Architectural Acoustics

M. David Egan

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Jennie E. Brown
(1887-1966)

About the Author

M. David Egan, P.E., is a consultant in acoustics and part-time professor at the College of Architecture, Clemson University. He has worked as a consultant in acoustics for Bolt Beranek and Newman (BBN) in Cambridge, Massachusetts, and has been principal consultant of his own firm in Anderson, South Carolina for over 15 years. His firm has consulted on over 400 building projects in the United States and abroad. A graduate of Lafayette College (B.S.) and the Massachusetts Institute of Technology (M.S.), where he studied acoustics under the late Professor Robert B. Newman, Professor Egan also has taught at Tulane University, Georgia Institute of Technology, University of North Carolina at Charlotte, and Washington University (St. Louis), and has lectured at numerous schools of design. He is the author of several books in the area of architectural technologies, including *Concepts in Architectural Acoustics* (McGraw-Hill, 1972), *Concepts in Thermal Comfort* (Prentice-Hall, 1975), *Concepts in Building Firesafety* (Wiley-Interscience, 1978 and Kajima Institute, Tokyo, 1981), and *Concepts in Architectural Lighting* (McGraw-Hill, 1983). In addition to consulting, teaching, and writing, Professor Egan is a fellow of the Acoustical Society of America (ASA), former director and two-term vice president of the National Council of Acoustical Consultants (NCAC), associate editor for NOISE/NEWS published by the Institute of Noise Control Engineering (INCE), and national awards coordinator for The Robert Bradford Newman Student Award Fund, Lincoln Center, Massachusetts.

Contents

Foreword

The need for practical working knowledge in the environmental sciences for those in the building professions will continue for the foreseeable future. Acoustics, like lighting and the thermal environment, is an environmental science that has become a recognized and respected discipline within the past half century. The fruits of these expanding bodies of scientific knowledge, i.e., practical engineering applications, are increasingly being taken seriously on a widespread basis by architects, engineers, and planners in the solutions of acoustical problems in and around buildings.

Although there are a few exceptions, adequate courses in acoustics have been notably lacking in schools of architecture and engineering. A number of us, including Professor M. David Egan, were fortunate in learning about acoustics at the Massachusetts Institute of Technology through the pioneering and inspirational teaching of the late Professor Robert B. Newman and his colleagues, Professors Leo Beranek and Richard Bolt. Some of their former students, like M. David Egan, have gone on to spread the word not only through design applications of their knowledge but also through lecturing and teaching efforts.

With his earlier book *Concepts in Architectural Acoustics* (McGraw-Hill, 1972), Professor Egan identified the pressing need for a textbook which would cut through to the core of the information needed to understand acoustics problems and to develop practical solutions. The book could hardly be called a textbook in the traditional sense, since the verbal descriptions were few and the major emphasis was on graphic displays of concepts as well as engineering data and problem-solving techniques. This unique approach, as he has found with his students at the Clemson University College of Architecture and elsewhere, appealed to most students of architecture and engineering (of all ages) who need comprehensive yet encapsulated treatments of the environmental sciences. *Concepts in Architectural Acoustics* became a widely used text not only in architectural schools but in the offices of practicing professionals as well. Indeed, many acoustical consultants recommend the book to clients when the need for a little more understanding of technical details exists.

In this new text, *Architectural Acoustics,* Professor Egan has retained all the desirable features of its predecessor and has updated the material with the experience gained this past decade, as well as added several new useful features such as checklists on design and problem areas in building acoustics. The clarity of the illustrations and format of tables of engineering data greatly enhance the usefulness of the book for reference. Like its predecessor, *Architectural Acoustics* emphasizes concepts and aids the designer/decisionmaker in judging the relative importance of acoustical considerations in the context of the overall building environmental system.

This book is an important contribution to the better understanding of building acoustics problems in a growing multidisciplinary design environment.

William J. Cavanaugh
Fellow, Acoustical Society of America
Natick, Massachusetts

Preface

The goal of this book is to present in a highly illustrated format the principles of design for good hearing and freedom from noise in and around buildings. The over 540 illustrations are not merely supplements to the text as with nearly all traditional books. In this book, the illustrations are the core of the coverage of basic principles of sound and hearing, sound absorption and noise reduction, sound isolation and criteria for noise, control of HVAC systems noise and vibrations, auditorium acoustics design, and electronic sound systems.

The book is written for architects, interior designers, engineers, and all others concerned with the design and construction of buildings who need to know the basics of architectural acoustics, but who do not have the time needed to digest wordy presentations. The book is a successor to *Concepts in Architectural Acoustics* (McGraw-Hill, 1972) with the overwhelming majority of the illustrations, case histories, and example problem solutions either entirely new or substantially revised.

The late Professor Robert B. Newman was the author's mentor and teacher in graduate school. His course on architectural acoustics was the inspiration to become an acoustical consultant. The message of that course, offered by Professor Newman for nearly four decades at the MIT School of Architecture and Planning and at the Harvard University Graduate School of Design, was that designers who understand the basic principles of acoustics possess an important new tool for shaping the built environment. The intentions of this book, therefore, are similar. That is, to diffuse knowledge of acoustics and to promote its creative applications in design. Hopefully, not only better acoustical environments, but also better buildings should result.

The book also contains numerous checklists of design aids, data tables of sound absorption and sound isolation properties for a wide variety of modern building materials, case study examples, and step-by-step practical problem solutions. Extensive references are provided so that the interested reader can dig deeper. The appendix includes a metric system conversion table for common building acoustics terms and a summary of useful formulas.

M. David Egan, P.E., FASA
Anderson, South Carolina

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Jeannie Egan edited the manuscript and text for the illustrations and reviewed the numerous drafts and proofs.

Gratitude is extended to Glen S. LeRoy, School of Architecture and Urban Design, University of Kansas, who prepared all the illustrations. Glen LeRoy's steadfast dedication to effective and innovative graphic communication techniques is deeply appreciated. Glen also prepared the illustrations for the author's books *Concepts in Thermal Comfort, Concepts in Building Firesafety,* and *Concepts in Architectural Lighting.*

It would be nearly impossible to name all the people who have influenced me in the fields of architecture and acoustical design, and thereby contributed to the preparation of this book, without inadvertently overlooking someone. Nevertheless, thanks are due to the following persons who provided reviews of portions of chapters in their area of special professional interest: James J. Abernethy, Eric Neil Angevine, Elliott H. Berger, John S. Bradley, Daniel R. Flynn, Ernest E. Jacks, John W. Kopec, Jerry G. Lilly, L. Gerald Marshall, James B. Moreland, Bynum Petty, Gregory C. Tocci, Keith W. Walker, Brian L. Williams, and Randolph E. Wright.

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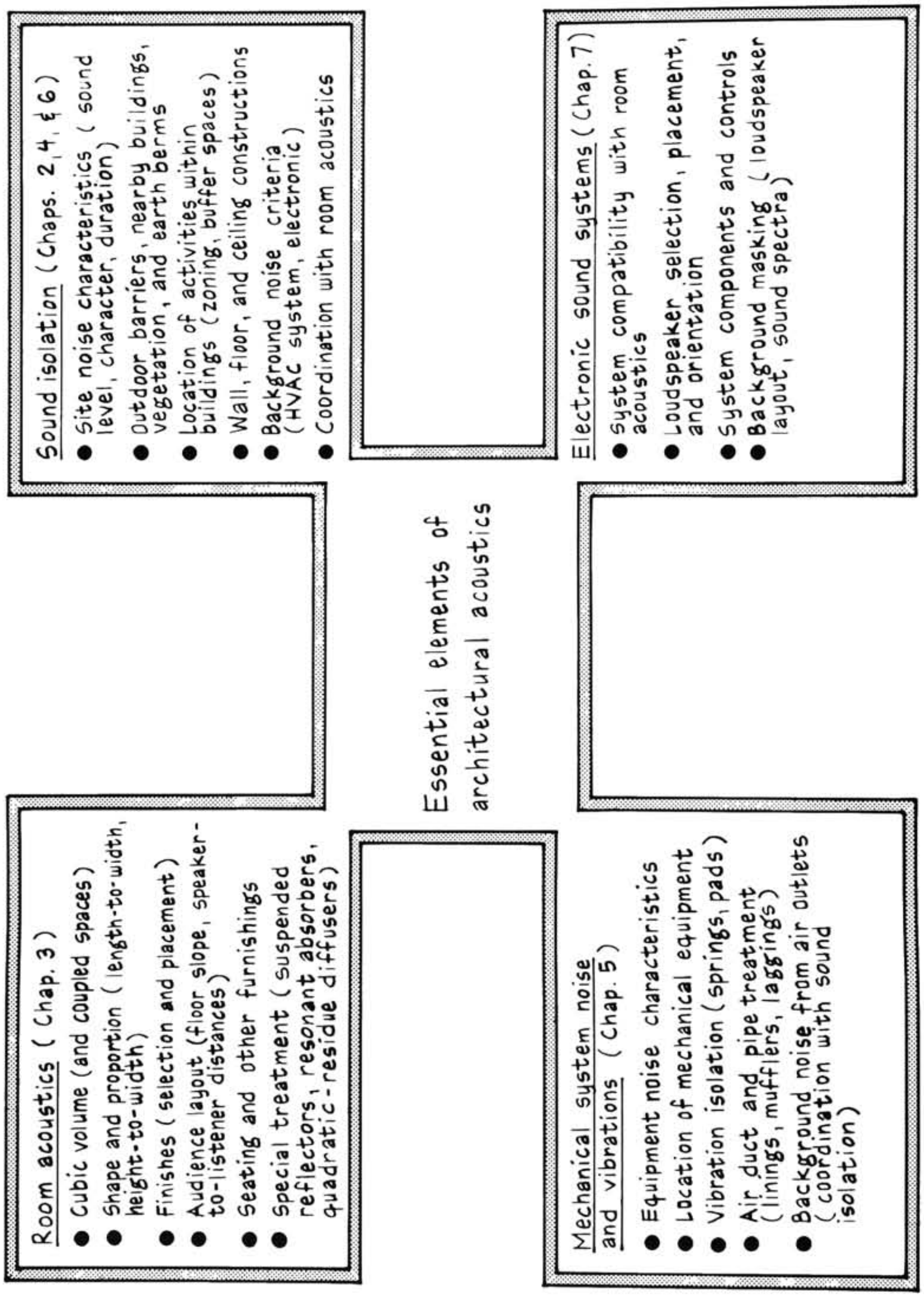
Introduction

