Introduction to Sound

Acoustics for the Hearing and Speech Sciences

Fourth Edition

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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 of 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 "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 "antilog$_{10}$ 2 = ?" is exactly the same as asking, "what is 10^2?" Once the concept is understood, 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 example, can be enhanced by solving problems. For that reason, the accompanying *Course Notes and Workbook for Introduction to Sound* 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 free-standing 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 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 of 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.

Preface to the Third Edition

The third edition of *Introduction to Sound* continues to retain the singular purpose to *teach* the fundamental concepts of acoustics to students in speech-language-hearing sciences. This edition differs from its predecessors, however, both substantively and cosmetically.

The principal changes are:

- Point-by-point construction of a sine wave is demonstrated by calculating sine θ at 11° intervals from 0° to 360° and then plotting the results (Chapter 2);
- Wave equations are used to explain why *particle displacement* must be 180° out of phase with *particle acceleration,* a relation that is seldom intuitively obvious (Chapter 2);
- A table of common logs has been added (Chapter 3);
- The *preferred center frequencies* for constant percentage bandwidth filters are listed, and the reasons for their selection are explained (Chapter 6);
- The "Summary of an Experiment on the Cat" has been deleted (Chapter 7);
- The universality of the inverse square law to physical phenomena other than sound is described (Chapter 8);
- The concepts of *constructive* and *destructive interference* are introduced in a discussion of standing waves (Chapter 8);
- The relation between *displacement* nodes and antinodes and *pressure* nodes and antinodes in consideration of standing waves in acoustic tubes is explained (Chapter 8);
- The higher modes of vibration of strings, and the commonalities between vibration of a string and the standing waves in tubes closed at both ends, are explained (Chapter 8);
- The discussion of sound *absorption* has been expanded to include differences in absorption coefficients as a function of frequency and among common absorbing materials (Chapter 8);
- The discussion of *total absorption,* including the *sabin* and *metric sabin,* has been expanded (Chapter 8);
- The relation between *absorption* and *reverberation time* has been elaborated to show their practical application to optimal and substandard room acoustics (Chapter 8);
- Fourteen equations have been added to the *Alphabetical Listing of Selected Equations;*
- *All illustrations* have been newly prepared with common formatting, several illustrations have been recomposed to achieve greater clarity, some new illustrations have been

prepared, and careful attention has been paid to ensure that all figures are "mathematically correct" (all chapters);

- *Practice Problems* and *Answers to Practice Problems* have been moved to a newly created *Course Notes and Workbook for Introduction to Sound,* which will be accompanied by *printed copies of several hundred PowerPoint slides* that some faculty might choose to use in their classes; and
- A concerted effort has been made to ensure that "nuisance errors" have been virtually eliminated.

In all instances, the modifications, additions, and deletions were driven by a single force: the change must promise to enhance teaching and improve comprehension of the fundamental concepts of acoustics.

Preface to the Fourth Edition

The fourth edition of *Introduction to Sound* is written to *teach* fundamental concepts of acoustics to students in the speech-language-hearing sciences and related behavioral science disciplines.

Chapter 10, *Room Acoustics*, is an important addition to the book. Although noisy and excessively reverberant rooms are annoying (think of the ubiquitous "sports bar"), our principle concern with the acoustical conditions in a room is: "*Can people, some with normal hearing and others with a moderate-to-severe hearing loss, understand speech easily?*"

Design/redesign plans for acoustical treatments of rooms should be formulated to optimize speech understanding. Hearing and speech scientists, audiologists, or speech-language pathologists should participate with acoustical engineers in that endeavor. To prepare for their role on the team, hearing and speech professionals must understand the fundamental principles of room acoustics. We must be thoroughly familiar with techniques for assessing the intelligibility of speech. It is our responsibility to be forceful and effective advocates for the special acoustical requirements of listeners who have moderate-to-severe hearing loss and those who wear hearing aids or other sound enhancement devices.

Hearing and speech professionals must be able to engage in meaningful dialogue with acoustical consultants in the development of plans for optimization of acoustical design/redesign treatments. Chapter 10 is devoted to fundamental concepts of room acoustics (e.g., reflection, "reverberant tails," absorption, signal-to-noise ratio, etc.). It also includes a chronicle of the research literature on intelligibility testing by focusing on two distinctly different approaches for determining how well speech is understood. One approach is the conventional psychometric test that uses monosyllabic words, sentences, or connected discourse. A second is an engineering-based model in which relevant acoustic parameters of speech and selected elements of the acoustic environment are joined in an algorithm to *predict* rather than *measure* speech intelligibility.

I emphasized the word *"teach"* in the opening sentence. The fourth edition reflects my belief that acoustical concepts can be understood by all of our students, including those who are not thoroughly grounded in mathematics and physics. I hope readers get the sense that as they *read the book* they are *listening to a lecture.*

An effective teacher calls on all the prosodic elements of our language by using many forms of "vocal emphasis." That does more than just enliven the lecture; it directs attention toward important facts and ideas. I have tried to deploy the writing parallels of "vocal emphasis" with a liberal use of *italics*, **boldface**, underlining, and sometimes all three when I think ***a concept deserves special emphasis***. I also make deliberate use of redundancy—some acoustical concepts are repeated in several different contexts to drive home the point that "*this concept is important to know and understand*."

There also some structural changes in the fourth edition. Some of the paragraphs in the earlier editions were too long. It often was a challenge for students to discern the really important messages embedded in the passage. Many of those lengthy paragraphs are now formatted differently. Key concepts have been extracted and presented in bulleted or numbered fashion. For example:

- The original eight chapters have been restructured into ten, more focused chapters.
- *Practice Problems* and the *Answers to Practice Problems* have been moved from *Course Notes and Workbook for Introduction to Sound* to the textbook and are also available on the PluralPlus companion website. See the inside front cover of your textbook for access instructions.
- A *Glossary* of important terms has been added as a complement to an *Alphabetical Listing of Selected Equations*.
- Finally, *Animations for Introduction to Sound* is now readily available to faculty and students. Visit https://sites.google.com/a/umn.edu/soundanimations to gain access to 17 dynamic representations of acoustic events. The animations show—in slow motion—events in acoustics that normally change too rapidly over time to be visualized. The topics include: vibrating tuning forks; pendular motion; simple harmonic motion; transverse and longitudinal wave motion; reflection of sound from plane, concave, and convex surfaces; standing waves; and so forth.

I hope the combination of new material and structural changes will accomplish my objective to *teach* the fundamental concepts of acoustics.

Acknowledgments

I pay a special tribute to my sons, Brandon and Jeffrey, and my daughters-in-law, Liz, and Kelsey. They encouraged me to emerge briefly from retirement and return to writing and teaching. This fourth edition is my "classroom," and I hope it will serve its purpose of *teaching* concepts in acoustics that are essential for students in the speech-language-hearing sciences.

Edward Carney has done a masterful job with updating and improving *Animations for Introduction to Sound*. His expertise has enhanced the quality of the animations as a valuable teaching tool. I am most grateful for his assistance and colleagueship.

I also acknowledge the special role of Jim Jerger in my professional life. His leadership, mentorship, and friendship were invaluable in shaping my career. Jim led by example. He stressed excellence in research and clarity of thought. Jim also advocated for simplicity in writing. I believe his article, "*Scientific writing can be readable*" (1962), should be required reading for all of our graduate students. Jim pointed me in new directions, and his support knew no boundaries. Jim, I cannot repay you, but I can say, "thank you for everything."

In Memory of Nancy E. Niccum, PhD
loyal and supportive wife,
Devoted and loving mother, valued colleague, and best friend

And to our Sons and Daughters-in-Law

Charles Brandon Speaks (Elizabeth Jensen-Speaks)
Jeffrey Bryant Speaks (Kelsey Lynn Speaks)

CHAPTER 1

The Nature of Sound Waves

"If a tree falls in a forest and no one is around to hear it, is there sound?" The answer depends on the distinction between two different perspectives for defining sound: *physical* and *psychological*.

Albers (1970) wrote that sound "in the strict sense, is a compressional wave that produces a sensation in the human ear" (p. 36). When "sensation of hearing" is included in the definition of sound, the *psychological* attributes of sound are invoked: 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 a 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 is tempting. It might seem that it would be easier to understand the *physical events* that characterize sound by reference to the psychological sensations or feelings that are associated with the many sounds that we experience daily. But the reverse is more correct; it is easier to explore the nature of the psychological sensations to sound if we thoroughly understand the physical characteristics.

An alternative is to define sound from a *physical* perspective. Sound is defined by reference to properties of the *source* of the event called "sound" and to properties of a *medium* in which, or along which, sound is transmitted. When *physical* properties of sound are emphasized, sound does exist *even if the receiver is absent or is not functional.* In other words, sound exist**s** even if no one is in the forest.

Many objects can serve as a source of sound: vocal folds; the strings of a piano, guitar, or violin; the membrane of a drum; the bars of a xylophone; the metal plates of cymbals; and so on. In each case there is one essential prerequisite for a body to be a source of sound —*it must be able to vibrate*. That requires two physical properties: **mass** and **elasticity**. All bodies in nature possess both of those two properties to some degree.

When a potential source of sound is set into *vibratory motion, or oscillation,* sound occurs, and the sound that is created can then be transmitted from the source through, or along, some medium. Air is probably the most familiar medium that we encounter. But, as we shall see, other molecular structures, such as, for example, water, wires, strings, glass, wood panels, steel rails, and so forth can also transmit sound. Because all molecular structures have some finite **mass** and **elasticity**, each is capable of being both a source of sound and a medium for its transmission. Of course, some structures will be more effective sources or more effective transmitters than others.

Although the properties that permit a structure to be a source of sound are essentially the same as 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 air as a medium for transmitting sound. Air consists of approximately 400 billion billion (4×10^{20}) molecules per cubic inch (**in.**). In the quiescent state (before a source of sound begins to vibrate), the air molecules move randomly at speeds that average nearly 940 miles per hour (**mph**), or 1,500 kilometers per hour (**kph**). Although molecular motion is random, the molecules maintain some *average distance* from one another. Thus, we can 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. For example, when the randomly moving air molecules impinge on the human eardrum (or any other structure), pressure is exerted on the drum. Interestingly, as we shall see later, *that does not yet produce a sensation of "hearing" sound*. At sea level that pressure, which is called "atmospheric pressure," amounts to about 14.7 pounds (**lb.**) per square in. (**lb./in.^{2}**), and 14.7 lb./in.^{2} in the English measurement system is equivalent to approximately 100,000 newtons (**N**) per square meter (**N/m^2**) or 1,000,000 dynes per square centimeter (**dynes/cm^2**) in the metric systems. The **N/m^2** and **dyne/cm^2** will be defined later when the concepts of both force and pressure 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 of 1 in.^{2} and extends from sea level to a height of more than 25 miles. At sea level, in the quiescent state, there is a pressure of approximately 14.7 lb./in.^{2} acting downward. At 10 miles above sea level, the pressure is reduced to about 1.57 lb./in.^{2}, and at a 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 essential physical properties: **mass** and **elasticity**.

Mass

Mass is *the amount of matter present.* Air is a gaseous matter, but the definition of mass also holds for liquids and solids.

Mass Contrasted with Weight

Mass sometimes is confused with **weight**. **Mass** refers to the quantity of matter present, whereas **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. If that person is flown to the moon, the same amount of matter is present, but because of the lessened gravitational pull, the weight amounts 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

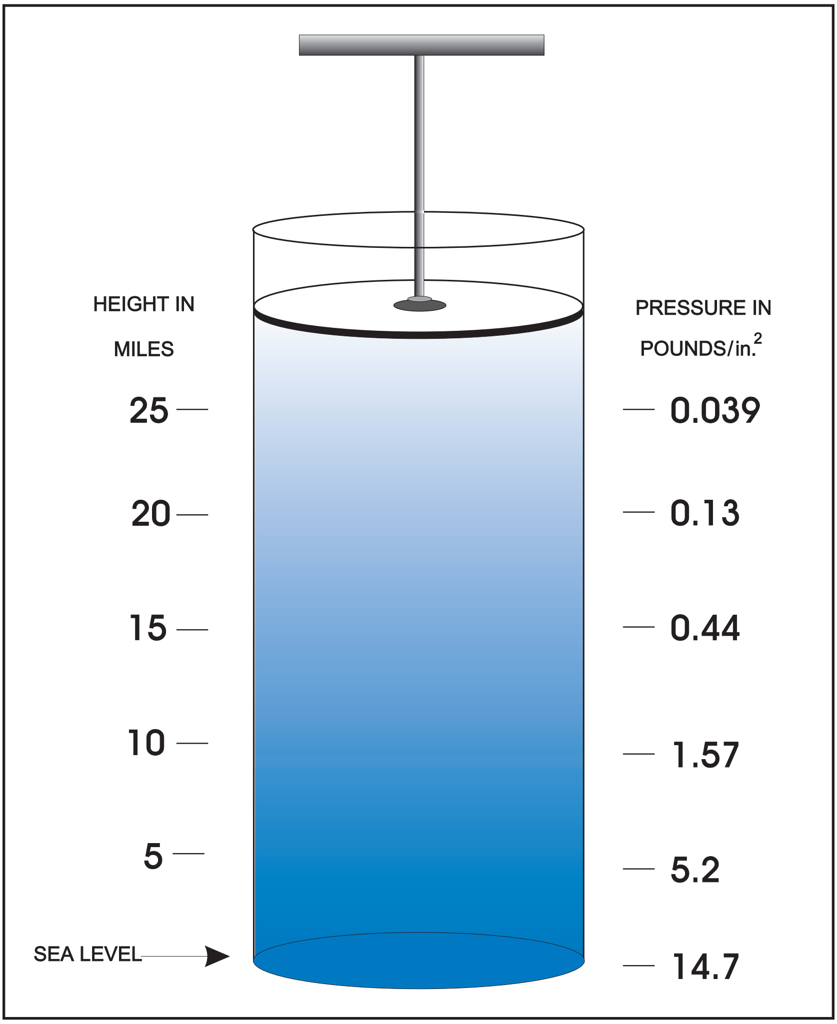

Figure 1–1. A cylindrical tube with a cross-sectional area of 1 in.^{2} that reflects how **pressure** and **density** in an air medium vary with height above sea level.

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.*

Air has weight as well as mass. 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 "throwing a lot of weight around."

Mass and Density

It also is important to distinguish between **mass** and **density**. Look again at the cylindrical tube filled with air in Figure 1–1. The air molecules are crowded closely together (darkened regions) near the bottom of the tube, whereas they are rather far apart (lighter regions) in the higher portions of the tube. This occurs because of the pull of gravity.

Because of gravity, the molecules of the atmosphere accumulate near the surface of the earth. A downward force causes the molecules to be 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 exert a force that causes 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—is 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 might make the distinction between mass and density clear. Imagine a grocery bag with a volume of 0.06 cubic meter that is filled with 50 loosely crumpled sheets of newspaper. If you pack the paper more tightly until the same amount of paper (50 sheets) occupies only half of the bag's volume (0.03 cubic meter), the same amount of matter is present—the **mass**—but the matter is packed into a smaller volume. After compression, the amount of mass per cubic meter—the **density**—has 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 what is meant by "a quantity *derived* from another quantity."

Elasticity (E)

Elasticity is the second property of a transmitting medium. All matter, whether 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 **elasticity.** We shall see subsequently that elasticity is more properly defined as *the ability to resist changes in shape, volume, or position* rather than the ability to recover from such changes.

Imagine a weight attached to a spring suspended from the ceiling. When the spring is stretched and then released, it returns to its original position (and beyond) unless it has been "overloaded." By "overloaded" we mean that the original stretching of the spring is sufficient to exceed its **elastic limit**. If the applied force exceeds the elastic limit, deformation is permanent. If the applied force exceeds the elastic limit by a sufficient amount, the object breaks.

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, such as tempered steel, the elastic limit is very large. The elastic limit of air is so large that it need not concern us.

With air, the concept of elasticity means *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 average—they are equidistant from each other, and that the density of the air is greater near the bottom of the tube.

Suppose we now insert a plunger into the cylinder and push downward. All molecules that were present in the full length of the tube are crowded (compressed) 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 *restored,* and the restoring force is **elasticity**.

PROPERTIES OF THE SOUND SOURCE

Let us now consider bodies that can serve as a *source of sound*. We will consider the same two properties that characterized the transmitting medium: **mass** (or density) and **elasticity**.

Vibratory Motion of a Tuning Fork

A tuning fork, as shown in Figure 1–2, is one source of sound. The tuning fork is a U-shaped metal bar. The prongs, or tines, of the fork have **mass** (a quantity of matter is present) and they also possess the restoring force of **elasticity**. Because of their elasticity, the tines of the fork return to their former position after they have been displaced. This is illustrated by striking the fork gently with a soft hammer. The tines are set into vibration, which takes the form of each tine moving back and forth.[1]

View Animation 1_2. The Vibrating Tuning Fork at
https://sites.google.com/a/umn.edu/soundanimations

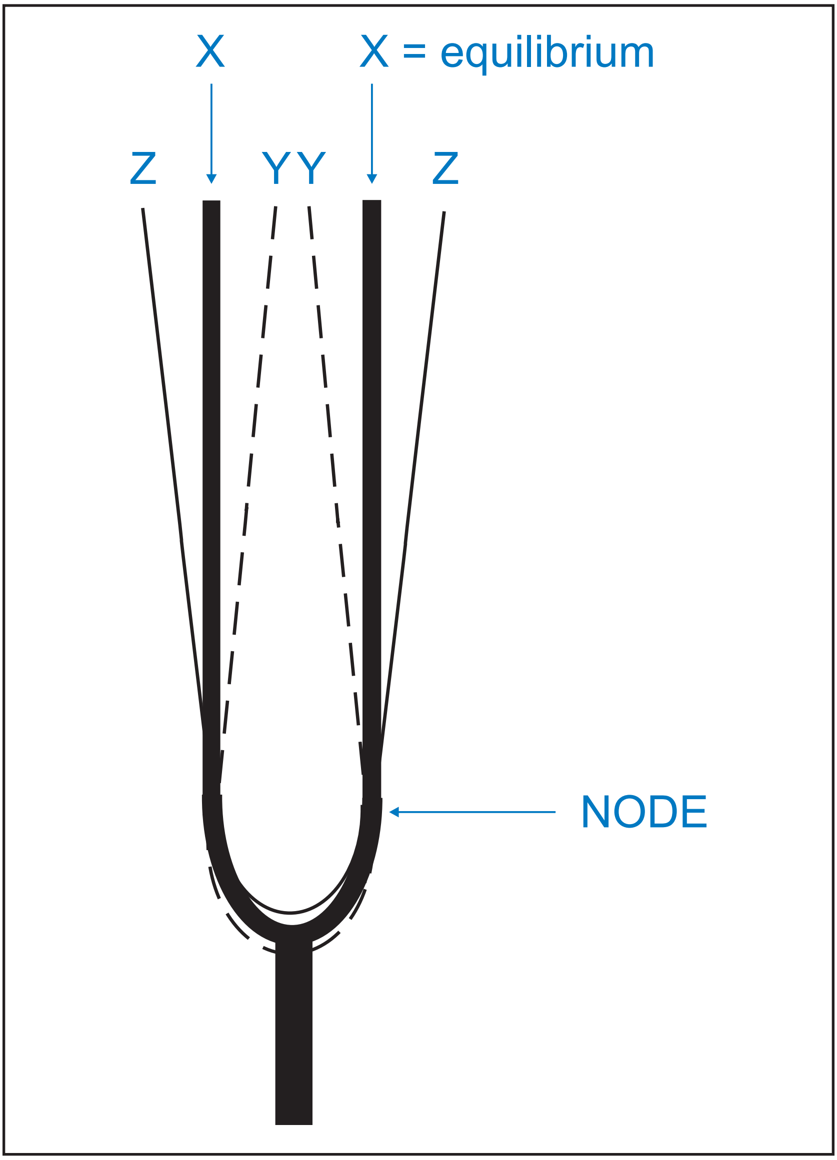

Figure 1–2. The vibratory pattern of a tuning fork, a U-shaped metal bar with the properties of **mass** and **elasticity**. Once struck, the tines move from **X** (equilibrium), to **Y** (maximum displacement in one direction), back to **X**, to **Z** (maximum displacement in the other direction), and back to **X** to complete one **cycle** of vibration.

Displacement from Equilibrium

Imagine that we can "zoom in" and observe the pattern of vibration of the two tines. The position of the fork before a force is applied is its *equilibrium position*, and the heavy solid lines labeled **X** in