HEARING

An Introduction to Psychological and Physiological Acoustics

SIXTH EDITION

STANLEY A. GELFAND

CRC Press
Taylor & Francis Group

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To Janice
In Loving Memory

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Preface

This is the sixth edition of a textbook intended to provide beginning graduate students with an introduction to the sciences of hearing, as well as to provide an overview of the field for more experienced readers.

The need for a current text of this type has been expanded by the advent of the professional doctorate in audiology, the AuD in addition to those in PhD programs in the speech and hearing sciences. However, an interest in hearing is by no means limited to audiologists and speech and hearing scientists. It includes readers with widely diverse academic backgrounds, such as psychologists, speech-language pathologists, physicians, deaf educators, industrial hygienists, linguists and engineers, among others. The result is a frustrating dilemma in which a text will likely be too basic for some of its intended readers and too advanced for others. Thus, the idea is to provide a volume sufficiently detailed to serve as a core text for graduate students with a primary interest in hearing, while at the same time avoiding a reliance on scientific or mathematical backgrounds not shared by those with different kinds of academic experiences.

Hearing science is an exciting area of study because of its broad, interdisciplinary scope, and even more because it is vital and dynamic. Research continuously provides new information to expand on the old and also causes us to rethink what was once well established. The reader (particularly the beginning student) is reminded that new findings occasionally disprove the "laws" of the past. Thus, this textbook should be treated as a first step; it is by no means the final word.

In addition to reflecting advances in the field, the sixth edition of *Hearing* has been strongly influenced by extensive comments and suggestions from both colleagues and graduate students. This has resulted in updates, changes, and additions to the material as well as several new and revised figures; but every effort has been made to maintain the fundamental characteristics of the prior editions wherever possible. These include the basic approach, structure, format, and the general (and often irregular) depth of coverage, the provision of references at the end of each chapter, and the provision of liberal references to other sources for further study. As one might expect, the hardest decisions involved choosing material that could be streamlined, replaced, or omitted, keeping the original orientation and flavor of the book, and avoiding a "state-of-the-art" treatise.

It is doubtful that all of the material covered in this text would be addressed in a single one-semester course, nor that it would be the only source used. It is more likely that this book would be used as a core text for a two-course sequence dealing with psychological and physiological acoustics, along with appropriately selected readings from the research literature and state-of-the-art books. Suggested readings are provided in context throughout the text to provide a firm foundation for further study.

My heartfelt appreciation is expressed to the numerous colleagues and students who provided me with valuable suggestions that have been incorporated into this and prior editions. I am especially indebted to my current and former colleagues and students in the Department of Linguistics and Communication Disorders at Queens College, the PhD Program in Speech-Language-Hearing Sciences, and the AuD Program at the City University of New York Graduate Center, and at the East Orange Veterans Affairs Medical Center. Thank you all for being continuous examples of excellence and for your valued friendships. I am also grateful to the talented and dedicated staff of CRC Press/Taylor & Francis Group, who contributed so much to this book and graciously arranged for the preparation of the indices and the proofreading of the final page proofs.

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Stanley A. Gelfand

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Physical concepts

This book is concerned with hearing, and what we hear is sound. Thus, both intuition and reason make it clear that a basic understanding of the nature of sound is prerequisite to an understanding of audition. The study of sound is acoustics. An understanding of **acoustics**, in turn, rests upon knowing several fundamental physical principles. This is so because acoustics is, after all, the physics of sound. We will therefore begin by reviewing a number of physical principles so that the following chapters can proceed without the constant need for the distracting insertions of basic definitions and concepts. The material in this chapter is intended to be a review of principles that were previously learned. Therefore, the review will be rapid and somewhat cursory, and the reader may wish to consult the American National Standard addressing acoustical terminology and a physics or acoustics textbook for a broader coverage of these topics (e.g., Pearce and David, 1958; van Bergeijk et al., 1960; Peterson and Gross, 1972; Beranek, 1986; Kinsler et al., 1999; Speaks, 1999; Everest, 2000; Rossing et al., 2002; Hewitt, 2005; Young and Freedman, 2007),* as well as the American National Standard addressing acoustical terminology (ANSI, 2004).

PHYSICAL QUANTITIES

Physical quantities may be thought of as being basic or derived, and as either scalars or vectors. The **basic quantities** of concern here are **time**, **length (distance)**, and **mass**. The **derived quantities** are the results of various combinations of the basic quantities (and other derived quantities), and include such phenomena as velocity, force, and work. If a quantity can be described completely in terms of *just* its *magnitude* (size), then it is a **scalar**. Length is a good example of a scalar. On the other hand, a quantity is a **vector** if it needs to be described by *both* its *magnitude* and its *direction*. For example, if a body moves 1 m from point x_1 to point x_2, then we say that it has been displaced. Here, the scalar quantity of length becomes the vector quantity of **displacement** when both magnitude and direction are involved. A derived quantity is a vector if any of its components is a vector. For example, force is a vector because it involves the components of mass (a scalar) and acceleration (a vector). The distinction between scalars and vectors is not just some esoteric concept. One must be able to distinguish between scalars and vectors because they are manipulated differently in calculations.

