BASIC THEORY

SOUND LEVEL

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Sound Level

A sound is made when an oscillating membrane disturbs the molecules in an elastic medium—and that disturbance is heard. While sounds may travel through solids or liquids, in the domain of architectural acoustics, we generally skew our discussion to the elastic medium of air (structure-borne sound notwithstanding). A nearby passing bus excites a window pane into vibration, which in turn excites the air molecules near the window, which in turn excite air molecules near the first group of air molecules, and so on, until the band of oscillating molecules reaches the ears of a listener; this creates a sound.

We say "The Wave" circles a full stadium, even if the participants don't themselves traverse the stadium's perimeter. Spectators merely stand up, then sit down. As each successive column of fans stands and sits, the wave propagates, though each particle (spectator) in the wave returns to its resting position (seated). Similarly, with propagating sound, each excited molecule returns to its steady state, but only after passing its energy to its neighboring molecules. Other parallel models exist to describe the propagation: the slinky, the water wave, the snapped towel, a crowded mosh pit with fans colliding.

Three characteristics describe the physics of sound:

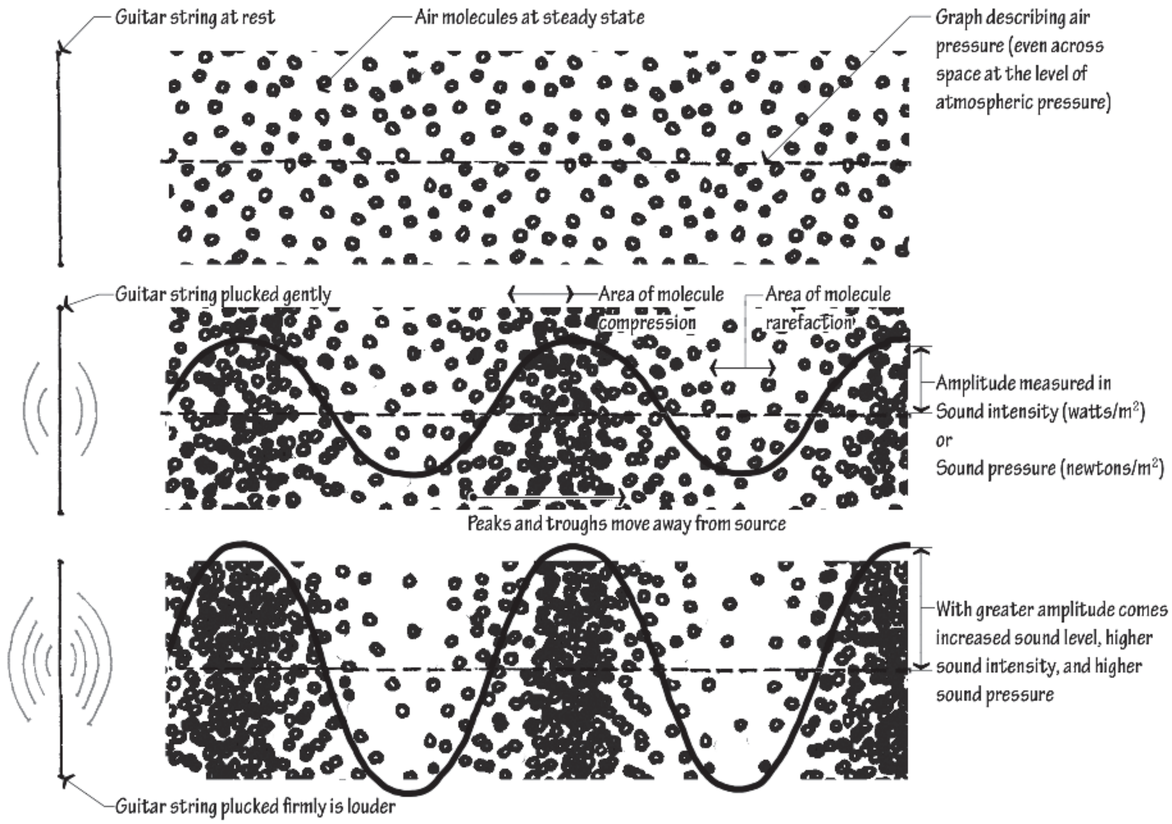
Sound level (or energy, strength, amplitude, loudness)

Frequency (or pitch, tone, wavelength)

Propagation (or path, elapsed time)

A hard-plucked guitar string displaces the adjacent air molecules more than a gently plucked one; the collision with the hard-plucked string whips the molecules farther out of their steady state position, and each successive column of molecules whips harder into the next, and so on. We hear these waves of increased compression and rarefaction as louder. In the stadium wave analogy, a louder sound would be akin to the sort of wave where the spectators stand all the way up and raise their arms in the air; a quieter sound would be the sort of wave where spectators remain seated and only raise their arms. Loudness is thus defined by a wave's amplitude.

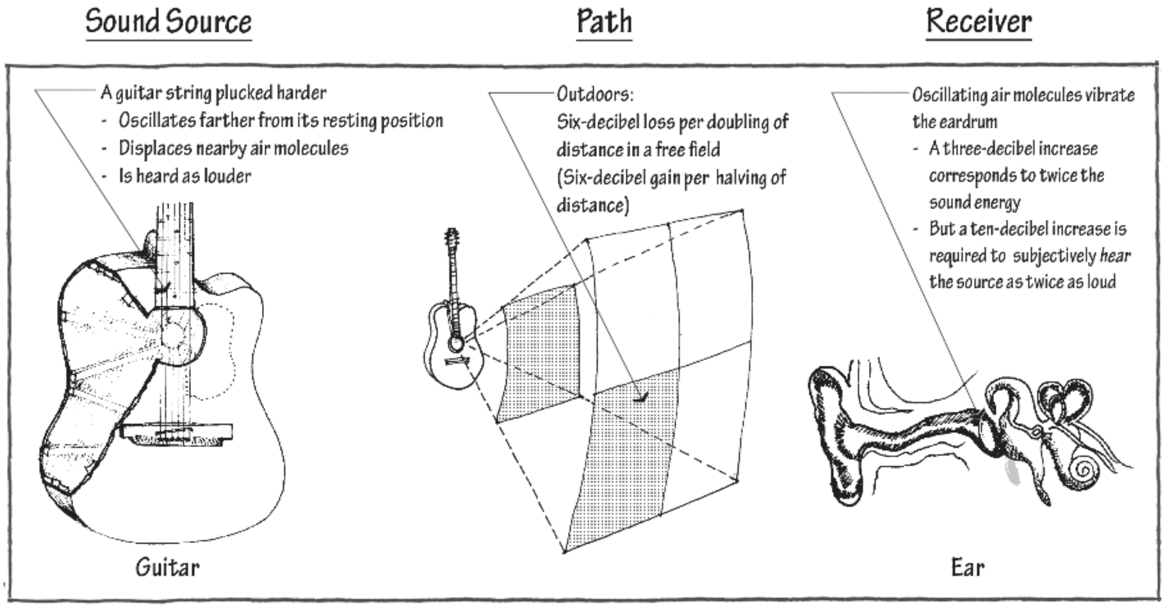
Not all vibrating membranes create a sound. If a vibrating element moves very little (less than the mean free path between molecules), it makes no sound because it fails to displace the adjacent molecules far enough that they collide into their neighbors. And if the vibrating element moves very slowly, the molecules simply move smoothly around the element, and again no sound is generated. The amplitude of the displacement may also fall below the threshold of human hearing, although our auditory system's sensitivity is remarkable. Very small sound pressures, relative to the ambient atmospheric pressures, are perceptible. Sounds generally blend together when we listen unconsciously, but with intentional listening, we can pick out a single instrument in a hundred-person orchestra, or listen to a story at a party even if the background noise far exceeds the speech signal.



