Introduction to Sound

Acoustics for the Hearing and Speech Sciences

SECOND EDITION

Charles E. Speaks

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Preface to the First Edition

This book was written to *teach* the fundamental concepts of acoustics, particularly to those who are interested in the discipline of the speech-language-hearing sciences. Readers who are thoroughly grounded in mathematics and physics should be able to move through the various topics quickly. Those who are less comfortable with basic concepts of physics, or with mathematics beyond elementary algebra, will require more careful study of some of the concepts, but ultimately the concepts should be understood.

Students of the speech-language-hearing sciences must have a thorough understanding of the elements of acoustics before they can successfully embark on more advanced study of both normal and disordered human communication. At the University of Minnesota, for example, students in the Department of Communication Disorders who pursue an undergraduate degree must complete a five-credit course in acoustics, which is *prerequisite* to registration in more advanced courses such as Speech Science, Hearing Science, Hearing Loss and Audiometry, Noise and Humankind, Cleft Palate: Oral-Facial Anomalies and Speech, and Voice Disorders. Treatment of the fundamental concepts of acoustics with two or three weeks of lectures in the context of a broader course such as "speech and hearing science" or "introduction to audiology" cannot, in our opinion, do justice to the topic or serve students well.

There are many aspects of sound that might interest readers other than students in the speech-language-hearing sciences. Why is a "sonic boom" created when an airplane exceeds the speed of sound? Why is a foghorn designed to emit a low-pitched sound instead of a high-pitched whistle? If you are hunting in the woods, why is your distant prey more likely to hear you if it is downwind from you? How do "whispering galleries" work? In what ways do echoes off a canyon wall behave like billiard balls bouncing off rails on the billiard table? When you contemplate purchasing a stereo system, what does the salesperson mean by terms such as frequency response, noise floor, dynamic range, signal-to-noise ratio, decibels, percentage harmonic distortion, and so on? The answers to these and other questions are sprinkled throughout the text.

In the opening sentence, the word "teach" was emphasized because the fundamental goal is to *teach* the important elements of acoustics, not just present the topics. Two examples should suffice. First, some readers will not know, or will have forgotten, what is meant by "$\text{antilog}_{10}\ 2$." However, everyone will certainly know that $10^2 = 100$. To understand the *concept* of antilogarithms, then, one needs only to realize that "$\text{antilog}_{10}\ 2 = ?$" is exactly the same as asking "what is 10^2?"

Once the concept is understod, all that remains is to learn the simple steps for solving antilog problems that are computationally, but not conceptually, more difficult. Second, learning of several concepts in acoustics, the decibel for exmaple, can be enhanced by solving problems. For that reason, the book includes nearly 400 practice problems that are followed by *answers and explanations* of how the correct answers were obtained.

The organization of the topics in the book reflects a combination of both logic and personal preference. For example, the concepts of antilogarithms and logarithms must be understood before one can study decibels, and it is difficult to imagine how one can understand complex sound waves without first mastering the concept of sinusoidal wave motion. The location of other topics within the book reflects the author's preference for teaching. Some might prefer, for example, to begin by reading about "fundamental and derived physical quantities" and "proportionality" from Chapter 1 and "scientific notation" from Chapter 3. Those topics, and some others, should be treated as freestanding modules to be addressed when the reader or teacher elects.

Preface to the Second Edition

The second edition of *Introduction to Sound* retains the singular purpose to *teach* the fundamental concepts of acoustics to students in the speech-language-hearing sciences. To help achieve that objective, this edition differs from its predecessor in three principal ways. **Practice Problems** and **Answers to Practice Problems** have been added for Chapters 1, 5, 7, and 8, and a new set of problems and answers has been added to Chapter 2.

A new section entitled **Frequently Misunderstood Concepts** has been appended to Chapters 1, 2, 4, 5, 6, and 8. An analysis of answers to examination questions by approximately 275 students over the past 3 years led to a distressing realization. Although the mean score was a satisfactory 80%, a few questions were missed consistently by more than half of the students. For example, in response to the question, "An increase in sound pressure by a factor of 4:1 corresponds to an increase by how many decibels?" many students responded with either 12 dB SPL or 12 dB IL rather than just 12 dB. The purpose of these new sections, therefore, is to call specific attention to the kinds of mistakes that previous students have made and to attempt further clarification on the basic concepts that had been misunderstood.

Finally, several faculty and student users identified a few errors that appeared in the first edition, and every effort has been made to correct them. I thank them all, and particular appreciation is expressed to Sid Bacon at Arizona State University and Peter Narins at UCLA for their helpful suggestions.

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Any list of persons who should be acknowledged would be woefully incomplete, but the contributions of some must be recognized. One group is my own mentors, including Francis Flynn, Edward Penson, Robert Bilger, Gordon Peterson, Martin Schultz, and James Jerger. The second and equally important group is former students, both undergraduate and graduate.

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What is sound? One can hardly resist referring to a question that often is posed in high school science courses. "If a tree falls in a forest and no one is around to hear it, is there sound?" Put in more modern terms, "If the Muzak system in the elevator is turned on, but there are no passengers, is there sound?"

Albers (1970) stated that sound "in the strict sense, is a compressional wave that produces a sensation in the human ear" (p. 36). We need not worry for the moment what Albers meant by a "compressional wave," but his reference to producing a "sensation of hearing" deserves comment. When "sensation of hearing" is included in the definition of sound, we emphasize the *psychological* attributes of sound: pitch, loudness, and timbre. In other words, from a psychological point of view, "sound is what we hear."

We certainly are aware of the many "sounds" around us — sounds such as human speech, the barking of a dog, the crying of an infant, the cooing of the dove or of a "significant other," music of all forms, thunder, traffic noises, and the exhilarating roar of water cascading down the side of a mountain. A psychological approach to defining sound might have an intuitive appeal because it might seem that it would be easy to understand the *physical events* that characterize sound by reference to the psychological sensations or feelings that are associated with the myriad of sounds that we experience daily.

An alternative is to define sound from a *physical* perspective. In this case, sound is defined by reference to properties of the source of the event that we call "sound" and to properties of a"medium" in which, or along which, sound is transmitted. When *physical* properties of sound are emphasized, sound is considered to exist *even if the receiver is absent or is not functional.* In other words, sound does exist even if no one is in the forest or if the elevator is empty. To understand the nature of sound, we must identify and describe the physical characteristics of the events that take place among the trees or within the high-rise building.

Many things can serve as a source of sound: vocal folds; the strings of a piano, guitar, or violin; the membrane on a drum; the bar on the xylophone; the metal plates of the cymbals; the whistle; the tapping of heel and toe in dance; and so on. We shall see that there is one principal prerequisite for a body to be a source of sound — it must be able to vibrate. If a body is to be set into vibratory motion, it must have the physical properties of **mass** and **elasticity**, and all bodies in nature possess both of those two properties to some degree.

When something happens to those potential sources *that causes them to be set into vibratory motion or oscillation,* "a sound event" occurs, and the event can then be transmitted from the source through or along some medium. Air is probably the most common medium that we are likely to encounter. But, as we shall see, other molecular structures such as, for example, water, wires, strings, or steel rails also can transmit sound. Because all molecular structures have some finite **mass** and **elasticity**, all are capable of being both a source of sound and a medium for its transmission. Of course, some structures will be more effective sources or transmitters than others.

Although the properties that permit a structure to be a source of sound are essentially identical to the properties that permit a medium to transmit sound, it is convenient to describe the properties of the transmitting medium and the properties of the source separately.

PROPERTIES OF THE TRANSMITTING MEDIUM

Consider the medium of air. Air consists of approximately 400 billion billion (4×10^{20}) molecules per cubic inch (in.). In the quiescent state (before a source of sound has been energized), the molecules are in random motion and are moving at speeds that average nearly 940 miles per hour (MPH), which corresponds to 1,500 kilometers per hour (KPH). During that random motion they maintain some *average distance* from one another, which allows us to envision the molecules as being distributed fairly evenly throughout the air space.

The billions upon billions of molecules exert a pressure on whatever they come in contact with. When, for example, the random motion causes the air molecules to impinge on the human ear drum (or any other structure), a pressure is exerted on the drum. Interestingly, as we shall see later, that does not produce a sensation of "hearing" sound. At sea level that pressure, which also is called "atmospheric pressure," amounts to about 14.7 pounds (lb) per square in., and 14.7 lb/in.^{2} in the English measurement system is equivalent to approximately 100,000 newtons (Nt) per square meter (Nt/m^2) or 1,000,000 dynes per square centimeter (dynes/cm^2) in the metric system. The Nt/m^2 and dyne/cm^2 as measures of pressure will be defined later when the concepts of both pressure and force are developed more fully.

To conceptualize the pressure in air, consider the cylindrical tube shown in Figure 1-1, which has a cross-sectional area equal to 1 in.^{2} and extends from sea level to a height of 25 miles above sea level. At sea level, in the quiescent state, there is a pressure acting downward that amounts to approximately 14.7 lb/in.^{2} At 10 miles above sea level, the pressure is reduced to about 1.57 lb/in.^{2}, and at the height of 25 miles it is only a negligible 0.039 lb/in.^{2}

Air, and all other bodies that can serve to transmit sound, is characterized by two important physical properties: **mass** and **elasticity**.

Mass

By mass we mean *the amount of matter that is present.* Air, of course, is gaseous matter, but the definition of mass also holds for the two other forms of matter: liquids and solids.

Mass Contrasted With Weight

Mass is often confused with **weight**, and it is important to distinguish between them. Whereas mass refers to the quantity of matter

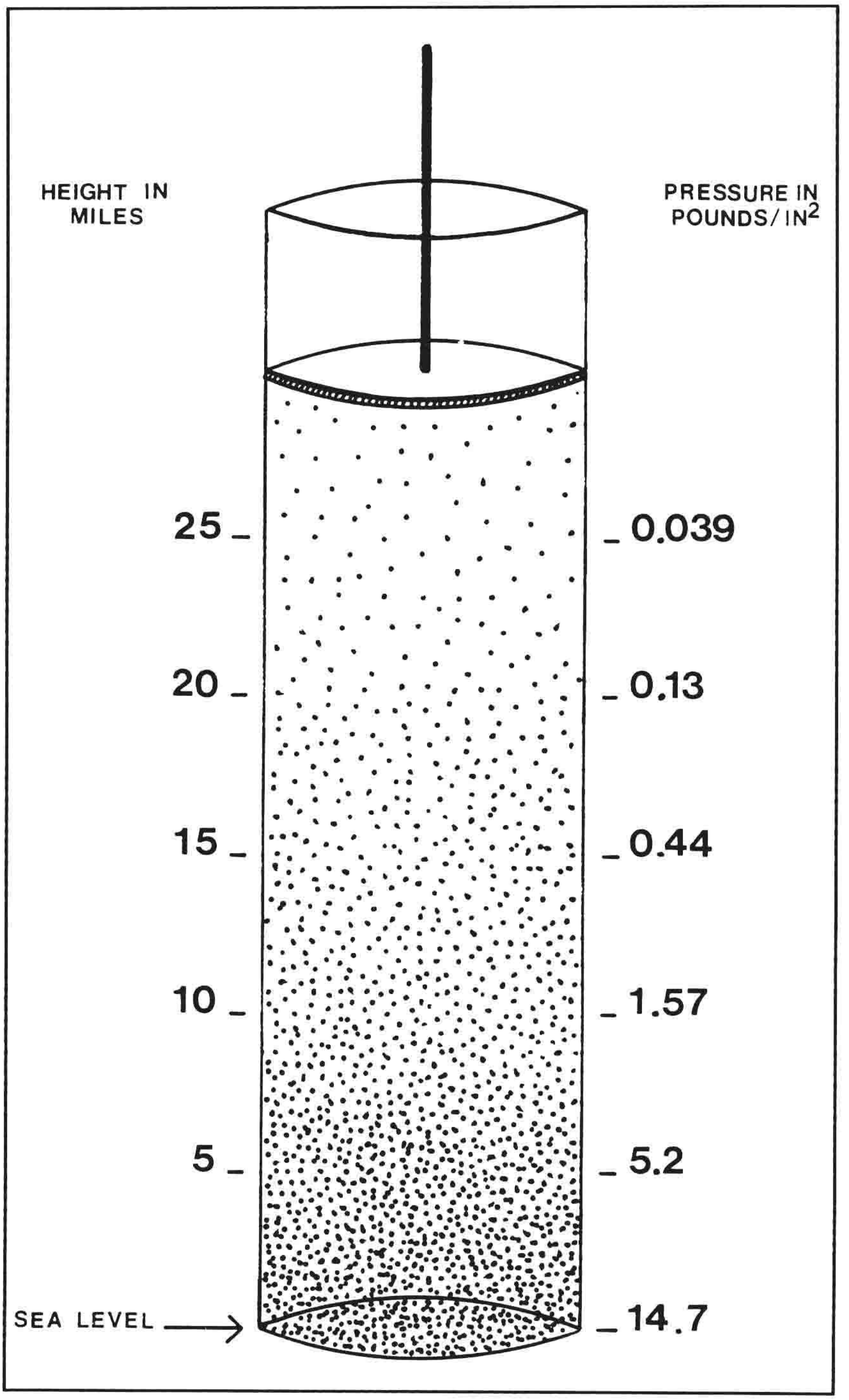

Figure 1–1. A cylindrical tube with a cross-sectional area of 1 in.^{2} that reflects how pressure and density in an air medium vary with height above sea level.

present, weight refers to the *attractive gravitational force exerted on a mass by the earth.* For example, a person is said to weigh 160 lb because the earth attracts the person with a force of 160 lb. However, if the person is flown to the moon, the same amount of matter will be present, but because of the lessened gravitational pull, the weight will only amount to about 27 lb because the force of gravity is only about one-sixth as great on the moon as it is on earth. The weight of an object is directly proportional to its mass, but weight and mass are simply different concepts. Weight is a force, whereas mass is the quantity of matter present.

Although it might be hard to imagine, air has weight as well as mass. In fact, a cubic meter of air weighs about 1.3 kilograms (kg), and the air in a classroom with the dimensions of 9 × 12 × 4 m weighs about 560 kg. For those who are not yet comfortable with meters and kilograms, a cubic yard (yd) of air weighs 35.1 ounces (oz), and the air in a classroom with the dimensions of 30 × 40 × 12 feet (ft) weighs about 1,170 lb. From that we might conclude that professors who deliver long lectures in a classroom of that size are truly "throwing a lot of weight around."

Mass and Density

It is also useful to distinguish between mass and **density**. Look again at the cylindrical tube filled with air in Figure 1–1. Notice that the air molecules are shown to be crowded together very closely near the bottom of the tube, whereas they are rather far apart in the higher regions of the tube. This occurs because of the pull of gravity.

Because of the force of gravity, the molecules of the atmosphere accumulate near the surface of the earth. There exists, therefore, a downward force or pressure (the distinction between force and pressure will be made subsequently) and the molecules are compressed into a smaller volume. The volume near the bottom of the tube is more densely packed, and when a greater number of molecules is compressed into a volume of a certain size, the density is increased.

Density (ρ) is *the amount of mass per unit volume.* For example, if we could exert a force that would cause a volume of 1 cubic in. of air to contain 800 billion billion (8×10^{20}) molecules instead of 400 billion billion (4×10^{20}), the density — the mass per unit volume — will have doubled. It is easy to see in Figure 1–1 that the amount of mass per unit volume in the cylinder decreases with increasing height above sea level.

It might be difficult to imagine the different densities associated with the invisible molecules in volumes of air, but there are more visible examples that should serve to make the distinction between mass and density clear. Imagine a grocery bag with a volume 0.06 cubic meters [about 2 cubic ft (2 ft^3)] that is filled with 50 loosely crumpled sheets of newspaper. If you now pack the paper more tightly until the same amount of paper (50 sheets) occupies only half of the bag's volume [0.03 cubic meters (0.03 m^3); about 1 cubic ft (1 ft^3)], the same amount of matter is present — the **mass** — but the matter will be packed into a smaller volume. After compression, the amount of mass per cubic meter — the **density** — will have doubled.

With respect to the first property of a transmitting medium, it is useful to refer to both the **mass** of a medium and to the **density** of a medium, a quantity derived from mass. We shall subsequently explain more explicitly what is meant by "a quantity that is *derived* from another quantity."

Elasticity (E)

The second property of a transmitting medium is **elasticity**. All matter, whether it be gaseous, liquid, or solid, undergoes distortion of either shape or volume or both when a force is applied to it. Moreover, all matter is characterized by the tendency to "recover" from that distortion. The property that enables recovery from distortion to either shape or volume is called **elasticity**.

Imagine a weight attached to a spring that is suspended from the ceiling. When the spring is stretched and then released, it will return to its original unstretched position (and beyond, but that will be the subject of a later topic), unless it has been "overloaded." By "overloaded" we mean that the original stretching of the spring was sufficient to exceed what is called its **elastic limit**.

A portable radio has a spring that holds the battery in place. If you remove the spring, you can verify that it is relatively easy to stretch it so far that it will not "spring back" when released. Its elastic limit was exceeded. In some forms of matter, the elastic limit is very small. In other forms of matter, such as tempered steel, the elastic limit is very large. The elastic limit of air is so very large that it need not concern us.

With air, the concept of elasticity can mean *the tendency of a volume of air to return to its former volume after compression.* Return again to the air-filled cylinder in Figure 1-1. We know that air molecules are present, that they are in random motion, that — on the average — they are equidistant from one another, and that the density of the air is greater near the bottom of the tube.

Suppose we now insert a plunger into the top of the cylinder and push downward. All of the molecules that are present in the full length of the tube will now be crowded into a smaller space; the **density** is increased. When the plunger is removed, the air molecules return to their former "position," or more appropriately, the air volume resumes the density that existed before compression. The density of the air is said to be *restored,* and the restoring force is called **elasticity**.

■ PROPERTIES OF THE SOUND SOURCE

Let us turn now from a discussion of transmitting media to a consideration of bodies that can serve as a source of sound. We will be concerned