wave that does not repeat as a function of time. Aperiodic sounds are generally perceived as noise.

distribution of energy for complex aperiodic sound disturbances. Think of it as an outline of the amplitude values across the frequency range (Figure 1–16B).

The spectral envelope is a line running horizontally across the spectral graph which, in this case, because it is a flat line, indicates that energy is distributed evenly throughout the frequency range. If the spectrum is showing an aperiodic signal other than white noise, the spectral envelope would not be completely flat, but rather would show variations where higher or lower energy regions within the frequency would be located. Figure 1–16B shows the spectrum for the speech sound /s/ (as in sun). In this instance there is a concentration of energy in the higher frequency range, and this concentration is shown by a rise or increase in the spectral envelope for the frequencies where the energy concentration is located (i.e., high frequencies).

RESONANCE

Another way in which sound is modified after production is by a phenomenon called resonance. There are different types of resonance, but all are based on the same principles. As discussed earlier, impedance is defined as the overall opposition to flow of energy. This overall opposition consists of three components: mass, stiffness, and resistance. To define mass, it may be best to define weight, which is mass acted on by gravity. We may further appreciate mass with the question, "Which weighs more: a pound of feathers or a pound of lead?" The answer to this allegedly humorous question is that by definition the two weigh the same. However, if we envision a pound of feathers and a pound of lead, we see that the bulk of the two is very different; that is, because the mass of feathers is less than the mass of lead, it requires a larger volume of feathers to achieve one pound in weight.

Stiffness may be envisioned as springiness or elasticity. If we stretch a rubber band, the further we stretch it, the stiffer it becomes. Resistance in a mechanical system is afforded by friction. In a hydraulic system, resistance is increased as we adjust the nozzle on a garden hose, allowing a small stream of water to flow with a lot of pressure (i.e., force per unit area), as we increase resistance, or decreasing resistance so that water flows in a larger volume with little pressure.

Mass and stiffness are energy-storing components of impedance, whereas resistance is an energy-dissipating component. We can appreciate this fact by thinking of rolling a lead ball up an incline. The larger the lead ball (i.e., the greater the mass), the more energy we must expend getting it up the incline. When the ball is released, it rolls down the incline, expending the energy that we put into rolling it up. That is, it stored that energy. The moral of the story is that the more the energy it takes to roll a ball up an incline, the more important it becomes to stay out of its way when it rolls down!

The energy storage aspect of stiffness becomes obvious if we think of compressing a spring or drawing a bow, as in bow and arrow. The more

Vocabulary Checkpoint

Spectral envelope: Graphic representation of the distribution of energy across frequency for a complex sound.

difficult it is to compress the spring or to draw the bow, the greater the reaction will be when either is released. The stiffness of the spring or bow has stored the energy put into compressing or drawing it.

Resistance changes the form of energy. We can neither create nor destroy energy; however, we can change its form, a process called **transduction**. On a cold day, we may rub our hands together to warm them. In doing this, friction, or resistance, changes some of the energy put into rubbing the hands together into heat energy. The mechanical energy then dissipates as heat or transduces into heat energy.

Mass, stiffness, and resistance are all present in different proportions in every system that will be of interest to us. We will not talk about each in isolation, but rather in which is proportionally greatest. It turns out that in any given system, the relative magnitude of the two energy-storing components of impedance (i.e., mass and stiffness) determines the rate at which a system will vibrate. Resistance will determine, other factors being constant, how long the system will vibrate. This can be demonstrated by taking a rubber band, putting just enough pull on it to make it straight, then plucking it. The rubber band will vibrate at a slow rate. Now if we stretch it tight and pluck it again, the rate of vibration will increase. The mass of the rubber band has remained the same, but as it is stretched tighter, the stiffness has increased (i.e., it becomes proportionally greater). Therefore, for any given system, the greater the stiffness component becomes relative to mass, the higher the rate of vibration.

One vibration equals one back-and-forth or one up-and-down excursion. The faster the rate of vibration, the more vibrations occur per unit time (i.e., the vibrations occur more frequently). Thus, the rate of vibration is termed the frequency of vibration. Considering these factors, as stiffness becomes proportionally greater than mass, the frequency of vibration increases. Conversely, as mass becomes relatively greater than stiffness, the frequency of vibration decreases. The frequency with which a system vibrates when set into vibration is called **resonant frequency** (or **natural frequency**). The resonant frequency of a system is determined by the relative magnitude of the mass and stiffness components of its impedance. The resonant frequency is that point at which the effects of mass and stiffness are equal, resulting in total opposition to energy flow determined by resistance alone (Figure 1–17).