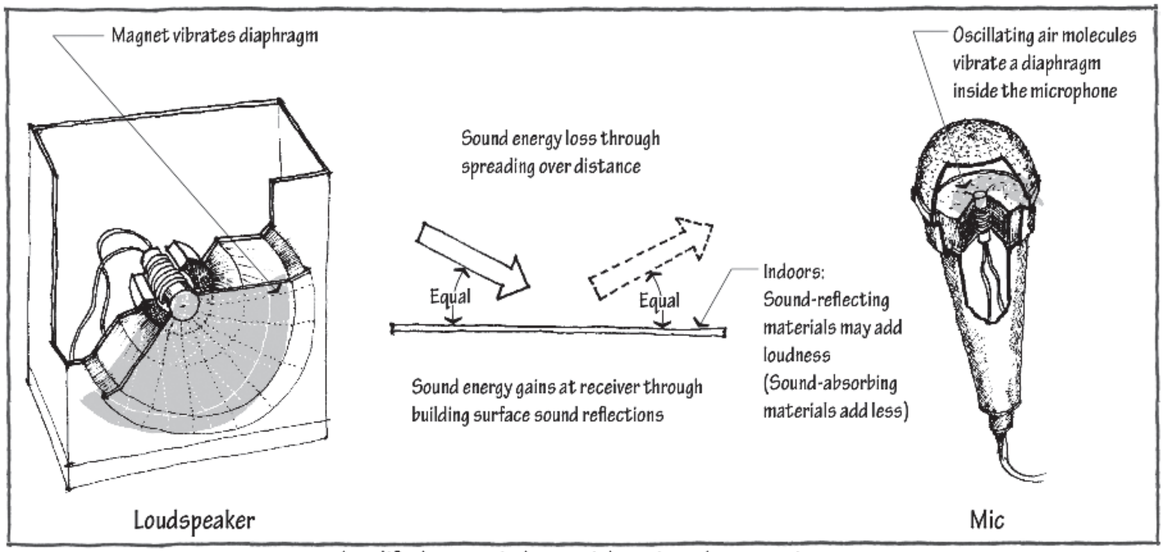
NOTE

For clarity, this model omits much of the true behavior of sound. Guitars, and most other musical instruments, do not produce sound at a single frequency (as drawn here), but rather at multiple frequencies simultaneously. A more complicated, but truer-to-life, illustration would incorporate several sine waves of varying size and a more complex molecule pattern.

Source Path Receiver



Unamplified source in a free field with a human receiver



Amplified source indoors with a microphone receiver

Sound measurements:
Sound power *(W)*, measured in watts
Sound power level *(L_w)*, measured in decibels

Receiver measurements:
Sound intensity *(I)*, measured in watts/m^2
Sound intensity level *(L_I)*, measured in decibels

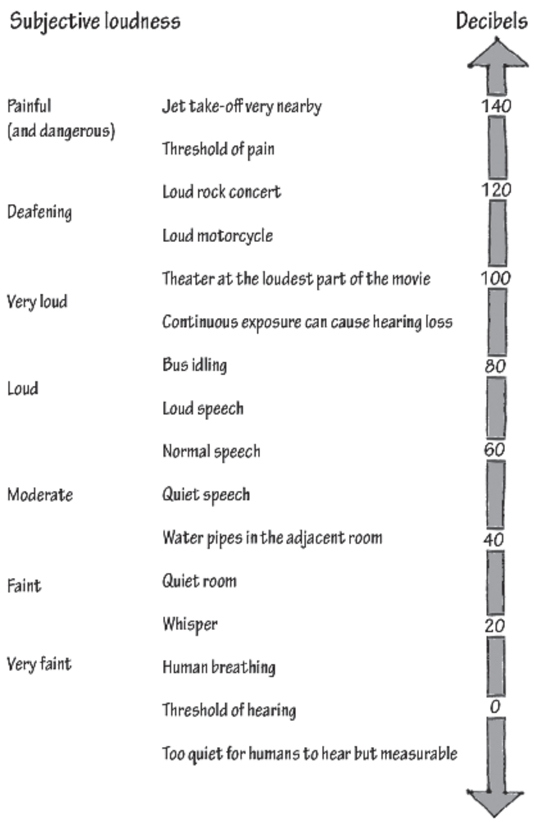
Sound pressure *(P)*, measured in newtons/m^2
Sound pressure level *(L_p or SPL)*, measured in decibels

Measuring Sound Level

Sound power (*W*) describes the strength at the *source*, and sound intensity (*I*) or sound pressure (*P*) describes the strength at the *receiver*, accounting for distance, room surface sound absorption, room geometry, and other environmental effects.

> Sound power is measured at a source (piano, noisy air conditioner, human voice), to quantify how much sound energy that source radiates:
>
> *W* = sound power, measured in watts
>
> A microphone measures in one of two different methods at a receiver to quantify how much sound is arriving:
>
> *I* = sound intensity, measured as the source power divided by the area over which the source energy has spread, expressed in the units watts/m^2
>
> or
>
> *P* = sound pressure measured as the amplitude of the sound wave, in the units newtons/m^2

While these three measures appropriately describe the physics of sound amplitude, they are nevertheless unappetizing in architectural acoustics applications, for three reasons. First, describing human response to sound in pressure or intensity overstates differences, because we don't hear 100 people clapping as subjectively 100 times louder than one person clapping. Second, the numbers expressed in newtons/m^2 or watts/m^2 are inconveniently small. A whisper measures at 0.000000001 watts/m^2, whereas a thunderclap measures at 0.1 watts/m^2. One is a hundred-million times the other, but both numbers seem small. (Sound pressures are not just small in their units of measure, but are also very small compared to the baseline of atmospheric pressure through which they move.) Finally, because it takes a hundred-million whispers to equal a thunderclap, the range of human hearing encompasses a vast range of values. If the sound intensity of human breathing is analogous to the geometric volume of a pea, then the sound intensity of a motorcycle would be analogous to the geometric volume of a house. For these three reasons, we use the decibel unit to both compress the yawning range of loudness values, and normalize the small-seeming numbers into values easier to consume. Zero decibels is normalized to the threshold of hearing, the quietest sound we can hear; 50 decibels is a quiet conversation; and 100 decibels can cause hearing loss over time.



To translate source amplitude, watts, to decibels (dB), convert sound *power* (W) to sound *power level* (L_W). Start with sound power, W, normalize it (divide it by a reference value), then compress its range (with a logarithm function):

$$L_W = 10 \log\left[\frac{W}{10^{-12}\,\text{watts}}\right]$$

To derive sound intensity *level* (L_I) in decibels, from sound intensity (I):

$$L_I = 10 \log\left[\frac{I}{10^{-12}\ \text{watts/m}^2}\right]$$

What did we do to convert sound intensity (I) in w/m^2 to sound intensity *level* (L_I) in decibels (dB)? First we found the measured sound intensity (I) at the microphone and divided that measurement by the reference value 10^{-12} w/m^2, the quietest sound human beings can hear. If the resulting ratio is 200, then we recognize the measured sound intensity as 200 times the sound intensity of the human hearing threshold. Finally, we compress the range of possible values by taking the logarithm of the ratio, and we translate to more convenient numbers by multiplying by 10. Using a reference value equal to the threshold of hearing, we ensure that a sound intensity *level* of zero dB corresponds to the quietest hearable sound because log 1 = 0.

To derive sound pressure *level* (L_p) in decibels from sound pressure (P) in newtons/m^2:

$$L_p = 20 \log\left[\frac{P}{2 \cdot 10^{-5}\ \text{newtons/m}^2}\right]$$

Sound intensity varies with the square of sound pressure, so the formulas are normalized such that sound intensity *level* (very nearly) equals sound pressure *level*. We typically measure with sound pressure level, and sound pressure level correlates best to the way we hear, but most of our calculations are performed using sound intensity level. In practice, values of the two metrics are fairly interchangeable. Because each is a unit-less ratio of the sound relative to a reference value, each can be expressed in decibels (dB).

The decibel unit provides some peculiar but consistent and easy-to-use rules of thumb. A sound, in a free field, drops by six decibels when measured at a distance twice as far away. Two identical sounds, when combined, produce a sound three decibels louder than either one alone. And for the human auditory system to perceive a sound as twice as loud, it will have to be amplified by 10 decibels (20 decibels is four times as loud, and so on). The reverse is also true. A point-source sound in a free field increases by six decibels when measured at half the distance; half the sound intensity translates to a three-decibel loss, and a 10-decibel loss sounds half as loud to the human ear.

Both speech and music rely on dynamic range, the vast span of sound levels between a whisper and a shout, between a pianissimo and a fortissimo passage. The dynamic range of symphonic music extends 70 decibels, so the loudest portions of the piece have 10 million times the energy of the quietest.

NOTE

Logarithms (base 10) compress the wide range of common sounds into a relatively narrow range of values because they are the exponents by which 10 is raised to produce a given number. For instance:

Log 1 = 10

Log 2 = 100

Log 3 = 1,000

Log 4 = 10,000

. . . . and so on, such that adding one and taking the Log equates to multiplying by 10 instead. Logarithms express numbers as orders of magnitude.

Originally, the unit of loudness did not include the 10 multiplier and was called the "bel" in honor of telephone inventor Alexander Graham Bell. After it was found that the just-noticeable difference (JND) for human loudness perception was approximately 1/10th of a bel, the 10 multiplier was added to the equation, and the unit was given the name "decibel."

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Measuring Sound Level

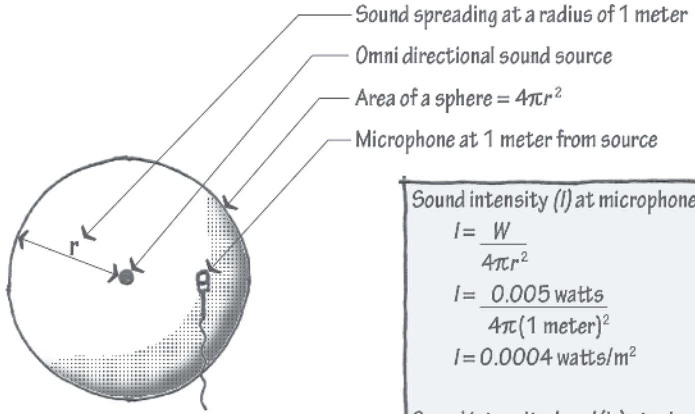
Sound power $(W) = 0.005$ watts

Sound power *level* (L_w):

$$L_w = 10 \log\left(\frac{W}{10^{-12}\,\text{watts}}\right)$$

$$L_w = 10 \log\left(\frac{0.005\,\text{watts}}{10^{-12}\,\text{watts}}\right)$$

$$L_w = 97\ \text{dB}$$



Sound intensity (I) at microphone in watts/m²:

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

$$I = \frac{0.005\,\text{watts}}{4\pi(1\,\text{meter})^2}$$

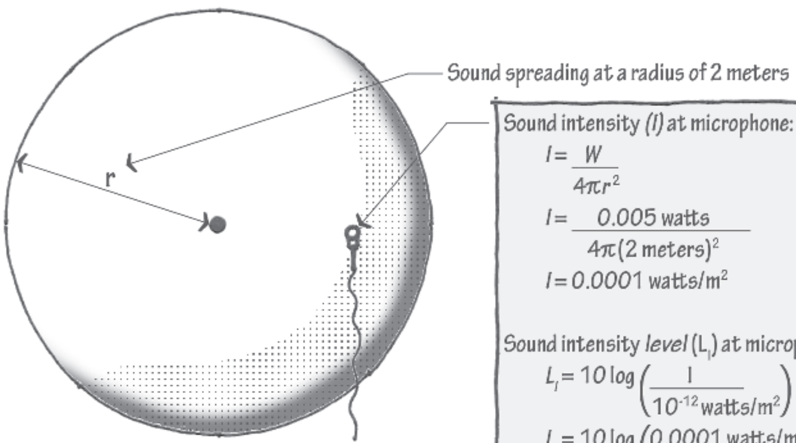
$$I = 0.0004\ \text{watts/m}^2$$

Sound intensity *level* (L_I) at microphone in decibels (dB):

$$L_I = 10 \log\left(\frac{I}{10^{-12}\,\text{watts/m}^2}\right)$$

$$L_I = 10 \log\left(\frac{0.0004\,\text{watts/m}^2}{10^{-12}\,\text{watts/m}^2}\right)$$

$$L_I = 86\ \text{dB}$$



Sound intensity (I) at microphone:

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

$$I = \frac{0.005\,\text{watts}}{4\pi(2\,\text{meters})^2}$$

$$I = 0.0001\ \text{watts/m}^2$$

Sound intensity *level* (L_I) at microphone in decibels (dB):

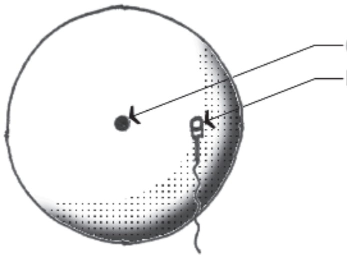
$$L_I = 10 \log\left(\frac{I}{10^{-12}\,\text{watts/m}^2}\right)$$

$$L_I = 10 \log\left(\frac{0.0001\,\text{watts/m}^2}{10^{-12}\,\text{watts/m}^2}\right)$$

$$L_I = 80\ \text{dB}$$

Note sound level drops by 6 dB per doubling of distance in a free field

Multiple Sound Sources



Sound intensity (I) at microphone in watts/m^2:

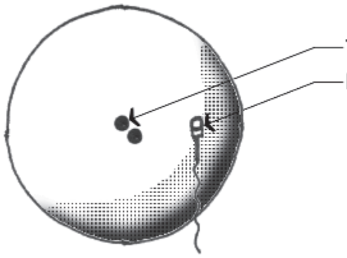
$$I = 0.0004 \text{ watts/m}^2$$

Sound intensity *level* (L_I) at microphone in decibels (dB):

$$L_I = 10 \log \left(\frac{I}{10^{-12} \text{ watts/m}^2} \right)$$

$$L_I = 10 \log \left(\frac{0.0004 \text{ watts/m}^2}{10^{-12} \text{ watts/m}^2} \right)$$

$$L_I = 86 \text{ dB}$$



Sound intensity (I) at microphone in watts/m^2:

$$I = 0.0004 \text{ watts/m}^2 + 0.0004 \text{ watts/m}^2$$

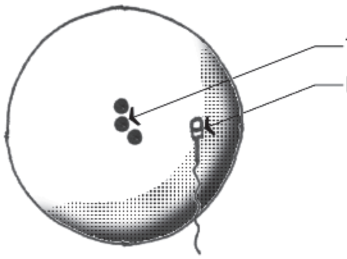
$$I = 0.0008 \text{ watts/m}^2$$

Sound intensity *level* (L_I) at microphone in decibels (dB):

$$L_I = 10 \log \left(\frac{I}{10^{-12} \text{ watts/m}^2} \right)$$

$$L_I = 10 \log \left(\frac{0.0008 \text{ watts/m}^2}{10^{-12} \text{ watts/m}^2} \right)$$

Note that sound level increases by 3 dB per doubling of sound energy → $L_I = 89 \text{ dB}$



Sound intensity (I) at microphone in watts/m^2:

$$I = 0.0004 \text{ watts/m}^2 + 0.0004 \text{ watts/m}^2 + 0.00006 \text{ watts/m}^2$$

$$I = 0.00086 \text{ watts/m}^2$$

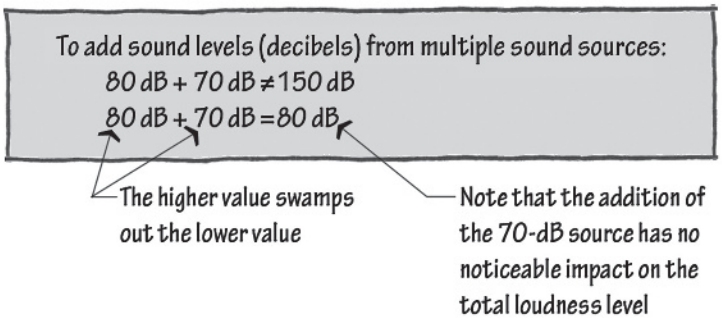
Sound intensity *level* (L_I) at microphone in decibels (dB):

$$L_I = 10 \log \left(\frac{I}{10^{-12} \text{ watts/m}^2} \right)$$

$$L_I = 10 \log \left(\frac{0.00086 \text{ watts/m}^2}{10^{-12} \text{ watts/m}^2} \right)$$

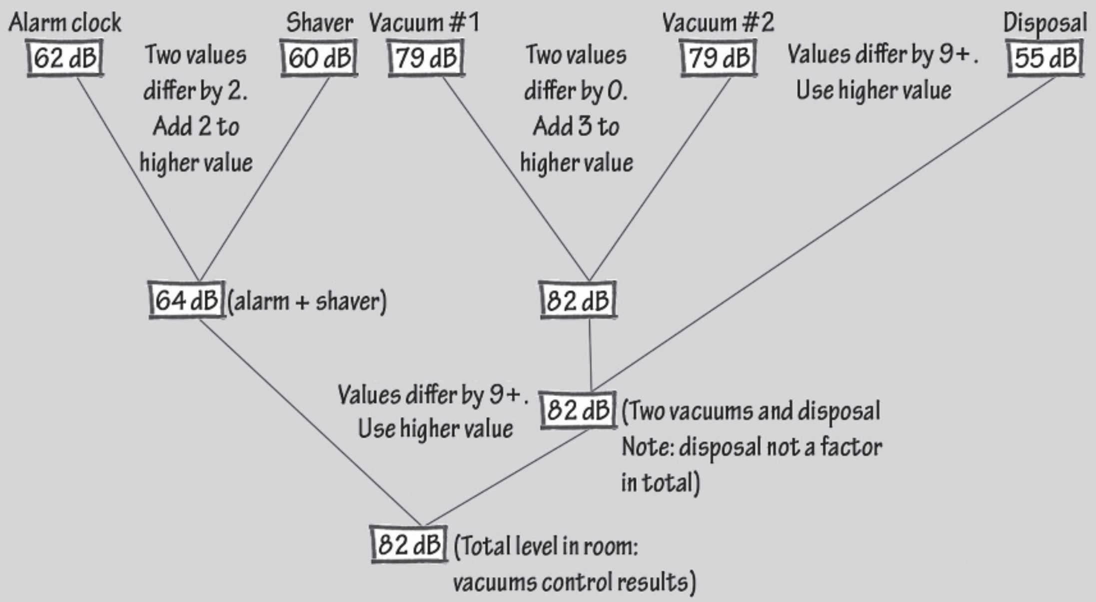
Note that because the third source was sufficiently quieter than the first two, the total sound level remains at 89 dB → $L_I = 89 \text{ dB}$

Decibel Addition



When two decibel values differ by	Add the following to the higher value
0 or 1	3
2 or 3	2
4 to 8	1
9 or more	0

Example:
An alarm clock (62 dB), electric shaver (60 dB), two vacuum cleaners (79 dB each), and garbage disposal (55 dB) are on in one room, all at once. Find the total sound level.

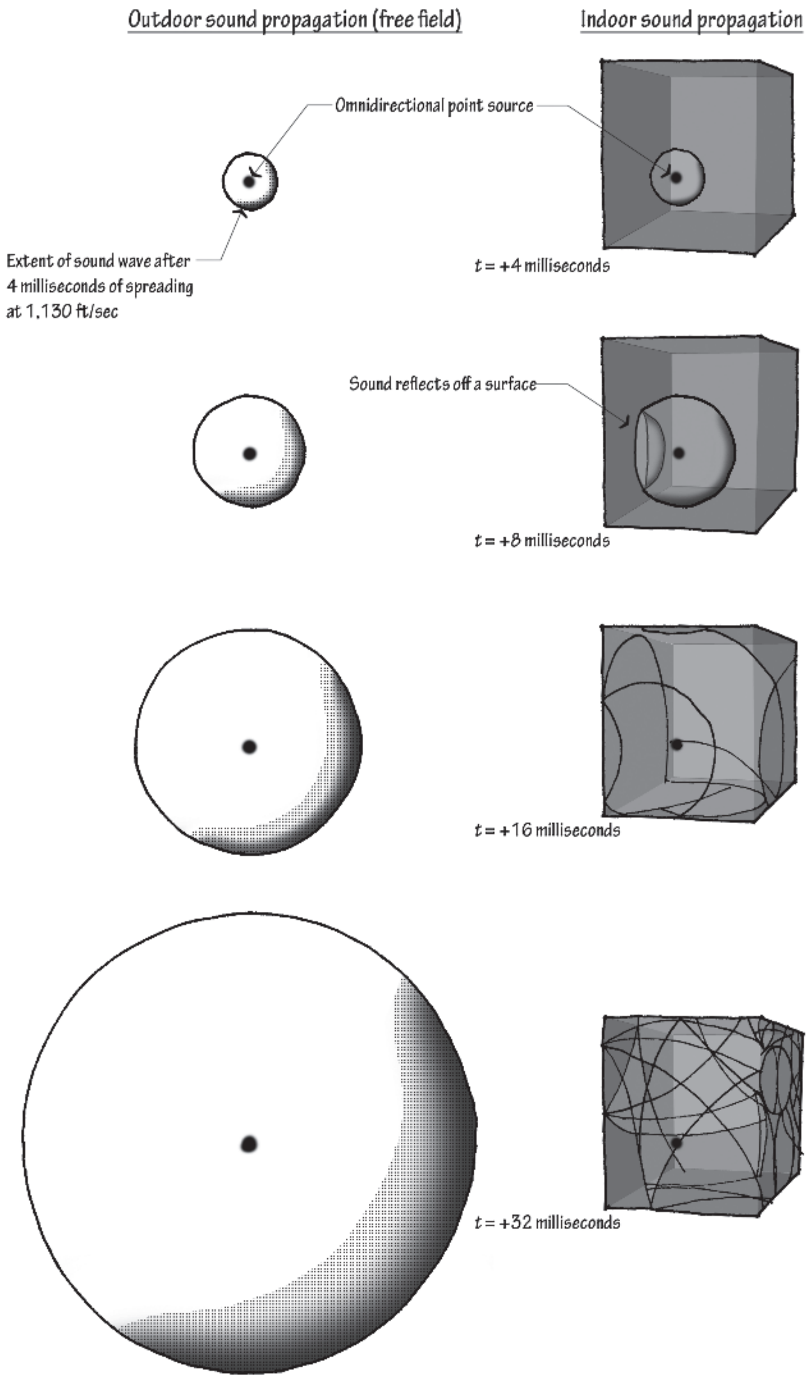


NOTE

The order in which one performs decibel addition is irrelevant. While this rule of thumb is an approximation, it is typically accurate to within one decibel.

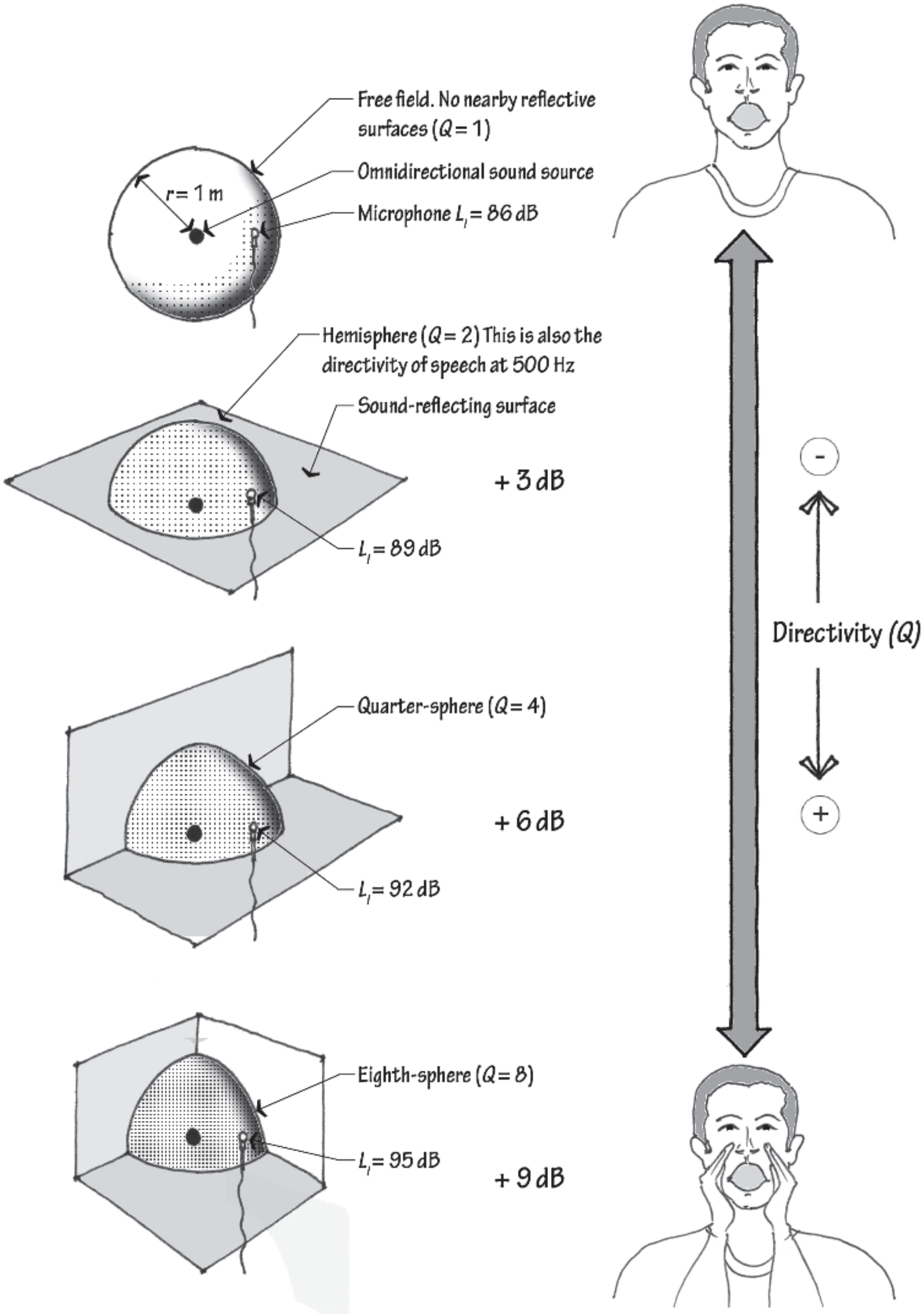
SOUND PROPAGATION

Sound Propagation



Direct sound decays at the same rate inside as outside, shedding six decibels per doubling of distance because the same sound energy is spread over four times the area every time the distance is doubled. What differs is the reflected sound off the room boundary surfaces inside. Depending on materiality, sound energy hitting a surface will reflect off a surface as the spreading sound-front sphere folds in on itself with each successive reflection.

Directivity



$$I = \frac{W \bullet Q}{4\pi r^2}$$

Where I is the intensity at a given angle

Q is the directivity, per the graphic, and

$4\pi r^2$ is the area of the sphere of radius r, over which the sound is spread

SOUND FREQUENCY

Frequency

In 1957 a seven-year-old boy, Joe Engressia, foiled the phone system. Blind since birth, abused at school, and possessing both a 172 IQ and perfect pitch, Engressia noticed a 2,600-Hz frequency pure tone buzzing in the background during long-distance calls. He discovered that whistling the same tone, the fourth E above middle C, disconnected the call. More experimentation led him to a system, later termed "phreaking," which tricked the phone company's computers into providing free long-distance calls for the whistler. Because long-distance calls were very expensive at the time, and because the phone company's computer was seen as the most complex of its time, phreaking became a 1970s pastime for a subculture of socially awkward teens interested in technology; it was the precursor to computer hacking. A young Steve Jobs, after reading a story on the phenomenon, recruited his friend Steve Wozniak, and the two of them designed, manufactured, and sold "blue boxes," electronic tone generators that allowed users to make free long-distance calls. Jobs once said, "If we hadn't made blue boxes, there would have been no Apple."

Sounds have a loudness associated with each frequency, and describing the quality of a sound in decibels without specifying the frequency content is a bit like describing the quality of the weather in temperature without mentioning if skies are clear or rainy. When sound includes abundant high-pitched or treble energy, it is said to be heavy on high-frequency content, and when sound includes abundant low-pitched or bass energy, it contains ample low-frequency content.

In the same way that a drumroll, when sufficiently rapid, begins to approach a tone to our ears rather than individual taps, sound is made up of beats per second. Each time a high-pressure wave of molecules impinges upon the listener, it's heard as a beat, and measured in hertz (Hz), or cycles per second. If the beats come one per second, it is said they have a frequency of one hertz. One hundred beats per second, or pressure waves per second, measures one hundred hertz.

Human hearing spans an audible range from 20 Hz to 20,000 Hz. Sounds with fewer than 20 beats per second are heard as separate thumps, rather than as a tone; sounds more than 20,000 hertz are inaudible altogether, as in a dog-whistle. If all the energy is focused at a single frequency, it is termed a "pure tone," which can be annoying to listen to. Tuning forks, car horns, truck back-up beepers, and whistles may be, or may approximate, pure tones. Notes produced by musical instruments, by contrast, have energy in patterns of frequencies, which are called "harmonic sounds." Most of the everyday sounds and noises we hear, including speech, traffic noise, and an audience clapping, are called "complex sounds," with varying levels of sound across the audible frequency spectrum.

Given that sound travels at a fixed rate of 1,128 feet per second (344 m/s) in air, it follows that higher-frequency sound with more rapid progressions of molecule compressions and rarefactions also features shorter dimensions between compressions. This distance, the wavelength, is described by the formula:

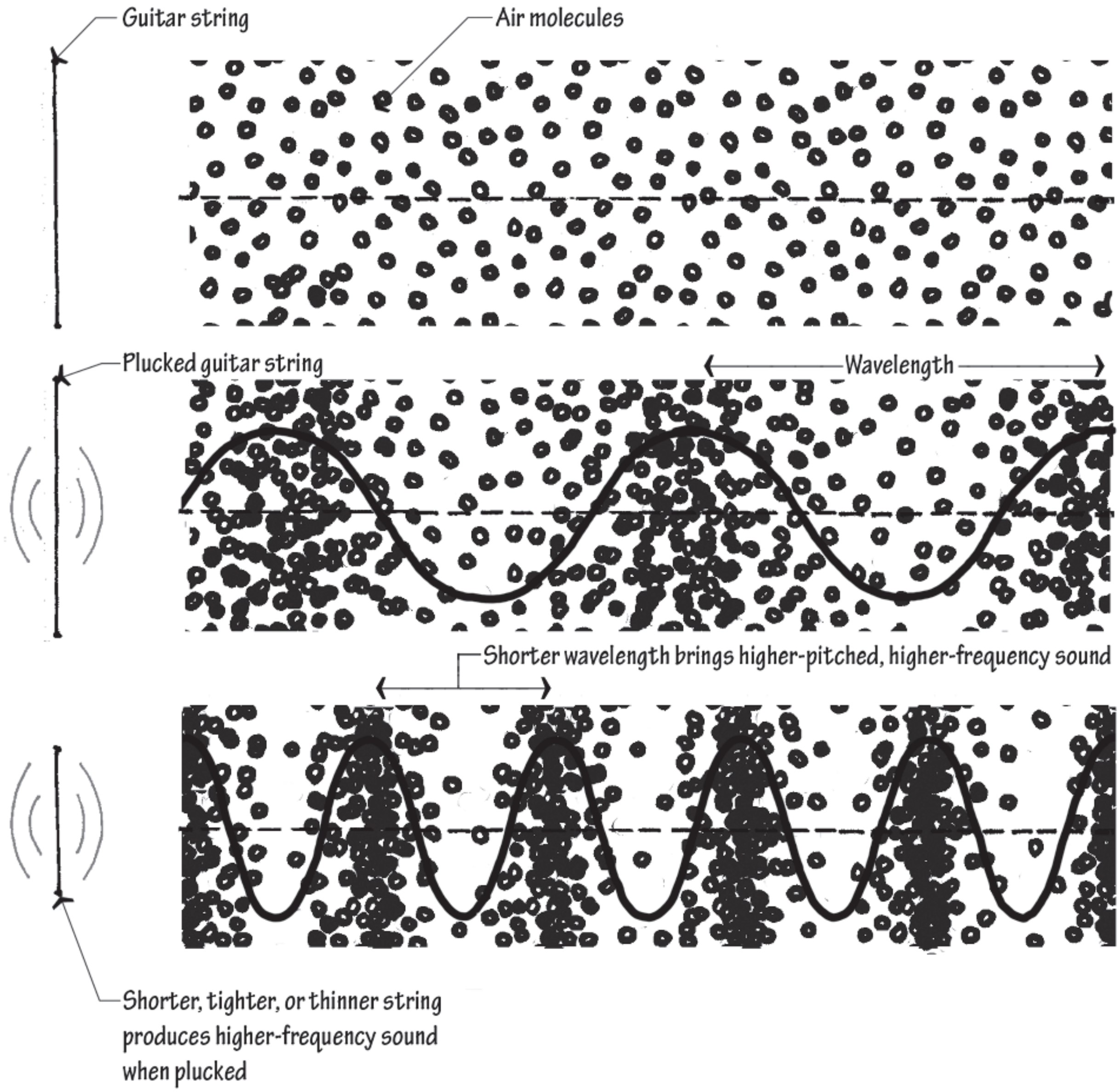
$$\lambda_{wavelength} = \frac{C_{speed\ of\ sound}}{f_{frequency}}$$

So given that the speed of sound is 1,128 feet per second, and middle C on the piano is 256 Hz, we see that the wavelength associated with middle C is calculated as:

$$\lambda_{wavelength} = \frac{1{,}128\,\text{ft}/\text{s}}{256\ \text{Hz}} = 4.4\ \text{ft}$$

Higher-frequency sounds have shorter wavelengths, and lower-frequency sounds have longer ones. The distance between compressions and rarefactions in the waveform describing middle C is thus about equal to the height of an adolescent child; the 20-Hz lowest audible bass tone is about the length of a small banquet room; and the 20,000-Hz highest audible treble tone is about the width of a finger. Bats, using echolocation to find something as small as a mosquito, transmit frequencies as high as 100,000 Hz so that the sound's wavelength will be small enough to "see" the insect. Bats chirp well above the human frequency perception threshold, in frequencies that high can't be heard by human beings. (Or, putting it another way, human beings can't hear wavelengths that small.) For the entire frequency range of human hearing, wavelengths are at the scale of architecture. This is important because when sound rays impinge on surfaces that are much longer than their wavelengths, they reflect in something approaching a ray; when they impinge upon surfaces that are much smaller than they are, they move right around them, like an ocean wave moving around a swimmer. As sound impacts a building surface that is of a similar dimension to the wavelength, the sound reflects and scatters.

Although healthy ears hear the full range, from 20 Hz to 20,000 Hz, the kind of cumulative hearing loss that most of us suffer shrinks that range over time. Depending on how loudly the music one listens to is played, and one's exposure to continuous loud sounds (greater than 80 decibels), it is common for tones above 17,000 Hz to lose audibility for those in their 20s, and tones above 10,000 Hz to lose audibility when we are in our 50s.



NOTE

For clarity, this model omits much of the true behavior of sound; it depicts pure tones, each at a single frequency. In reality, guitars make notes, composites of tones with a frequency pattern. For instance, a 440-Hz note includes pure tone energy at 440 Hz (called the fundamental frequency), with progressively decreasing loudness at frequencies equal to multiples of the fundamental: 880 Hz, 1,320 Hz, 1,760 Hz, and so on. To hear a demonstration of this concept, visit www.smackmypitchup.com and click on "curriculum," then on "1.6 Pure Tones and Complex Sounds."

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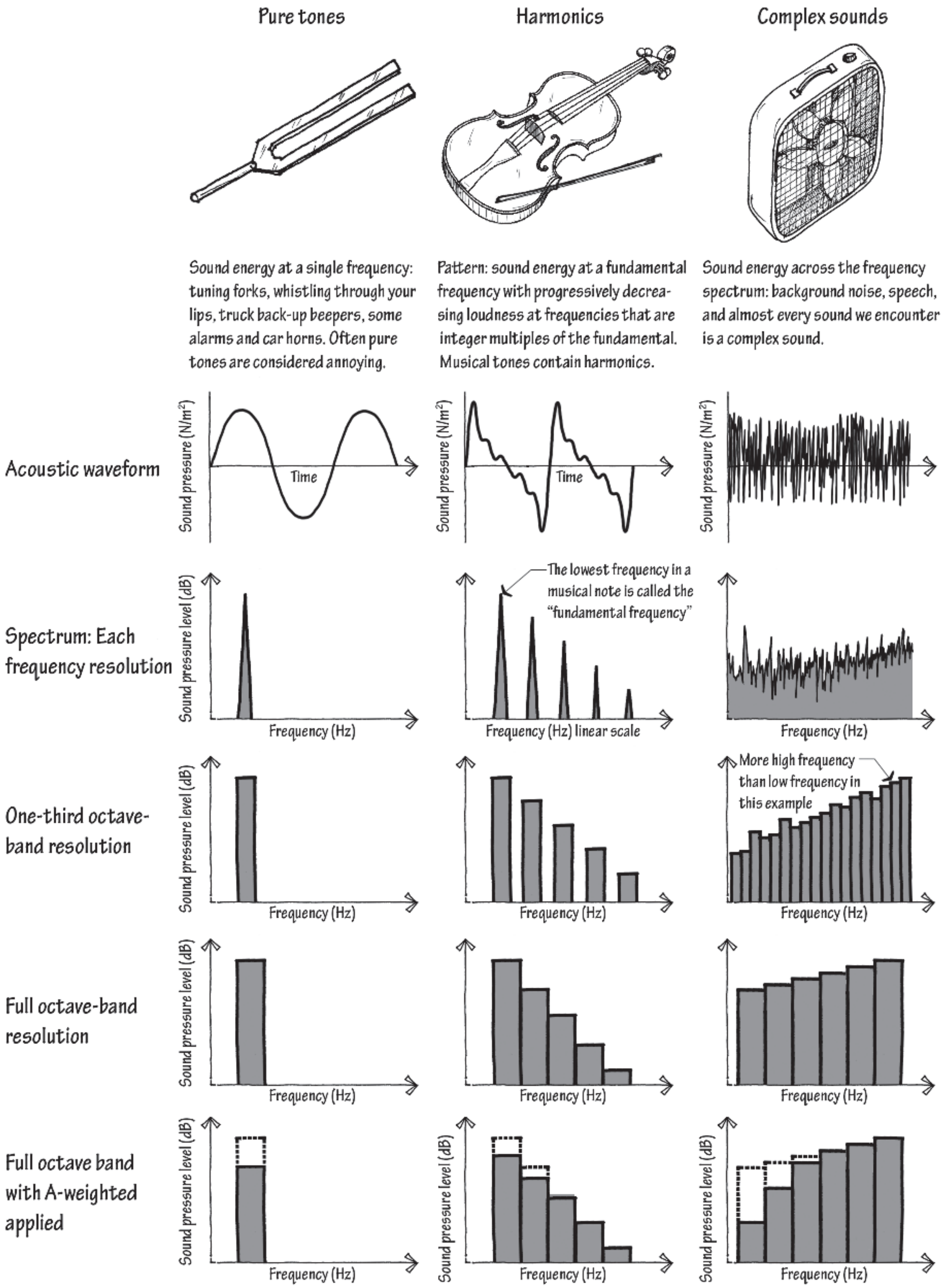
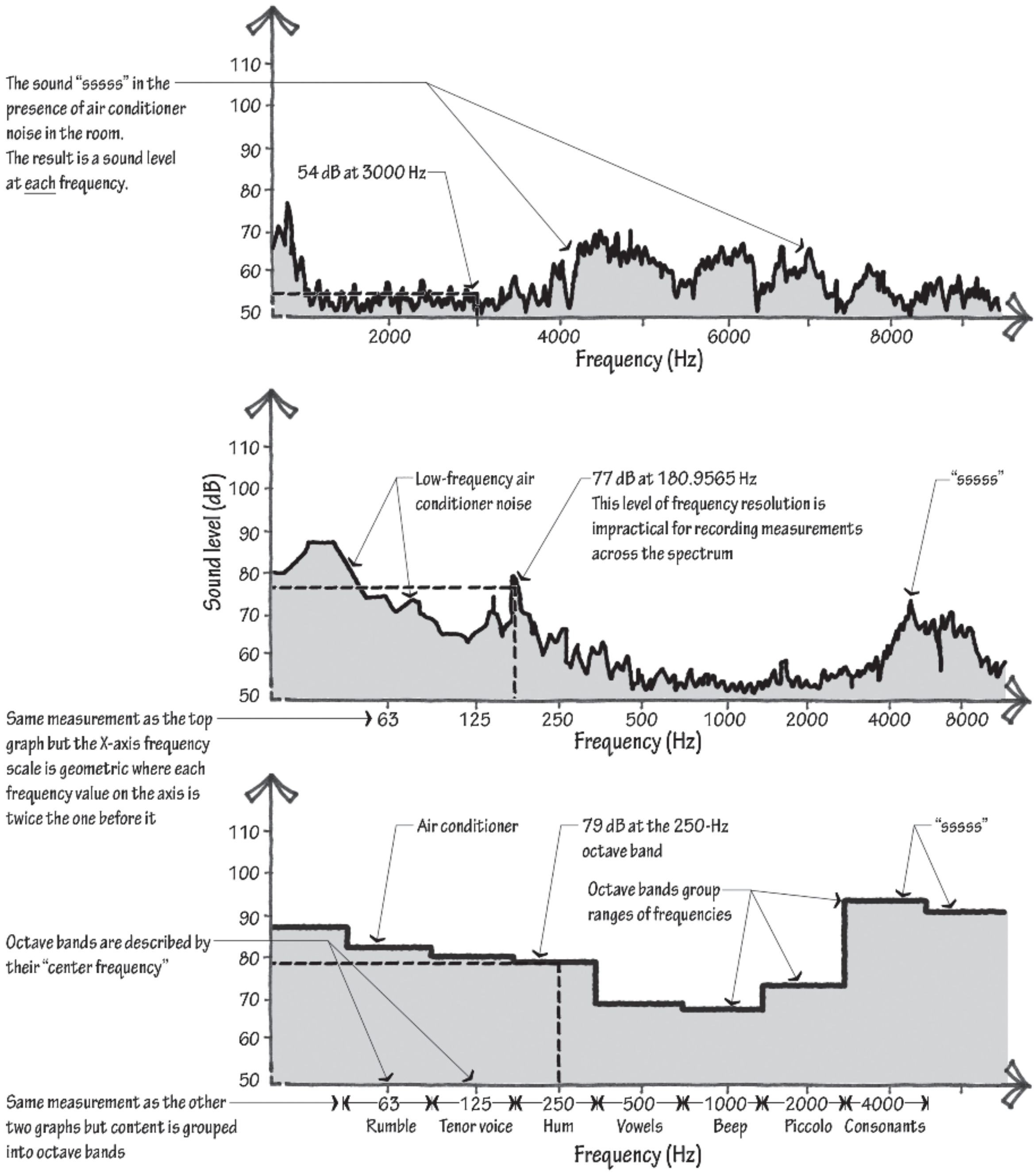


Octave Bands

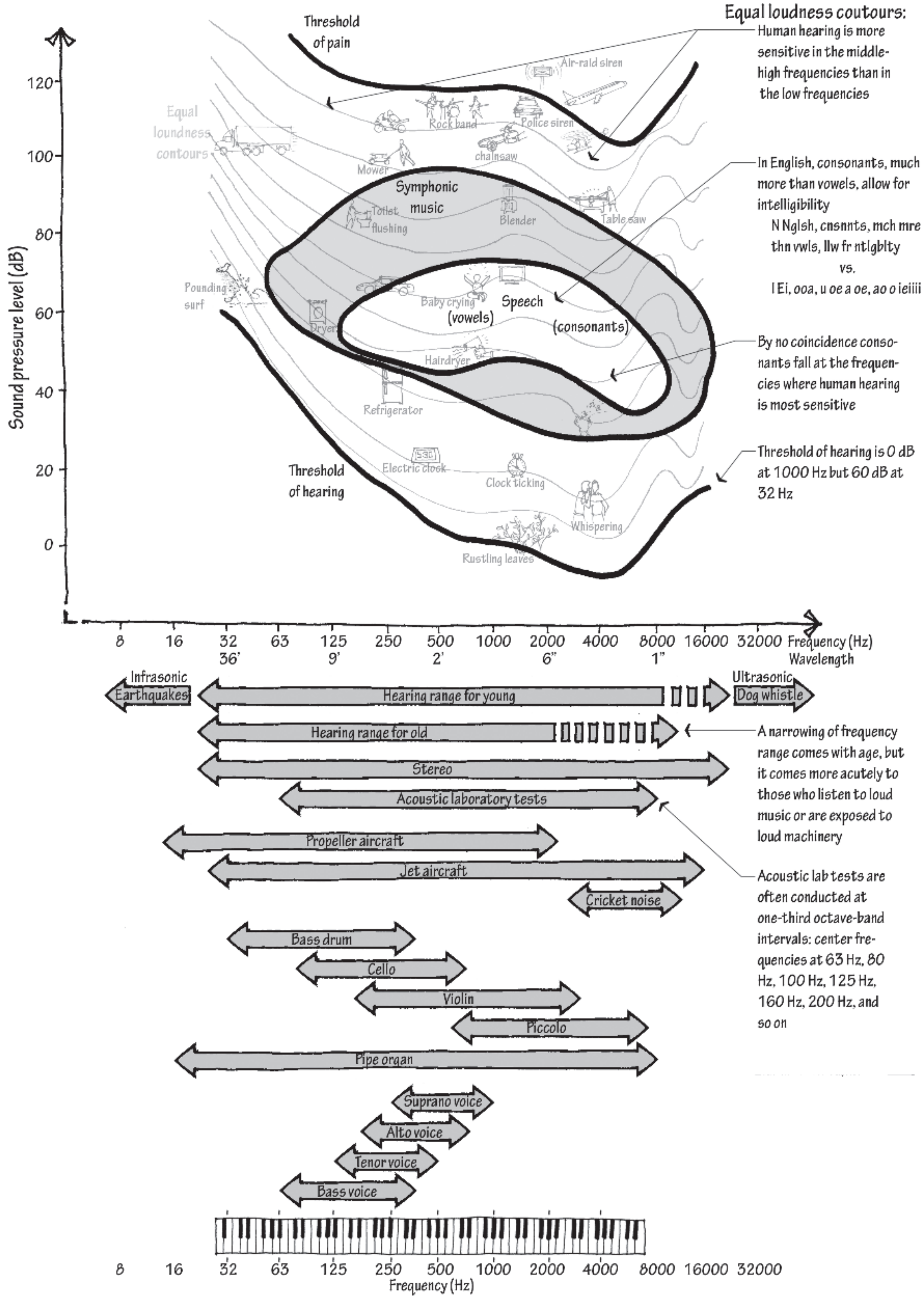
Although describing sound loudness in the absence of frequency paints a one-dimensional picture of the sound, describing sound loudness at *each* frequency would be cripplingly over-detailed. The frequency spectrum in the figure that follows describes the sound "sssssss," measured in a room with a fair amount of low-frequency background noise from a noisy mechanical system. In the absence of a graph, we would need to list decibel values at *each* frequency to explain this sound. For instance, 66 decibels at 100 Hz, 67 decibels at 101 Hz, 67 decibels at 102 Hz, and so on. Even that level of detail omits the decibel values between integer frequency values, for instance 77 decibels at 180.9565 Hz.

To simplify the content of a sound spectrum without abandoning the important descriptive role of frequency, we use the octave band. Grouping frequency ranges into bands with upper and lower limits on the frequency domain, octave bands allow for the definition of loudness across the frequency spectrum, divided into finite and practical-to-use groupings of frequencies. To better account for the way human brains perceive pitch, individual octave bands (each described by the frequency of its geometric center) encompass unequal ranges of frequencies. For instance, the octave band centered on 250 Hz includes all the frequencies between 177 Hz and 354 Hz, a range spanning a total of 354 – 177 = 177 Hz. The octave band centered at 2,000 Hz spans from 1,414 Hz to 2,828 Hz, a range spanning a total of 2,828 – 1,414 = 1,414 Hz. The 2,000-Hz octave band, therefore, includes many times more frequencies than the 250-Hz octave band.

Each successive octave band's center point frequency is set at twice the frequency of the previous octave band's center frequency: 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, and 4,000 Hz. (These are the octave bands with which architectural acoustics concerns itself.) When a measurement's purpose warrants more frequency resolution than provided by full octave bands, one may use one-third octave band resolution instead.


The sound "sssss" in the presence of air conditioner noise in the room.
The result is a sound level at each frequency.
54 dB at 3000 Hz
110
100
90
80
70
60
50
2000
4000
6000
8000
Frequency (Hz)
Sound level (dB)
Low-frequency air conditioner noise
77 dB at 180.9565 Hz
This level of frequency resolution is impractical for recording measurements across the spectrum
"sssss"
Same measurement as the top graph but the X-axis frequency scale is geometric where each frequency value on the axis is twice the one before it
63
125
250
500
1000
2000
4000
8000
Frequency (Hz)
Air conditioner
79 dB at the 250-Hz octave band
"sssss"
Octave bands group ranges of frequencies
Octave bands are described by their "center frequency"
Same measurement as the other two graphs but content is grouped into octave bands
63
125
250
500
1000
2000
4000
Rumble
Tenor voice
Hum
Vowels
Beep
Piccolo
Consonants
Frequency (Hz)

Sound Level Perception and Frequency



Researchers conducted a great many tests with a great number of subjects to develop the family of equal-loudness contours shown in this illustration. Any two points on a given curve line will, subjectively and on average, be judged equally loud. Note the sharp drop in human sensitivity to low-frequency sounds (which is why amplifiers boost bass), the peak sensitivity at the frequencies associated with consonants in speech (they contain the most information as to what is being said), and the relatively flat human response in the rectangle between 150 Hz to 6,000 Hz and 45 dB to 85 dB (again the content of human speech).

A-Weighted Decibels

The chapter began by describing sound level in the absence of frequency, then introduced frequency to better describe the quality of the sound, and then introduced the octave band to simplify description of frequency. Yet even the grouped frequency description provided by octave band measurements can be clumsy when comparing sound levels. An officer attempting to discern if a loud party exceeds the local noise ordinance, a machine operator attempting to discern if the equipment he uses is likely to cause permanent hearing damage, or a researcher attempting to discern best practices in maintaining quiet elementary school cafeterias, might prefer using a single-number measure of loudness, weighted to reflect the varying sensitivity of human hearing across the frequency spectrum. For these straightforward and simplified measures of comparative loudness, we use A-weighted decibels (dBA).

Because of the geometry of the human ear and the particulars of the human auditory system, 90 decibels at 125 hertz sounds subjectively quieter than 90 decibels at 1,000 hertz. A-weighting first adjusts the measured octave-band decibel levels to account for human decreased sensitivity to sound level at low frequencies, then uses decibel addition of the newly weighted Sound Level values at each octave band. The result is a single decibel level, roughly aligned with perceived loudness.

This is the first value introduced in what will be a series of single-number metrics used in architectural acoustics. As with the others in this family of easier-to-use values, the benefit from its simplicity should be balanced against the loss of important frequency resolution detail.

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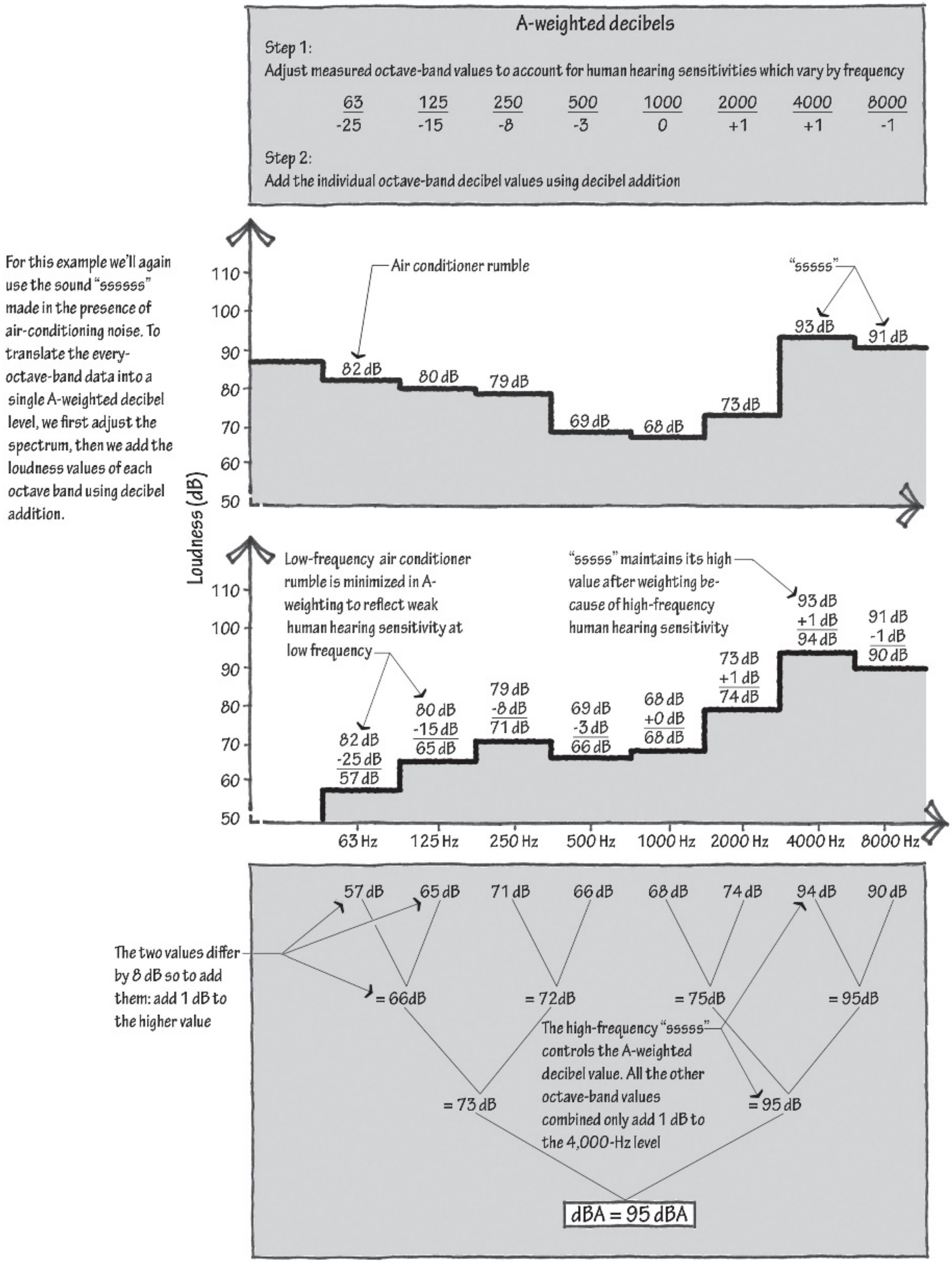

The Special Case of Low-Frequency Sound

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Middle- and high-frequency sound wavelengths occupy dimension on the order of the scale of the diameter of the human ear canal. It is these frequencies, then, that resonate in our auditory system, which is why we are more sensitive to frequencies at 500 Hz and above than to those at 250 Hz and below. Our ears' sensitivities to these frequencies reflect an evolutionary preference for speech communication through higher-frequency consonants. We now capitalize on that sensitivity when creating the sound spectrum for car horns, truck back-up beepers, sirens, alarm clocks, and other machine-generated noises intended to get our attention. Because of our sensitivity to mid- and high-frequency sounds, and because of mid- and high-frequencies' outsized role in promoting speech intelligibility, the field of architectural acoustics justifiably focuses its attention on this window of the sound spectrum.

Yet low-frequency sounds should command our attention too, despite our diminished sensitivity to them. That is because bass tones more easily move through barriers such as car windows, building skins, and room partitions. They are more omnidirectional, more readily bend around buildings, and diffract around outdoor roadway barriers; in the presence of dance music, they vibrate our chest cavities and shake our ceiling tiles. Researchers now believe that pure tones at about 22.5 Hz may trigger a fight-or-flight response in people. Low-frequency sounds are what build up annoying resonances (also called standing waves) in small spaces such as music practice rooms, but they also give us a desired sense of "warmth" in a symphony hall.

Picture a swimmer in an ocean with a nearby sea wall. When the waves come, they smack the long sea wall and bounce back out to sea. But those same waves don't ricochet off the relatively small swimmer—they diffract around him instead. In the same way, middle- and high-frequency sounds, whose wavelengths are short compared to building surfaces, can be easily modeled in geometric acoustics, using rays and arrows. That model breaks down and loses its usefulness when the wavelengths are long relative to the room surfaces. Modal low-frequency sounds behave more like waves and less like rays. They are more difficult to model in space, yet more sensitive to the geometric particulars of the source, surface, and receiver locations. At low frequencies, two adjacent seats in a theater may experience remarkably different sound fields—or they may experience almost identical sound fields.

Electronically amplified "thumping" music has high bass content, but so might a television or a movie playing in the adjacent cinema. Truck engines, bus engines, train engines, and aircraft jet engines have low-end content—as do car, motorcycle, personal watercraft, and snowmobile engines (and that is before some vehicle operators intentionally modify their exhaust systems to sound more throaty and muscular). Finally, fans, pumps, elevators, garbage disposals, generators, trash compactors, and garage door openers—many of the machines found in buildings—generate considerable low-frequency noise.

References

Cavanaugh, W. et al. (ed.). 2010. *Architectural Acoustics*, 2nd ed. John Wiley & Sons. Hoboken, NJ, pp. 1–23.

Egan, M. D. 2007. *Architectural Acoustics*. J. Ross Publishing. Plantation, FL, pp. 1–36.

Long, M. 2006. *Architectural Acoustics*. Elsevier. Burlington, MA, pp. 37–71.

Mehta, M. et al. 1998. *Architectural Acoustics*. Merrill Prentice Hall. Upper Saddle River, NJ, pp. 1–20.

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Sound Level Data								
Source	**dBA**	**Absorption Coefficient (Hz)**						
		63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Outside								
Highway at 50 ft (15m)	**78**	78	78	75	73	75	69	62
Highway at 200 ft (60m)	**66**	70	69	62	59	63	60	52
Primary road at 50 ft (15m)	**64**	67	63	60	57	61	58	50
Primary road at 200 ft (60m)	**51**	63	57	48	42	47	45	38
Large cooling tower at 50 ft (15m)	**63**	69	62	56	54	55	57	58
Small cooling tower at 50 ft (15m)	**61**	68	65	56	55	57	53	52
Truck reverse beep	**94**	82	78	77	76	94	66	63
Car starting	**92**	90	81	80	86	87	86	86
Car alarm	**90**	55	51	70	79	78	82	87
Basketball dribble	**87**	90	91	82	79	82	81	77
Bus idling	**81**	83	83	80	73	78	73	67
Loud car radio	**74**	73	77	73	73	69	66	52
Car idling	**69**	81	81	67	62	61	57	53
Ambient rain noise	**63**	72	63	58	56	56	56	57
Ocean wave, water's edge	**54**	62	60	54	51	49	45	42
Inside								
Movie theater	**103**	125	113	100	95	90	92	89
Slammed door	**90**	98	87	86	86	86	83	75
Vacuum	**84**	63	72	70	79	76	80	76
Beneath wood stairs	**83**	84	91	83	78	74	75	73
Alarm clock buzzer	**81**	43	39	63	81	74	74	66
Elementary school cafeteria	**81**	62	61	68	75	79	75	68
Hair dryer	**81**	80	76	71	75	77	74	75
Toilet flushing	**81**	49	65	86	81	70	66	62
Television	**76**	58	70	74	70	69	72	64
Acoustic guitar	**74**	62	75	79	71	67	62	54
Cell phone ring	**74**	48	55	54	52	70	67	69
Faucet	**73**	46	50	50	56	57	68	69
Restaurant with music	**69**	71	69	66	66	66	60	52
Normal conversation	**68**	47	53	54	36	66	56	52
Door closed normally	**66**	70	66	64	59	60	58	60
Oven exhaust fan	**64**	43	43	55	63	61	51	46
Boiling water	**58**	50	54	58	52	52	52	49
Dehumidifier	**57**	53	55	56	56	52	49	44
Small heat pump	**54**	60	59	55	49	47	47	41
Microwave	**52**	38	47	55	51	46	39	30
Noisy refrigerator	**51**	56	49	57	49	40	34	30
Office with computers	**48**	55	52	51	45	42	37	30
Noisy diffuser	**47**	54	50	47	43	42	40	35
Water pipes from adjacent wall	**42**	51	50	44	39	33	32	29