Almost all acoustical situations can be described by three parts: source, path, and receiver. Sometimes the *source* (human speech, HVAC equipment) can be made louder or quieter. For example, strategic placement of reflecting surfaces near the speaker in lecture rooms, churches, and auditoriums can reinforce and evenly distribute sound to all listeners. The *path* (air, earth, building materials) can be made to transmit more or less sound. When required, double-wall and other complex constructions can be designed to interrupt the sound path, thereby providing satisfactory sound isolation and privacy. The *receiver* (usually humans, although sometimes animals or sensitive medical equipment) also can be affected. Usually building occupants will hear better, or be more comfortable, if distracting HVAC system noise can be controlled or if intruding environmental noise can be isolated or removed. In most situations, it is best to focus on all three parts. For example, concentrating only on the direct path for sound travel through common walls may at best result in costly overdesign or at worst, no solution at all!

Acoustical requirements always should be considered during the earliest stages of design. Even though corrections can be accomplished during the mid- and latter stages of design, it usually is very difficult to change shapes, room heights, and adjacencies within buildings when spatial relationships and budgets have been fixed. Similarly, deficiencies in completed spaces are often extremely difficult and costly to correct. For example, the addition of an electronic, sound-reinforcing system to an auditorium which is excessively reverberant may exaggerate deficiencies rather than improve listening conditions. This kind of acoustical surprise should not occur if designers understand the basic principles of acoustics. Successful designers provide the spatial relationships, cubic volumes, shapes, and the like so their buildings maintain design quality while best serving their intended purposes, whether it be for work, play, or rest.

Designers should not rely on oversimplified articles in trade magazines, misleading advertisements and incomplete technical data from manufacturers, or highly specialized texts written in technical jargon. The goal of this book, therefore, is to provide a comprehensive framework for the study of acoustics as well as a long-term resource for designers. The designer should be able to anticipate the acoustical problems inherent to most buildings, solve those of a routine nature, and determine when professional assistance is required. A reference source for information on qualified acoustical consultants is the biennial *Directory* of the National Council of Acoustical Consultants (NCAC). The Acoustical Society of America (ASA) also maintains a listing of persons and firms offering acoustical consulting services.

The designer who understands the essential elements of architectural acoustics will be able to best collaborate with acoustical consultants by asking the right questions, identifying alternative solutions, and implementing successful designs. The illustration below identifies essential elements of architectural acoustics and the corresponding chapters in the book.



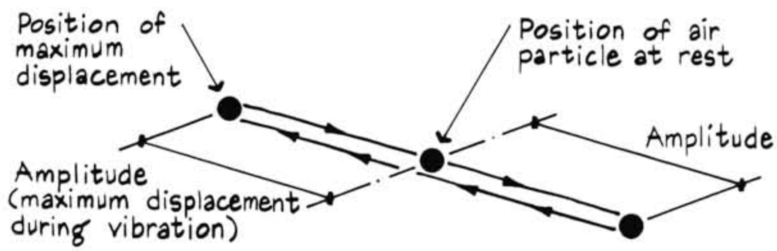
Chapter 1

Basic Theory

Sound is a vibration in an elastic medium such as air, water, most building materials, and the earth.* An elastic medium returns to its normal state after a force is removed. *Pressure* is a force per unit area. Sound energy progresses rapidly, producing extremely small changes in atmospheric pressure, and can travel great distances. However, each vibrating particle moves only an infinitesimal amount to either side of its normal position. It "bumps" adjacent particles and imparts most of its motion and energy to them. A full circuit by a displaced particle is called a *cycle* (see illustration below). The time required for one complete cycle is called the *period* and the number of complete cycles per second is the *frequency* of vibration. Consequently, the reciprocal of frequency is the period. Frequency is measured in cycles per second, the unit for which is called the hertz (abbreviated Hz).

Vibration of Particle in Air

The back and forth motion of a complete cycle is shown below.



Pure Tones

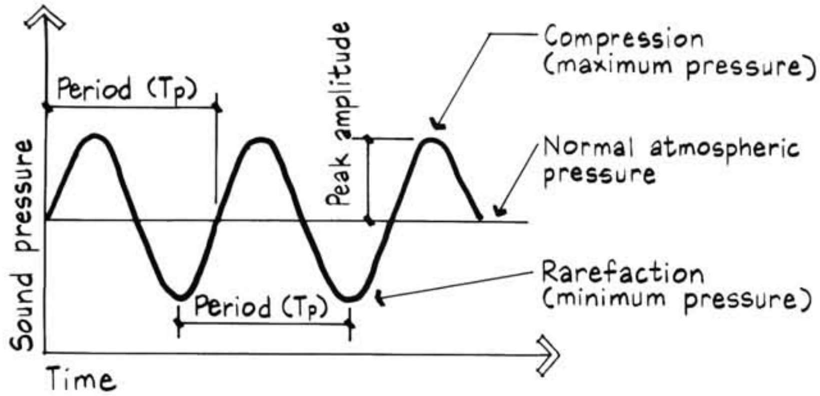
A *pure tone* is vibration produced at a single frequency. Shown below is the variation in pressure caused by striking a tuning fork, which produces an almost pure tone by vibrating adjacent air molecules. Symphonic music consists of numerous tones at different frequencies and pressures (e.g., a tone is composed of a fundamental frequency with multiples of the fundamental, called *harmonics*). To find the period corresponding to a frequency of vibration, use the following formula:

$$T_p = \frac{1}{f}$$

where T_p = period (s/cycle)
f = frequency (cycles/s or Hz)

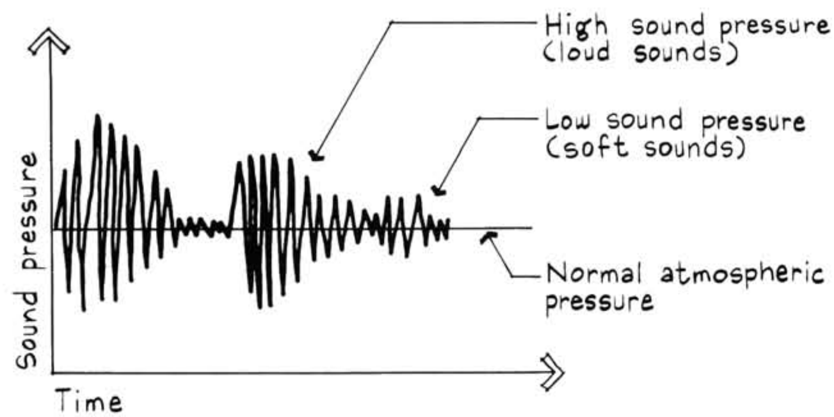
Noise is unwanted sound (e.g., annoying sound made by other people or very loud sound which may cause hearing loss).

For example, a frequency of 63 Hz has a period T_p of $1/63 \simeq 0.02$ s/cycle (roughly 30 times longer than the period at 2000 Hz).