The basic quantities may be more or less appreciated in terms of one's personal experience, and are expressed in terms of conventionally agreed upon units. These units are values that are measurable and repeatable. The unit of **time (t)** is the **second (s)**, the unit of **length (L)** is the **meter (m)**, and the unit of **mass (M)** is the **kilogram (kg)**. There is a common misconception that mass and weight are synonymous. This is actually untrue. Mass is related to the density of a body, which is the same for that body no matter where it is located. On the other hand, an object's weight is related to the force of gravity upon it, so that weight changes as a function of gravitational attraction. It is common knowledge that an object weighs more on earth than it would on the moon, and that it weighs more at sea level than it would in a high-flying airplane. In each of these cases, the mass of the body is the same in spite of the fact that its weight is different.

* While no longer in print, the interested student may be able to find the classical books by Pearce and David (1958), van Bergeijk et al. (1960), and Peterson and Gross (1972) in some libraries.

A brief word is appropriate at this stage regarding the availability of several different systems of units. When we express length in meters and mass in kilograms we are using the units of the *Système International d'Unités*, referred to as the **SI** or the **MKS system**. Here, MKS stands for *meters*, *kilograms*, and *seconds*. An alternative scheme using smaller metric units coexists with MKS, which is the **cgs system** (for *centimeters*, *grams*, and *seconds*), as does the English system of weights and measures. Table 1.1 presents a number of the major basic and derived physical quantities we will deal with, their units, and their conversion factors.*

Velocity (v) is the speed at which an object is moving, and is derived from the basic quantities of displacement (which we have seen is a vector form of length) and time. On average, velocity is the distance traveled divided by the amount of time it takes to get from the starting point to the destination. Thus, if an object leaves point x_1 at time t_1 and arrives at x_2 at time t_2, then we can compute the average velocity as

$$v = \frac{(x_2 - x_1)}{(t_2 - t_1)} \tag{1.1}$$

If we call $(x_2 - x_1)$ displacement (x) and $(t_2 - t_1)$ time (t), then, in general:

$$v = \frac{x}{t} \tag{1.2}$$

Because displacement (x) is measured in meters and time (t) in seconds, velocity is expressed in meters per second (m/s).

In contrast to **average velocity** as just defined, **instantaneous velocity** is used when we are concerned with the speed of a moving body at a *specific moment* in time. Instantaneous velocity reflects the speed at some point in time when the displacement and time between that point and the next one approaches zero. Thus, students with a background in mathematics will recognize that instantaneous velocity is equal to the derivative of displacement with respect to time, or

$$v = \frac{dx}{dt} \tag{1.3}$$

As common experience verifies, a fixed speed is rarely maintained over time. Rather, an object may speed up or slow down over time. Such a change of velocity over time is **acceleration (a)**. Suppose we are concerned with the average acceleration of a body moving between two points. The velocity of the body at the first point is v_1 and the time as it passes that point is t_1. Similarly, its velocity at the second point and the time when it passes this point are, respectively, v_2 and t_2. The **average acceleration** is the difference between these two velocities divided by the time interval involved:

$$a = \frac{(v_2 - v_1)}{(t_2 - t_1)} \tag{1.4}$$

or, in general:

$$a = \frac{v}{t} \tag{1.5}$$

If we recall that velocity corresponds to displacement divided by time (Equation 1.2), we can substitute x/t for v, so that

$$a = \frac{\frac{x}{t}}{t} = \frac{x}{t^2} \tag{1.6}$$

Therefore, acceleration is expressed in units of meters per second squared (m/s^2) or centimeters per second squared (cm/s^2).

The acceleration of a body at a given moment is called its **instantaneous acceleration**, which is the derivative of velocity with respect to time, or

$$a = \frac{dv}{dt} \tag{1.7}$$

* Students with a penchant for trivia will be delighted to know the following details. (1) One second is the time needed to complete 9,192,631,770 cycles of radiation of cesium-133 atoms in an atomic clock (for an interesting and informative discussion, see Finkleman et al., 2011). (2) The reference value for 1 kg of mass is that of a cylinder of platinum–iridium alloy kept in the International Bureau of Weights and Measures in France. (3) One meter is 1,650,763.73 times the wavelength of orange-red light emitted by krypton-86 under certain conditions.