Looking at this from a slightly different perspective, any system will respond (i.e., be set into vibration) most readily when stimulated at its resonant frequency. This can be demonstrated in a variety of ways. If we were to take a set of tuning forks and, one at a time, strike each fork, then place the base of the fork on a table, we would find

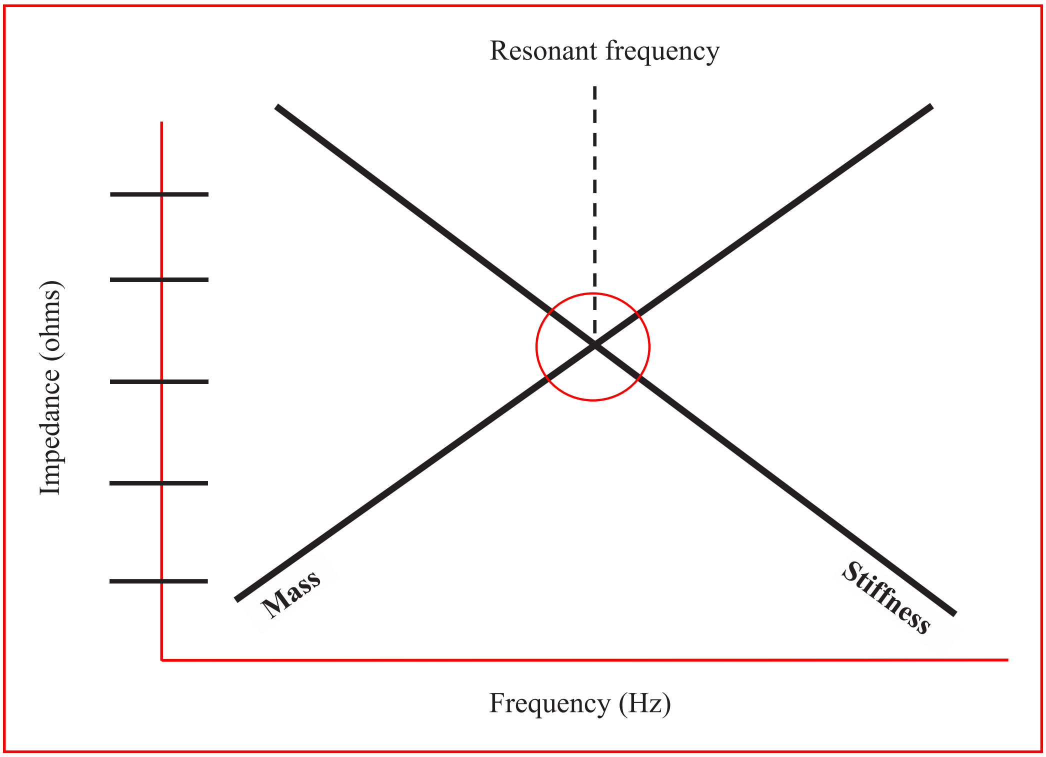

FIGURE 1–17. Resonant frequency.

that the loudness of one fork would increase much more than that of the others. The frequency of the tuning fork producing the greatest increase in loudness would be very close to the resonant frequency of the table. That is called **sounding board resonance** (or **sounding board effect**) and occurs because the tabletop is set into vibration, thereby considerably increasing the size of the vibrating surface and creating a source of sound in addition to our tuning fork.

In conducting this experiment, we also note that although the tone becomes louder at the resonant frequency, we hear it for a shorter time than we would if we simply struck the tuning fork and listened to it. This is caused in part by the increase in resistance afforded by air to vibration of the whole tabletop versus that afforded to the two prongs of the tuning fork. In larger part this is caused by the energy being imparted to the tabletop, resulting in a more rapid use of energy.

Vocabulary Checkpoint

Mass: Any form of matter (solid, liquid or gas). Also, one energy-storing component of impedance. Maximally opposes high-frequency energy.

The rate at which the magnitude of vibration, and subsequently the loudness of the resultant sound, decrease is called **damping**. When the sound diminishes rapidly, we refer to the system as being heavily damped; if it diminishes slowly, it is lightly damped. Using tuning forks with a resonant frequency of vibration that is different from the resonant frequency of the tabletop, we note very little change in loudness as we touch the base of the fork to the tabletop, but the sound will be heard for about as long as if we were not to touch it to the tabletop. This occurs because very little of the original energy is being imparted to the tabletop. That is, the opposition to the transfer of energy (i.e., the impedance) is large for those frequencies remote from the resonant frequency.