Complex Sounds

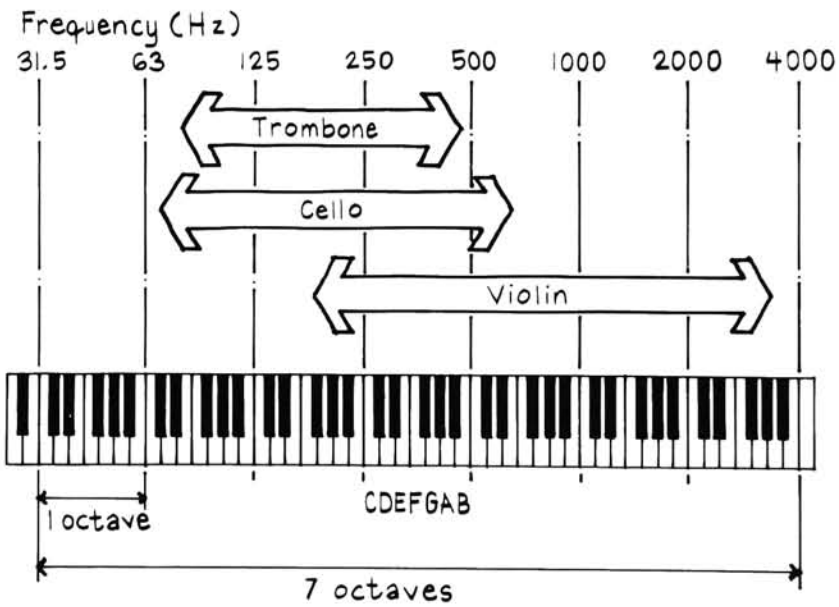
The variation in pressure caused by speech, music, or noise is shown below. Most sounds in the everyday world are complex, consisting of a variety of pressures which vary with time. The threshold of hearing for humans is one-millionth of normal atmospheric pressure.



FREQUENCY OF SOUND

Frequency is the rate of repetition of a periodic event. Sound in air consists of a series of compressions and rarefactions due to air particles set into motion by a vibrating source. The frequency of a sound wave is determined by the number of times per second a given molecule of air vibrates about its neutral position. The greater the number of complete vibrations (called *cycles*), the higher the frequency. The unit of frequency is the hertz (Hz). *Pitch* is the subjective response of human hearing to frequency. Low frequencies generally are considered "boomy," and high frequencies "screechy" or "hissy."

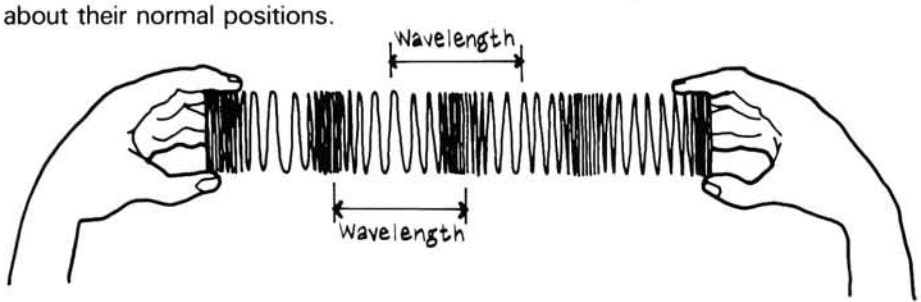
Most sound sources, except for pure tones, contain energy over a wide range of frequencies. For measurement, analysis, and specification of sound, the frequency range is divided into sections (called *bands*). One common standard division is into 10 octave bands identified by their center frequencies: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz. An octave band in sound analysis, like an octave on the piano keyboard shown below, represents a frequency ratio of 2:1. Octave-band ranges of three other musical instruments are also shown below.



Further divisions of the frequency range (e.g., one-third or one-tenth octave bands) can be used for more detailed acoustical analyses. Sound level meters can measure energy within octave bands by using electronic filters to eliminate the energy in the frequency regions outside the band of interest. The sound level covering the entire frequency range of octave bands is referred to as the *overall* level.

WAVELENGTH

As sound passes through air, the to-and-fro motion of the particles alternately pushes together and draws apart adjacent air particles, forming regions of rarefaction and compression. *Wavelength* is the distance a sound wave travels during one cycle of vibration. It also is the distance between adjacent regions where identical conditions of particle displacement occur, as shown below by the wire spring (called a "slinky" toy). When shaken at one end, the wave moves along the slinky, but the particles only move back and forth about their normal positions.



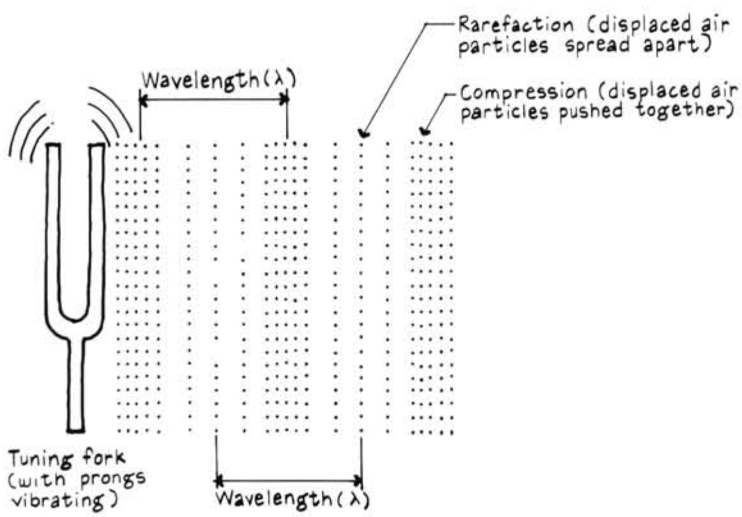
Sound waves in air also are analogous to the ripples (or waves) caused by a stone dropped into still water. The concentric ripples vividly show patterns of molecules transferring energy to adjacent molecules along the surface of the water. In air, however, sound spreads in all directions.

To find the wavelength of sound in air at a specific frequency, use the following formula:

$$\lambda = \frac{1130}{f}$$

where λ = wavelength (ft)
f = frequency (Hz)

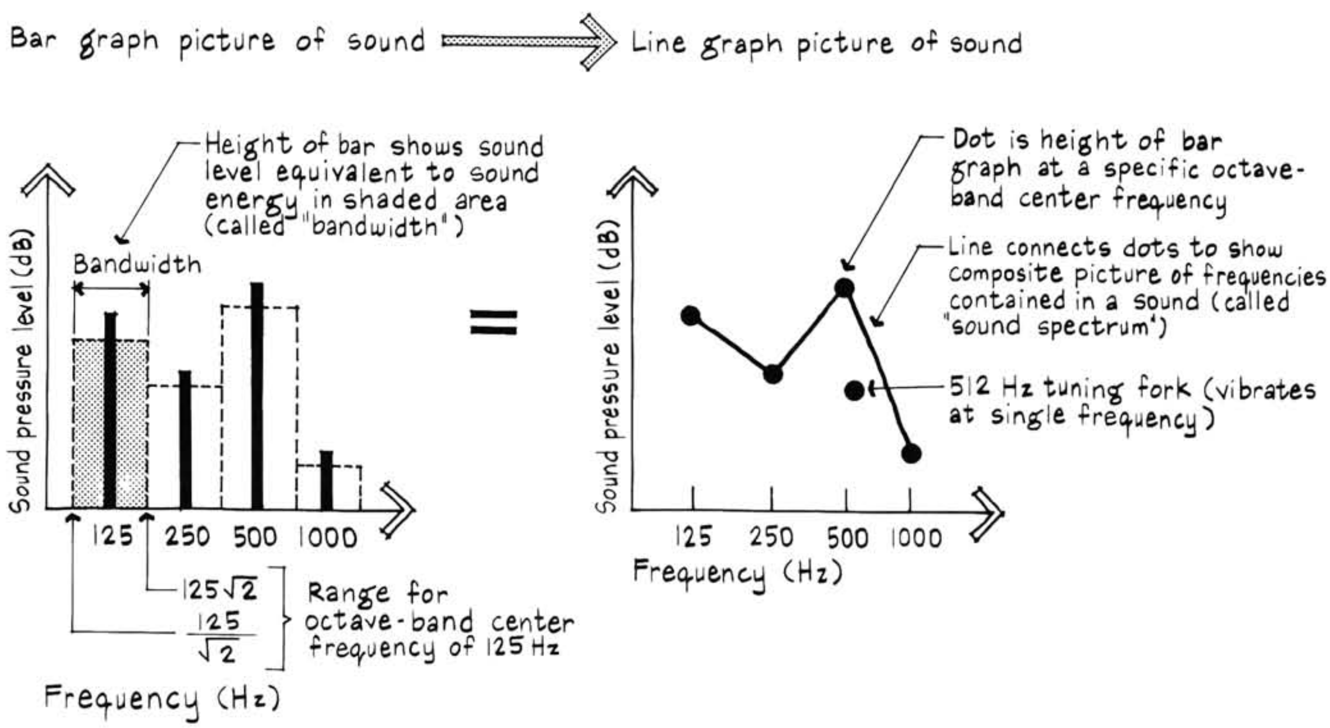
Shown below is the wavelength in air from the to-and-fro motion of a vibrating tuning fork. The movement of the prongs alternately compresses and rarefies adjacent air particles. This cyclical motion causes a chain reaction between adjacent air particles so that the waves (but *not* the air particles) propagate away from the tuning fork. Remember sound travels, but the elastic medium only vibrates.