Table 1.1 Principal physical quantities

Quantity	Formula	SI (MKS) units	cgs units	Equivalent values
Time (t)	t	second (s)	s	
Mass (M)	M	kilogram (kg)	gram (g)	1 kg = 1000 g
Displacement (x)	x	meter (m)	centimeter (cm)	1 m = 100 cm
Area (A)	A	m^2	cm^2	$1\ m^2 = 10^4\ cm^2$
Velocity (v)	v = x/t	m/s	cm/s	1 m/s = 100 cm/s
Acceleration (a)	a = v/t $= x/t^2$	m/s^2	cm/s^2	$1\ m/s^2 = 100\ cm/s^2$
Force (F)	F = Ma = Mv/t	newton (N) $kg \cdot m/s^2$	dyne (d) $g \cdot cm/s^2$	$1\ N = 10^5\ d$
Work (w)	w = Fx	joule (J) N · m	erg d · cm	$1\ J = 10^7$ erg
Power (P)	P = w/t = Fx/t = Fv	watt (W)	watt (W)	$1\ W = 1\ J/s = 10^7$ erg/s
Intensity (I)	I = P/A	W/m^2	W/cm^2	Reference values: $10^{-12}\ W/m^2$ or $10^{-16}\ W/cm^2$
Pressure (p)	p = F/A	pascal (Pa) N/m^2	microbar (μbar) d/cm^2	Reference values: $2 \times 10^{-5}\ N/m^2$ (μPa) or $2 \times 10^{-4}\ d/cm^2$ (μbar)[a]

[a] The reference value for sound pressure in cgs units is often written as 0.0002 dynes/cm^2.

Recalling that velocity is the first derivative of displacement (Equation 1.3), and substituting, we find that acceleration is the second derivative of displacement:

$$a = \frac{d^2x}{dt^2} \tag{1.8}$$

Common experience and Newton's first law of motion tell us that if an object is not moving (is at rest), then it will tend to remain at rest, and that if an object is moving in some direction at a given speed, that it will tend to continue doing so. This phenomenon is **inertia**, which is the property of mass to continue doing what it is already doing. An outside influence is needed in order to make a stationary object move, or to change the speed or direction of a moving object. That is, a **force (F)** is needed to overcome the body's inertia. Because a change in speed is acceleration, we may say that force is that which causes a mass to be accelerated, that is, to change its speed or direction. The amount of force is equal to the product of mass times acceleration (Newton's second law of motion):

$$F = Ma \tag{1.9}$$

Recall that acceleration corresponds to velocity over time (Equation 1.5). Substituting v/t for a (acceleration) reveals that force can also be defined in the form

$$F = \frac{Mv}{t} \tag{1.10}$$

where **Mv** is the property of **momentum**. Stated in this manner, force is equal to momentum over time.

Because force is the product of mass and acceleration, the amount of force is measured in $kg \cdot m/s^2$. The unit of force is the **newton (N)**, which is the force needed to cause a 1-kg mass to be accelerated by 1 kg · m/s^2 (i.e., 1 N = kg · m/s^2). It would thus take a 2-N force to cause a 2-kg mass to be accelerated by 1 m/s^2, or a 1-kg mass to be accelerated by 2 kg · m/s^2. Similarly, the force required to accelerate a 6-kg mass by 3 m/s^2 would be 18 N. The unit of force in cgs units is the **dyne**, where 1 dyne = 1 g · cm/s^2 and 10^5 dynes = 1 N.

Actually, many forces tend to act upon a given body at the same time. Therefore, the force referred to in Equations 1.9 and 1.10 is actually the resultant or net force, which is the net effect of all forces acting upon the object. The concept of net force is clarified by a few simple examples: If two forces are both pushing on a body in the same direction, then the net force would be the sum of these two forces. (For example, consider a force of 2 N that is pushing an object toward the north, and a second force of 5 N that is also pushing that object in the same direction. The net force would be 2 N + 5 N, or 7 N and the direction of acceleration would be to the north.) Alternatively, if two forces are pushing on the same body but in opposite directions, then the net force is the difference between the two, and the object will be accelerated in the direction of the greater force. (Suppose, for example, that a 2-N force is pushing an object toward the east and that a 5-N force is simultaneously pushing it toward the west. The net force would be 5 N – 2 N, or 3 N which would cause the body to accelerate toward the west.)

If two equal forces push in opposite directions, then net force would be zero, in which case there would be no change in the motion of the object. This situation is called **equilibrium**. Thus, under conditions of equilibrium, if a body is already moving, it will continue in motion, and if it is already at rest, it will remain still. That is, of course, what Newton's first law of motion tells us.

Experience, however, tells us that a moving object in the real world tends to slow down and will eventually come to a halt. This occurs, for example, when a driver shifts to "neutral" and allows his car to coast on a level roadway. Is this a violation of the laws of physics? Clearly, the answer is no. The reason is that in the real world a moving body is constantly in contact with other objects or mediums. The sliding of one body against the other constitutes a force opposing the motion, called **friction** or **resistance**. For example, the coasting automobile is in contact with the surrounding air and the roadway; moreover, its internal parts are also moving one upon the other.

