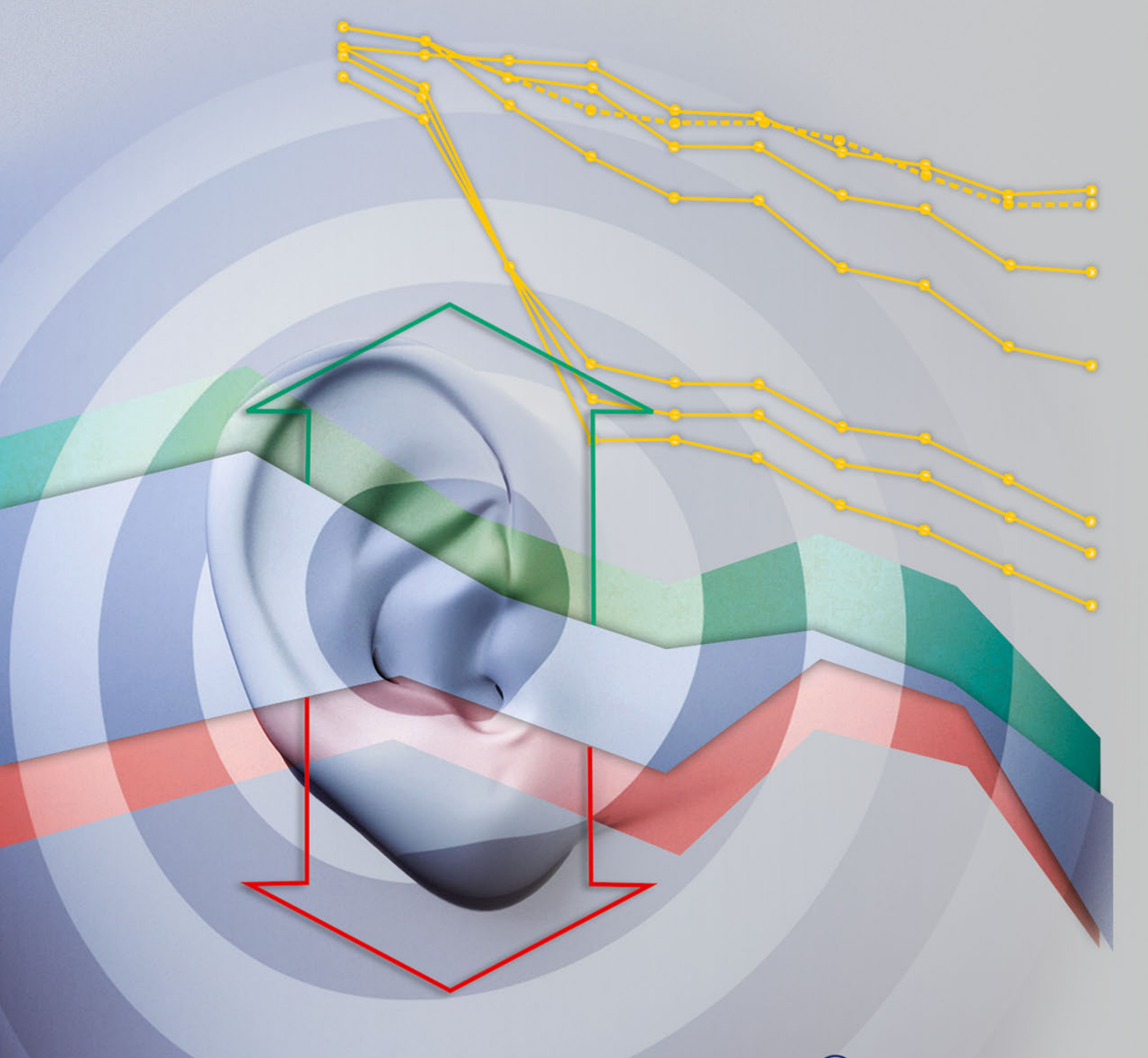
Essentials of Audiology

Stanley A. Gelfand

Fourth Edition



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Essentials of Audiology

Fourth Edition

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To Janice

In loving memory

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Preface

What is audiology? *Audiology* is the clinical profession that deals with hearing and balance disorders. It is also the scientific study of normal and abnormal audition and related areas in the broadest sense.

What is an audiologist? An *audiologist* is a practitioner of audiology as a clinical profession. Audiologists are principally concerned with the identification, evaluation and management of patients with auditory and balance disorders, as well as with the prevention of hearing impairment. The scope of audiological practice also includes such diverse areas as the evaluation of the vestibular system, noise assessment, and hearing conservation, as well as the physiological monitoring of various neurological functions during surgical procedures. As a result, audiologists possess a broad scope of knowledge and skills, and often have interests in common with a variety of other disciplines such as speech-language pathology; speech and hearing science; education of the deaf and hearing impaired; engineering; acoustics; industrial hygiene; musicology; medicine; physiology; psychology; linguistics; and vocational counseling.

Much like many other scholarly professions, pursuing a career in audiology involves a rigorous course of doctoral education and training. Most audiologists earn the Doctor of Audiology (Au.D.) degree, while others with research and academic as well as clinical interests obtain a Ph.D. Some pursue both. In addition, those qualified to practice audiology are usually certificated by the American Speech-Language-Hearing Association (ASHA) and/or the American Academy of Audiology (AAA), as well as possessing professional licenses from the states in which they practice.

So who is this book for? Introductory audiology is an essential and fundamental aspect of the education of all students who are interested in the two related professions of Speech-Language Pathology and Audiology. This book is primarily intended to serve as a comprehensive introductory text for students who are preparing to enter both of these fields. As such, it tries to address the needs of two rather different groups of students. Those planning a career in audiology need a broad overview of the field and a firm understanding of its many basic principles so that they have a solid foundation for futures as doctors of audiology in clinical practice. The audiological needs of future speech-language pathologists are just as important, and go well beyond knowing the auditory implications of speech, language and related disorders, and being able to understand audiological reports. Speech-language pathologists often find themselves working hand-in-hand with their audiological colleagues. They also need to perform certain audiological procedures themselves when these fall within the speech-language pathology scope of practice, especially when screening is involved; and they regularly make interpretations and referrals that are of audiological relevance. Moreover, speech-language pathologists often work with patients who have hearing losses and auditory processing disorders directly and on an ongoing basis. They frequently must explain the nature and management of auditory disorders to family members, teachers and other professionals. This is especially true in school settings and long-term care facilities. What's more, cochlear implant and other multidisciplinary programs are enhancing the scope and depth of interactions among speech-language pathologists and audiologists, and are making a knowledge and understanding of audiology all the more important for budding speech-language pathologists. With considerations like these in mind, I hope that students who become speech-language pathologists will find this text useful as a reference source long after their audiology courses have been completed. (Of course, I do admit hoping that at least a few speech-language pathology students will be attracted to a career in audiology by what they read here.)

This textbook attempts to provide a comprehensive overview of audiology at the introductory level; including such topics as acoustics, anatomy and physiology, sound perception, auditory disorders and the nature of hearing impairment, methods of measurement, screening, clinical assessment and clinical management. It is intended to serve as the core text for undergraduate students in speech, language and hearing, and might also serve the needs of beginning-level graduate students who need to learn or review the fundamentals of audiology. It is anticipated that the material will be covered in a one-, two- or three-term undergraduate sequence, depending on the organization of the communication sciences and disorders curriculum at a given college or university. For example, the first three chapters are often used the text for an undergraduate hearing science course, while selections from the other chapters might be used in one or two audiology courses.

With these considerations in mind, I have tried to prepare a textbook that is extensive enough for professors pick and choose material that provides the right depth and scope of coverage for a particular course. For example, text readings can be assigned to cover clinical masking at almost any level from simple to complex by selecting various sections of Chapter 9. It is unlikely that all of that chapter will be assigned in a single undergraduate class. However, the material is there if needed for further study, to provide the groundwork for a term-paper or independent study report, or for future reference. I have tried to provide relatively extensive reference lists are provided for similar reasons.

This fourth edition was undertaken to provide the beginning student with an up-to-date coverage of a field that is steadily developing, as well as to take advantage of accumulating experience to improve upon what is included and how it is presented. Many developments and changes have taken place since the third edition was published. Some of them are in areas of rapidly unfolding development like cochlear implants and related technologies and in electrophysiological assessment. But most of them are the slow, methodical and often subtle—albeit important—advances that unfold over time in an active clinical science. Others changes reflect the influence of systematic reviews, changes in guidelines, expert position papers, standards and regulations which affect clinical practices and technical matters. Of course, there are always a few developments that surfaced the day *after* the prior edition was printed—a frustration to the textbook author, but the kind of thing that makes audiology such an exciting and interesting field.

As with the prior editions, this one was influenced by the input graciously provided by of many audiologists involved in clinical practice, research, and teaching and student supervision. In addition, considerable attention was given to the comments and insights of students who were taking or recently completed introductory audiology courses, including those who used the third edition of this text as well as other books. The content and especially the style of the text were substantially influenced by their advice. As a result of their insights, the current edition retains a writing style that has been kept as conversational and informal as possible; and only classroom-proven examples and drawings are included. Similarly, clinical masking, acoustic immittance and screening have been kept in separate chapters; the material on audiological management continues to be spread over two chapters; and the history of audiology has been omitted. The use of gender-specific pronouns (*he, she, him, her,* etc.)—originally undertaken with great trepidation—was very well received in all three prior editions, and has been continued in this one. Its purpose is to maximize clarity for the benefit of the reader. The alternative would have resulted in longer phrases and a more formal style, and would have detracted from the goal of providing the student with text that is maximally reader-friendly (or at least minimally unfriendly). This style also makes the material considerably easier to follow by using different genders for the clinician and patient when describing clinical procedures and interactions. Gender fairness is maintained by referring to both genders in both roles more-or-less equally throughout the text.

This book would not exist without the influence of many very special people. I am particularly grateful to my colleagues and students in the Department of Linguistics and Communication Disorders at Queens College, and in the Au.D. Program and the Ph.D. Program in Speech Language and Hearing Sciences at the City University of New York Graduate Center. I would also like to express my appreciation to the extraordinary, talented and dedicated professionals at Thieme Medical Publishers, who have been so helpful, cooperative and supportive throughout the process of preparing this book, in spite of its demanding and dyslexic author. With sincere apologies to anyone inadvertently omitted, I would like to extend my heartfelt thanks to the following individuals for their influence, insights, advice, encouragement, assistance, support, and friendship: Moe Bergman, Arthur Boothroyd, Lauren Calandruccio, Kenny Chumbley, Joseph Danto, Becky Dille, Lillian and Sol Gelfand, Irving Hochberg, Gertrude and Oscar Katzen, Arlene Kraat, William Lamsbeck, Harry Levitt, John Lutolf, Dave Mason, Maurice Miller, Natascha Morris, Elizabeth Palumbo, Neil Piper, John Preece, Brian Scanlan, Teresa Schwander, Shlomo Silman, Carol Silverman, Anne Sydor, Helen and Harris Topel, Barbara Weinstein, and Mark Weiss.

Finally, my greatest appreciation is expressed to Janice, whose memory will always be a blessing and inspiration; and to my wonderful children, Michael, Joshua and Erin, and Jessica and Robert for their love, encouragement, support, insight and unimaginable patience.

Stanley A. Gelfand

1 Acoustics and Sound Measurement

We begin our study of audiology by reviewing the nature of sound because, after all, sound is what we hear. The science of sound is called acoustics, which is a branch of physics, and relies on several basic physical principles. Many useful sources are available for students wishing to pursue the areas covered in this chapter in greater detail (e.g., Beranek 1986; Gelfand 2010; Hewitt 1974; Kinsler, Frey, Coppens, & Sanders 1982; Peterson & Gross 1972; Sears, Zemansky, & Young 1982).

Physical Quantities

The basic physical quantities are mass, time, and length (or distance). All other physical quantities are derived by combining these three basic ones, as well as other derived quantities, in a variety of ways. The principal basic and derived quantities are summarized in **Table 1.1**. These basic quantities are expressed in terms of conventional units that are measurable and repeatable. The unit of **mass (M)** is the **kilogram (kg)** or the **gram (g)**; the unit of **length (L)** is the **meter (m)** or the **centimeter (cm)**; and the unit of **time (t)** is the **second (s)**. Mass is not really synonymous with weight even though we express its magnitude in kilograms. The mass of a body is related to its density, but its weight is related to the force of gravity. If two objects are the same size, the one with greater density will weigh more. However, even though an object's mass would be identical on the earth and the moon, it would weigh less on the moon, where there is less gravity.

When we express mass in kilograms and length in meters, we are using the meter–kilogram-second or **MKS** system. Expressing mass in grams and length in centimeters constitutes the centimeter-gram-second or **cgs** system. These two systems also have different derived quantities. For example, the units of force and work are called newtons and joules in the MKS system, and dynes and ergs in the cgs system, respectively. We will emphasize the use of MKS units because this is the internationally accepted standard in the scientific community, known as the **Systeme Internationale (SI)**. Equivalent cgs values will often be given as well because the audiology profession has traditionally worked in cgs units, and the death of old habits is slow and labored. These quantities are summarized with equivalent values in MKS and cgs units in **Table 1.1**. In addition, the correspondence between scientific notation and conventional numbers, and the meanings of prefixes used to describe the sizes of metric units are shown for convenience and ready reference in **Table 1.2** and **Table 1.3.**

Quantities may be scalars or vectors. A **scalar** can be fully described by its magnitude (amount or size), but a **vector** has both direction and magnitude. For example, length is a scalar because an object that is one meter long is always one meter long. However, we are dealing with a vector when we measure the distance between two coins that are one meter apart because their relationship has both magnitude and direction (from point x_1 to point x_2). This quantity is called **displacement (d)**. Derived quantities will be vectors if they have one or more components that are vectors; for example, velocity is a vector because it is derived from displacement, and acceleration is a vector because it involves velocity. We distinguish between scalars and vectors because they are handled differently when calculations are being made.

Velocity Everyone knows that "55 miles per hour" refers to the speed of a car that causes it to travel a distance of 55 miles in a one-hour period of time. This is an example of **velocity (v)**, which is equal to the amount of displacement (d) that occurs over time (t):

$$v = \frac{d}{t}$$

Table 1.1 Principal physical quantities

Quantity	Formula	MKS (SI) units	cgs units	Comments
Mass (M)	M	kilogram (kg)	gram (g)	1 kg = 10^3 g
Time (t)	t	second (s)	s	
Area (A)	A	m^2	cm^2	1 m^2 = 10^4 cm^2
Displacement (d)	d	meter (m)	centimeter (cm)	1 m = 10^2 cm
Velocity (v)	v = d/t	m/s	cm/s	1 m/s = 10^2 cm/s
Acceleration (a)	a = v/t	m/s^2	cm/s^2	1 m/s^2 = 10^2 cm/s^2
Force (F)	F = Ma = Mv/t	kg • m/s^2 newton (N)	g • cm/s^2 dyne	1 N = 10^5 dyne
Pressure (p)	p = F/A	N/m^2 pascal (Pa)	dyne/cm^2 microbar (μbar)	2 × 10^{-5} N/m^2 or 20 μPa (reference value) 2 × 10^{-4} dyne/cm^2 or μbar (reference value)
Work (W)	W = Fd	N • m joule (J)	dyne • cm erg	1 J = 10^7 erg
Power (P)	P = W/t = Fd/t = Fv	joule/s watt (w)	erg/s watt (w)	1 w = 1 J/s = 10^7 erg/s
Intensity (I)	I = P/A	w/m^2	w/cm^2	10^{-12} w/m^2 (reference value) 10^{-16} w/cm^2 (reference value)

Displacement is measured in meters and time is measured in seconds (sec); thus, velocity is expressed in meters per second (m/s). Velocity is the vector equivalent of speed because it is based on displacement, which has both magnitude and direction. When we take a trip we usually figure out the distance traveled by making a mental note of the starting odometer reading and then subtracting it from the odometer reading at the destination (e.g., if we start at 10,422 miles and arrive at 10,443 miles, then the distance must have been 10,443 – 10,422 = 21 miles). We do the same thing to calculate the time it took to make the trip (e.g., if we left at 1:30 and arrived at 2:10, then the trip must have taken 2:10 – 1:30 = 40 minutes). Physical calculations involve the same straightforward approach. When an object is displaced, it starts at point x_1 and time t_1 and arrives at point x_2 and time t_2. Its *average velocity* is simply the distance traveled (x_2 – x_1) divided by the time it took to make the trip (t_2 – t_1):

$$v = \frac{x_2 - x_1}{t_2 - t_1}$$

The term *instantaneous velocity* describes the velocity of a body at a *particular moment* in time. For the math-minded, it refers to the velocity when the displacement and time between one point and the next one approach zero, that is, the derivative of displacement with respect to time:

$$v = \frac{dx}{dt}$$

Acceleration Driving experience has taught us all that a car increases its speed to get onto a highway, slows down when exiting, and also slows down while making a turn. "Speeding up" and "slowing down" mean that the velocity is changing over time. The change of velocity over time is **acceleration (a)**. Suppose a body is moving between two points. Its velocity at the first point is v_1, and the time at that point is t_1. Similarly, its velocity at the second point is v_2 and the time at that point is t_2. *Average accelera-*

Table 1.2 Expressing numbers in standard notation and scientific notation

Standard notation	Scientific notation
0.000001	10^{-6}
0.00001	10^{-5}
0.0001	10^{-4}
0.001	10^{-3}
0.01	10^{-2}
0.1	10^{-1}
1	10^{0}
10	10^{1}
100	10^{2}
1,000	10^{3}
10,000	10^{4}
100,000	10^{5}
1,000,000	10^{6}
3600	3.6×10^{3}
0.036	3.6×10^{-2}
0.0002	2×10^{-4}
0.00002	2×10^{-5}

tion is the difference between the two velocities ($v_2 - v_1$) divided by the time interval ($t_2 - t_1$):

$$a = \frac{v_2 - v_1}{t_2 - t_1}$$

In more general terms, acceleration is written simply as

$$a = \frac{v}{t}$$

Because velocity is the same as displacement divided by time, we can replace v with d/t, so that

$$a = \frac{d/t}{t}$$

which can be simplified to

$$a = \frac{d}{t^2}$$

Consequently, acceleration is expressed in units of *meters per second squared (m/s^2)* in the MKS system. When measurements are made in cgs units, acceleration is expressed in centimeters per second squared (cm/s^2).

Acceleration at a given moment is called *instantaneous acceleration*, and quantitatively oriented readers should note it is equal to the derivative of velocity with respect to time, or

$$a = \frac{dv}{dt}$$

Table 1.3 Examples of prefixes used to express metric units

			Multiply by	
Prefix	**Symbol**	**Definition**	**Standard notation**	**Scientific notation**
micro	μ	millionths	1/1,000,000 *or* 0.000001	10^{-6}
milli	m	thousanths	1/1000 *or* 0.001	10^{-3}
cent	c	hundredths	1/100 *or* 0.01	10^{-2}
deci	d	tenths	1/10 *or* 0.1	10^{-1}
deka	da	tens	10	10^{1}
hecto	h	hundreds	100	10^{2}
kilo	k	thousands	1000	10^{3}
mega	M	millions	1,000,000	10^{6}

Because velocity is the first derivative of displacement, we find that acceleration is the second derivative of displacement:

$$a = \frac{d^2x}{dt^2}$$

Force An object that is sitting still will not move unless some outside influence causes it to do so, and an object that is moving will continue moving at the same speed unless some outside influence does something to change it. This commonsense statement is Newton's first law of motion. It describes the attribute of **inertia**, which is the property of mass to continue doing what it is already doing. The "outside influence" that makes a stationary object move, or causes a moving object to change its speed or direction, is called **force (F)**. Notice that force causes the moving object to change velocity or the motionless object to move, which is also a change in velocity (from zero to some amount). Recall that a change of velocity is acceleration. Hence, force is that influence (conceptually a "push" or "pull") that causes a mass to be accelerated. In effect, the amount of "push" or "pull" needed depends on how much mass you want to influence and the amount of acceleration you are trying to produce. In other words, force is equal to the product of mass times acceleration:

$$F = Ma$$

Since acceleration is velocity over time (v/t), we can also specify force in the form

$$F = \frac{Mv}{t}$$

The quantity Mv is called **momentum**, so we may also say that force equals momentum over time.

The amount of force is measured in kg • m/s^2 because force is equal to the product of mass (measured in kg) and acceleration (measured in m/s^2). The *unit of force* is the **newton (N)**, where one newton is the amount of force needed to cause a 1 kg mass to be accelerated by 1 m/s^2; hence, 1 N = 1 kg • 1 m/s^2. (This might seem very technical, but it really simplifies matters; after all, it is easier to say "one newton" than "one kg • m/s^2."). It would take a 2 N force to cause a 1 kg mass to be accelerated by 2 m/s^2, or a 2 kg mass to be accelerated by 1 m/s^2. A 4 N force is needed to accelerate a 2 kg mass by 2 m/s^2, and a 63 N force is needed to accelerate a 9 kg mass by 7 m/s^2. In the cgs system, the unit of force is called the **dyne**, which is the force needed to accelerate a 1 g mass by 1 cm/s^2; that is, 1 dyne = 1 g • cm/s^2. It takes 10^5 dynes to equal 1 N.

Many different forces are usually acting upon an object at the same time. Hence, the force we have been referring to so far is actually the **net** or **resultant force**, that is, the "bottom line" effect of all the forces that act upon an object. If a force of 3 N is pushing an object toward the right and a second force of 8 N is also pushing that object toward the right, then the net force would be 3 + 8 = 11 N toward the right. In other words, if two forces push a body in the same direction, then the net force would be the sum of those two forces. Conversely, if a 4 N force pushes an object toward the right at the same time that a 9 N force pushes it toward the left, then the net force is 9 – 4 = 5 N toward the left. Thus, if two forces push an object in opposite directions, then the net force is the difference between the two opposing forces, and it causes the object to accelerate in the direction of the greater force. If two *equal* forces push in *opposite* directions, then the net force is zero. Because the net force is zero it will not cause the motion of the object to change. The situation in which net force is zero is called **equilibrium**. In this case, a moving object will continue moving and an object that is **at rest** (i.e., not moving) will continue to remain still.

Friction When an object is moving in the real world, it tends to slow down and eventually comes to a halt. This happens because anything that is moving in the real world is always in contact with other bodies or mediums. The sliding of one body on the other constitutes a force that opposes the motion, called **resistance** or **friction**.

The opposing force of friction or resistance depends on two parameters. The first factor is that the amount of friction depends on the nature of the materials that are sliding on one another. Simply stated, the amount of friction between two given objects is greater for "rough" materials than for "smooth" or "slick" ones, and is expressed as a quantity called the *coefficient of friction.* The second factor that determines how much friction occurs is easily appreciated by rubbing the palms of your hands back and forth on each other. First rub slowly and then more rapidly. The rubbing will produce heat, which occurs because friction causes some of the mechanical energy to be converted into heat. This notion will be revisited later, but for now we will use the amount of heat as an indicator of the amount of resistance. Your hands become hotter when they are rubbed together more quickly. This illustrates the notion that the amount of friction depends on the *velocity* of motion. In quantitative terms,

$$F = Rv$$

where F is the force of friction, R is the coefficient of friction between the materials, and v is the velocity of the motion.

Elasticity and restoring force It takes some effort (an outside force) to compress or expand a spring; and the compressed or expanded spring will bounce back to its original shape after it is released. Compressing or expanding the spring is an example of deforming an object. The spring bouncing back to its prior shape is an example of elasticity. More formally, we can say that **elasticity** is the property whereby a deformed object returns to its original form. Notice the distinction between deformation and elasticity. A rubber band and saltwater taffy can both be stretched (deformed), but only the rubber band bounces back. In other words, what makes a rubber band *elastic* is not that it stretches, but rather that it bounces back. The more readily a deformed object returns to its original form, the more elastic (or stiff) it is.

We know from common experiences, such as using simple exercise equipment, that it is relatively easy to *begin* compressing a spring (e.g., a "grip exerciser"), but that it gets progressively harder to *continue* compressing it. Similarly, it is easier to *begin* expanding a spring (e.g., pulling apart the springs on a "chest exerciser") than it is to *continue* expanding it. In other words, the more a spring-like material (an elastic element) is deformed, the more it *opposes* the applied force. The force that opposes the deformation of an elastic or spring-like material is known as the **restoring force**. If we think of deformation in terms of how far the spring has been compressed or expanded from its original position, we could also say that the restoring force increases with displacement. Quantitatively, then, restoring force (F_R) depends on the stiffness (S) of the material and the amount of its displacement as follows:

$$F_R = Sd$$

Pressure Very few people can push a straight pin into a piece of wood, yet almost anyone can push a thumbtack into the same piece of wood. This is possible because a thumbtack is really a simple machine that concentrates the amount of force being exerted over a larger area (the head) down to a very tiny area (the point). In other words, force is affected by the size of the area over which it is applied in a way that constitutes a new quantity. This quantity, which is equal to force divided by area (A), is called **pressure (p)**, so

$$p = \frac{F}{A}$$

Because force is measured in newtons and area is measured in square meters in MKS units, pressure is measured in newtons per square meter (N/m^2). The unit of pressure is the **Pascal (Pa)**, so that 1 Pa = 1 N/m^2. In the cgs system, pressure is measured in dynes per square centimeter ($dynes/cm^2$), occasionally referred to as **microbars (µbars)**.

Work and energy As a physical concept, **work (W)** occurs when the force applied to a body results in its displacement, and the amount of work is equal to the product of the force and the displacement, or

$$W = Fd$$

Because force is measured in newtons and displacement is measured in meters, work itself is quantified in newton-meters (N • m). For example, if a force of 2 N displaces a body by 3 m, then the amount of work is 2 × 3 = 6 N. There can only be work if there is displacement. There cannot be work if there is no displacement (i.e., if d = 0) because work is the product of force and displacement, and zero times anything is zero. The MKS unit of work is the **joule (J)**. One joule is the amount of work that occurs when one newton of force effects one meter of displacement, or 1 J = 1 N • m. In the cgs system, the unit of work is called the erg, where 1 erg = 1 dyne • cm. One joule corresponds to 10^7 ergs.

Energy is usually defined as the capability to do work. The energy of a body at rest is **potential** energy and the energy of an object that is in motion is **kinetic** energy. The total energy of a body is the sum of its potential energy plus its kinetic energy, and work corresponds to the exchange between these two forms of energy. In other words, energy is not consumed when work is accomplished; it is converted from one form to the other. This principle is illustrated by the simple example of a swinging pendulum. The pendulum's potential energy is greatest when it reaches the extreme of its swing, where its motion is momentarily zero. On the other hand, the pendulum's kinetic energy is greatest when it passes through the midpoint of its swing because this is where it is moving the fastest. Between these two extremes, energy is being converted from potential to kinetic as the pendulum speeds up (on each down swing), and from kinetic to potential as the pendulum slows down (on each up swing).

Power The rate at which work is done is called **power (P)**, so that power can be defined as work divided by time,

$$P = \frac{W}{t}$$

The unit of power is called the **watt (w)**. One unit of power corresponds to one unit of work divided by one unit of time. Hence, one watt is equal to one joule divided by one second, or 1 w = 1 J/s. Power is also expressed in watts in the cgs system, where work is measured in ergs. Since 1 J = 10^7 erg, we can also say that 1 w = 107 erg/s.

Power can also be expressed in other terms. For example, because W = Fd, we can substitute Fd for W in the power formula, to arrive at

$$P = \frac{Fd}{t}$$

We know that v = d/t, so we can substitute v for d/t and rewrite this formula as

$$P = Fv$$

In other words, power is also equal to force times velocity.

Intensity Consider a hypothetical demonstration in which one tablespoonful of oil is placed on the surface of a still pond. At that instant the entire amount of oil will occupy the space of a tablespoon. As time passes, the oil spreads out over an expanding area on the surface of the pond, and it therefore also thins out so that much less than all the oil will occupy the space of a tablespoon. The wider the oil spreads the more it thins out, and the proportion of the oil covering any given area gets smaller and smaller, even though the total amount of oil is the same. Clearly, there is a difference between the amount of oil, per se, and the concentration of the oil as it is distributed across (i.e., divided by) the surface area of the pond.

An analogous phenomenon occurs with sound. It is common knowledge that sound radiates outward in every direction from its source, constituting a sphere that gets bigger and bigger with increasing distance from the source, as illustrated by the concentric circles in **Fig. 1.1**. Let us imagine that the sound source is a tiny pulsating object (at the center of the concentric circles in the figure), and that it produces a finite amount of power, analogous to the fixed amount of oil in the prior example. Consequently, the sound power will be divided over the ever-expanding surface as distance increases from the source, analogous to the thinning out of the widening oil slick. This notion is represented in the figure by the thinning of the lines at greater distances from the source. Suppose we measure how much power registers on a certain fixed amount of surface area (e.g., a square inch). As a result, a progressively smaller proportion of the original power falls onto a square inch as the distance from the source increases, represented in the figure by the lighter shading of the same-size ovals at increasing distances from the source.

The examples just described reveal that a new quantity, called **intensity (I),** develops when power

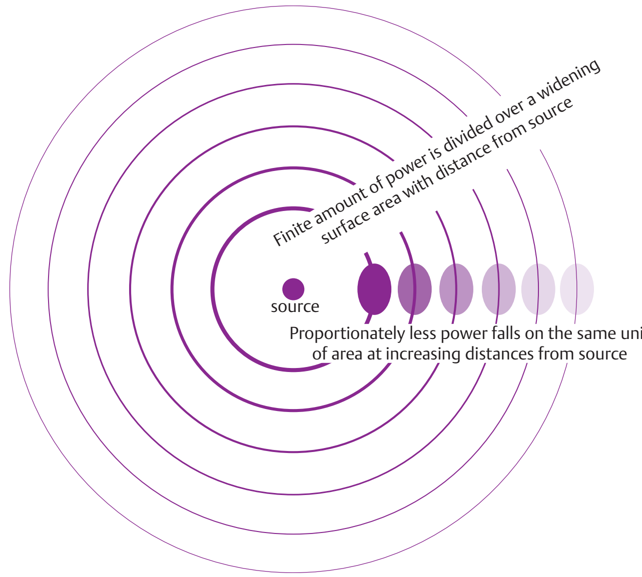

Fig. 1.1 Intensity (power divided by area) decreases with distance from the sound source because a fixed amount of power is spread over an increasing area, represented by the thinning of the lines. Proportionately less power falls on the same unit area (represented by the lighter shading of the ovals) with increasing distance from the source.

is distributed over area. Specifically, intensity is equal to power per unit area, or power divided by area, or

$$I = \frac{P}{A}$$

Because power is measured in watts and area is measured in square meters in the MKS system, intensity is expressed in watts per square meter (w/m^2). Intensity is expressed in watts per square centimeter (w/cm^2) in the cgs system.

Intensity decreases with increasing distance from a sound source according to a rule called the **inverse square law**. It states that the amount of intensity drops by 1 over the square of the change in distance. Two examples are illustrated in **Fig. 1.2**. Frame **a** shows that when the distance from a loudspeaker is doubled from 5 m to 10 m, the amount of intensity at 10 m will be one quarter of what it was at 5 m (because $1/2^2 = 1/4$). Similarly, frame **b** shows that tripling the distance from 5 m to 15 m causes the intensity to fall to one ninth of its value at the closer point because $1/3^2 = 1/9$.

An important relationship to be aware of is that power is equal to pressure squared,

$$P = p^2$$

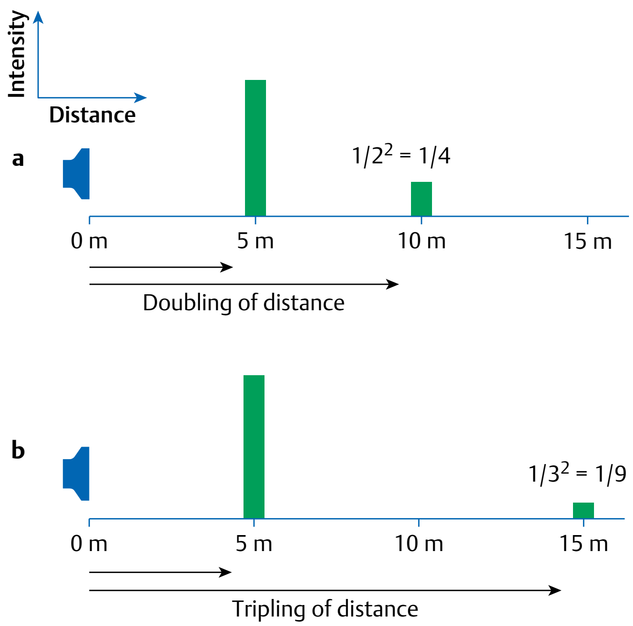

Fig. 1.2 Illustrations of the inverse square law. **(a)** Doubling of distance: The intensity at 10 m away from a loudspeaker is one quarter of its intensity at 5 m because $1/2^2 = 1/4$. **(b)** Tripling of distance: The intensity at 15 m away from the sources is one ninth of its intensity at 5 m because $1/3^2 = 1/9$.

and pressure is equal to the square root of power,

$$p = \sqrt{P}$$

In addition, intensity is proportional to pressure squared,

$$I \propto p^2$$

and pressure is proportional to the square root of intensity,

$$p \propto \sqrt{I}$$

This simple relationship makes it easy to convert between sound intensity and sound pressure.

The Nature of Sound

Sound is often defined as a form of vibration that propagates through the air in the form of a wave. **Vibration** is nothing more than the to-and-fro motion (oscillation) of an object. Some examples include a playground swing, a pendulum, the floorboards under a washing machine, a guitar string, a tuning fork prong, and air molecules. The vibration is usually called **sound** when it is transferred from air particle to air particle (we will see how this happens later). The vibration of air particles might have a simple pattern such as the tone produced by a tuning fork, or a very complex pattern such as the din heard in a school cafeteria. Most naturally occurring sounds are very complex, but the easiest way to understand sound is to concentrate on the simplest ones.

Simple Harmonic Motion

A vibrating tuning fork is illustrated in **Fig. 1.3**. The initial force that was applied by striking the tuning fork is represented by the green arrow in frame 1. The progression of the drawings represents the motion of the prongs at selected points in time after the fork has been activated. The two prongs vibrate as mirror images of each other, so that we can describe what is happening in terms of just one prong. The *insert* highlights the motion of the right prong. Here the center position is where the prong would be at rest. When the fork is struck the prong is forced inward as shown by arrow **a**. After reaching the leftmost position it bounces back (arrow **b**), accelerating along the way. The rapidly moving prong overshoots the center and continues rightward (arrow **c**). It slows down along the way until it stops for an instant at the extreme right, where it reverses direction again and starts moving toward the left (arrow **d**) at an ever-increasing speed. It overshoots the center again, and as before, the prong now follows arrow **a**, slowing down until it stops momentarily at the extreme left. Here it reverses direction again and repeats the same process over and over again. One complete round trip (or replication) of an oscillating motion is called a **cycle**. The number of cycles that occur in one second is called **frequency**.

This form of motion occurs when a force is applied to an object having the properties of inertia and elasticity. Due to its elasticity, the deformation of the fork caused by the applied force is opposed by a restoring force. In the figure the initial leftward force is opposed by a restoring force in the opposite direction, that is, toward the right. The rightward restoring force increases as the prong is pushed progressively toward the left. As a result, the movement of the prong slows down and eventually stops. Under the influence of its elasticity the prong now reverses direction and starts moving rightward. As the restoring force brings the prong back toward the center, we must also consider its mass. Because the prong has mass, inertia causes it to accelerate as it moves back

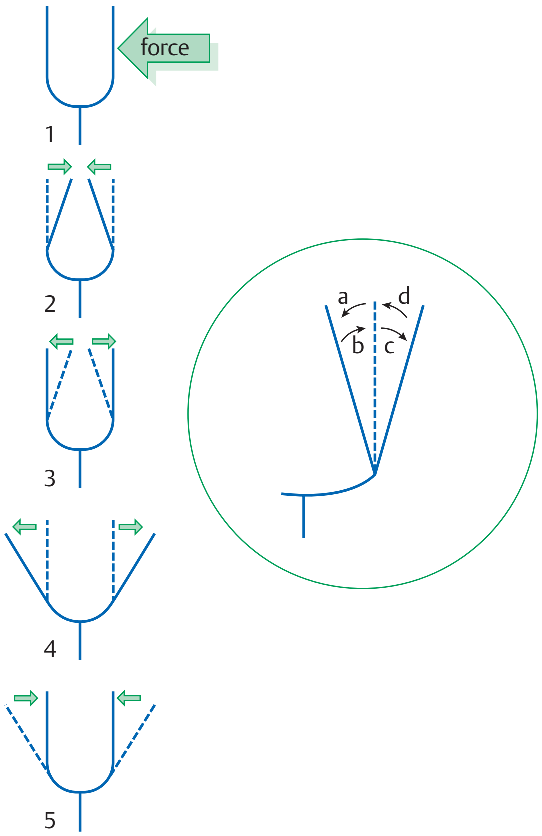

Fig. 1.3 After being struck, a tuning fork vibrates or oscillates with a simple pattern that repeats itself over time. One replication (cycle) of this motion is illustrated going from frames 1 to 5. The arrows in the insert highlight the motion of one of the prongs.

toward its center resting position. In fact, the prong is moving at its maximum speed as it passes through the resting position. The force of inertia causes the prong to overshoot the center and continue moving rightward. The deformation process begins again once the prong overshoots its resting position. As a result, opposing elastic restoring forces start building up again, now in the leftward direction. Just as before, the increasing (leftward) restoring force eventually overcomes the rightward inertial force, thereby stopping the prong's displacement at the rightmost point, and causing a reversal in the direction of its movement. Hence, the same course of events is repeated again, this time in the leftward direction; then rightward, then leftward, etc., over and over again. This kind of vibration is called **simple harmonic motion (SHM)** because the oscillations repeat themselves at the same rate over and over again.

We know from experience that the oscillations just described do not continue forever. Instead, they dissipate over time and eventually die out completely. The dying out of vibrations over time is called **damping**, and it occurs due to resistance or friction. Resistance occurs because the vibrating prong is always in contact with the surrounding air. As a result, there will be friction between the oscillating metal and the surrounding air molecules. This friction causes some of the mechanical energy that has been supporting the motion of the tuning fork to be converted into heat. In turn, the energy that has been converted into heat is no longer available to maintain the vibration of the tuning fork. Consequently, the sizes of the oscillations dissipate and eventually die out altogether.

A diagram summarizing the concepts just described is shown in Fig. 1.4. The curve in the figure represents the tuning fork's motion. The amount of displacement of the tuning fork prong around its resting (or center) position is represented by distance above and below the horizontal line. These events are occurring over time, which is represented by horizontal distance (from left to right). The initial displacement of the prong due to the original applied force is represented by the dotted segment of the curve. Inertial forces due to the prong's mass and elastic restoring forces due to the elasticity of the prong are represented by labeled arrows. Damping of the oscillations due to friction is shown by the decline in the displacement of the curve as time goes on. The curve in this diagram is an example of a **waveform**, which is a graph that shows displacement (or another measure of magnitude) as a function of time.

Sound Waves

Tuning fork vibrations produce sound because the oscillations of the prongs are transmitted to the surrounding air particles. When the tuning fork prong moves to the right, it displaces air molecules to its right in the same direction. These molecules are thus displaced to the right of their own resting positions. Displacing air molecules toward the right pushes them closer to the air particles to their right. The pressure that exists among air molecules that are not being disturbed by a driving force (like the tuning fork) is known as *ambient or atmospheric pressure*. We can say that the rightward motion of the tuning fork prong exerts a force on the air molecules that pushes them together relative to their undisturbed, resting situation. In other words, forcing the air molecules together causes an increase in air pressure relative to the ambient pressure that existed among the undisturbed molecules. This state of positive air pressure is called **compression**. The amount of compression increases as the prong continues displacing

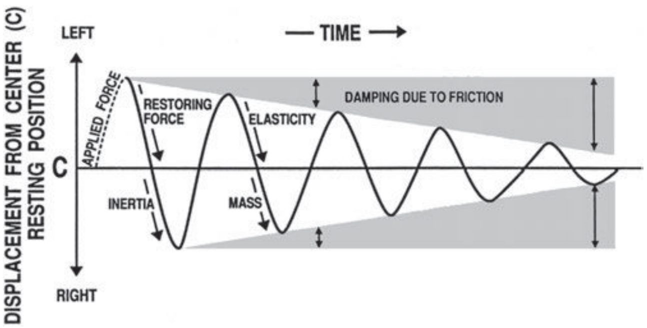

Fig. 1.4 Diagrammatic representation of tuning fork oscillations over time. Vertical displacement represents the amount of the tuning fork prong displacement around its resting position. Distance from left to right represents the progression of time. (From Gelfand 2010, courtesy of Informa.)

the air molecules rightward. A maximum amount of positive pressure occurs when the prong and air molecules reach their greatest rightward displacement.

The tuning fork prong then reverses direction, overshoots its resting position, and proceeds to its leftmost position. The compressed air molecules reverse direction along with the prong. This occurs because air is an elastic medium, so the particles compressed to the right develop a leftward restoring force. Small as they are, air particles do have mass. Therefore, inertia causes the rebounding air particles to overshoot their resting positions and to continue toward their extreme leftward positions. As the particles move leftward, the amount of compression decreases and is momentarily zero as they pass through their resting positions. As they continue to move to the left of their resting positions, the particles are now becoming increasingly farther from the molecules to their right (compared with when they are in their resting positions). We now say that the air particles are rarefied compared with their resting states, so that the air pressure is now below atmospheric pressure. This state of lower than ambient pressure is called **rarefaction**. When the air particles reach the leftmost position they are maximally rarefied, which means that the pressure is maximally negative. At this point, the restoring force instigates a rightward movement of the air molecules. This movement is enhanced by the push of the tuning fork prongs that have also reversed direction. The air molecules now accelerate rightward (so that the amount of rarefaction decreases), overshoot their resting positions, and continue to the right, and so on. The tuning fork vibrations have now been transmitted to the surrounding particles, which are now also oscillating in simple harmonic motion. Sounds that are associated with simple harmonic motion are called **pure tones**.

Let us consider one of the air molecules that has already been set into harmonic motion by the tuning fork. This air particle now vibrates to-and-fro in the same direction that was originally imposed by the vibrating prong. When this particle moves toward its right it will cause a similar displacement of the particle that is located there. The subsequent leftward motion is also transmitted to the next particle, etc. Thus, the oscillations of one air particle are transmitted to the molecule next to it. The second particle is therefore set into oscillation, which in turn initiates oscillation of the next one, and so forth down the line. In other words, each particle vibrates back and forth around its own resting point, and causes successive molecules to vibrate back and forth around their own resting points, as shown schematically in **Fig. 1.5**. Notice that each molecule vibrates "in place" around its own average position; it is the vibratory pattern that is transmitted through the air.

This propagation of vibratory motion from particle to particle constitutes the sound wave. This wave appears as alternating compressions and rarefactions radiating from the sound source in all directions, as already suggested in **Fig. 1.1**. The transmission of particle motion along with the

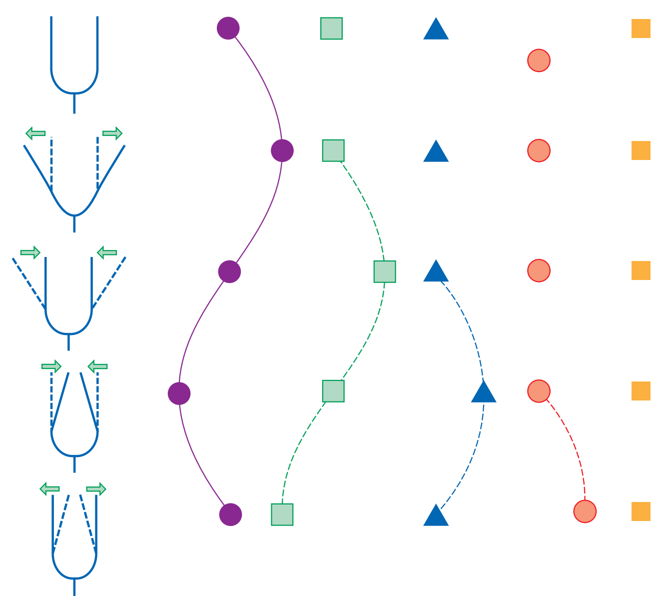

Fig. 1.5 Sound is initiated by transmitting the vibratory pattern of the sound source to nearby air particles, and then the vibratory pattern is passed from particle to particle as a wave. Notice how it is the pattern of vibration that is being transmitted, whereas each particle oscillates around its own average location.