SOUND SPECTRUM

Because most sounds are complex, fluctuating in pressure, level, and frequency content, the relationships between sound pressure level and frequency are required for meaningful analysis (data so plotted are called a *sound spectrum*). This requirement is similar to indoor climate control, where thermal comfort cannot be specified as a 70°F temperature alone because comfort also depends on relative humidity, air motion, and so on. Sound spectra are used to describe the magnitude of sound energy at many frequencies. The frequency scale given below is an *octave-band scale* because the ratio of successive frequencies is 2:1, the ratio for an octave in music. In acoustics, the extent or width of octave bands is geometric. For example, the octave band for a center frequency of 125 Hz contains sound energy from $125 \div \sqrt{2}$ Hz to $125 \times \sqrt{2}$ Hz.

The line graph at the right depicts the octave-band spectrum for a noise consisting of the sound energy measured within octave bands (see bar graph at left). The line graph is plotted at the respective center frequencies of the bands. Also shown on the graph is the sound level of a 512-Hz tuning fork. Note that the tuning fork produces sound energy at a single frequency only. A tuning fork will vibrate at the same frequency if struck lightly or forcefully, but the sound levels produced can differ greatly.



If a pianist uses both forearms to simultaneously strike as many piano keys as possible, the resulting noise will be *broadband* because the sound produced will be spread throughout a wide range of frequencies. A graph of this noise, therefore, would plot as a wide, flat spectrum.

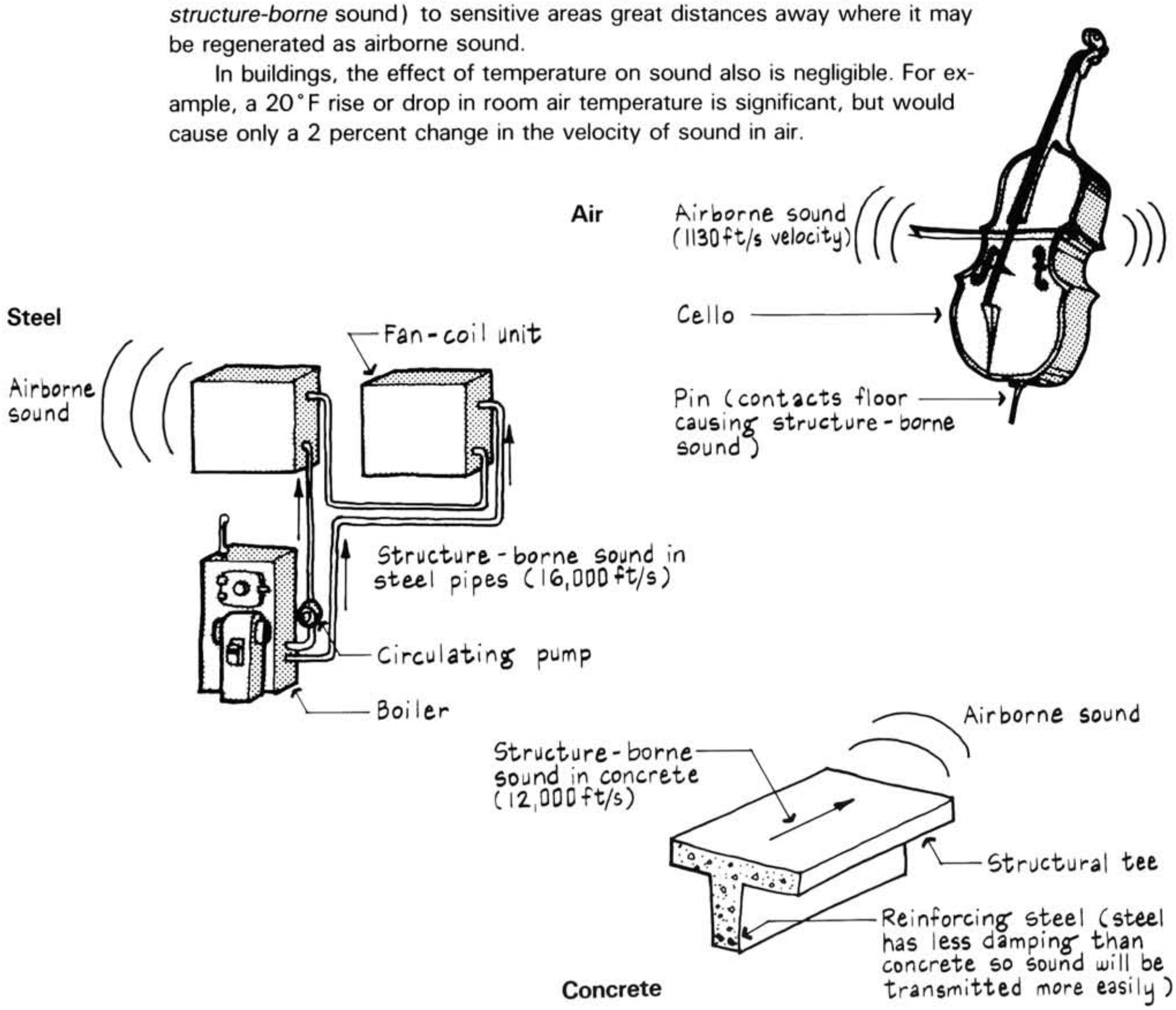
VELOCITY OF SOUND

Sound travels at a *velocity* that depends primarily on the elasticity and density of the medium. In air, at normal temperature and atmospheric pressure, the velocity of sound is approximately 1130 feet per second (ft/s), or almost 800 mi/h. This is extremely slow when compared to the velocity of light, which is about 186,000 mi/s, but much faster than even hurricane winds.

In building air distribution systems, the air velocity at registers, diffusers, and in ducts is so much slower than the velocity of sound that its effect can be neglected. For example, an extremely high air velocity of 2000 ft/min (about 33 ft/s) in a duct is less than 3 percent of the velocity of sound in air. Consequently, airborne sound travels with equal ease upstream and downstream within most air ducts!

However, sound may travel at a very fast 16,000 ft/s along steel pipes and duct walls as shown below. It is therefore important to block or isolate paths where sound energy can travel through building materials (called *structure-borne* sound) to sensitive areas great distances away where it may be regenerated as airborne sound.

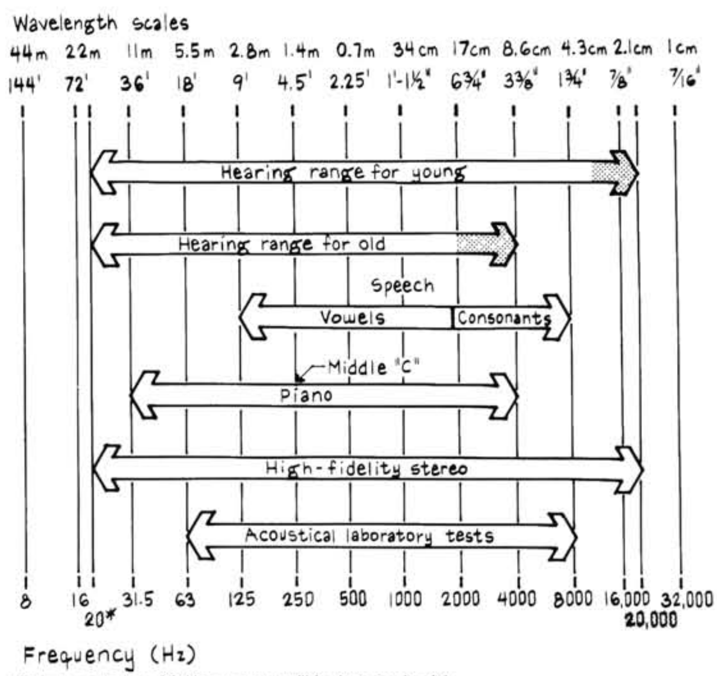
In buildings, the effect of temperature on sound also is negligible. For example, a 20°F rise or drop in room air temperature is significant, but would cause only a 2 percent change in the velocity of sound in air.



FREQUENCY RANGES OF AUDIBLE SOUNDS

Hearing ranges for both young and older persons ($>$ 20 years old) are shown below. A healthy young person is capable of hearing sound energy from about 20 to 20,000 Hz. Hearing sensitivity, especially the upper frequency limit, diminishes with increasing age even without adverse effects from diseases and noise—a condition called *presbycusis*. Long-term and repeated exposure to intense sounds and noises of everyday living can cause permanent hearing damage (called *sociocusis*), and short-term exposure can cause temporary loss. Consequently, the extent of the hearing sensitivity for an individual depends on many factors, including age, sex, ethnicity, previous exposure to high noise levels from the workplace, gunfire, power tools, rock music, etc. All other hearing losses (e.g., caused by mumps, drugs, accidents) are called *nosocusis*. An audiologist should be consulted if a "ringing" sensation occurs in ears after exposure to moderately loud noise or if sounds seem muffled or dull.