The opposing force of friction depends on two factors. Differing amounts of friction occur depending upon what is sliding on what. The magnitude of friction between two given materials is called the **coefficient of friction**. Although the details of this quantity are beyond current interest, it is easily understood that the coefficient of friction is greater for "rough" materials than for "smooth" or "slick" ones.

The second factor affecting the force of friction is easily demonstrated by an experiment the reader can do by rubbing the palms of his hands back and forth on one another. First rub slowly and then rapidly. Not surprisingly, the rubbing will produce heat. The temperature rise is due to the conversion of the mechanical energy into heat as a result of the friction, and will be addressed again in another context. For the moment, we will accept the amount of heat as an indicator of the amount of friction. Note that the hands become hotter when they are rubbed together more rapidly. Thus, the amount of friction is due not only to the coefficient of friction (R) between the materials involved (here, the palms of the hands), but also to the velocity (v) of the motion. Stated as a formula, the force of friction (F) is thus

$$F = Rv \tag{1.11}$$

A compressed spring will bounce back to its original shape once released. This property of a deformed object to return to its original form is called **elasticity**. The more elastic or stiff an object, the more readily it returns to its original form after being deformed. Suppose one is trying to compress a coil spring. It becomes increasingly more difficult to continue squeezing the spring as it becomes more and more compressed. Stated differently, the more the spring is being deformed, the more it opposes the applied force. The force that opposes the deformation of a spring-like material is called the **restoring force**.

As the example just cited suggests, the restoring force depends on two factors; the elastic modulus of the object's material and the degree to which the object is displaced. An **elastic modulus** is the ratio of stress to strain. **Stress** (s) is the ratio of the applied force (F) to the area (A) of an elastic object over which it is exerted, or

$$s = F/A \tag{1.12}$$

The resulting relative displacement or change in dimensions of the material subjected to the stress is called **strain**. Of particular interest is **Young's modulus**, which is the ratio of compressive stress to compressive strain. **Hooke's law** states that stress and strain are proportional within the elastic limits of the material, which is equivalent to stating that a material's elastic modulus is a constant within these limits. Thus, the restoring force (F) of an elastic material that opposes an applied force is

$$F = Sx \tag{1.13}$$

where S is the stiffness constant of the material and x is the amount of displacement.

The concept of "work" in physics is decidedly more specific than its general meaning in daily life. In the physical sense, **work (w)** is done when the application of a force to a body results in its displacement. The amount of work is therefore the product of the force applied and the resultant displacement, or

$$w = Fx \tag{1.14}$$

Thus, work can be accomplished only when there is displacement: If the displacement is zero, then the product of force and displacement will also be zero no matter how great the force. Work is quantified in Newton-meters (N · m); and the unit of work is the **joule (J)**. Specifically, one joule (1 J) is equal to 1 N · m. In the cgs system, work is expressed in **ergs**, where 1 erg corresponds to 1 dyne-centimeter (1 d · cm).

The capability to do work is called **energy**. The energy of an object in motion is called **kinetic energy** and the energy of a body at rest is its **potential energy**. **Total energy** is the body's kinetic energy plus its potential energy. Work corresponds to the change in the body's kinetic energy. The energy is not consumed, but rather is converted from one form to the other. Consider, for example, a pendulum that is swinging back and forth. Its kinetic energy is greatest when it is moving the fastest, which is when it passes through the midpoint of its swing. On the other hand, its potential energy is greatest at the instant that it reaches the extreme of its swing, when its speed is zero.

We are concerned not only with the amount of work, but also with how fast it is being accomplished. The rate at which work is done is **power (P)** and is equal to work divided by time,

$$P = w/t \tag{1.15}$$

in joules per second (J/s). The **watt (W)** is the unit of power, and 1 W is equal to 1 J/s. In the cgs system, the watt is equal to 10^7 ergs/s.

Recalling that w = Fx, then Equation 1.15 may be rewritten as

$$P = Fx/t \tag{1.16}$$

If we now substitute v for x/t (based on Equation 1.2), we find that

$$P = Fv \tag{1.17}$$

Thus, power is equal to the product of force and velocity.

The amount of power per unit of area is called **intensity (I)**. In formal terms,

$$I = P/A \tag{1.18}$$

where I is intensity, P is power, and A is area. Therefore, intensity is measured in watts per square meter (W/m^2) in SI units, or in watts per square centimeter (W/cm^2) in cgs units. Because of the difference in the scale of the area units in the MKS and cgs systems, we find that **10^{-12} W/m²** corresponds to **10^{-16} W/cm²**. This apparently peculiar choice of equivalent values is being provided because they represent the amount of intensity required to just barely hear a sound.

