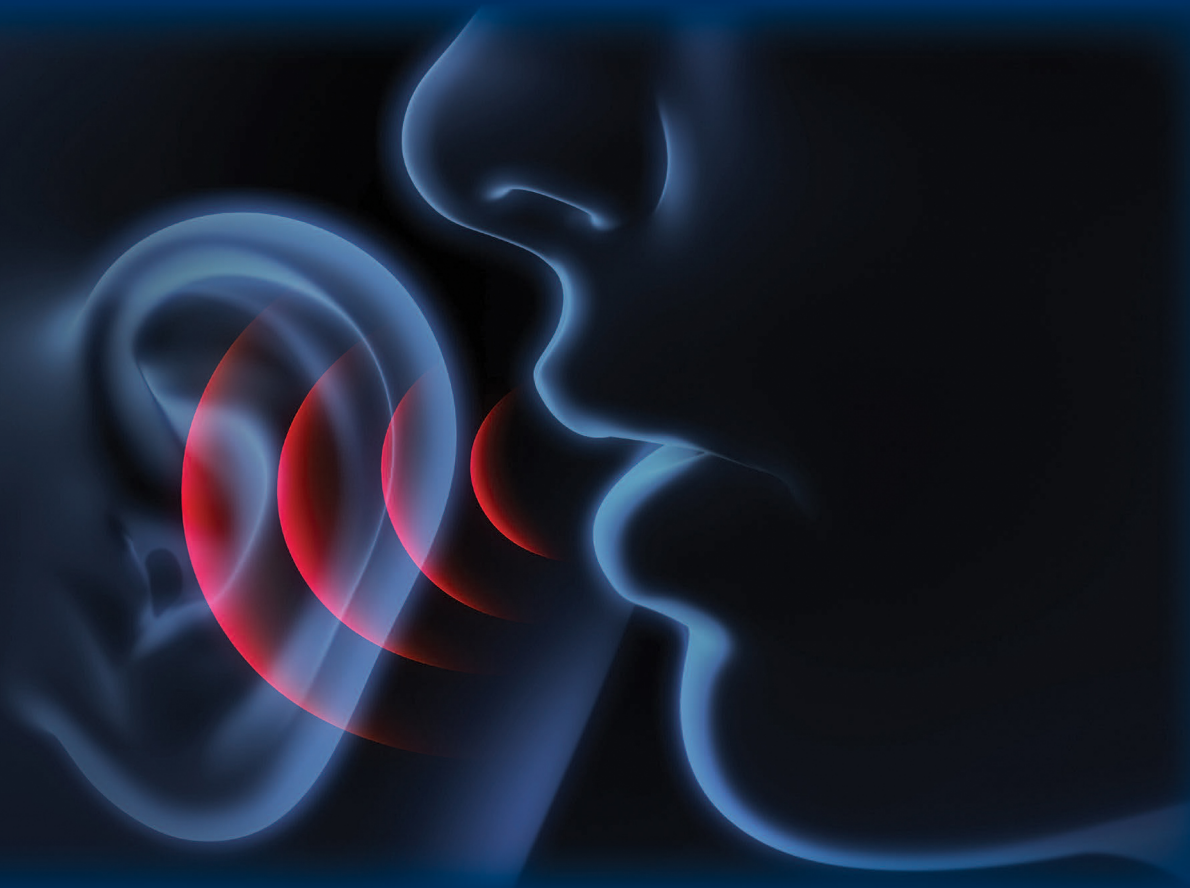


HEARING SCIENCE FUNDAMENTALS

SECOND EDITION

Norman J. Lass
Jeremy J. Donai



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Hearing Science Fundamentals

SECOND EDITION

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Hearing Science Fundamentals

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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, wide-band 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 audi-

tory 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.



ACKNOWLEDGMENTS

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 suc-

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Dr. Lass would like to thank his family, colleagues, and mentors who have supported him throughout his career. Their support has meant a great deal to him over the years. He would also like to thank all of his former students for their time and assistance with his academic endeavors. You were a critical component of his success in academia. Lastly, Dr. Lass would also like to thank Dr. Jeremy Donai for agreeing to collaborate on the most recent edition of this text.



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The image features a light blue background with several sets of concentric, wavy lines in a slightly darker shade of blue. These lines are arranged in a way that suggests sound waves or ripples. A solid, medium-blue horizontal band runs across the middle of the image. Centered within this band is the text "SECTION I" in a white, sans-serif font, and below it, the word "Acoustics" in a larger, white, serif font.

SECTION I
Acoustics

1

BASIC ACOUSTICS

KEY TERMS

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

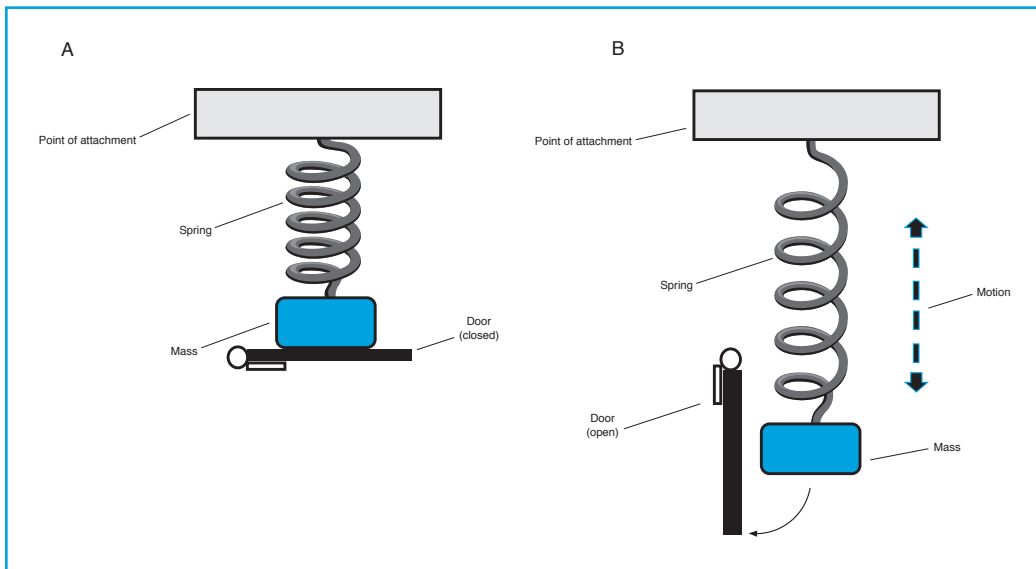


FIGURE 1–1. Schematic of the spring-mass model.

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/cm², with the dyne being a measure of force and square centimeters (cm²) a measure of area. Currently, pressure is measured in units of pas-

cals (Pa), in honor of Blaise Pascal, a 17th-century mathematician. For example, 0.0002 dyne/cm² 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

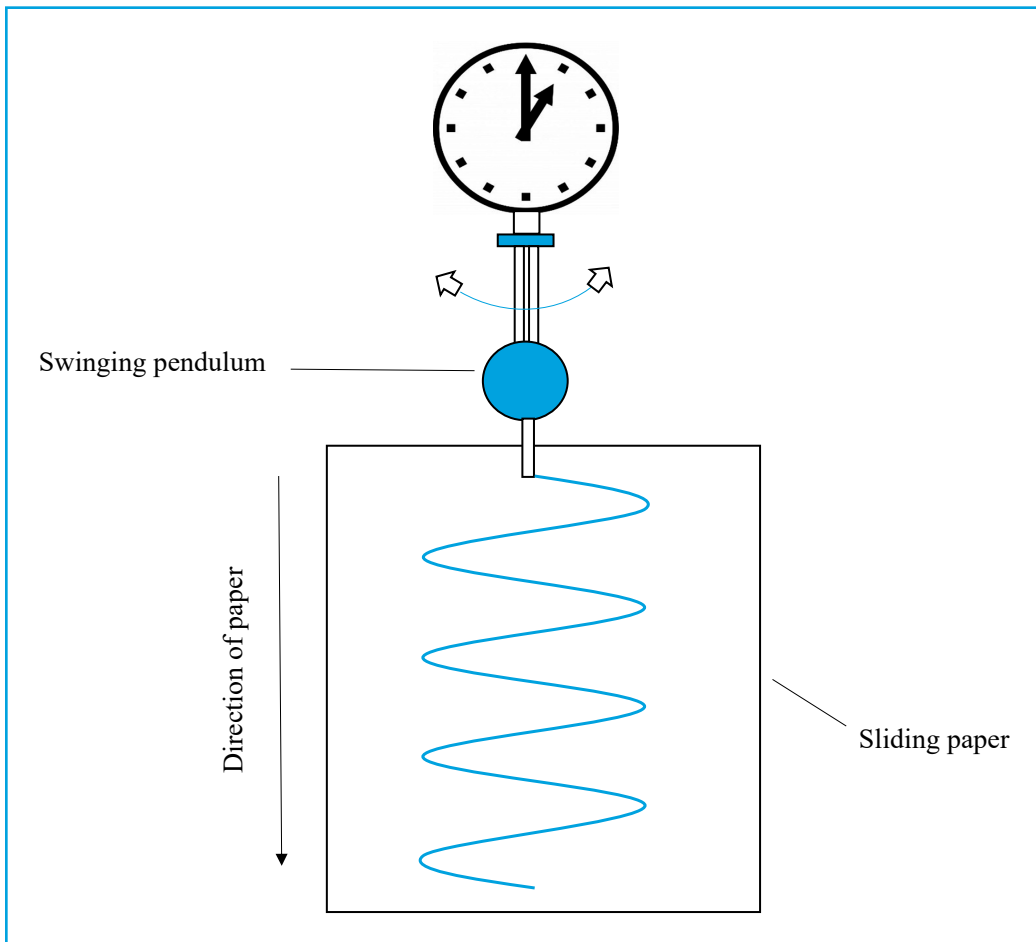


FIGURE 1–2. Example of sinusoidal motion.

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 move-

ment 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 **clinical audiometer** (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.

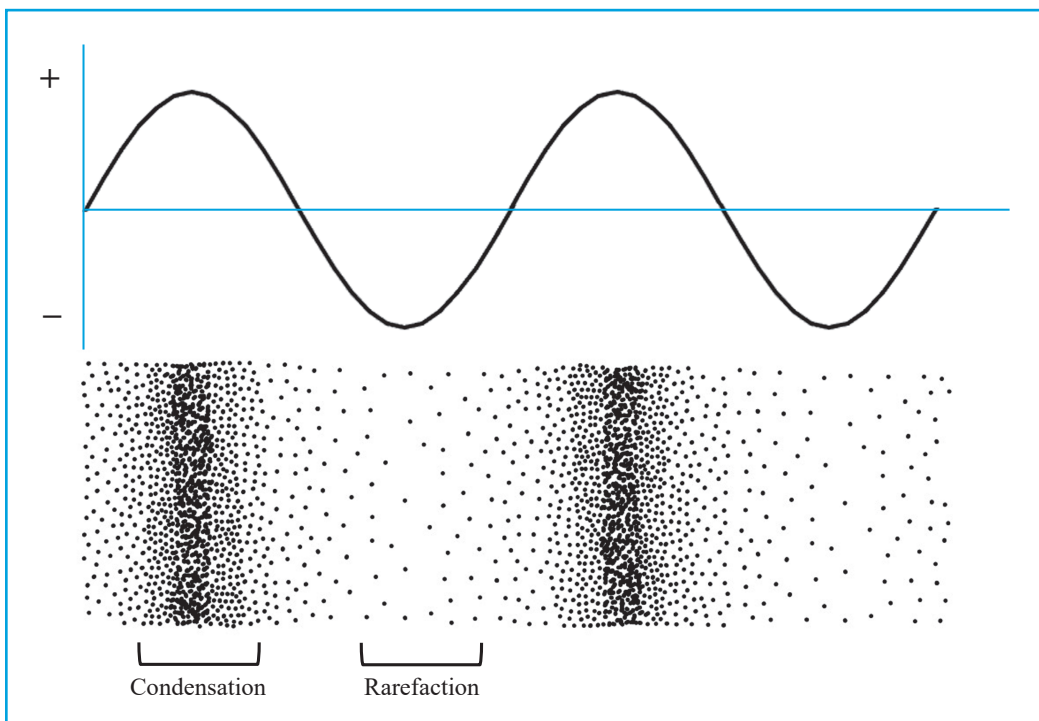


FIGURE 1–3. Condensation and rarefaction.