Also shown below are frequency ranges for human speech (divided into *consonants*, which contain most of the information for articulation, and *vowels*), piano music, stereo sounds, and acoustical laboratory tests (e.g., tests used to determine absorption and isolation properties of building materials). Human speech contains energy from about 125 to 8000 Hz. Women's vocal cords are generally thinner and shorter than men's, so the wavelengths produced are smaller. This is the reason the female frequency of vibration for speech is normally higher. Wavelengths in SI and English units are indicated by the scales at the top of the graph above the corresponding frequency.



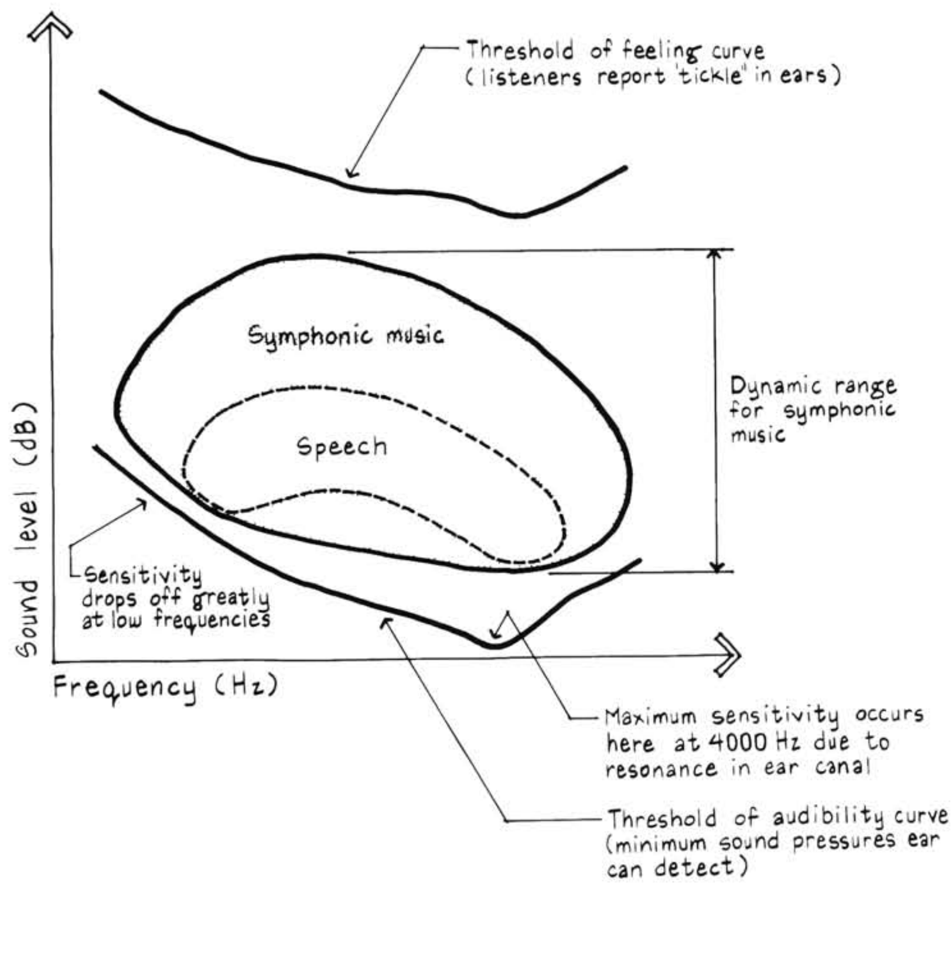
*Vibrations below 20 Hz are *not* audible, but can be felt.

Reference

E. H. Berger et al. (eds.), *Noise and Hearing Conservation Manual*, American Industrial Hygiene Association, Akron, Ohio, 1986.

SENSITIVITY OF HEARING

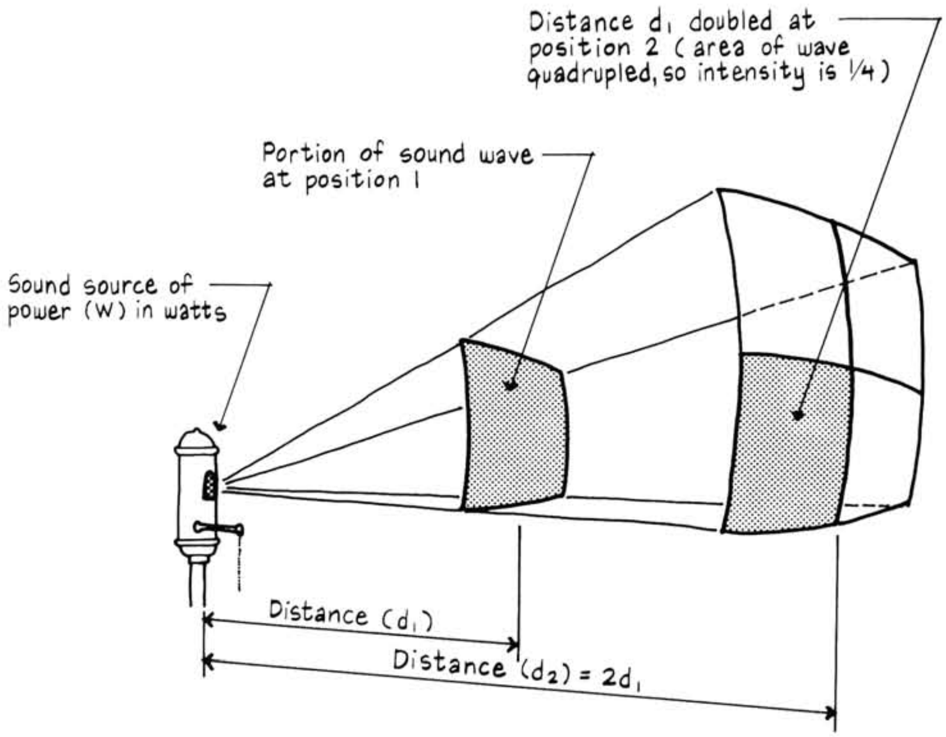
The graph below shows the tremendous range of sound levels in decibels (abbreviated dB)* and frequency in hertz over which healthy young persons can hear. Also shown on the graph is the frequency range for "conversational" speech, which occurs in the region where the ear is most sensitive. For comparison, the region where symphonic music occurs is indicated on the graph by the large shaded area extending at mid-frequencies from below 25 dB to over 100 dB (called *dynamic range*). The dynamic range for individual instruments can vary from 30 dB (woodwinds) to 50 dB (strings). The lowest level of musical sound energy that can be detected by the audience largely depends on the background noise in the music hall (see Chap. 4), and the upper level depends on the acoustical characteristics of the hall (see Chap. 3). Electronically amplified rock music in arenas and coliseums far exceeds the maximum sound levels for a large symphonic orchestra. Rock music, purposefully amplified to be at the threshold of feeling ("tingling" in the ear), is considered to be a significant cause of sociocusis.



**Decibel* is the unit used to express the pressure (or intensity) level of sound energy. In this book, *sound level* is always measured in decibels by precision sound level meters at a specific frequency or weighting.*

INVERSE-SQUARE LAW

Sound waves from a point source outdoors with no obstructions (called *free-field* conditions) are virtually spherical and expand outward from the source as shown below. A point source has physical dimensions of size that are far less than the distance an observer is away from the source.



Power is a basic quantity of energy flow. Although both acoustical and electric energies are measured in watts, they are different forms of energy and cause different responses. For instance, 10 watts (abbreviated W) of electric energy at an incandescent lamp produces a very dim light, whereas 10 W of acoustical energy at a loudspeaker can produce an extremely loud sound. Peak power for musical instruments can range from 0.05 W for a clarinet to 25 W for a bass drum.

The intensity from a point source outdoors at a distance d away is the sound power of the source divided by the total spherical area $4\pi d^2$ of the sound wave at the distance of interest. This relationship can be expressed as:

$$I = \frac{W}{4\pi d^2}$$

where I = sound intensity (W/m^2)
W = sound power (W)
d = distance from sound source (m)

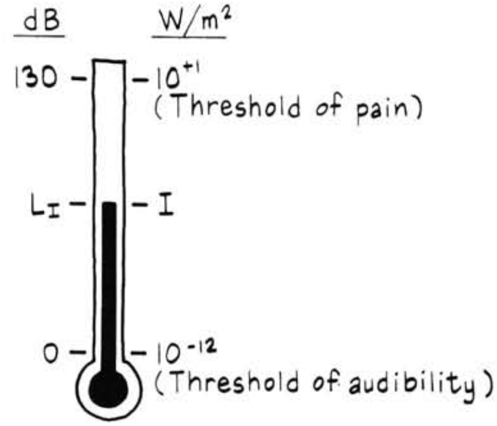
If the distance is measured in feet, multiply the result by 10.76, because 1 m^2 equals 10.76 ft^2.