An understanding of intensity will be better appreciated if one considers the following. Using for the moment the common knowledge idea of what sound is, imagine that a sound source is a tiny pulsating sphere. This *point source* of sound will produce a sound wave that will radiate outward in every direction, so that the propagating wave may be conceived of as a sphere of ever-increasing size. Thus, as distance from the point source increases, the power of the sound will have to be divided over the ever-expanding surface. Suppose now that we measure how much power registers on a one-unit area of this surface at various distances from the source. As the overall size of the sphere is getting larger with distance from the source, so this one-unit sample must represent an ever-decreasing proportion of the total surface area. Therefore, less power "falls" onto the same area as the distance from the source increases. It follows that the magnitude of the sound appreciated by a listener would become less and less with increasing distance from a sound source.

The intensity of a sound decreases with distance from the source according to an orderly rule as long as there are no reflections, in which case a **free field** is said to exist. Under these conditions, increasing the distance (D) from a sound source causes the intensity to decrease to an amount equal to 1 over the square of the change in distance ($1/D^2$). This principle is known as the inverse-square law. In effect, the **inverse square law** says that doubling the distance from the sound source (e.g., from 1 to 2 m) causes the intensity to drop to $1/2^2$ or 1/4 of the original intensity. Similarly, tripling the distance causes the intensity to fall to $1/3^2$, or 1/9 of the prior value; four times the distance results in $1/4^2$, or 1/16 of the intensity; and a tenfold increase in distance causes the intensity to fall $1/10^2$, or 1/100 of the starting value.

Just as power divided by area yields intensity, so force (F) divided by area yields a value called **pressure (p)**:

$$p = F/A \tag{1.19}$$

so that pressure is measured in N/m^2 or in dynes/cm^2. The unit of pressure is called the **pascal (Pa)**, where 1 Pa = 1 N/m^2. As for intensity, the softest audible sound can also be expressed in terms of its pressure, for which $\mathbf{2 \times 10^{-5}\ N/m^2}$ and $\mathbf{2 \times 10^{-4}}$ **dynes/cm²** are equivalent values.

DECIBEL NOTATION

The range of magnitudes we concern ourselves with in hearing is enormous. As we shall discuss in Chapter 9, the sound pressure of the loudest sound that we can tolerate is on the order of 10 million times greater than that of the softest audible sound. One can immediately imagine the cumbersome task that would be involved if we were to deal with such an immense range of numbers on a linear scale. The problems involved with and related to such a wide range of values make it desirable to transform the absolute physical magnitudes into another form, called **decibels (dB)**, which make the values both palatable and rationally meaningful.

One may conceive of the decibel as basically involving two characteristics, namely ratios and logarithms. First, the value of a quantity is expressed in relation to some meaningful baseline value in the form of a ratio. Because it makes sense to use the softest sound one can hear as our baseline, we use the intensity or pressure of the softest audible sound as our reference value.

As introduced earlier, the **reference sound intensity** is 10^{-12} W/m^2 and the equivalent **reference sound pressure** is 2×10^{-5} N/m^2. Recall also that the equivalent corresponding values in cgs units are 10^{-16} W/cm^2 for sound intensity and 2×10^{-4} dynes/cm^2 for sound pressure. The appropriate reference value becomes the denominator of our ratio and the absolute intensity or pressure of the sound in question becomes the numerator. Thus, instead of talking about a sound having an absolute intensity of 10^{-10} W/m^2, we express its intensity relatively in terms of how it relates to our reference, as the ratio:

$$\frac{(10^{-10}\,W/m^2)}{(10^{-12}\,W/m^2)}$$

which reduces to simply 10^2. This intensity ratio is then replaced with its common logarithm. The reason is that the linear distance between numbers having the same ratio relationship between them (say, 2:1) becomes wider when the absolute magnitudes of the numbers become larger. For example, the distance between the numbers in each of the following pairs increases appreciably as the size of the numbers becomes larger, even though they all involve the same 2:1 ratio: 1:2, 10:20, 100:200, and 1000:2000. The logarithmic conversion is used because equal ratios are represented as equal distances on a logarithmic scale.

The decibel is a relative entity. This means that the decibel in and of itself is a dimensionless quantity, and is meaningless without knowledge of the reference value, which constitutes the denominator of the ratio. Because of this, it is necessary to make the reference value explicit when the magnitude of a sound is expressed in decibel form. This is accomplished by stating that the magnitude of the sound is whatever number of decibels with respect to the reference quantity. Moreover, it is common practice to add the word "level" to the original quantity when dealing with dB values. Intensity expressed in decibels is called **intensity level (IL)** and sound pressure in decibels is called **sound pressure level (SPL)**. The reference values indicated above are generally assumed when decibels are expressed as **dB IL** or **dB SPL**. For example, one might say that the intensity level of a sound is "50 dB *re*: 10^{-12} W/m²" or "50 dB IL."

The general formula for the decibel is expressed in terms of power as

$$PL_{dB} = 10 \cdot \log\left(\frac{P}{P_0}\right) \quad (1.20)$$

where P is the power of the sound being measured, P_0 is the reference power to which the former is being compared, and PL is the **power level**. Acoustical measurements are, however, typically made in terms of intensity or sound pressure. The applicable formula for decibels of intensity level is thus:

$$IL_{dB} = 10 \cdot \log\left(\frac{I}{I_0}\right) \quad (1.21)$$

where I is the intensity (in W/m²) of the sound in question, and I_0 is the reference intensity, or 10^{-12} W/m². Continuing with the example introduced above, where the value of I is 10^{-10} W/m², we thus find that

$$\begin{aligned} IL_{dB} &= 10 \cdot \log\left(\frac{10^{-10}\ \mathrm{W/m^2}}{10^{-12}\ \mathrm{W/m^2}}\right) \\ &= 10 \cdot \log 10^2 \\ &= 10 \times 2 \\ &= 20\,\mathrm{dB} \quad \textit{re}{:}\,10^{-12}\ \mathrm{W/m^2} \end{aligned}$$

In other words, an *intensity* of 10^{-10} W/m² corresponds to an **intensity level** of 20 dB *re*: 10^{-12} W/m², or 20 dB IL.

Sound intensity measurements are important and useful, and are preferred in certain situations. (See Rasmussen [1989] for a review of this topic.) However, most acoustical measurements involved in hearing are made in terms of sound pressure, and are thus expressed in decibels of **sound pressure level**. Here, we must be aware that intensity is proportional to pressure squared:

$$I \propto p^2 \quad (1.22)$$

and

$$p \propto \sqrt{I} \quad (1.23)$$

As a result, converting the dB IL formula into the equivalent equation for dB SPL involves replacing the intensity values with the squares of the corresponding pressure values. Therefore,

$$SPL_{dB} = 10 \cdot \log\left(\frac{p^2}{{p_0}^2}\right) \quad (1.24)$$

where p is the measured sound pressure and p_0 is the reference sound pressure (2×10^{-5} N/m²). This formula may be simplified to

$$SPL_{dB} = 10 \cdot \log\left(\frac{p}{p_0}\right)^2 \quad (1.25)$$

Because the logarithm of a number squared corresponds to two times the logarithm of that number (log x = 2 · log x), the square may be removed to result in

$$SPL_{dB} = 10 \cdot 2 \cdot \log\left(\frac{p}{p_0}\right) \quad (1.26)$$

Therefore, the simplified formula for decibels of SPL becomes

$$SPL_{dB} = 20 \cdot \log\left(\frac{p}{p_0}\right) \quad (1.27)$$

where the value of 20 (instead of 10) is due to having removed the square from the earlier described version of the formula. One *cannot* take the intensity ratio from the IL formula and simply insert it into the SPL formula, or vice versa. The square root of the intensity ratio yields the *corresponding* pressure ratio, which must then be placed into the SPL equation. Failure to use the proper terms will result in an erroneous doubling of the value in dB SPL.

By way of example, a sound pressure of 2×10^{-4} N/m^2 corresponds to an SPL of 20 dB (*re*: 2×10^{-5} N/m^2), which may be calculated as follows:

$$\begin{aligned} \text{SPL}_{\text{dB}} &= 20 \cdot \log\left(\frac{2\times10^{-4}\ \text{N/m}^2}{2\times10^{-5}\ \text{N/m}^2}\right) \\ &= 20 \cdot \log 10^1 \\ &= 20 \times 1 \\ &= 20\,\text{dB} \quad re\text{: } 10^{-5}\ \text{N/m}^2 \end{aligned}$$

What would happen if the intensity (or pressure) in question were the same as the reference intensity (or pressure)? In other words, what is the dB value of the reference itself? In terms of intensity, the answer to this question may be found by simply using 10^{-12} W/m^2 as both the numerator (I) and denominator (I_0) in the dB formula; thus,

$$\text{IL}_{\text{dB}} = 10 \cdot \log\left(\frac{10^{-12}\ \text{W/m}^2}{10^{-12}\ \text{W/m}^2}\right) \tag{1.28}$$

Because anything divided by itself equals 1, and the logarithm of 1 is 0, this equation reduces to

$$\begin{aligned} \text{IL}_{\text{dB}} &= 10 \cdot \log 1 \\ &= 10 \times 0 \\ &= 0\,\text{dB} \quad re\text{: } 10^{-12}\ \text{W/m}^2 \end{aligned}$$

Hence, 0 dB IL is the intensity level of the reference intensity. Just as 0 dB IL indicates the intensity level of the reference intensity, so 0 dB SPL similarly implies that the measured sound pressure corresponds to that of the reference

$$\text{SPL}_{\text{dB}} = 20 \cdot \log\left(\frac{2\times10^{-5}\ \text{N/m}^2}{2\times10^{-5}\ \text{N/m}^2}\right) \tag{1.29}$$

Just as we saw in the previous example, this equation is solved simply as follows:

$$\begin{aligned} \text{SPL}_{\text{dB}} &= 20 \cdot \log 1 \\ &= 20 \times 0 \\ &= 0\,\text{dB} \quad re\text{: } 10^{-5}\ \text{N/m}^2 \end{aligned}$$

In other words, 0 dB SPL indicates that the pressure of the sound in question corresponds to the reference sound pressure of 2×10^{-5} N/m^2. Notice that 0 dB does *not* mean "no sound." Rather, 0 dB implies that the quantity being measured is equal to the reference quantity. Negative decibel values indicate that the measured magnitude is smaller than the reference quantity.

Recall that sound intensity drops with distance from the sound source according to the inverse-square law. However, we want to know the effect of the inverse-square law in terms of *decibels of sound pressure level* because sound is usually expressed in these terms. To address this, we must first remember that pressure is proportional to the square root of intensity. Hence, pressure decreases according to the inverse of the distance change (1/D) instead of the inverse of the square of the distance change (1/D^2). In effect, the *inverse-square law* for *intensity* becomes an *inverse-distance law* when we are dealing with *pressure*. Let us assume a doubling as the distance change, because this is the most useful relationship. We can now calculate the size of the decrease in decibels between a point at some distance from the sound source (D_1, e.g., 1 m) and a point at twice the distance (D_2, e.g., 2 m) as follows:

$$\begin{aligned} \text{Level drop in SPL} &= 20 \cdot \log(D_2/D_1) \\ &= 20 \cdot \log(2/1) \\ &= 20 \cdot \log 2 \\ &= 20 \times 0.3 \\ &= 6\,\text{dB} \end{aligned}$$

In other words, the inverse-square law causes the sound pressure level to decrease by 6 dB whenever the distance from the sound source is doubled. For example, if the sound pressure level is 60 dB at 1 m from the source, then it will be $60 - 6 = 54$ dB when the distance is doubled to 2 m, and $54 - 6 = 48$ dB when the distance is doubled again from 2 to 4 m.

HARMONIC MOTION AND SOUND

What is sound? It is convenient to answer this question with a formally stated sweeping generality. For example, one might say that sound is a form of vibration that propagates through a medium (such as air) in the form of a wave. Although this statement is correct and straightforward, it can also be uncomfortably vague and perplexing. This is so because it assumes knowledge of definitions and concepts that are used in a very precise way, but which are familiar to most people only as "gut-level" generalities. As a result, we must address the underlying concepts and develop a functional vocabulary of physical terms that will not only make the general definition of sound meaningful, but will also allow the reader to appreciate its nature.

Vibration is the to-and-fro motion of a body, which could be anything from a guitar string to the floorboards under the family refrigerator, or a molecule of air. Moreover, the motion may have a very simple pattern as produced by a tuning fork, or an extremely complex one such as one might hear at lunchtime in an elementary school cafeteria. Even though few sounds are as simple as that produced by a vibrating tuning fork, such an example provides what is needed to understand the nature of sound.

Figure 1.1 shows an artist's conceptualization of a vibrating tuning fork at different moments of its vibration pattern. The heavy arrow facing the prong to the reader's right in Figure 1.1a represents the effect of applying an initial force to the fork, such as by striking it against a hard surface. The progression of the pictures in the figure from (a) through (e) represents the movements of the prongs as time proceeds from the moment that the outside force is applied.

Even though both prongs vibrate as mirror images of one another, it is convenient to consider just one of them for the time being. Figure 1.2 highlights the right prong's motion after being struck. Point C (center) is simply the position of the prong at rest. Upon being hit (as in Figure 1.1a) the prong is pushed, as shown by arrow 1, to point L (left). The prong then bounces back (arrow 2), picking up speed along the way. Instead of stopping at the center (C), the rapidly moving prong overshoots this point. It now continues rightward (arrow 3), slowing down along the way until it comes to a halt at point R (right). It now reverses direction and begins moving leftward (arrow 4) at an ever-increasing speed, so that it again overshoots the center. Now, again following arrow 1, the prong slows down until it reaches a halt at L, where it reverses direction and repeats the process.

The course of events just described is the result of applying a force to an object having the properties of elasticity and inertia (mass). The initial force to the tuning fork displaces the prong. Because the tuning fork possesses the property of elasticity, the deformation caused by the applied force is opposed by a restoring force in the opposite direction. In the case of the single prong in Figure 1.2, the initial force toward the left is opposed by a restoring force toward the right. As the prong is pushed farther to the left, the magnitude of the restoring force increases relative to the initially applied force. As a result, the prong's movement is slowed down, brought to a halt at point L, and reversed in direction. Now, under the influence of its elasticity, the prong starts moving rightward. Here, we must consider the mass of the prong.