CAVITY (ACOUSTICAL) RESONANCE

A standard laboratory demonstration of cavity resonance consists of inserting one end of a straight tube open at both ends into a beaker of water (Figure 1–18). The end of the tube inserted into the water can be viewed as closed, and the unsubmerged end is considered open. A vibrating tuning fork is then placed over the open end of the

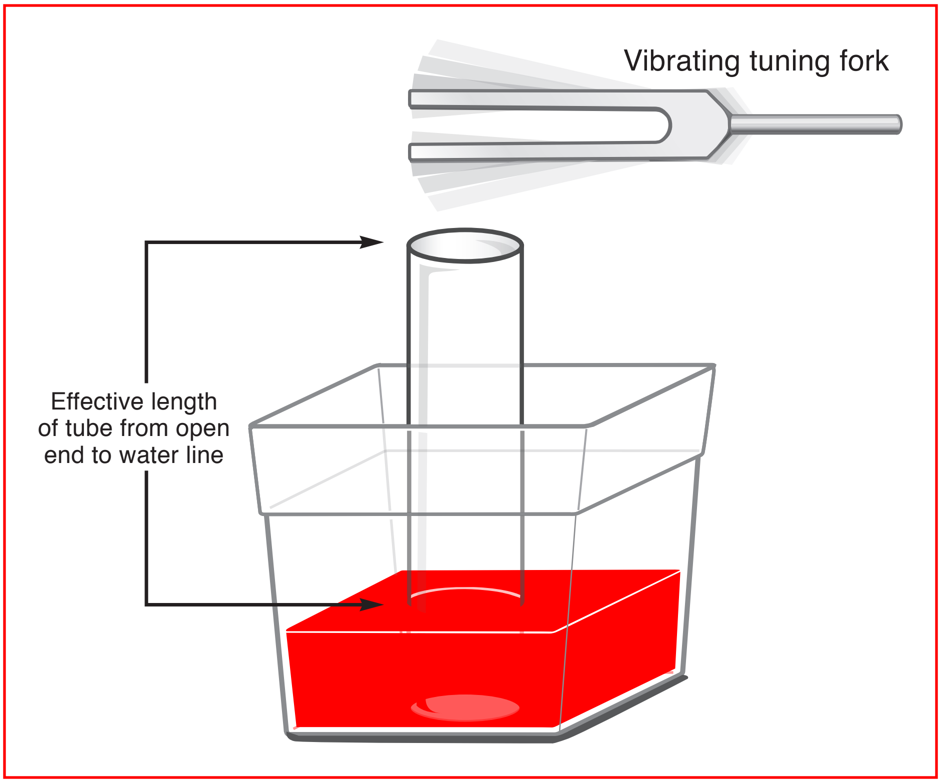

FIGURE 1–18. Demonstration of resonance.