The *inverse-square law* for sound is:

$$\frac{I_1}{I_2} = \left(\frac{d_2}{d_1}\right)^2$$

where I = sound intensity (W/m^2)
d = distance from sound source (ft or m)

Note: To derive the inverse-square law, consider a wavefront at positions 1 and 2 as shown on the above illustration. At position 1, $W = I_1 4\pi d_1^2$, and at position 2, $W = I_2 4\pi d_2^2$. Since the energies are the same (because the source is the same), $I_1 4\pi d_1^2 = I_2 4\pi d_2^2$. Therefore, $I_1/I_2 = d_2^2/d_1^2$, which is the inverse-square law for sound.



Ernst Weber and Gustav Fechner (nineteenth-century German scientists) discovered that nearly all human sensations are proportional to the logarithm of the intensity of the stimulus. In acoustics, the *bel* unit (named in honor of Alexander Graham Bell) was first used to relate the *intensity* of sound to an *intensity level* corresponding to the human hearing sensation. Sound intensity level in bels equals the logarithm of the intensity ratio I/I_0, where I_0 is the minimum sound intensity audible to the average human ear at 1000 Hz. *Decibels* (prefix deci- indicates that logarithm is to be multiplied by 10) can be found by the following formula:

$$L_I = 10 \log \frac{I}{I_0}$$

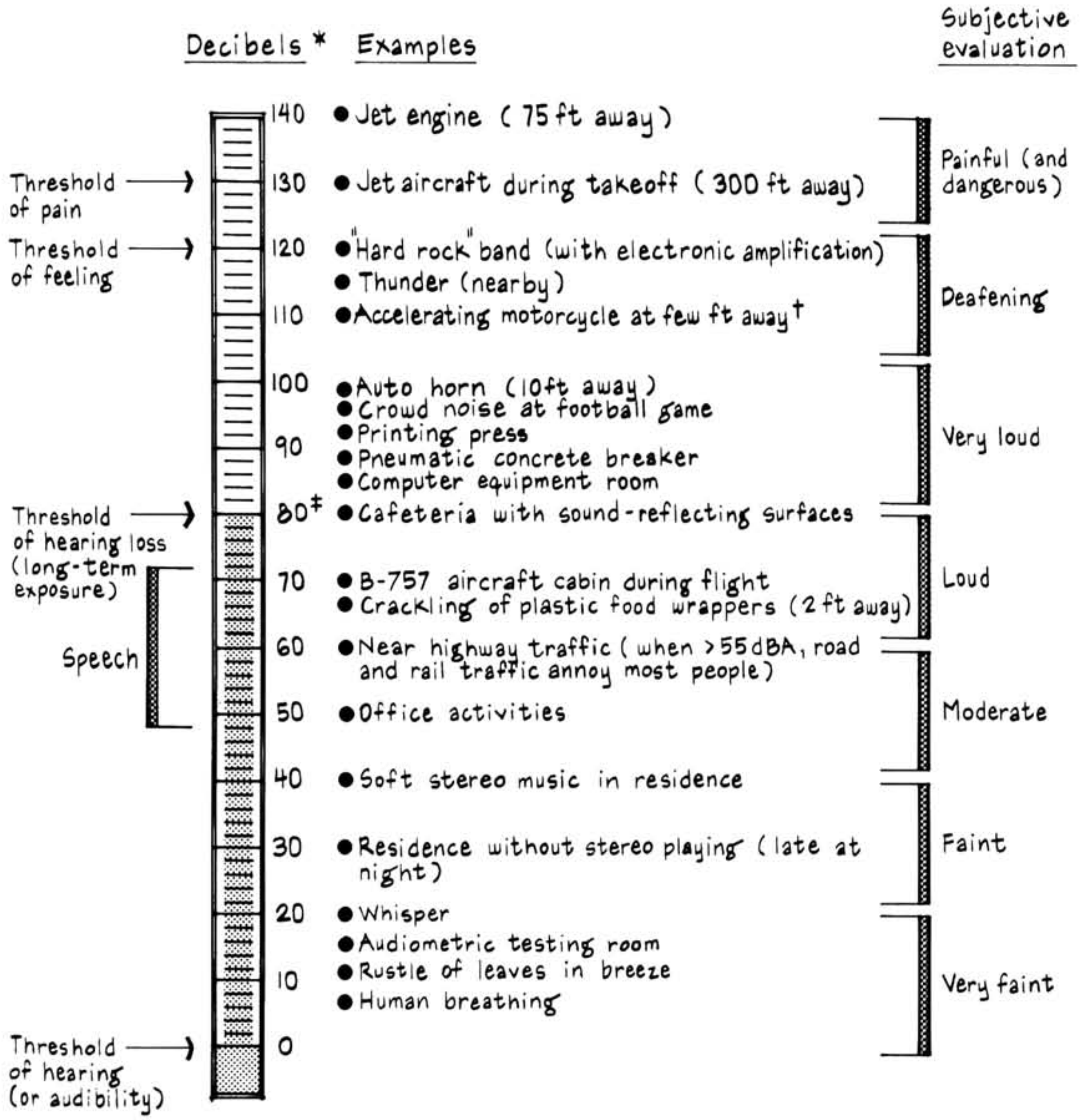
where L_I = sound intensity level (dB)
I = sound intensity (W/m^2)
I_0 = reference sound intensity, 10^{-12} (W/m^2)

The illustration on the following page gives the decibel level of some familiar sounds. The human hearing range from the threshold of audibility at 0 dB to the threshold of pain at 130 dB represents a tremendous intensity ratio of 10 trillion (10,000,000,000,000) to 1. This is such a wide range of hearing sensitivity that it may be hard to imagine at first. For example, if a bathroom scale had a sensitivity range comparable to that of the human ear, it would have to be sensitive enough to weigh both a human hair and a 30-story building! Logarithms allow the huge range of human hearing sensitivity to be conveniently represented by smaller numbers.

It is difficult to measure sound intensity directly. However, sound intensity is proportional to the square of sound pressure, which can more easily be measured by sound level meters. In air under normal atmospheric conditions, sound intensity level and sound pressure level are nearly identical.

COMMON SOUNDS IN DECIBELS

Some common, easily recognized sounds are listed below in order of increasing sound levels in decibels. The sound levels shown for occupied rooms are only example activity levels and do *not* represent criteria for design. Note also that thresholds vary among individuals.



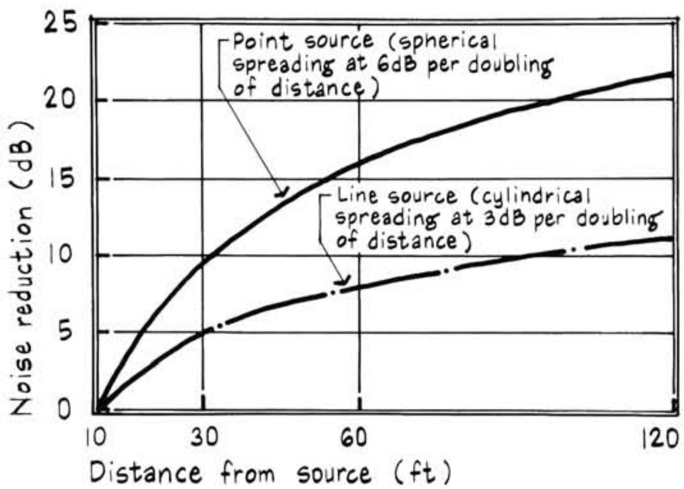
*dBA are weighted values measured by a sound level meter. See page 31 for details of electronic weighting networks which modify the sensitivity of meters.

†50 ft from a motorcycle can equal the noise level at less than 2000 ft from a jet aircraft.

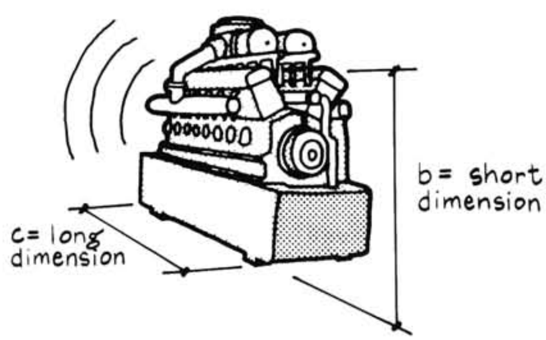
‡Continuous exposure to sound energy above 80 dBA can be hazardous to health and can cause hearing loss for some persons.

NOISE REDUCTION WITH DISTANCE

Outdoors in the open and away from obstructions, sound energy from *point sources* drops off by 6 dB for each doubling of the distance from the source. (According to the inverse-square law, the intensity ratio for a doubling of distance is $2^2 = 4$, and the corresponding decibel reduction is 10 log 4, or 6 dB.) Sound energy from *line sources* (e.g., stream of automobiles or railroad cars) drops off by 3 dB for each doubling of distance. This is because line sources consist of successive point sources which reinforce each other. Thus the spread of sound energy is cylindrical, *not* spherical. Cylindrical surface areas increase in proportion to the radius (distance), whereas spherical surface areas increase in proportion to the square of the radius. The graph below shows noise reduction due to distance for point and line sources. Additional reductions can be caused by large buildings, earth berms, trees and vegetation, and other environmental effects (see Chap. 4).