As the restoring force brings the prong back toward its resting position (C), the inertial force of its mass causes it to increase in speed, or accelerate. When the prong passes through the resting position, it is actually moving fastest. Here, inertia does not permit the moving mass (prong) to simply stop, so instead it overshoots the center and continues its rightward movement under the force of

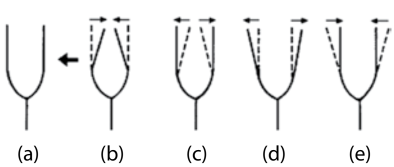

Figure 1.1 Striking a tuning fork (indicated by the heavy arrow) results in a pattern of movement that repeats itself over time. One complete cycle of these movements is represented from frames (a) through (e). Note that the two prongs move as mirror images of one another.

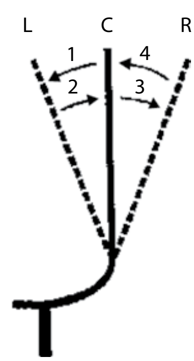

Figure 1.2 Movements toward the right (R) and left (L) of the center (C) resting position of a single tuning fork prong. The numbers and arrows refer to the text.

its inertia. However, the prong's movement is now resulting in deformation of the metal again once it passes through the resting position. Elasticity therefore comes into play with the buildup of an opposing (now leftward) restoring force. As before, the restoring force eventually equals the applied (now inertial) force, thus halting the fork's displacement at point R and reversing the direction of its movement. Here, the course of events described above again comes into play (except that the direction is leftward), with the prong building up speed again and overshooting the center (C) position as a result of inertia. The process will continue over and over again until it dies out over time, seemingly "of its own accord."

Clearly, the dying out of the tuning fork's vibrations does not occur by some mystical influence. On the contrary, it is due to **resistance**. The vibrating prong is always in contact with the air around it. As a result, there will be **friction** between the vibrating metal and the surrounding air particles. The friction causes some of the mechanical energy involved in the movement of the tuning fork to be converted into heat. The energy that has been converted into heat by friction is no longer available to support the to-and-fro movements of the tuning fork. Hence, the oscillations die out as continuing friction causes more and more of the energy to be converted into heat. This reduction in the size of the oscillations due to resistance is called **damping**.

The events and forces just described are summarized in Figure 1.3, where the tuning fork's motion is represented by the curve. This curve represents the displacement to the right and left of the center (resting) position as the distance above and below the horizontal line, respectively. Horizontal distance from left to right represents the progression of time. The initial dotted line represents its initial displacement due to the applied force. The elastic restoring forces and inertial forces of the prong's mass are represented by arrows. Finally, damping is shown by the reduction in the displacement of the curve from center as time goes on.

The type of vibration just described is called **simple harmonic motion (SHM)** because the to-and-fro movements repeat themselves at the same rate over and over again. We will discuss the nature of SHM in greater detail below with respect to the motion of air particles in the sound wave.

The tuning fork serves as a sound source by transferring its vibration to the motion of the surrounding air particles (Figure 1.4). (We will again concentrate on the activity to the right of the fork, remembering that a mirror image of this pattern occurs to the left.) The rightward motion of the tuning fork prong displaces air molecules to its right in the same direction as the prong's motion. These molecules are thus displaced to the right of their resting positions, thereby being forced closer and closer to the particles to their own right. In

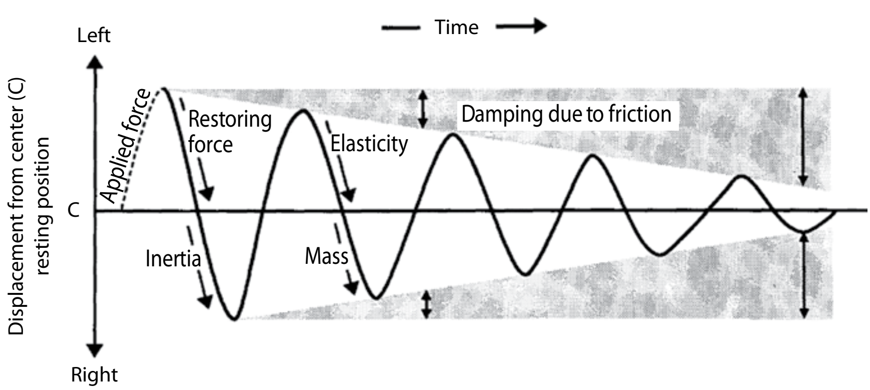

Figure 1.3 Conceptualized diagram graphing the to-and-fro movements of the tuning fork prong in Figure 1.2. Vertical distance represents the displacement of the prong from its center (C) or resting position. The dotted line represents the initial displacement of the prong as a result of some applied force. Arrows indicate the effects of restoring forces due to the fork's elasticity, and the inertia due to its mass. The damping effect due to resistance (or friction) is shown by the decreasing displacement of the curve as time progresses, and is highlighted by the shaded triangles (and double-headed arrows) above and below the curve.