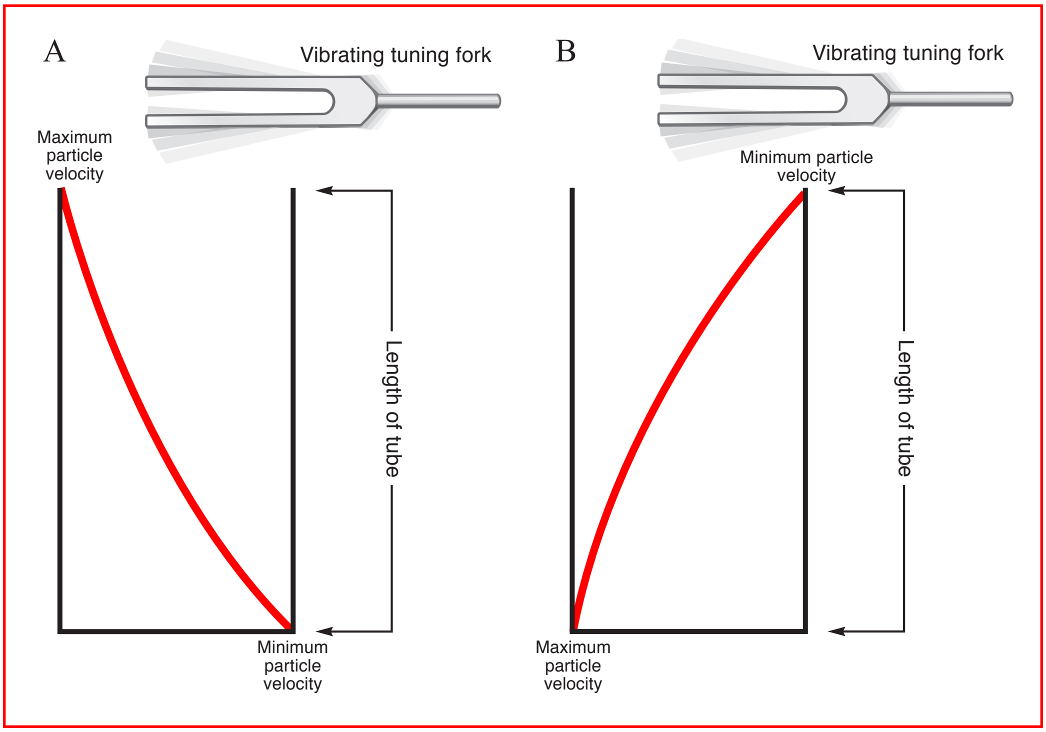

FIGURE 1–19. Velocity curve for tube resonance (A). Pressure curve for tube resonance (B).

tube. As the tube is slowly moved up and down in the water, a certain length of tube above the water (its effective length) is created that causes an increase in the perceived amplitude of the tuning fork's tone. At this point, the length of tube above the water provides the tube with the same natural frequency of vibration (i.e., resonant frequency) as that of the vibrating tuning fork. The vibrations of the tuning fork are exciting the molecules composing the column of air within the length of tube above the water line. Amplitude becomes maximal (i.e., resonance occurs) when the tube length is such that standing wave patterns representing air molecular velocity (i.e., speed) and pressure (i.e., force per unit area) are established within the tube (Figures 1–19A and 1–19B).

The standing wave pattern referring to the velocity (i.e., speed) of the air molecules within the tube represents a condition where the molecules

Vocabulary Checkpoint

Resonant frequency: Frequency at which a system will most easily be set into vibration. It is the point at which the effects of mass and stiffness are equal.

are showing maximum velocity at the open end of the tube and minimum velocity at the closed end of the tube when the tube is being excited by the vibrations of the tuning fork. The speed of movement of the molecules between the extreme ends of the tube follows a curvilinear line (Figure 1–19A). The velocity or speed of air particle movement is in reference to the oscillatory movements of air molecules around a fixed point. Because of the elastic and inertial properties of the medium, these air particles do not move very far from a fixed point (i.e., **rest position**) when they are set in motion.

Sound, which is a disturbance in the particles of a medium, travels through the medium, but the medium's particles remain relatively fixed, allowing the sound disturbance to cause them to oscillate about a fixed point to which they are anchored. Therefore, the speed of the oscillations of the air particles would be greatest at the open end of the tube and least at the closed end of the tube when the tube is excited by a sound source having the same natural frequency of vibration (i.e., resonant frequency) as the tube itself. Tube length, as suggested by the laboratory demonstration in Figure 1–18, appears to be a critical factor in the determination of the natural (i.e., resonant) frequencies at which the column of air inside a particular tube will vibrate.

A pressure (i.e., force per unit area) curve can also be drawn to represent molecular activity within the tube when resonance is occurring. The pressure curve shows that while resonance is occurring, there is minimum particle pressure at the open end of the tube and maximum particle pressure at the closed end of the tube. The pressures on the molecules between the extreme ends follow a curvilinear line (Figure 1–19B).

There appears to be an inverse relationship between the velocity and pressure curves that represent cavity or tube resonance (Figure 1–19). The speed of oscillatory behavior for a particular air molecule is greatest at points along the length of the tube where the pressure being applied to that molecule by the vibrating sound source is least (i.e., the open end of the tube). Conversely, the speed of oscillatory behavior for a particular air molecule is least at points along the length of the tube where the pressure being applied to that molecule by the vibrating sound source is greatest (i.e., the closed end of the tube).

If the tuning fork in the laboratory demonstration (see Figure 1–18) had a natural frequency of 500 Hz and was set into vibration over the open end of the tube, careful movement of the tube up and down in the water would show that resonance would occur in the tube when its length from its open end to the water line is 17 cm (Figure 1–20). This length of tube would allow for the establishment of the velocity and pressure standing wave patterns needed for resonance to occur within the tube when being excited by a 500-Hz sound source (tuning fork).

The speed of molecular movement and the pressure on the air molecules making up the column of air in the tube would enable appropriate standing wave patterns to be established. Tube length that has been adjusted to accommodate the excitatory frequency of the tuning fork (500 Hz), is critical to the resonance characteristics of the tube. This is because the tube length needed