An *area source*, produced by several adjacent line sources (e.g., rows of cheering spectators at sports events) or large radiating surfaces of mechanical equipment, has little reduction of sound energy with distance close to the source. Within distances of b/π to c/π, where b is the short and c the long dimension of an area source, sound energy drops off by 3 dB for each doubling of distance. Beyond distances of c/π, the drop-off will be 6 dB for each doubling of distance outdoors (cf., E. J. Rathe, "Note on Two Common Problems of Sound Propagation," *Journal of Sound and Vibration*, November 1969, pp. 472-479).



Logarithm Basics

The first step to find the *logarithm* of a number is to express it as a digit from 1 to 9 multiplied by 10 to a power. A logarithm usually consists of two parts—the *characteristic*, which is the power of 10, and the *mantissa*, which is the decimal found in log tables (or from pocket calculators). In solving logarithms, remember that

$$
\begin{aligned}
10^5 &= 100{,}000 \\
10^4 &= 10{,}000 \\
10^3 &= 1000 \\
10^2 &= 100 \\
10^1 &= 10 \\
10^0 &\equiv 1 \quad (\equiv \text{ means } \textit{equal to} \text{ by definition}) \\
10^{-1} &= 0.1 \\
10^{-2} &= 0.01 \\
10^{-3} &= 0.001
\end{aligned}
$$

and when the decimal point is shifted to the left by n places, the number is to be multiplied by 10^n; when the decimal is shifted to the right by n places, the number is to be divided by 10^n. This may seem complicated at first, but after reviewing a few examples it should become routine.

$4{,}820{,}000.0 = 4.82 \times 10^6 \simeq 5 \times 10^6$ ($\simeq$ means *approximately equal to*)

Numbers ending in 0.5 and greater should be rounded up as shown by the example above. If less than 0.5, the decimal should be dropped.

$$0.0000258 = 2.58 \times 10^{-5} \simeq 3 \times 10^{-5}$$

$$8{,}400{,}000{,}000.0 = 8.4 \times 10^9 \simeq 8 \times 10^9$$

The following shortened logarithm table can be used to quickly find the mantissa of numbers from 1 to 9.

A USEFUL LOG TABLE

Number	Mantissa
1	0
2	0.3
3	0.48
4	0.6
5	0.7
6	0.78
7	0.85
8	0.9
9	0.95

In almost all acoustical problems, it is not necessary to work with small fractions of decibels. Use either the log table above, or a four-place log table, and round the final answer to the nearest decibel. A pocket calculator that finds an entire logarithm in one step is very handy when working with decibels.

The following examples represent logs of very large and very small numbers. Remember, the first step is to arrange the number as a digit times 10 to a power.

$$\log(4{,}820{,}000.0) = \log(5 \times 10^6) = 6.7 = 6.7$$

enter number
column to find

$$\log(0.0000258) = \log(3 \times 10^{-5}) = -\log\left(\frac{1}{3} \times 10^5\right)$$

$$= -\log(0.33 \times 10^5) = -\log(3 \times 10^4) = -4.48$$

$$\log(8{,}400{,}000{,}000.0) = \log(8 \times 10^9) = 9.9$$

Antilogarithms

The *antilogarithm* of a quantity, such as antilog (x), is the number for which the quantity x is the logarithm. For example,

$$\text{antilog}(6.7) = 5 \times 10^6 = 5 \times 10^6$$

enter mantissa
column to find

$$\text{antilog}(-4.48) = -3 \times 10^4 = \frac{1}{3} \times 10^{-4} = 0.33 \times 10^{-4} = 3 \times 10^{-5}$$

When the mantissa of a log falls between values in the log table on page 15, use the closest mantissa to find the corresponding number from 1 to 9.

Properties of Logs

1. $\log xy = \log x + \log y$
2. $\log \dfrac{x}{y} = \log x - \log y$
3. $\log x^n = n \log x$
4. $\log 1 = 0$*

*This property is important in acoustical analysis because openings in building elements have no resistance to sound flow which then can be expressed as 0 dB of isolation.

Powers of 10 Review

Remember, the symbol 10^3 is a shorthand notation for $10 \times 10 \times 10 = 1000$. Also, the product of two powers of the same number has an exponent equal to the sum of the exponents of the two powers:

$$10^2 \times 10^3 = (10 \times 10) \times (10 \times 10 \times 10) = 10^5$$

or

$$10^2 \times 10^3 = 10^{(2+3)} = 10^5$$

Additional examples follow:

$$10^7 \times 10^5 = 10^{(7+5)} = 10^{12}$$

$$\frac{10^{-9}}{10^{-12}} = 10^{-9} \times 10^{+12} = 10^{(-9+12)} = 10^3$$

When combining exponents, be careful of the signs. Dividing by a negative exponent such as 10^{-12} is equivalent to multiplying by its reciprocal, 10^{+12}.

$$\frac{10^{-3}}{10^{-12}} = 10^{-3} \times 10^{+12} = 10^{(-3+12)} = 10^9$$

You have now learned to handle powers of 10 and logarithms, which are fundamental relationships needed to describe how humans perceive sound and how building materials affect sound energy. Several examples are presented below and on the following pages.

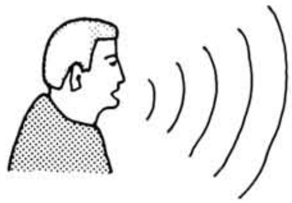
Examples

1. The intensity I of a rock music group is 8.93×10^{-2} W/m^2. Find the corresponding sound intensity level L_I.

$$L_I = 10 \log \frac{I}{10^{-12}}$$

$$= 10 \log \frac{8.93 \times 10^{-2}}{10^{-12}} = 10 \log (8.93 \times 10^{10})$$

$$L_I = 10\ (10.9509) = 110 \text{ dB}$$



2. Loud speech, measured at 3 ft away, has a sound intensity level L_I of 73 dB. Find the corresponding intensity I.

$$L_I = 10 \log \frac{I}{10^{-12}}$$

$$73 = 10 \log \frac{I}{10^{-12}}$$

Next, divide both sides of the equation by 10.

$$7.3 = \log \frac{I}{10^{-12}}$$

The above expression states that the log of a ratio $(I/10^{-12})$ is equal to 7.3. When the number for which the log is 7.3 (i.e., antilog) is found, set it equal to the ratio.

$$\text{antilog } (7.3) = 1.995 \times 10^{7}$$

from mantissa table
or pocket calculator

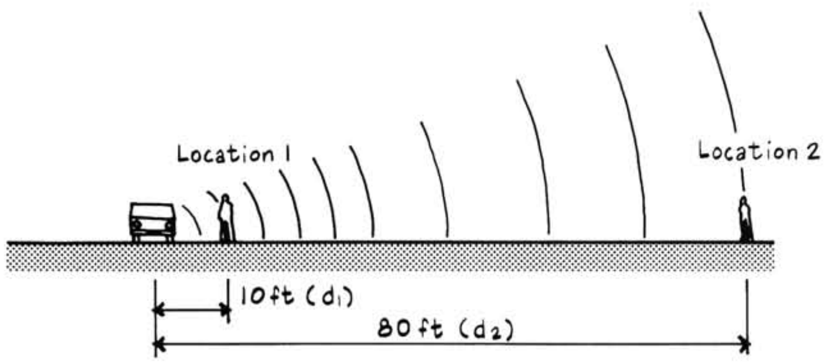
Therefore,

$$1.995 \times 10^{7} = \frac{I}{10^{-12}}$$

and by cross multiplication

$$I = 1.995 \times 10^{7} \times 10^{-12} = 1.995 \times 10^{-5} \text{ W/m}^2$$

EXAMPLE PROBLEM (INVERSE-SQUARE LAW)



1. A car horn outdoors produces a sound intensity level L_I of 90 dB at 10 ft away. To find the intensity I_1 at this first location, use

$$L_I = 10 \log \frac{I}{10^{-12}}$$

$$90 = 10 \log \frac{I_1}{10^{-12}}$$

$$9.0 = \log \frac{I_1}{10^{-12}}$$

$$\text{antilog } (9.0) = 1.0 \times 10^9$$

$$1.0 \times 10^9 = \frac{I_1}{10^{-12}}$$

$$I_1 = 1.0 \times 10^9 \times 10^{-12} = 10^{-3} \text{ W/m}^2 \text{ at 10 ft away}$$

2. If the sound intensity I is known at a given distance in feet away from the source, sound power W can be found by the following formula.

$$I = \frac{W}{4\pi d^2} \times 10.76$$

By cross multiplication

$$W = 4\pi d^2 \times \frac{1}{10.76} \times I$$

Since $I_1 = 10^{-3}$ W/m² at 10 ft away

$$W = 4 \times 3.14 \times 10^2 \times \frac{1}{10.76} \times 10^{-3} = 0.12 \text{ W}$$

3. The intensity level L_I at 80 ft away can be found by the inverse-square law. First, find the sound intensity I_2 at the location 80 ft away.

$$\frac{I_1}{I_2} = \left(\frac{d_2}{d_1}\right)^2$$

$$\frac{10^{-3}}{I_2} = \left(\frac{80}{10}\right)^2$$

$$\frac{10^{-3}}{I_2} = 64$$

$$64I_2 = 10^{-3}$$

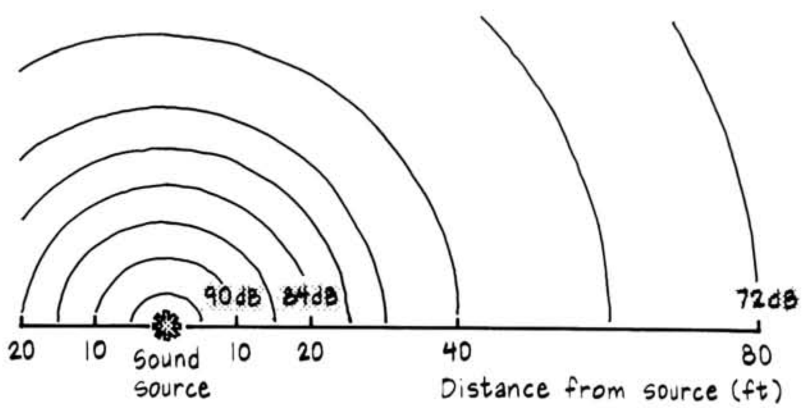
$$I_2 = \frac{1}{64} \times 10^{-3} = 1.56 \times 10^{-5} \text{ W/m}^2 \text{ at 80 ft away}$$

Next, find L_I.

$$L_I = 10 \log \frac{I_2}{10^{-12}} = 10 \log \frac{1.56 \times 10^{-5}}{10^{-12}}$$

$$L_I = 10 \log (1.56 \times 10^{7}) = 10(7.1931) = \textbf{72 dB} \text{ at 80 ft}$$

This means a listener moving from location 1 at 10 ft away to location 2 at 80 ft away would observe a change in intensity level of 18 dB (that is, 90 dB − 72 dB). This reduction would be judged by most listeners as "very much quieter" (see table on the following page). However, a car horn at 72 dB would still be considered "loud" by most people.



Note: From 10 to 80 ft away is three doublings of distance (i.e., 10 to 20 ft, 20 to 40 ft, and 40 to 80 ft). Therefore, three doublings × 6 dB/doubling = 18 dB reduction and $L_I = 90 - 18 = 72$ dB at 80 ft away.

CHANGES IN SOUND LEVEL

The table below is an approximation of human sensitivity to changes in sound level. Sound intensity is not perceived directly at the ear; rather it is transferred by the complex hearing mechanism to the brain where acoustical sensations can be interpreted as *loudness*. This makes hearing perception highly individualized. Sensitivity to noise also depends on frequency content, time of occurrence, duration of sound, and psychological factors such as emotion and expectations (cf., O. L. Angevine, "Individual Differences in the Annoyance of Noise," *Sound and Vibration*, November 1975). Nevertheless, the table is a reasonable guide to help explain increases or decreases in sound levels for many architectural acoustics situations.

Change in Sound Level (dB)	Change in Apparent Loudness
1	Imperceptible (except for *tones*)
3	Just barely perceptible
6	Clearly noticeable*
10	About twice (or half) as loud
20	About 4 times (or one-fourth) as loud

*For example, distance to the point source outdoors is halved or doubled.

The change in intensity level (or *noise reduction*, abbreviated NR) can be found by:

$$\mathrm{NR} = L_1 - L_2$$

and

$$\mathrm{NR} = 10 \log \frac{I_1}{I_2}$$

where NR = difference in sound levels between two conditions (dB)
I_1 = sound intensity under one condition ($\mathrm{W/m^2}$)
I_2 = sound intensity under another condition ($\mathrm{W/m^2}$)

Note: By substitution of the inverse-square law expression from page 11 into the above formula

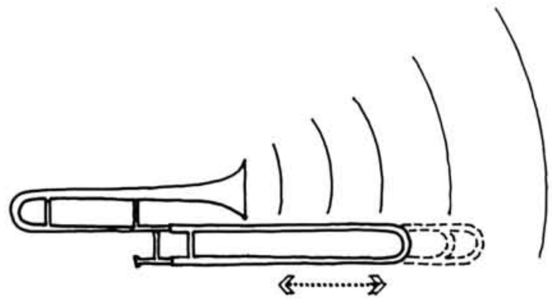
$$\mathrm{NR} = 10 \log \left(\frac{d_2}{d_1}\right)^2$$

and therefore, in terms of distance ratio d_2/d_1

$$\mathrm{NR} = 20 \log \left(\frac{d_2}{d_1}\right)$$

for point sources outdoors, where d's are the distances.

EXAMPLE PROBLEM (MUSIC MAN)



The measured sound intensity level L_I of one trombone is 80 dB. To find the sound intensity level L_I from 76 trombones, first find the intensity I_1 of one trombone.

$$L_I = 10 \log \frac{I_1}{I_0}$$

$$80 = 10 \log \frac{I_1}{10^{-12}}$$

$$8.0 = \log \frac{I_1}{10^{-12}}$$

$$1.0 \times 10^8 = \frac{I_1}{10^{-12}}$$

$$I_1 = 1.0 \times 10^8 \times 10^{-12}$$

$$I_1 = 10^{-4}\ \text{W/m}^2 \text{ for one trombone}$$

To combine the intensities of 76 trombones, each producing 80 dB at a listener's position, find the intensity I_2 of 76 trombones. I_2 will be $76 \times I_1 = 76 \times 10^{-4}\ \text{W/m}^2$.

$$L_I = 10 \log \frac{I_2}{I_0}$$

$$= 10 \log \frac{76 I_1}{10^{-12}} = 10 \log \frac{76 \times 10^{-4}}{10^{-12}}$$

$$= 10 \log (7.6 \times 10^9)$$

$$L_I = 10\ (9.8808) = 99 \text{ dB for 76 trombones}$$

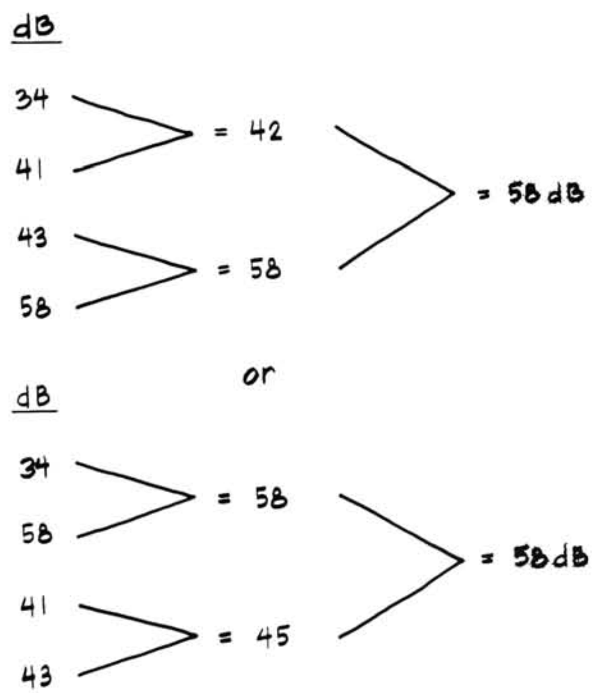
This is not as great an increase as might at first be expected. It would take 100,000 trombones to reach the threshold of pain at 130 dB (although the threshold of disgust might be reached at a much lower level). A composer is aware that a large number of instruments playing the same score may not produce a tremendous sound impression. Large numbers of instruments are used to achieve the desired *tonal texture* or blend in the overall sound from the individual instruments. For example, one solo violin by its location and frequency range may dominate portions of an orchestral performance.

DECIBEL ADDITION

Because decibels are logarithmic values, they cannot be combined by normal algebraic addition. For example, when the decibel values of two sources differ by 0 to 1 dB, 3 dB should be added to the higher value to find the combined sound level. Therefore, the sound level of two violins, each playing at 60 dB, would be 60 + 3 = 63 dB, *not* 60 + 60 = 120 dB (which would be near the threshold of pain!). This is similar to lighting, where two 35-W fluorescent lamps are not twice as bright as one. The following table can be used to rapidly combine sound levels.

When Two dB Values Differ by	Add the Following dB to the Higher Value
0 or 1	3
2 or 3	2
4 to 8	1
9 or more	0

When several decibel values are to be added, use the table to find the combined value by adding the decibels two at a time. For example, to find the combined sound level of 34 dB, 41 dB, 43 dB, and 58 dB, add as follows:



Notice that 43 + 58 = 58 dB and 34 + 58 = 58 dB because the higher sound level (by > 9 dB) swamps out the lower sound level.

To find the combined sound level of 82 dB, 101 dB, 106 dB, 102 dB, 90 dB, and 78 dB, add as follows: