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CHAPTER 5

ARCHITECTURAL ACOUSTICS

"Soon silence will have passed into legend. Man has turned his back on silence. Day after day he invents machines and devices that increase noise and distract humanity from the essence of life."

—Jean Arp

"When I am working on a problem, I never think about beauty. I think only of how to solve the problem. But when I am finished, if the solution is not beautiful, I know it is wrong."

—R. Buckminster Fuller

5.1 INTRODUCTION

Acoustical design is often neglected or minimized. Although a failure in acoustics is not as fatal as a failure in structures, a failure in acoustics can be very serious nevertheless. Sometimes a failure can be very costly as in the rehabilitation of Lincoln Center's Philharmonic (now Avery Fisher) Hall in New York City. Since an easy fix did not work, the hall had to be completely gutted and rebuilt at great expense.

Most times a failure in architectural acoustics can be fixed at more modest cost, but it will be an annoyance for the owner and an embarrassment for the architect. This author experienced such a case when he started teaching in a newly completed architecture school building. Because the classrooms had all six surfaces made of exposed concrete, speech was not understandable. The multiple reflections off the hard surfaces kept any sound from decaying quickly. Thus, during lectures the students were hearing not only the latest spoken word but also the delayed reflections of previous words. In acoustics this problem is described as an excessively long reverberation time. The problem was fixed by hiring an architectural acoustics consultant who specified sound-absorbing panels to be installed on the rear and rear side walls (Fig. 5.1). Normally, such consultants are only required for special

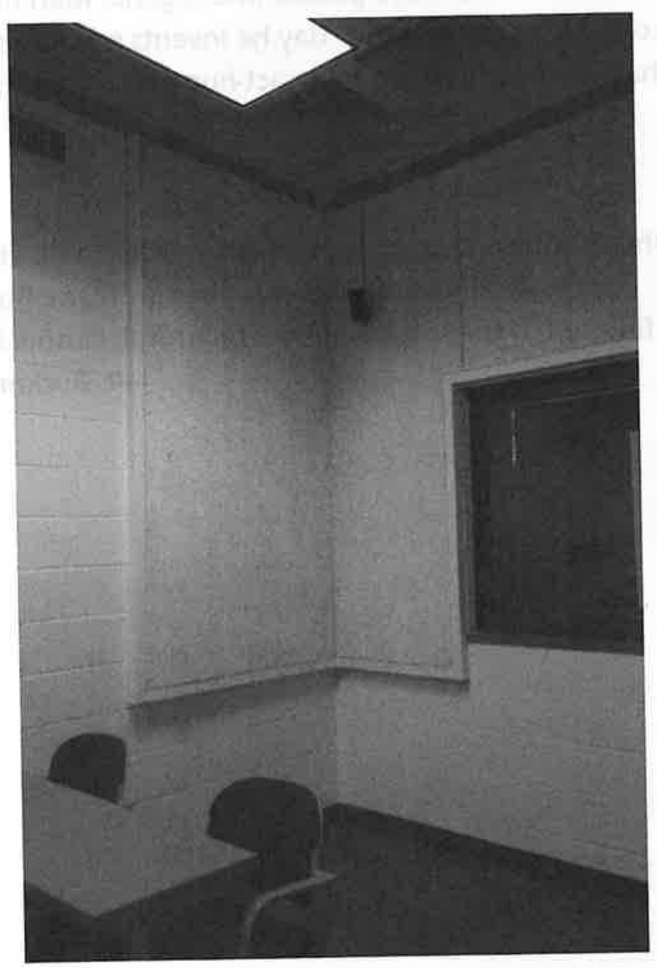


Fig. 5.1 Because the classrooms in this building were designed with all six surfaces of exposed concrete, the strong multiple reflections created a reverberation time that was much too long for speech. The classrooms were unusable until an acoustical consultant was hired. He fixed the problem by adding the absorbing panels seen on the rear wall and the rear portion of the side walls.

or very difficult problems in architectural acoustics, since any architect with a basic knowledge of acoustics can design a classroom with good acoustics. The architect of this project may never have studied architectural acoustics or it was not covered in enough detail.

The worst situation may be the case when the failure of architectural acoustics is not great enough to require action but serious enough to lower the quality and performance of the architecture for the life of the building. For example, we have all experienced spaces such as restaurants in which it was difficult to hear what was being said. When people cannot understand a conversation, they end up talking lauder which usually makes the problem even worse. Whether we realized it or not, the problem could have been the poor acoustics. After learning about acoustics, it will be easier to spot such faulty designs and know how to fix them.

The main goals of architectural acoustics are to maximize the hearing of speech or music and to minimize noise. There are two reasons for minimizing noise: (1) noise interferes with hearing and (2) noise is usually objectionable in itself and very loud noise can be a health hazard. Like lighting, where quality is much more important than quantity, architectural acoustics is more concerned with creating a high-quality sound environment than with creating high sound levels. Although a study of architectural acoustics usually starts with the physics of sound, we will first take a quick look at some of its history.

5.2 A SHORT HISTORY OF ARCHITECTURAL ACOUSTICS

Although the science of architectural acoustics started in the early twentieth century, many of its principles were already understood and used in ancient Greek and Roman theaters. In those theaters, the seating was always semicircular because of the importance of minimizing the distance between actor and audience (Fig. 5.2a). The raised stage, combined with a

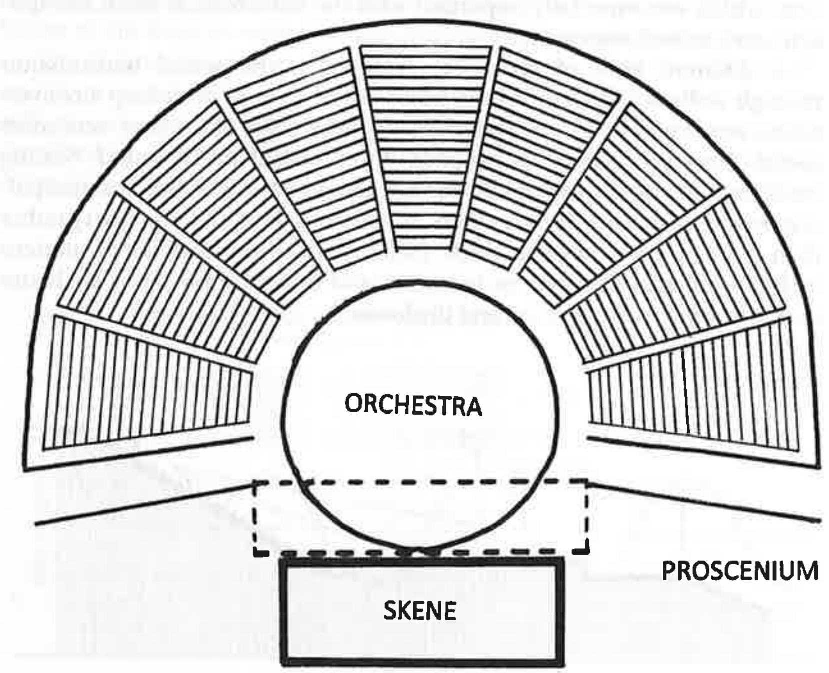


Fig. 5.2a The designers of Greek and Roman theaters understood the basics of good architectural acoustics. The radial plan minimized the distance from the speaker to the receiver. The skene and later the proscenium helped to both reflect sound to the audience and create a barrier for noise from outside.

steep slope for the seating, allowed both direct sight and sound lines. The architects of these early theaters recognized a basic principle of acoustics: *if you can see well, you can hear well* (Fig. 5.2b). To help them project their voices, the actors often stood on resonating sound boxes, which amplified the sound the same way the sound boxes of guitars and violins do. The smooth hard stone floor of the stage was a good reflector to direct additional sound to the audience. The actors also wore masks with mouths shaped as funnels to direct the sound at the audience. In effect, the masks had built-in megaphones.

Some Greek theaters and most Roman theaters had a proscenium, a wall behind the stage, which helped reflect the sound towards the audience. A short roof over the stage reflected additional sound to the audience. Besides magnifying the sound, the proscenium also minimized noise from outside (Fig. 5.2b). The ancient Greeks, more than the Romans, placed their theater on the side of a hill to both minimize the required construction effort and the noise from the city center.

The Roman architect Vitruvius wrote about architectural acoustics for theaters in his *Ten Books on Architecture*. He wrote, for example, that reflections off hard materials like stone can make speech difficult to understand. He was describing both the problems of the echo and reverberation time.

In the Middle Ages, when Christian churches and cathedrals were again built of stone, the sound would reflect back and forth and, thus, die out slowly. As stated before, the long duration of a sound makes speech very difficult to understand. Each new word has to compete with the lingering sound of the last word spoken. On the other hand, the long reverberation time of these stone churches promoted singing, chanting, and later organ music. Thus, the nature of church music was a response to the acoustical qualities of the space in which it was performed. Fortunately, since the spoken part of the mass was mostly in Latin, it mattered little if people could not hear the words clearly in large cathedrals. Since smaller churches produce shorter reverberation times, they provide better speech recognition, which was especially important with the Reformation when the spoken word gained importance.

A different kind of acoustical problem is the sound transmission through walls and doors. To keep noise out of a room or to keep a conversation secret within a room, the massive stone walls of the past were most useful. However, even thick wooden doors leaked much sound. Sealing cracks and keyholes helped but was not always sufficient. Renaissance palaces sometimes used double doors at least one foot (30 cm apart) rather than a single door twice as thick. Here, again, the principles of modern architectural acoustics help us to understand that multiple layers are better than one layer of equal mass and thickness.

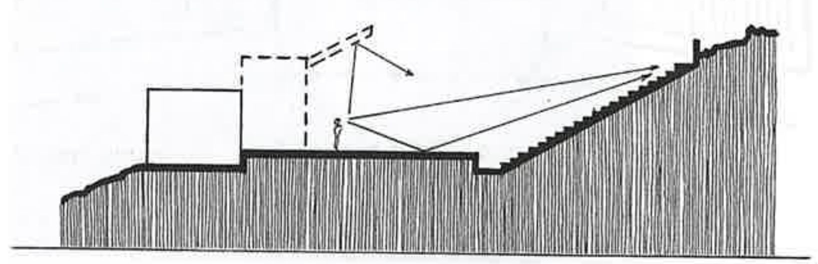


Fig. 5.2b The steep rise of the seating allowed not only good sight lines but also good sound lines. The hard smooth floor of the raised orchestra (now called stage) reflected more sound to the audience.

Although a failure in the application of acoustics is normally not a matter of life and death, there are a few exceptions. In 214 BCE, Philip V of Macedon attacked the Greek City of Illyria. When spies brought back news that Philip's men were digging under the walls, the architect, Trypho of Alexandria, devised the following countermeasure. At ground level, all around the inside of the walls, he hung bronze vessels. Any that vibrated indicated that there was digging below (Hunt, 1978). Acoustical principles tell us today that the sounds generated by the diggers' metal tools hitting soil and rock is structure-borne instead of airborne, and structure-borne sounds travel fast and far. Another life and death application of acoustics can be found in the shogun's palace in Kyoto, Japan, where the floorboards were built on clever devices that squeaked whenever someone stepped on the floor. In a palace where the indoor partitions and doors were made of paper, this squeaky "nightingale" floor protected the shogun from assassins.

In the eighteenth century, the science of general acoustics was started by the French scientist and mathematician Joseph Sauveur; in the nineteenth century, major advances were made by the German Hermann von Helmholtz, and in the early twentieth century, American W. C. Sabine started the science of architectural acoustics.

5.3 THE PHYSICS OF SOUNDS

Sound is a form of energy that travels as a wave. The energy in the wave moves great distances but the wave medium only oscillates in place. A wave traveling in water demonstrates this phenomenon. When a water wave moves across a body of water, the water itself only bobs up and down. The movement of the water is, therefore, transverse to the direction of the wave. Unlike a water wave, a sound wave moving through air causes the air molecules to move forward and backward in the same direction as the wave, thereby alternately compressing and rarefying the air (Fig. 5.3a). Waves of this kind are called longitudinal rather than transverse waves.

The distance from one wave crest to the next is called the wavelength and is measured in feet or meters. Tuning forks of different pitch or tone will generate sounds with different wavelengths. Thus, a tone can be described by its **wavelength**. The vertical distance between the maximum compression (peak of wave) and the maximum rarefaction (trough of

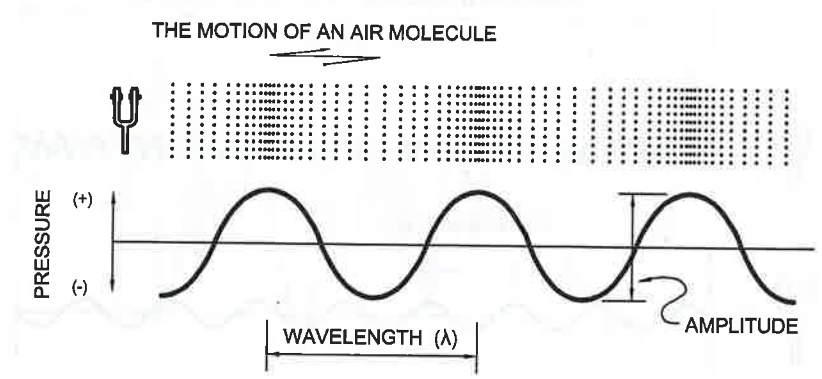


Fig. 5.3a A source of sound, such as a vibrating tuning fork, alternately compresses and rarifies the air. These compressions and rarefactions move away from the source as a longitudinal wave. However, the air molecules just oscillate forward and backward and essentially remain in the same place. The compressions that are above normal air pressure and the rarefactions that are below normal air pressure can be graphed as a conventional wave.

wave) is called **amplitude** (Fig. 5.3a). In audio equipment, it is usually called volume and people perceive amplitude as loudness.

Similar to the concentric waves generated when a pebble is dropped into calm water, concentric spherical waves (Fig. 5.3b) are created by a source of sound. These waves move out from the source at a speed of about 1,130 feet per second (344 mps) in air. Thus, in one second the wave travels 1,130 feet (344 m). This distance could also be measured in a multiple of wavelengths (Fig. 5.3c). Note that the distance traveled in one second is the product of the wavelength times the number of wavelengths in one second, which is called the **frequency**. Thus, the distance covered in one second (speed) is equal to the product of wavelength and frequency, or

$$\text{speed} = \text{wavelength} \times \text{frequency}$$

Therefore, since the speed of sound is essentially constant, a high frequency would correspond to a short wavelength and a low frequency would correspond to a long wavelength (Fig. 5.3c). Because of their interconnected relationship a wave can be equally well defined by either its

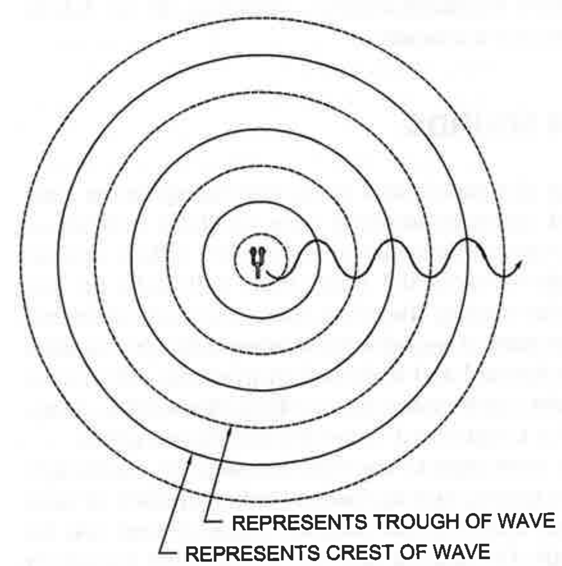


Fig. 5.3b Sound moves out from a source as concentric waves. In a section of the spherical wave, the solid circles represent maximum compression, while the dashed circles represent maximum rarefaction.

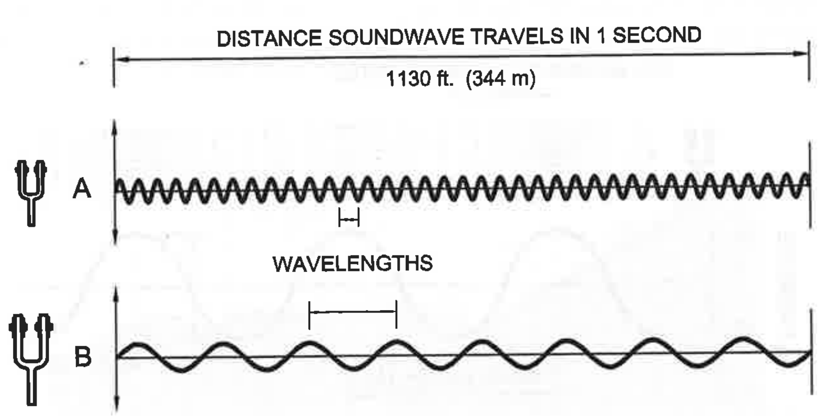


Fig. 5.3c Tuning fork A has a high frequency and, therefore, a short wavelength, while tuning fork B has a low frequency and, therefore, a long wavelength. Thus, frequency and wavelength are inverse to each other, meaning that when one increases the other one decreases.

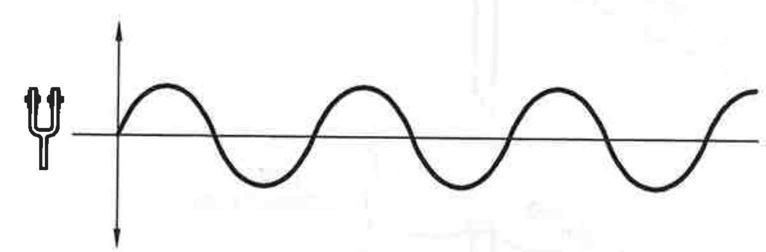
frequency or wavelength, just as one can describe a coin by either its head or its tail. The relationship between wavelength and frequency is inverse, so when one gets larger the other gets smaller. By convention, however, sounds are most often described by their frequency.

Tuning forks are unusual in that they generate sounds at a particular frequency or tone, while most other sources of sound generate a mixture of many frequencies and many amplitudes (Fig. 5.3d). In physics, the amplitude of a sound wave refers to the sound pressure, which is related but not identical to sound loudness, because the human ear is not equally sensitive to all frequencies of sound. The biology and perception of hearing will be discussed later.

A wave can interact with solid materials in several ways: reflection, diffraction, refraction, absorption, or transmission. The specific interaction is not only a function of the size, surface features, and composition of a material but also a function of the frequency or wavelength of the wave. The following rule helps explain some of the interactions between waves and materials.

Rule: When the wavelength of a sound is very small compared to the size of the material surface with which it interacts, it can be visualized and described as a ray, where, for example, the angle of incidence equals the angle of reflection.

We can assume light to behave as a ray, because its wavelength is tiny compared to everyday objects (i.e., one to a million). However, the wavelengths of sound are in the range of everyday objects. Long wavelengths are around 30 ft. (10 m), whereas short wavelengths are around 1½ in (4 cm). Thus, short wavelength (high frequency) sounds can be treated as rays in most cases (Fig. 5.3e). However, long-wavelength (low-frequency) sounds will only act as rays when they hit objects about their own size (e.g., large walls and ceilings). Consequently, when any sound hits a large surface, we can treat the sound wave as a ray, whereas only short wavelength (high frequency) sounds can be treated as rays when they impinge on small objects such as columns.



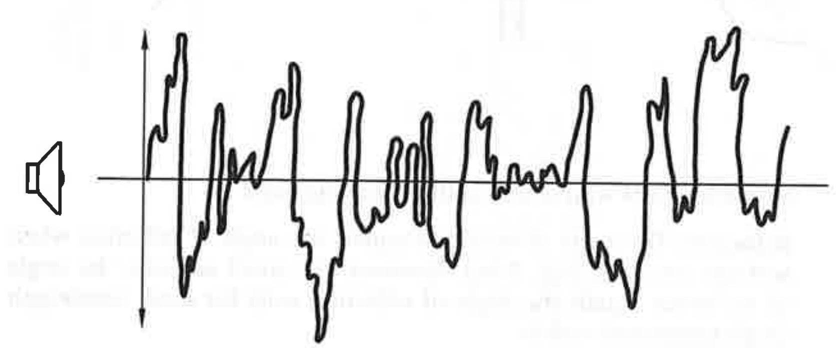


Fig. 5.3d Tuning forks are unusual in that they create sounds at one frequency (wavelength) and an almost constant amplitude that only slowly declines with time. Most sounds are complex with both frequency (wavelength) and amplitude changing constantly.

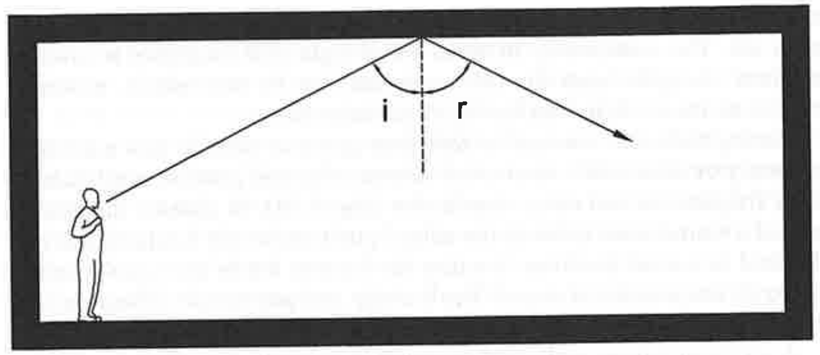


Fig. 5.3e Sound waves can be treated as rays when their wavelength is smaller or about the same size as the object on which they impinge. Thus, for room surfaces the angle of incidence equals the angle of reflection for most sound frequencies.

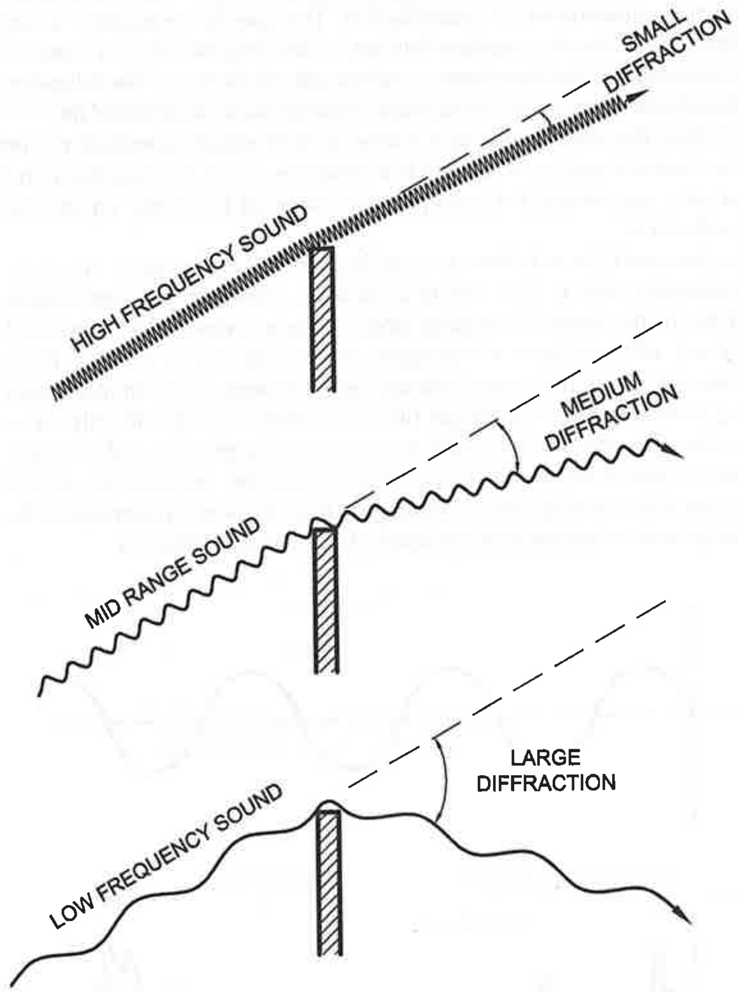


Fig. 5.3f Low-frequency sounds diffract (bend) more around an edge than high-frequency sounds. Thus, it is easier to hear low-frequency sounds around the corner than high-frequency sounds.

Sound interacts with matter in the following ways:

Reflection: The angle of incidence equals the angle of reflection when surfaces are large (Fig. 5.3e). However, for small surfaces, the angle of incidence equals the angle of reflection only for short wavelength (high-frequency) sounds.

Diffraction: When a sound reaches the edge of a wall, the sound waves will diffract, or bend (Fig. 5.3f). The amount of diffraction is a function of the wavelength. Long-wavelength (low-frequency) sounds will diffract more than high-frequency sounds. Figure 5.3g shows how sounds with different frequencies are refracted by a window. Sound also diffracts after passing through a small hole or slit. The opening acts as if it were a source of sound but of lower intensity than the original source (Fig. 5.3h).

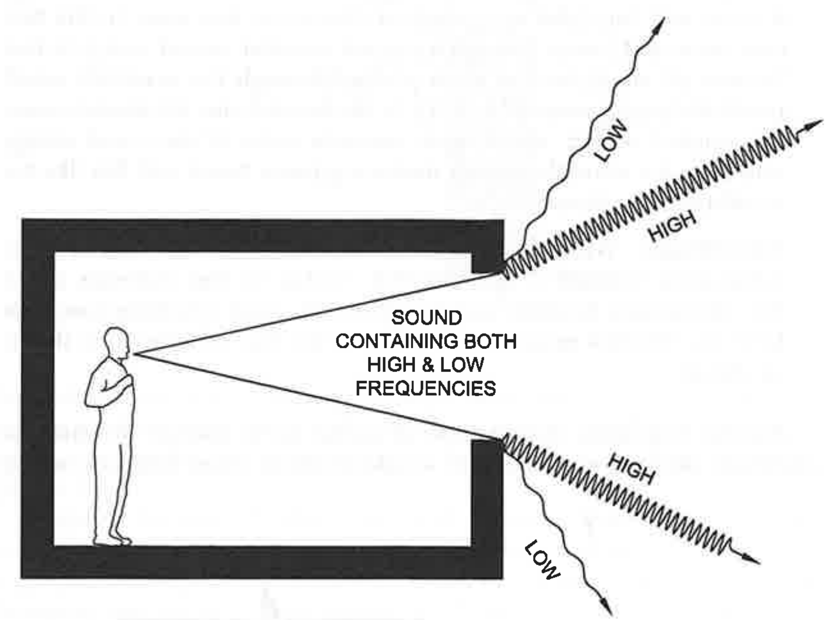


Fig. 5.3g Because the window opening is large compared to the short wavelength of high-frequency sounds, there is little bending of those waves.

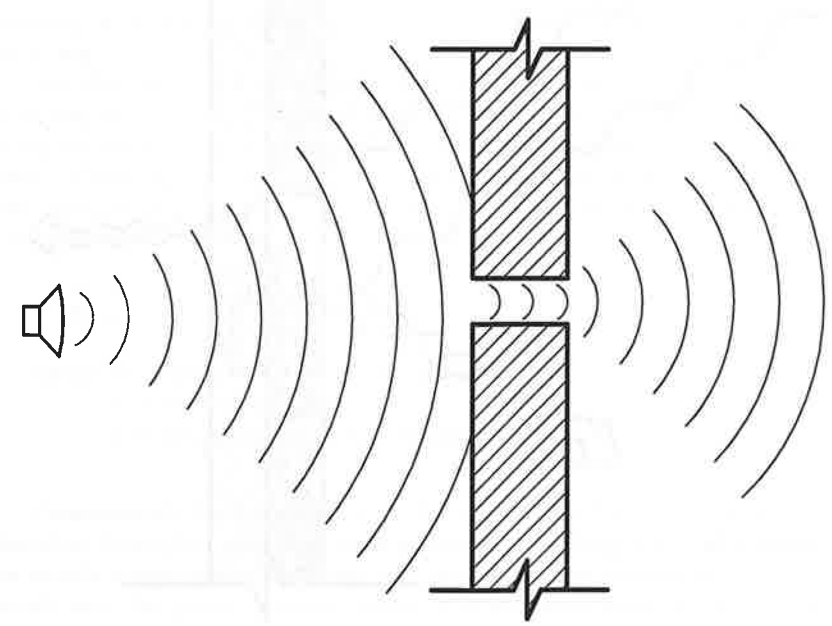


Fig. 5.3h Small openings act as a source of a whole new spreading wave. Examples of small openings include: cracks around doors, keyholes, and penetrations through walls or floors for pipes, conduits, and ducts.

Refraction: The bending of a wave as it passes from one medium to another is called refraction. The best known example is light passing through a prism. Sound refraction is rarely a problem in buildings, but it can happen outdoors when sound passes from cooler denser air to warm less dense air or vice versa. Outdoors over long distances, sound can be either bent down to the ground or bent up away from the ground depending on the temperature of different air masses.

Absorption: As sound passes through a material, some of its energy is converted into heat as a result of friction in two ways. In the first case, as sound passes through a porous material, sound energy is lost because of air friction as air is pushed through the material's small pores and passageways (Fig. 5.3i). In the second case, the sound causes the material to flex, which again converts some of the sound energy into heat. For example, sounds makes a gypsum board wall flex like the membrane of a drum.

Transmission: Whatever sound is not reflected or absorbed is transmitted through a material (Fig. 15.3j). In real materials all of the interactions between sound and matter occur simultaneously. We label the different materials according to the type of interaction that is strongest.

Another important characteristic of sound is the manner in which its amplitude declines with distance. Outdoors in an open field, the sound

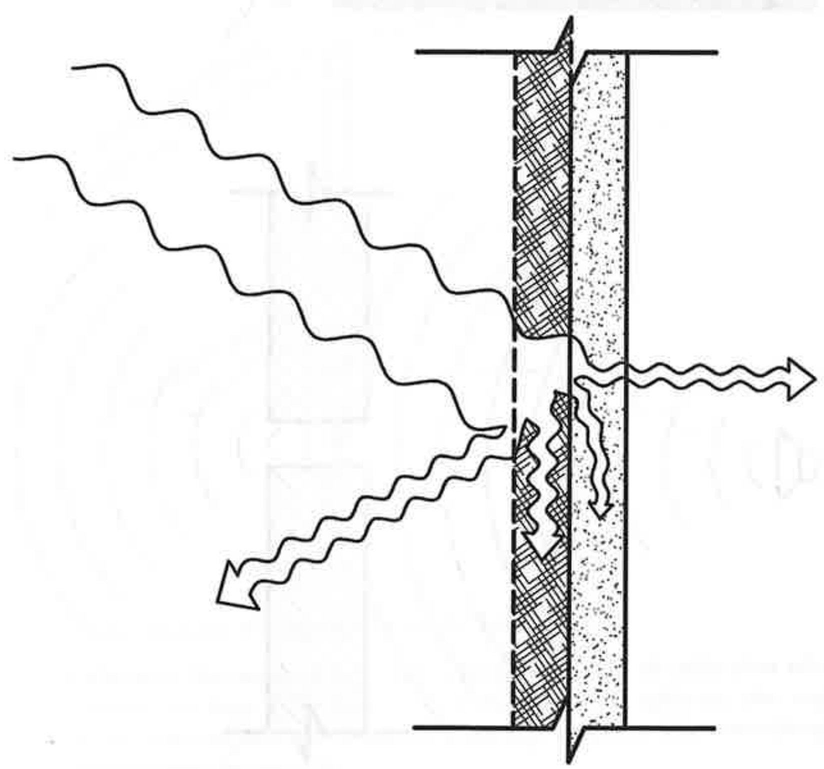


Fig. 5.3i Materials are called absorptive if most of the sound energy is converted into heat within the material. However, some sound will be reflected and some transmitted.

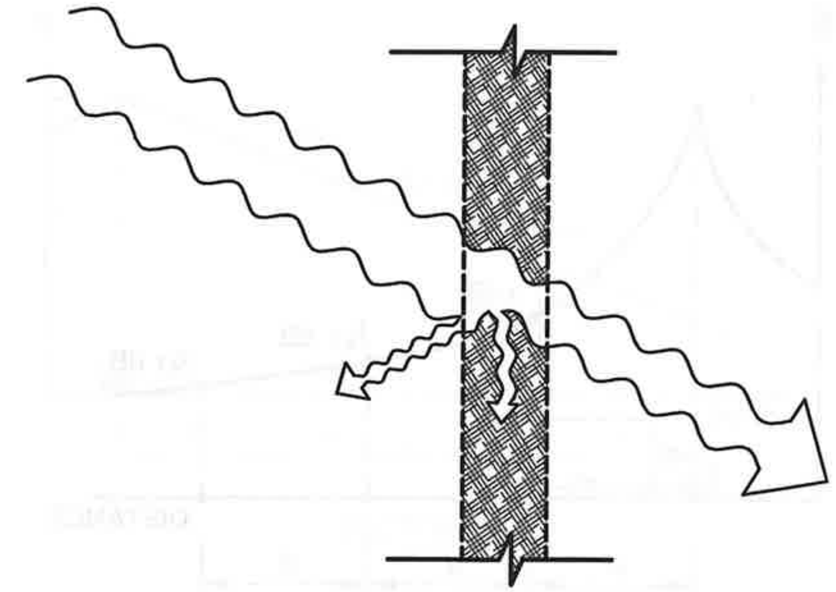


Fig. 5.3j Materials that transmit sound also reflect and absorb a small portion of the incident sound.

level of a point source, such as a single noisy truck, decreases with the square of the distance (Fig. 5.3k). However, if the sound source is linear such as a busy highway, the sound level decreases linearly with distance (Fig. 5.3l).

Indoors, because of reflections off the walls, ceiling, and floor, the sound level from a point source decreases with distance as shown in Fig. 5.3m. At first, the sound level decreases exponentially as in a free field. However, near the walls, the combined reflections of the walls, ceiling, and floor create a fairly constant sound level. The area near the walls, where most of the sound is the result of reflections, is called the **reverberant field**. Thus, the sound level in a room drops significantly at first when moving away from a point source but soon levels off as the reflections dominate.

Besides affecting sound levels, reflections also determine how long a sound exists. The time it takes in a particular space for a sound to drop 60 **decibels**, a measure of loudness, is called the **reverberation time** of that space. The reverberation time is directly proportional to the volume of a space and inversely proportional to the absorption of the surfaces.

Thus $T = \dfrac{V}{S}$

where: T = reverberation time in seconds
V = volume of space
S = absorption of surfaces given in sabins

Consequently, large rooms with reflecting surfaces have very long reverberation times (i.e., speech may be garbled). Many large railroad stations or mostly empty sports halls have this problem when announcements are made over the public address system. On the other hand, small rooms

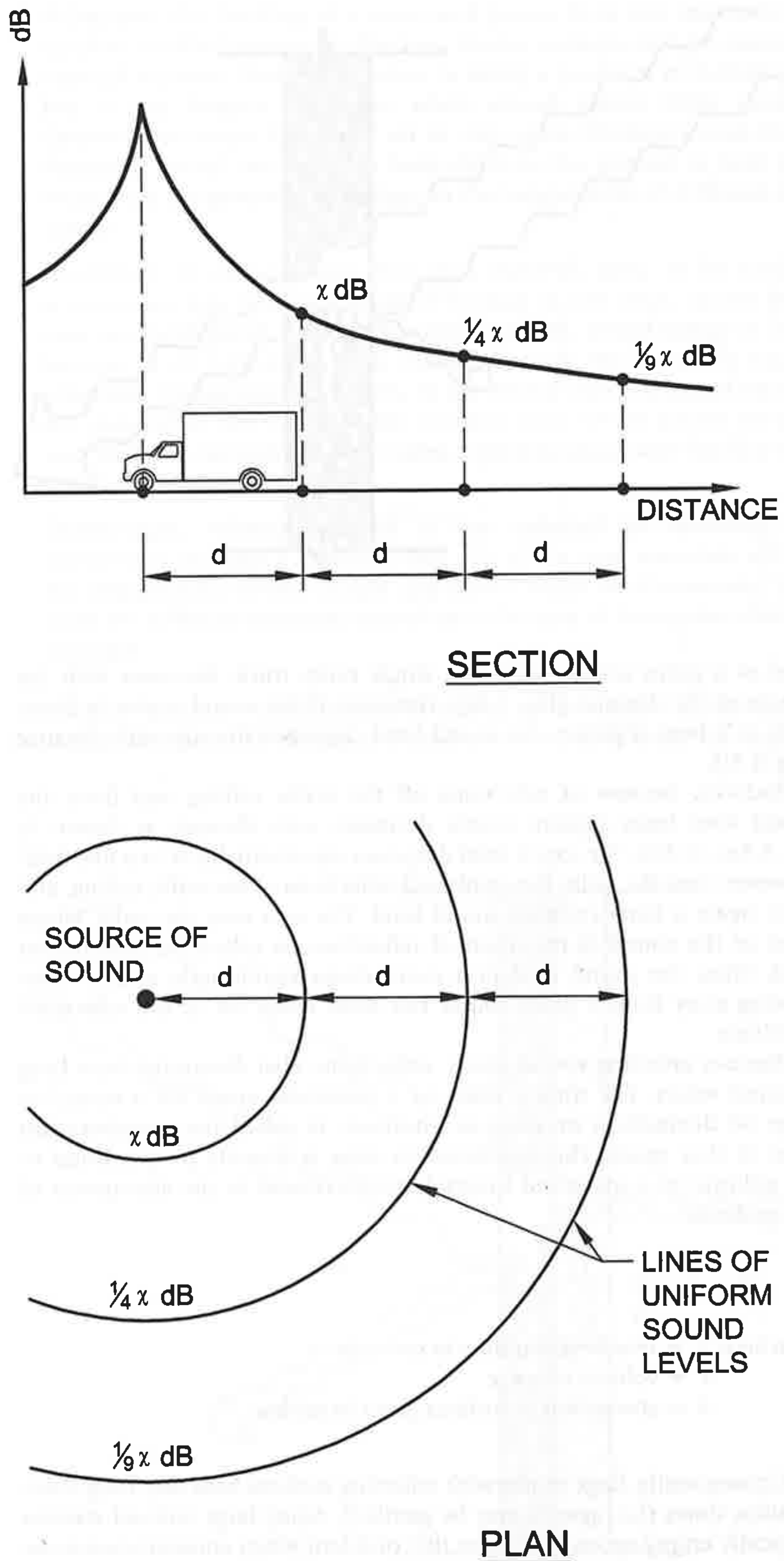


Fig. 5.3k Outdoors in an open field, the sound pressure level from a point source decreases with the square of the distance. Thus, when the distance is doubled the sound pressure level will be only one-quarter as great.

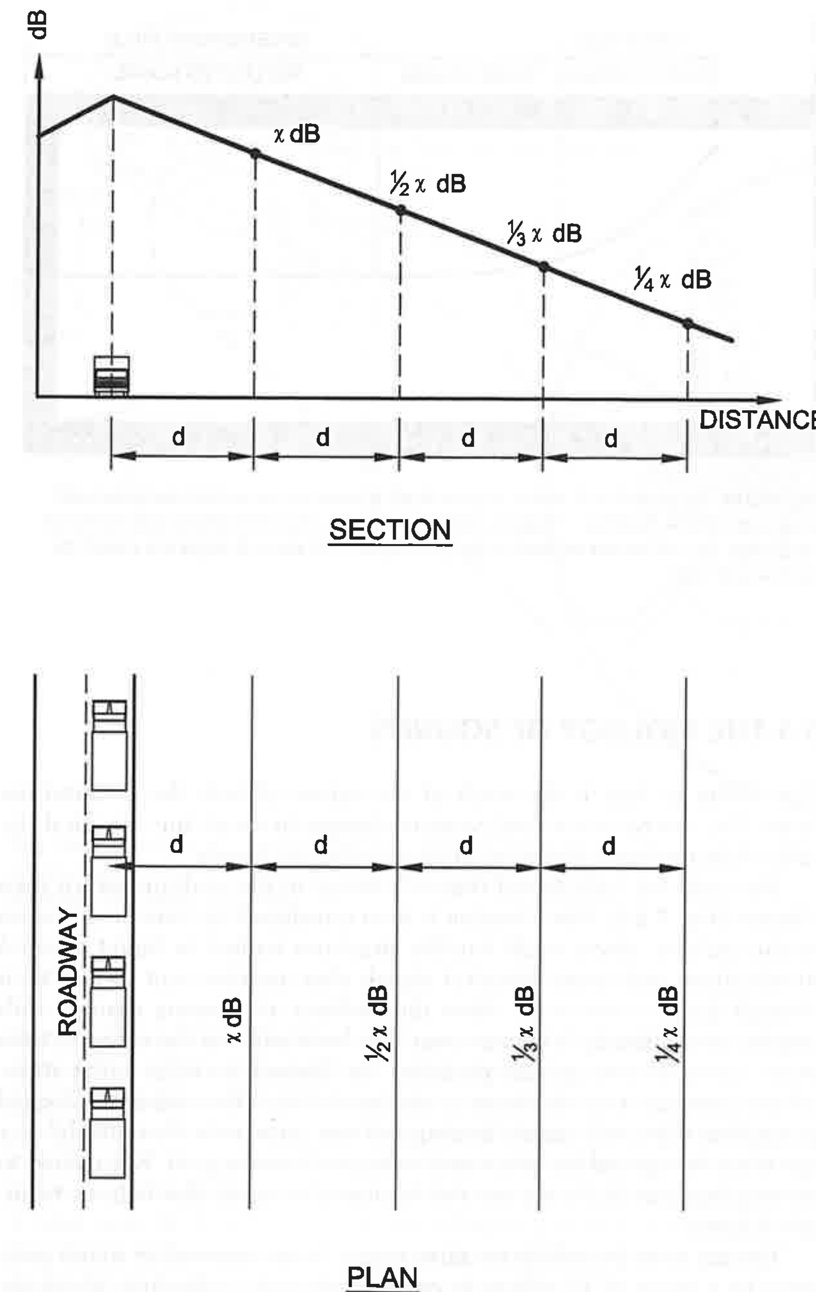


Fig. 5.3l Outdoors in an open field, the sound pressure level from a linear source will decrease linearly with the distance. Thus, when the distance is doubled the sound pressure level is halved.

with much absorbing material like living rooms have very short reverberation times (i.e., speech is clear).

The amount of sound absorption in a room (measured in **sabins**) is a function of both the area and absorption characteristics of the materials, which will be discussed in a later section. The unit of sabins is named after the scientist Sabine. The reverberation time of a space is critical and will also be discussed further in later sections.

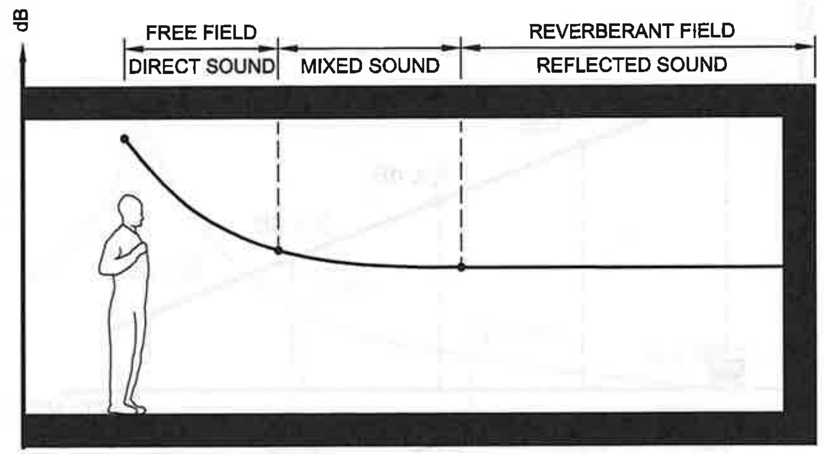


Fig. 5.3m The sound level within a space from a point source at first decreases with the square of the distance. However, close to the walls, the reflected sounds reinforce each other so that the sound level is fairly constant. This zone of a space is called the reverberant field.

5.4 THE BIOLOGY OF SOUNDS

Our ability to hear is the result of the nature of both the ears and the brain. The ears convert sound pressure changes in the air into electrical signals, while the brain makes meaning out of those signals.

The outer ear collects and channels sound to the eardrum, which then vibrates (Fig. 5.4a). This vibration is then transferred by three small bones to the cochlea, where small hairlike structures bathed in liquid respond to vibrations and create electrical signals that are then sent to the brain through the auditory nerve. Since the ambient air pressure changes with weather and altitude, it is important that both sides of the eardrum have equal access to atmospheric pressure. The Eustachian tubes bring atmospheric pressure from the throat to the inner side of the eardrums. Clogged Eustachian tubes will impair hearing and can cause pain. Fortunately, they can often be opened by either swallowing or chewing gum. Not related to hearing but part of the ear are the semicircular canals that help us maintain balance.

The ear is an incredibly sensitive organ. It can respond to sound pressures in a range of 10 trillion to one. To respond to this huge range the ear must respond in a nonlinear fashion. For this reason, loudness is usually measured by a logarithmic scale called **decibels (dB)** named after the scientist Alexander Graham Bell. This scale makes it easier to quantify our perception of loudness which is only related to but not the same as sound pressure (Fig. 5.4b). The dB scale starts at the threshold of hearing rather than zero sound pressure. The upper reaches of the dB scale describe sounds that are loud enough to damage our ears.

The ear responds not only to the amplitude (sound pressure) of waves but also to their frequency in terms of cycles per second (Hz). Most of the information in sound is carried by changes in frequency, and the human ear can hear sound frequencies in a range from about 20 Hz to 20,000 Hz.

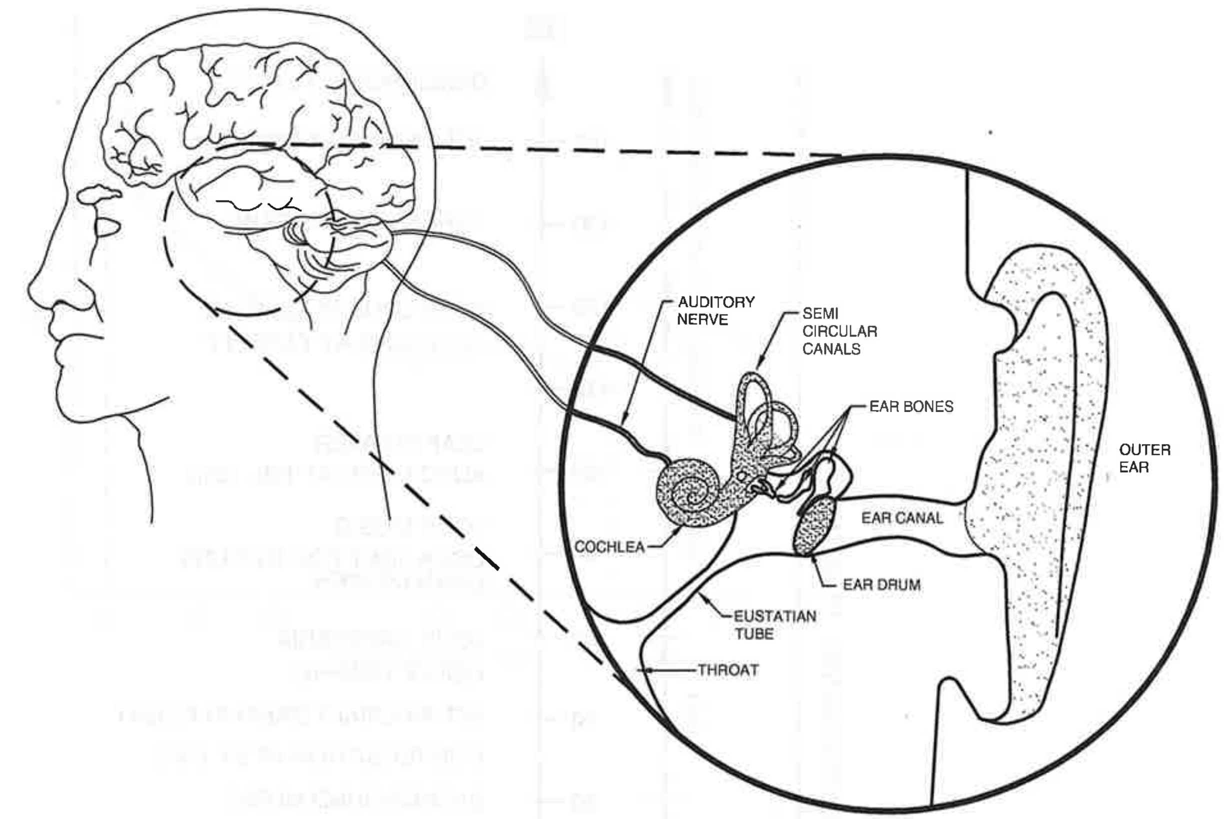


Fig. 5.4a Hearing is accomplished by the combined action of the ears and brain. The eardrum converts airborne sound to structure-borne sound. Three small bones then transfer the sound to the liquid-filled cochlea in which hairlike structures convert vibrations into electrical signals.

Many animals, such as dogs and bats, can hear sounds at frequencies higher than 20,000 Hz, which are called ultrasounds. Whales can hear frequencies as high as 150,000 Hz.

It is important to note that human ears are not equally sensitive to sounds at all frequencies. It takes more sound pressure to create equal loudness at low frequencies than high frequencies (Fig. 5.4c). For example, it takes only 54 dB at 5,000 Hz to sound equally loud as 108 dB at 20 Hz. This fact is extremely important as can be seen by comparing Figures 5.4c and 5.4d. Note that the ear is most sensitive to sounds around 4,000 Hz (point B in Fig. 5.4c) and that this frequency corresponds to consonants in human speech (point B in Fig. 5.4d). Most information in speech is transmitted through the consonants with the vowels mainly acting as smooth transitions between the consonants. Some languages, such as Hebrew, don't bother to write out the vowels because the consonants are sufficient to communicate most written messages. Figure 5.4d also shows how the ranges of speech and music compare to the total range of human hearing (20–20,000 Hz).

Because building materials respond differently to different frequencies, it is wrong to assume that an acoustical design has the same effect on all frequencies. Thus, for greater accuracy it would be appropriate to analyze

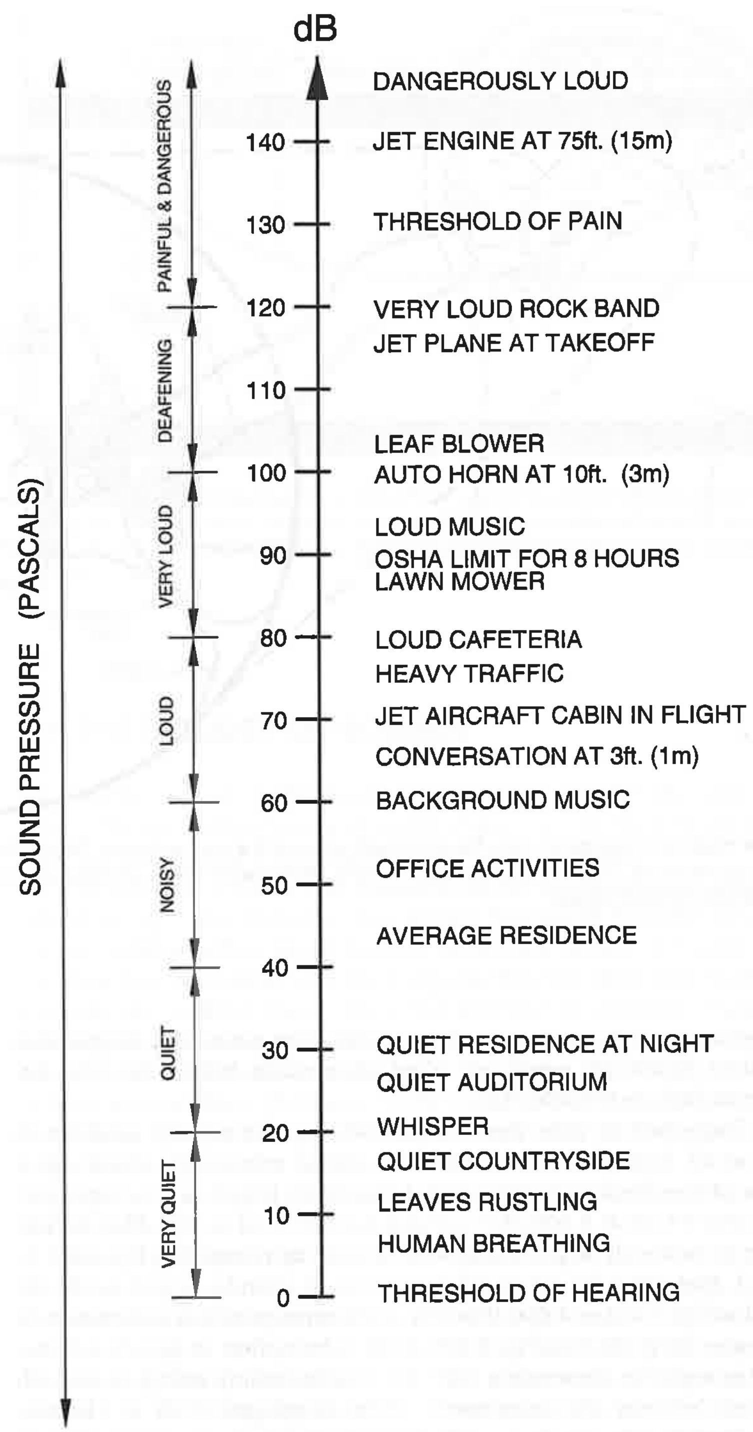


Fig. 5.4b The decibel (dB) scale differs from a sound pressure scale measured in pascals in two ways: (1) it is logarithmic and (2) its zero point is the threshold of hearing, while zero for sound pressure would be atmospheric pressure.

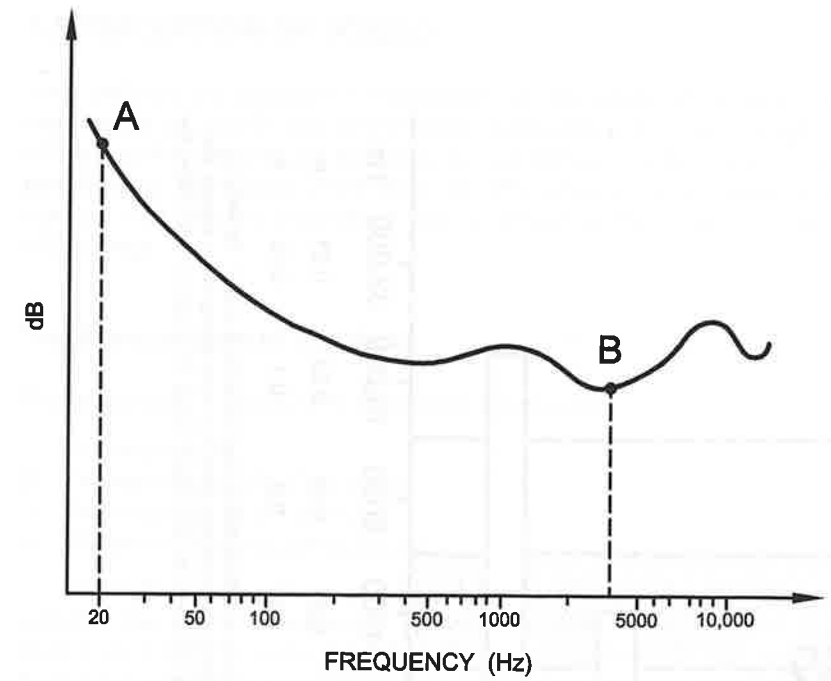


Fig 5.4c This equal loudness curve demonstrates that it takes much more loudness (energy) at some frequencies to sound equally loud to other frequencies. The graph shows that for the most part, the human ear is more sensitive to high-frequency than low-frequency sounds. Point "B" represents the most sensitive frequency (about 4,000 Hz) for most people.

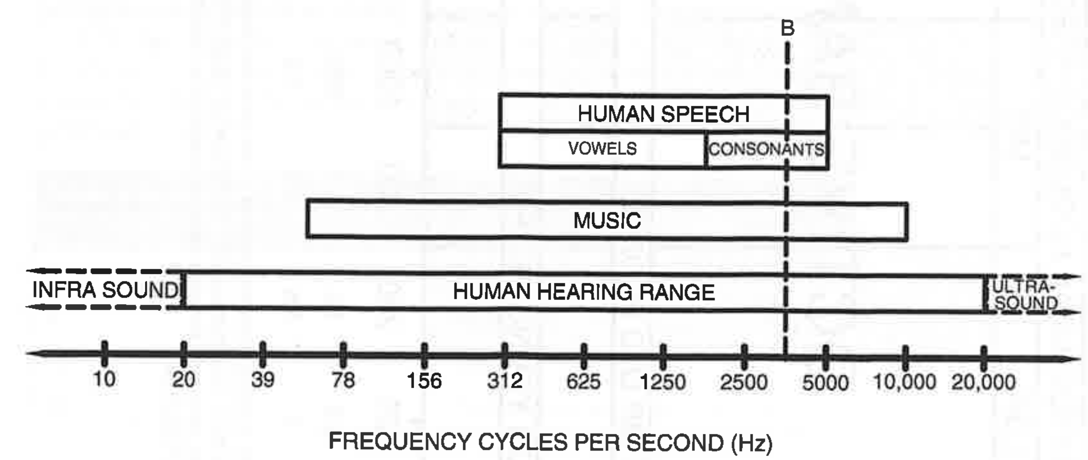


Fig. 5.4d Most human beings hear in a range of frequencies from about 20 to 20,000 Hz. Music is performed using much of that large range, but speech is limited to the shorter range of about 300 to 7,000 Hz. Point "B" represents the most sensitive frequency for most people, and it is near the center of the range for consonants.

a design for every frequency. Of course, that is impractical, and fortunately good results are achieved by breaking the whole range of human hearing into three parts: low, medium, and high frequencies. For more precise acoustical design, the whole range of human hearing can be broken into about ten octave frequency bands identified by the frequencies at their centers (Fig. 5.4e). Note that each octave has twice the frequency of the previous lower one.

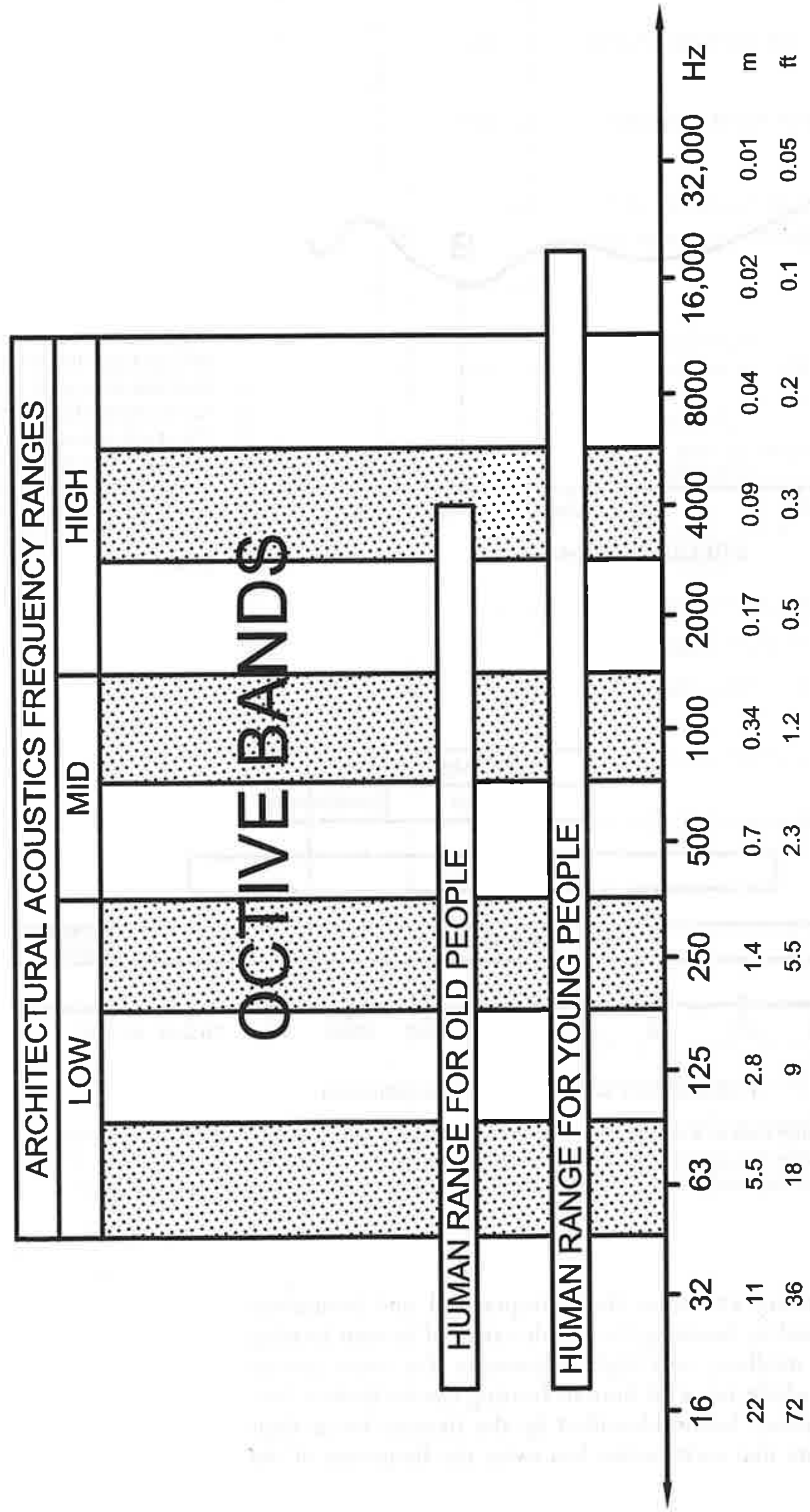


Fig. 5.4e Because neither the human ear nor building materials respond in the same way to all frequencies, acoustical design must consider a sound's behavior at its different frequencies. To make this requirement more manageable, the frequency range of human hearing is broken into parts. For more approximate design, the range is divided into three parts: low, medium, and high. For more detailed analysis, the frequency range is broken into ten octave bands. This diagram also shows the wavelengths that correspond with the given frequencies.

5.5 PERCEPTION OF SOUND

Since architectural acoustics is concerned with the sound environment as experienced by people and not scientific instruments, it is the perception of hearing that concerns us. Although the perception of sound is very complex because the human brain does the perceiving, there are some phenomena that are well understood and important to the acoustical design of buildings.

The Phenomenon of Loudness

The perception of loudness is affected by four factors:

1. Sound pressure
2. The age and health of the hearer
3. The frequency of the sound
4. The presence of a masking sound

Although the dB scale approximates loudness fairly well, it does not consider the effect of frequency. To account for the effect of frequency, several modified dB scales have been created (e.g., dBA, dBB, dBC, etc.). Fortunately, for basic architectural acoustics it is not necessary to be concerned with the modified dB scales. In this book, we will just consider the basic dB scale. See again Fig. 5.4b to see how decibels relate to such perceptions as loud (60 to 80 dB), quiet (20 to 40 dB), and so on.

It is important to remember that the dB scale is logarithmic. Thus, it only takes a 10 dB change to either double or halve the loudness of a sound. See Table 5.5A to better understand how a change in decibels is perceived.

Table 5.5a Change of dB Perceptions

Change in dB	Perception of loudness change
3	Barely noticeable
6	Noticeable
10	Twice or half as loud
20	Four times or one-quarter as loud

Because it is not possible to add the decibels of more than one source of sound algebraically, use the rules of thumb below for combining unequal sound sources, or use Table 5.5B to find the resultant dB level when combining identical sound sources.

Rules of thumb for Combining Sounds:

1. To combine two sounds of almost *equal* loudness, add 3 decibels to the louder sound.
2. To combine two sounds of *different* loudness, use the dB of the louder source only.
3. For more than two sounds, combine any two of them using rule 1 or 2, and then take that resultant and combine it with another sound. Repeat as often as necessary, or see Table 5.5B.

Table 5.5b Multiple Source dB Levels

Number of Identical Sources	dB to Be Added to One Source	Increase in Perceived Loudness*
2	3	just noticeable
4	6	noticeable
10	10	doubling
100	20	four times louder

*The increased perceived loudness as compared to one source.

Because loudness is a complex phenomenon, there have been many attempts to simplify it. Besides the various dB scales there are also the **phon** and **sone** scales. However, they are little used except to rate the loudness of bathroom and kitchen exhaust fans.

The Phenomenon of Apparent Source

Because people are **binaural**, we can determine the direction of a sound source. From the small difference in time that it takes for a sound wave to reach each ear, the brain can determine the direction of the sound source. When there are two identical sound sources, such as loudspeakers symmetrically located, the brain will perceive the sound as coming from a point between them (Fig. 5.5a). However, since the ears are separated horizontally, the brain does not perceive a vertical separation. Thus, a loudspeaker above a speaking person does not change the perception that the sound is coming from the person (Fig. 5.5b). When a sound is reflected off a wall and the direct sound is blocked, the brain will perceive the sound as originating at its virtual location (Fig. 5.5c).

The Phenomenon of the Echo

When a reflected sound of sufficient intensity arrives at the ears more than about 60 milliseconds after the direct sound, it is perceived as a distinct second sound or echo. Since sound travels 1130 fps (344 mps) it will travel about 70 ft. (21 m) in 60 milliseconds. Thus, if the path of a reflected sound is about 70 ft. (21 m) longer than the direct sound, a clear echo will be heard (Fig. 5.5d).

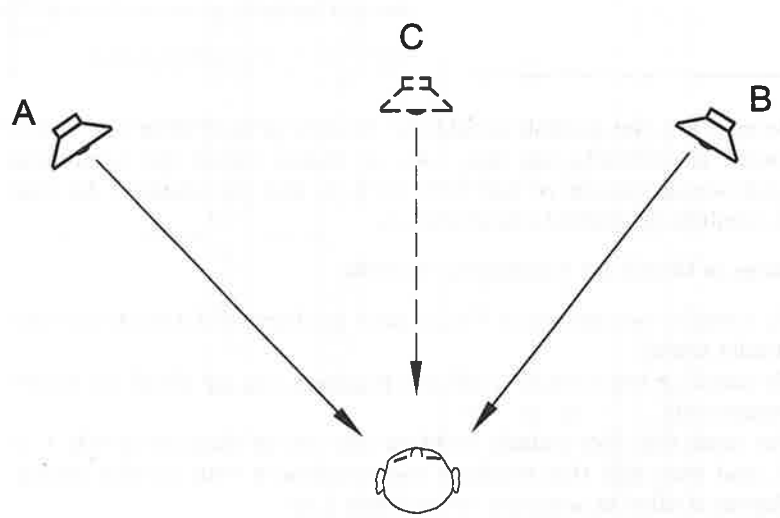


Fig. 5.5a Because of our two ears, the brain can judge the direction of a sound source based on the slight difference in arrival time. However, if there are two equal sources (A&B) symmetrically located, the brain perceives the origin to be midway between them (C).

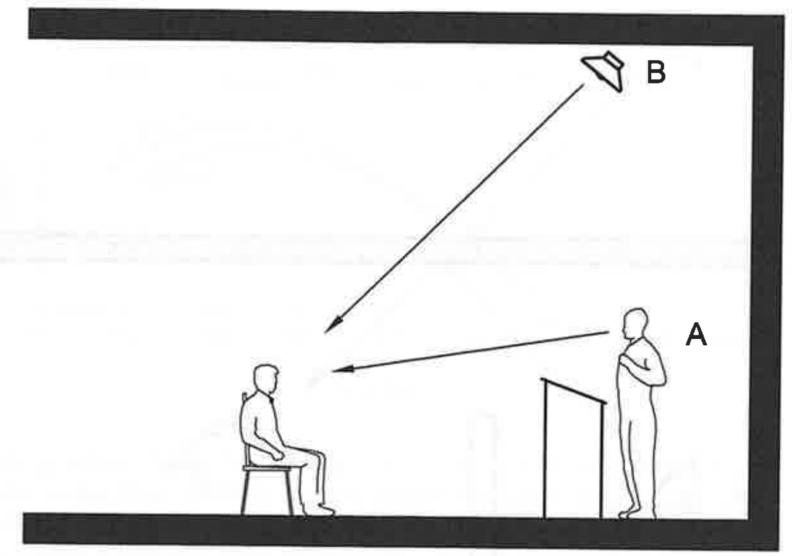


Fig. 5.5b Because the ears are separated horizontally, vertical separation of sound sources does not change the perceived direction. The sound will be perceived as coming from the speaker (A) even if most of the sound comes from the loudspeaker above (B).

The Phenomenon of Noise

Sound can be communication or noise as determined by the brain of the receiver. The annoyance of noise is proportional to its loudness, is greater for high-frequency than low-frequency sounds, and is greater for intermittent than continuous sounds. Noise is also more annoying if it has information content not relevant to the receiver. Thus, the noise of hearing nonrelevant speech is more annoying than the meaningless noise of a motor.

The Phenomenon of Dead and Live Spaces

Spaces with a long reverberation time are called "live" spaces. They are good for augmenting the richness and loudness of musical sounds. On the other hand, spaces with a short reverberation time are called "dead" spaces and are good for speech, because the sounds in them are more distinct. See Fig. 5.5e for the relationship of reverberation time to speech and music.

The Phenomenon of Gender Recognition

In most cases, we can tell the gender of a person just by hearing that person talk. In music, we use terms such as baritone, tenor, and soprano to describe the tonal range of the singer, and these terms usually predict the gender of the singer. Basses have the lowest range, and sopranos have the highest range.

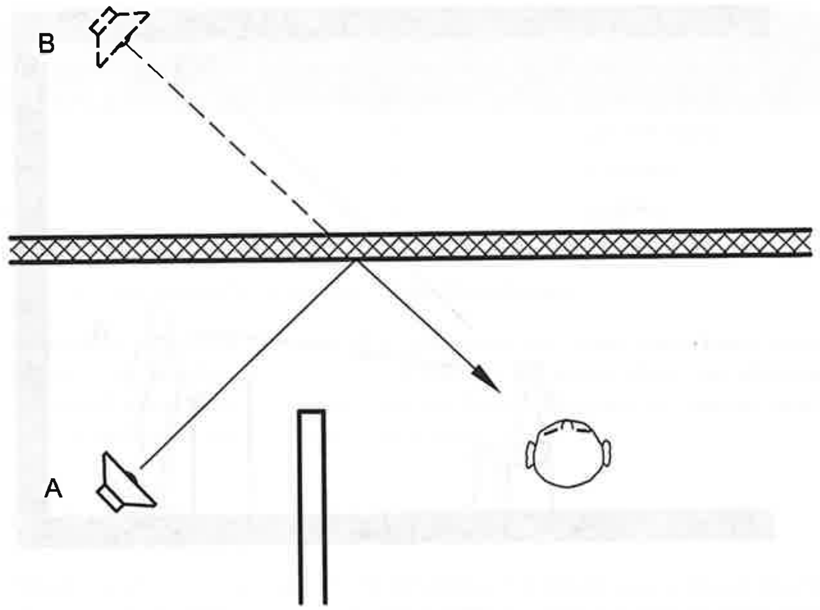


Fig. 5.5c Just as a mirror creates a virtual image, a wall can create a virtual sound source.

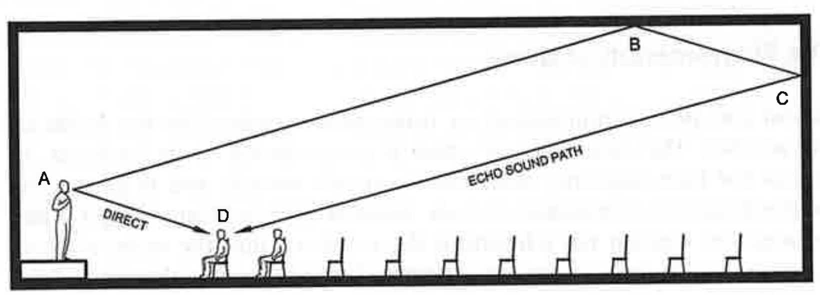


Fig. 5.5d If path A-B-C-D is more than 70 ft. (21 m) longer than path A-D, a distinct echo will be heard.

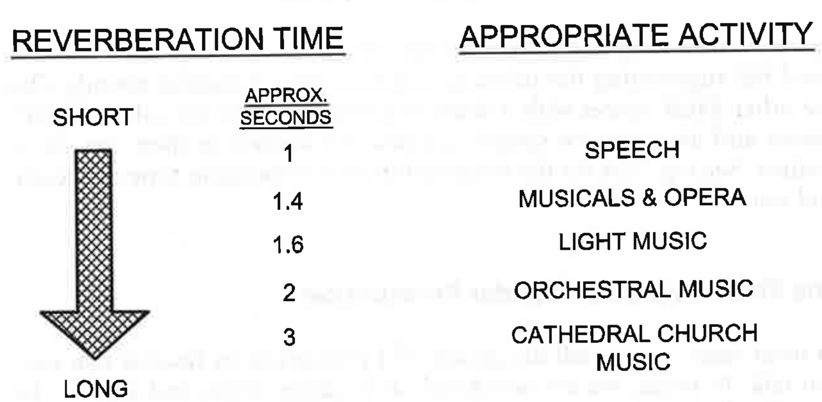


Fig. 5.5e The function of a space will determine the appropriate reverberation time. For clarity, speech should have a short reverberation time while music is enriched by a longer reverberation time.

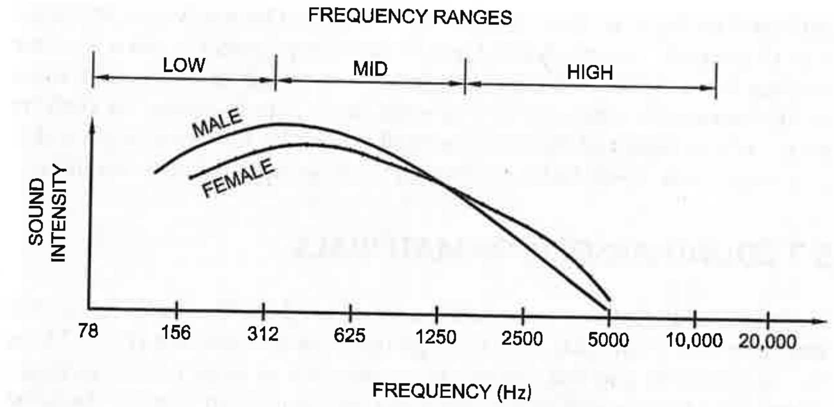


Fig. 5.5f We perceive female voices to be higher than male voices not because they contain higher frequencies but because their higher frequencies have more intensity and because their low frequencies have less intensity than that of male voices.

The graph in Figure 5.5f shows how the speech of typical males and females varies. Note that the range is almost the same. What varies is the sound intensity (loudness) at various frequencies. Female voices have more sound intensity at high frequencies, whereas male voices have more intensity at low frequencies. Our brain perceives these differences of sound intensity as a gender difference.

5.6 SOUND AND HEALTH

Sound can cause both physical and psychological problems. Except for very loud music, it is usually sound in the form of noise that is the problem, and noise can be defined as sound that carries no information for the receiver.

Noise levels as low as 75 dB can cause such problems as headaches, digestive problems, abnormally high heartbeat, high blood pressure, anxiety, and nervousness. Even lower noise levels can cause sleeping problems, while slightly higher noise levels can cause permanent hearing loss. For this reason, the Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor prohibits workers from being exposed to noise levels above 85 dB that exist for a duration of more than 8 hours. The louder the sound, the shorter the allowable duration. For example, exposure to a 100 dB noise level may not exceed one hour. When noise levels are above permitted limits, hearing protection devices must be used.

In a noisy world, quiet is very desirable. Thus, noise and intensity of sounds should be limited as much as possible. Instead of adding background music as many department stores do, the Target™ chain supplies quiet in order to attract customers.

Since noise is not only disturbing and distracting but also a health problem, much of the field of architectural acoustics is concerned with the control of noise. Figure 5.6 shows that any noise system consists of a source,

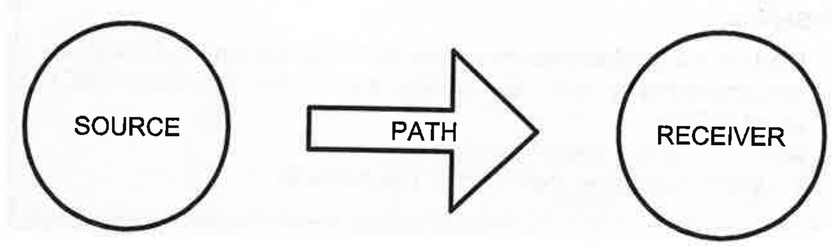


Fig. 5.6 The "noise system" consists of the source, the path, and the receiver. The architect's focus is on the source and path.

path, and receiver. As usual, a problem should first be resolved at its source if at all possible. The mechanical and electrical equipment is often a source of noise that a building designer can control. Although architects have some control over some other sources of noise, they mainly control its path by means of the design of the building itself. Thus, the following sections discuss noise control with building elements such as walls, ceilings, and floors.

5.7 SOUND-ABSORBING MATERIALS

Most **sound-absorbing materials** are composed of fibrous or open cell structures that let air pass right through their tiny passageways (Fig. 5.7). As the air moves in and out, friction with the walls of these narrow passages causes the sound waves to lose their energy. Sound can also be absorbed by **panel absorbers** which flex under the impact of sound. The flexing also converts sound energy into heat energy. There are also **volume resonators**, which usually consist of hollow concrete blocks that have open slits for the sound waves to enter. Both the panel absorbers and the volume resonators are usually used where noise of a specific frequency is the problem.

Sound-absorbing materials are used to either reduce noise or reverberation time. The performance of sound-absorbing materials is described by the **sound absorption coefficient** (SAC), which can vary from 0 to 1, where zero equals no sound absorption and one equals complete sound absorption. Since materials respond differently to sounds of different frequencies, the SAC is available for most of the frequency bands described in Fig. 5.4e (i.e., 125, 250, 500, 1000, 2000, and 4000 Hz). To calculate the actual sound absorption of a material used in a space the SAC must be multiplied by the exposed surface area of that material. To find the total sound absorption of a room, the actual sound absorption of all exposed surfaces must be added up. The total sound absorption of a room is given in units called **sabins** (see Sidebox 5.7).

For common types of noise problems, it is possible to simplify the quantitative performance of sound-absorbing materials by using the **noise reduction coefficient** (NRC), which is the average SAC for the frequency bands of 250, 500, 1000, and 2000 Hz. Table 5.7 gives the NRC for common building materials. The noise reduction coefficient (NRC), like the SAC, is a number between 0 and 1 where a value of zero indicates no absorption and a value of one indicates full absorption. Use the following rules of thumb when designing and specifying sound-absorbing materials.

Rules of Thumb for Sound-Absorbing Materials

1. They are most effective for high-frequency sounds.
2. Thicker materials will absorb more sound, including more low-frequency sound.
3. Since many sound-absorbing materials are soft and fragile, they are better used on ceilings than walls.
4. The decorative and protective covers of sound-absorbing materials must be very thin and open (e.g., open-weave fabric or perforated films and sheets).
5. For a given area of sound-absorbing material, it is better to distribute it than to concentrate it in one location.

SIDEBOX 5.7

Sabins

The total sound absorption in a room (sabins) is the sum of all room surfaces multiplied by their respective sound absorption coefficients (SAC)

sabins = $\sum S \cdot a$

where S = surface area of a material

a = sound absorption coefficient of that material

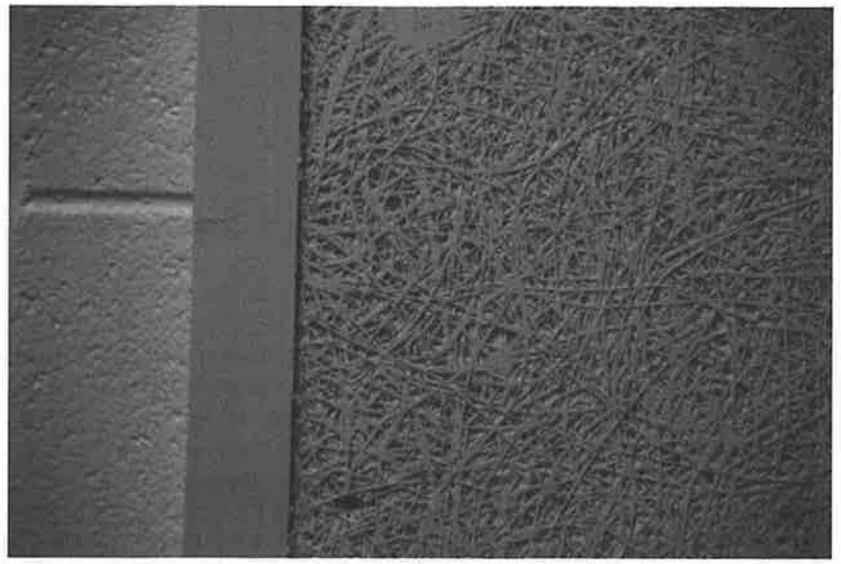


Fig. 5.7 This sound-absorbing panel consists of loose shredded wood held together with a minimum of Portland cement, which also makes the material fire resistant. A Tectum board is shown.

Table 5.7 The Noise Reduction Coefficient (NRC)

Category	NRC	Material Type
REFLECTIVE	0.00	–No sound absorption –Smooth hard surfaces (concrete, smooth brick, glazed tile, still water)
	0.05	–Hard surfaces (rough concrete, normal brick, thick glass, gypsum board, plaster)
	0.10	–Hard but thin panel over an air space or insulation (gypsum boards or wood panels attached to studs or joists)
	0.15	–Hard but very thin panel (ordinary window glass, thin plywood panel) –Lightweight drapery –Dense evergreen tree
	0.20	–Light carpet
	0.35	–Heavy carpet
ABSORPTIVE	0.45	–Rough soil
	0.55	–Heavy carpet on foam rubber pad
	0.60	–Heavyweight drapery –Grass or gravel
	0.65 to 0.95	–Sound-absorbing panels
	0.90	–Fresh snow
	1.0	–Complete sound absorption

5.8 APPLICATION OF SOUND-ABSORBING MATERIALS

Sound-absorbing materials can be used to:

a. Reduce noise
b. Reduce reverberation time
c. Reduce or eliminate echoes
d. Prevent sound from being focused by concave surfaces such as domes

Noise Reduction

For noise reduction, use Table 5.8, which gives the recommended noise reduction coefficient (NRC) appropriate for most common types of spaces. The table also gives recommendations on where to apply the sound-absorbing material. The ceiling is usually the best location, and it should be fully covered. Some types of noisy spaces also require sound-absorbing material on the walls. Rooms with special acoustical needs, such as theaters, have specific requirements that are described later in section 5.15.

Although sound-absorbing materials are very useful in reducing noise, at best the materials can reduce the noise level by half (i.e. 10 dB). Thus, reducing or eliminating the source of sound has the most potential and should always come first. Furthermore, sound-absorbing materials help little near the source of sound where the direct sound and not the reflected sounds predominate.

Reverberation-Time Reduction

Since reverberation time is a result of sounds reflecting back and forth between reflective room surfaces, sound-absorbing materials will reduce the reflections and thereby the reverberation time.

Sound-absorbing materials on the ceiling and floor may not be sufficient if the walls' surfaces are large, as in rooms with high ceilings. In such cases, some sound-absorbing material should also be placed on the walls (Fig. 5.8a).

Table 5.8 Recommendations for the Use of Sound Absorbing Materials

Type of room	Recommended NRC* of the material used	Application	
		Ceiling	Walls
Most types of ordinary rooms	0.65–0.75	Full	None
Lobbies, corridors, and gymnasiums	0.65–0.75	Full	Upper
Restaurants, cafeterias and kitchens	Over 0.75	Full	None
Rooms with many noisy machines	Over 0.75	Full	Full
Open-plan offices**	Over 0.80	Full	Full

Note: This table is based on "Architectural Acoustics" by M. David Egan, page 79
*NRC = Noise reduction coefficient
**Open-plan offices have additional requirements described in Section 5.12.

Reduce or Eliminate Echoes

As mentioned before, if the reflected sound path is 70 ft. (21 m) or longer than the direct sound path, a distinctly separate sound will be heard and an echo will result (see again Fig. 5.5d). By covering the offending reflective surfaces with sound-absorbing materials, the echo can be eliminated (Fig. 5.8b). When the echo is caused by parallel walls, delayed sound can repeat more than once. Such a **flutter echo** can be avoided either by using absorbing materials on the walls or by not having the walls be parallel. However, even when the sounds are not distinctly separate, a slight overlap reduces clarity. Thus, it is best not to have strong reflected sounds whose paths are more than 50 ft. (15 m) longer than that of the direct sound.

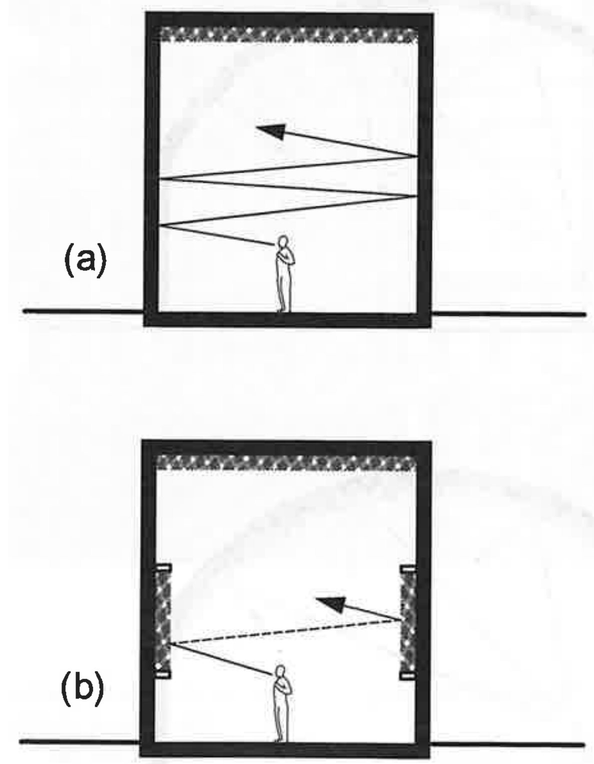


Fig. 5.8a Rooms with hard surfaces tend to have long reverberation times (a). Usually sound-absorbing material on the ceiling and floor is sufficient to shorten the reverberation time. In certain cases, as with very large rooms or small rooms with high ceilings, the reverberation time will still be too long. It is then necessary to add sound absorbing material to the walls (b).

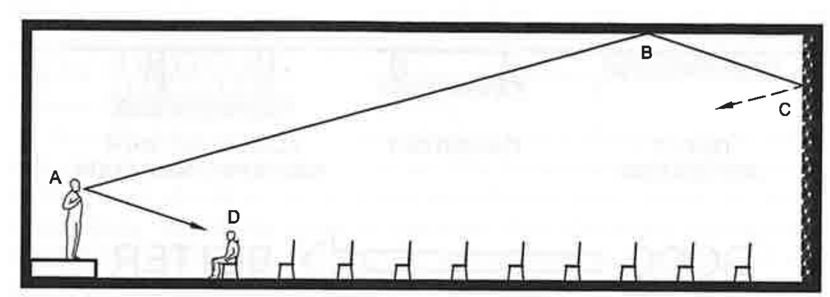


Fig. 5.8b To prevent echoes that result when the path of the reflected sound is more than 70 ft. (21 m) longer than the direct sound, it is common for theaters and auditoriums to have their back walls covered with sound-absorbing material.

Prevent Sound Focusing

Since concave surfaces focus sound, they should be avoided as much as possible in both section and plan. When concave surfaces are necessary, they should be covered with a sound-absorbing material (Fig. 5.8c).

The amount of sound absorption depends not only on the type of material but also on its thickness and mounting method. Since surface mounting is least effective, for a given thickness of sound-absorbing material an air space should be created behind the material. However, filling that air space with more sound-absorbing material is even better (Fig. 5.8d). Figure 5.8e shows a building with thick wall panels protected

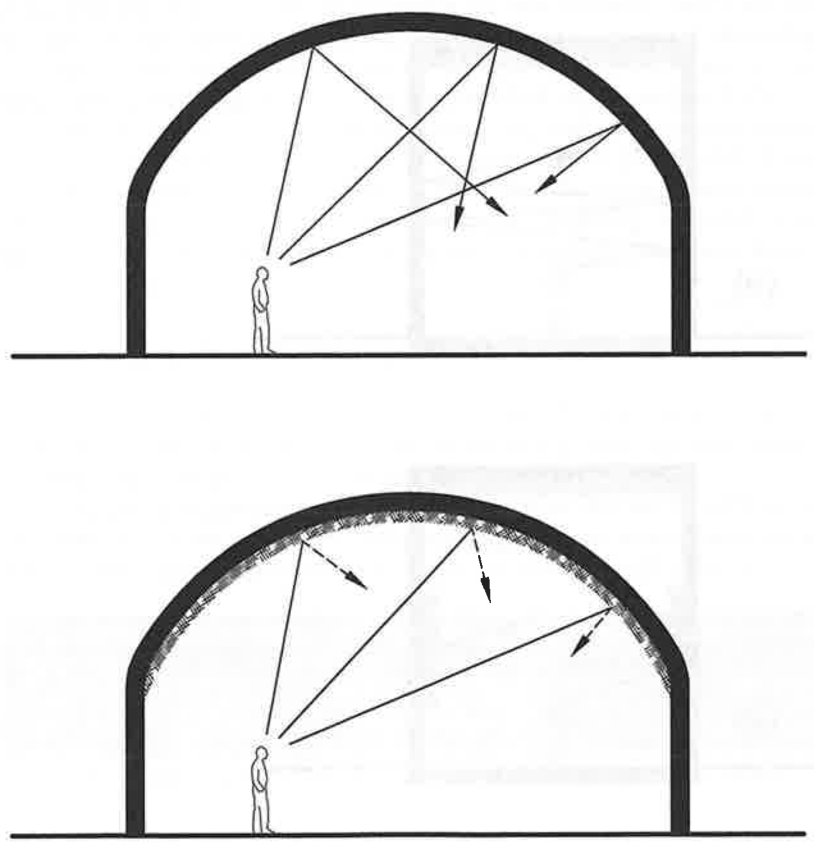


Fig. 5.8c Concave surfaces are problematic because they focus sound. If the quality of sound is important in the space, then the concave surfaces should be covered with sound-absorbing material.

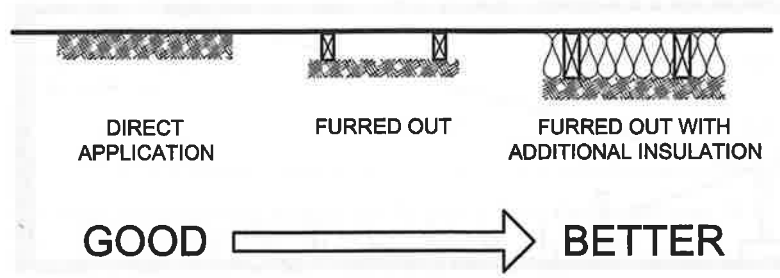


Fig. 5.8d Thicker sound-absorbing materials are always best, but with thin panels an air space behind the material is better than direct mounting.

Fig. 5.8e Because of the large amount of glass in this church, the limited area of absorbent wall panels had to be very effective. Elegant frames make the thick panels a positive element of the design (see especially each side of the central window). Additional sound absorption is achieved in the ceiling by leaving an appropriately sized space between the ceiling boards with acoustical ceiling tiles behind them. Shown is the sanctuary of the Roslyn Episcopal Conference and Retreat Center in Richmond, Virginia. *Products and acoustical design by Acoustical Solutions, Inc.*

with an attractive frame, and Figure 5.8f shows thick decoratively shaped panels padded with wool.

As mentioned before, when the ceiling and floor cannot provide enough sound absorption, the upper walls should also be used (Fig. 5.8g). For aesthetic reasons, heavy drapes are sometimes used for or over the sound-absorbing material. When the walls cannot be used or are insufficient, as in large spaces with many windows, acoustical panels can be suspended from the ceiling (Fig. 5.8h). In some spaces, the best solution may be to assemble the panels into three-dimensional objects in order to increase the sound absorption (Fig. 5.8i).

To control the noise in a room, the first step is always to try to eliminate or reduce the source of the noise. The second step, described in this section, is to absorb as much of the sound as possible. When the sound comes from outside the space in question, then the sound transmission through the walls, ceiling, floor, doors, and windows must be reduced, and that is covered in the next section.

Fig. 5.8f This wall art consists of cloth-covered shapes stuffed with wool to create sound-absorbing wall panels of various shapes called "Woolbubbles."
Courtesy: Woolbubbles from Wobedo Desiogn AB. Photographers Anna Diehl.

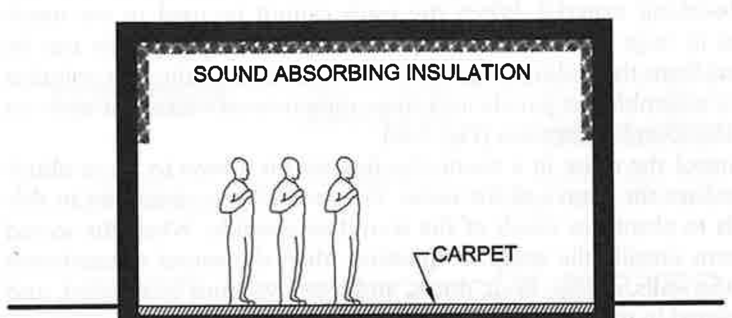


Fig. 5.8g If the ceiling and floor are not of sufficient area or are not available, the upper walls can be used for mounting sound-absorbing materials.

Fig. 5.8h Suspended acoustical panels hang from the vaulted ceiling of the atrium in the Contemporary Art Center of Virginia. The building is used for a variety of events such as weddings, meetings, and conventions. The highest row of panels are very bright because of the skylight.
Products and acoustical design by Acoustical Solutions, Inc.

Fig. 5.8i These cylinders made of sound-absorbing material expose a large surface area to sound.
Photo courtesy of Acoustical Solutions, Inc.

5.9 SOUND TRANSMISSION

Since it is almost always desirable to prevent sound transmission between rooms, walls and floors should be designed to minimize sound transmission. Unwanted sound, usually called noise, is transmitted from one room to the next when the sound in the source room causes the partition to vibrate, which in turn causes the air in the receiving room to vibrate (Fig. 5.9). Since low-frequency sounds are better able to make a wall or floor vibrate, they are transmitted more than high-frequency sounds. Any characteristics of the wall or floor that inhibits its ability to vibrate will, therefore, reduce sound transmission. Mass is the most obvious characteristic since it takes a lot of energy to move (vibrate) mass.

A less obvious characteristic of the wall or floor to transmit sound is limpness. After all, the stiffer the wall, the more it vibrates like a drum. Thus, lead with its very high mass and softness (limpness) is the best material to use to reduce sound transmission, but it is little used because of its cost and health issues. Unfortunately, since the commonly used gypsum board is rather light and stiff, it is a good transmitter of sound. Furthermore, the studs that support the gypsum boards on each side, as in a conventional partition, effectively transmit the sound from one gypsum board to the other. To prevent the air spaces inside a wall from also transmitting the sound, the spaces can be filled with sound-absorbing materials.

Besides mass, limpness, and cavities filled with sound-absorbing materials, sound transmission can also be reduced by the addition of a dampening material. For example, sheet metal used for a wall would have its back side covered by a tarlike mastic to dampen the vibration of the sheet metal.

Any strong sound barrier is only successful if there is no easy way to get around or through it. Consequently, a wall or floor designed to reduce sound transmission will fail if there are holes or cracks that allow the sound to squeeze through the barrier. For example, a hairline crack will degrade a wall by about 6 dB, which is a noticeable increase in loudness. Even a keyhole will degrade a wall by 3 dB. Thus, to minimize sound transmission a wall or floor should be airtight. A wall of low sound transmission will also fail if the sound can outflank the barrier, which is often made possible by a continuous ceiling plenum above the partitions.

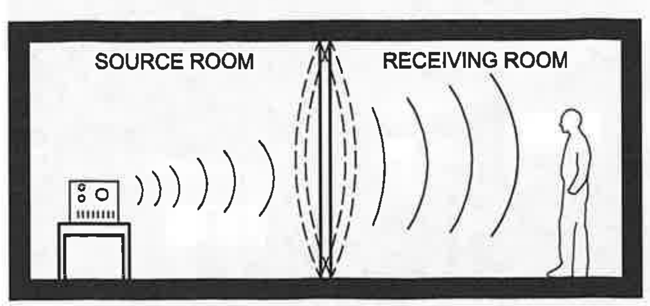


Fig. 5.9 The sound in the source room makes the wall vibrate, which in turn makes the air in the receiving room vibrate.

5.10 DESIGN FOR LOW SOUND TRANSMISSION

The effectiveness of a wall or floor in reducing sound transmission (noise) is quantified by the **transmission loss (TL)**, a rating system measured in dBs. For example, if the source room in Fig. 5.10a has a noise level of 100 dB, and if the resulting noise level in the receiving room is only 70 dB, the wall provides a Transmission Loss of 30 dB. Since objects respond differently to different frequencies, the transmission loss (TL) of any particular wall or floor will vary with frequency. Thus, TL is a good way to deal with a problem where the noise consists of a specific frequency.

However, since the most common problem is the transmission of speech and/or music over a wide range of frequencies, the concept of **sound transmission class (STC)** was developed. The sound reduction of a wall or floor over a range of frequencies is described by its sound transmission class (STC) rating, which is a weighted average of the TL at certain frequencies. Thus, if the noise in the source room of Fig. 5.10a were mostly speech and music, the wall could be described as having an STC of 30 (100-70 = 30). Table 5.10A shows how various STC levels are perceived.

As mentioned before, to minimize sound transmission, as much mass as possible should be used. However, since mass is expensive, very thick mass walls or floors should be used only if they provide other benefits such a structural support. Instead of great thickness of mass, use a moderate amount of mass divided into two layers separated by an air space

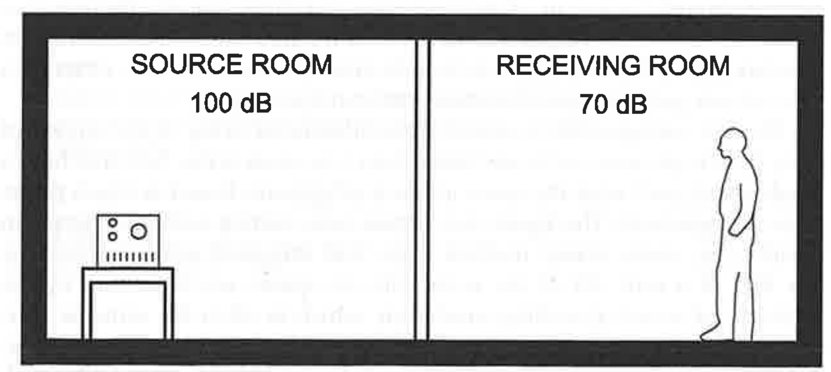


Fig. 5.10a If the noise level in the source room is 100 dB and in the receiving room 70 dB, then the transmission loss (TL) of the partition is 30 dB.

TABLE 5.10A Perception of Stc Values*

STC	Perception in Sound Transmission
30	Small reduction
40	Blocks normal talk
50	Blocks loud talk
60	Sufficient for sleeping
70	Blocks most loud music
>75	Blocks most sound

*after Mehta 1999 page 116

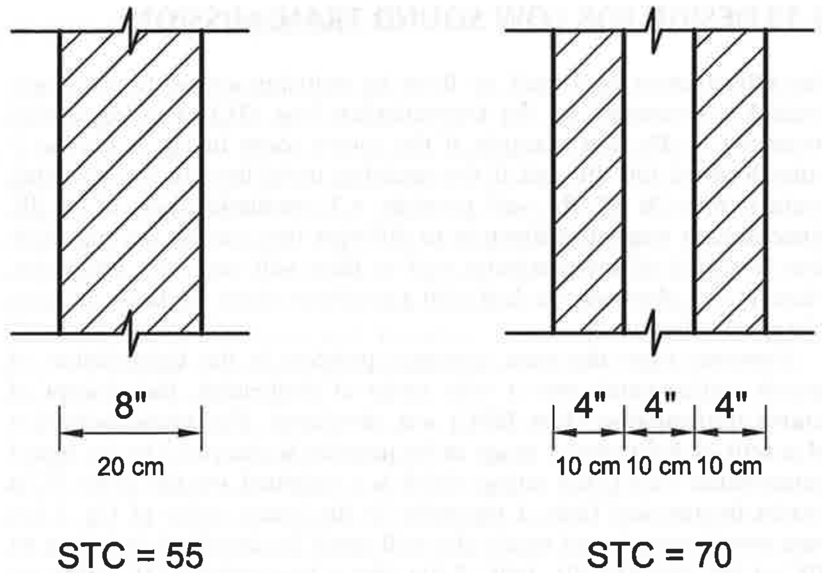


Fig. 5.10b The greater the mass of a wall or floor, the greater is the reduction in sound transmission. However, the sound reduction is even greater if the mass is used in layers. For example, 8 in. (20 cm) of masonry will have a sound transmission class (STC) that is 15 units higher if used as two 4 in. (10 cm) layers separated by an air space than a single wall 8 in. (20 cm) thick.

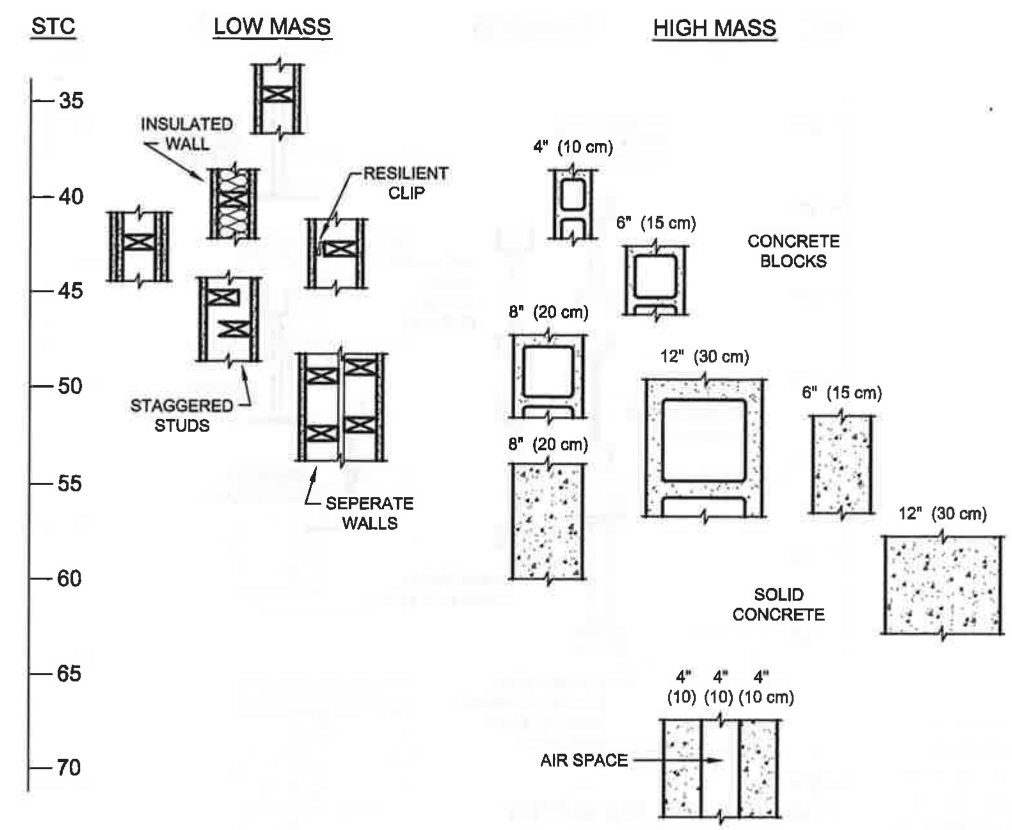
(Fig. 5.10b). A stud wall with gypsum boards on each side is an example of two mass layers separated by an air space. However, stud walls are more effective noise barriers if multiple layers of gypsum board are used on each side to increase the mass. To further reduce sound transmission, use a different number of gypsum boards on each side (e.g., one and two or two and three). Also, it is very important that the studs should support the gypsum boards by means of resilient clips or rubber spacers. There is also available a new type of gypsum board that reduces sound transmission. It consists of two layers of gypsum boards loosely bonded to each other by a visco-elastic polymer glue that dampens sound energy.

The STC ratings of various wall types, illustrated in Fig. 5.10c, show not only how high-mass walls are better than low-mass walls, but also how a double stud wall with the same amount of gypsum board is much better than a single wall. The figure also shows how adding additional gypsum boards (i.e., more mass), resilient clips, and staggered studs can increase the STC of a wall. All of the walls with air spaces would benefit by the addition of sound-absorbing insulation, which is often the same as thermal insulation. Sound-absorbing insulation in the cavity is especially effective, if the studs are prevented from easily transmitting the sound by such methods as the use of resilient clips or staggered studs.

The STC values of typical windows and doors are illustrated in Fig. 5.10d. In windows both thicker glazing and a larger air space (i.e., double glazing) increase the STC rating. A hollow metal door filled with sound-absorbing material is the best choice for doors. In both doors and windows, gaskets are required to prevent the sound from short circuiting through cracks and gaps. Figure 5.10e illustrates the strategies required for a low-sound-transmission door.

Since noise often comes through floors, the STC of floor systems should also be considered. Figure 5.10f illustrates the STC ratings of typical floorsystems.

To minimize sound transmission from a noisy to a quiet room, the first design considerations should include: making the noisy room less noisy,



NOTES:
1. ADD 5 TO STC WHEN INSULATION IS ADDED INSIDE WALL.
2. ADD 5 TO STC WHEN STEEL RATHER THAN WOOD STUDS ARE USED.

Fig. 5.10c The sound transmission class (STC) of various wall types is shown. Note that high-mass walls are better at reducing sound transmission than low-mass walls. The hollow walls would be improved if sound-absorbing material were added. This is especially true if the studs are prevented from easily transmitting the sound.

placing the noisy room far from the quiet room, minimizing the linear feet of connecting wall, or separating the rooms with a closet. If possible, use double doors with a deep vestibule. Make sure there are no paths that will allow sound to outflank the wall or floor. Figure 5.10g illustrates the problem of non-full-height partitions. It is critical to have airtight seals at doors, pipe and duct penetrations, and at all construction joints. Without acoustical sealant properly installed a wall with a nominal STC of 50 will only perform as one with an STC of about 30.

Rules for Minimizing Noise Transmission

1. Design airtight construction (use acoustical sealant at all edges and joints).
2. Require high-quality construction.
3. Use high-mass materials.
4. Use limp (not stiff) materials (e.g., a curtain of thick fabric).

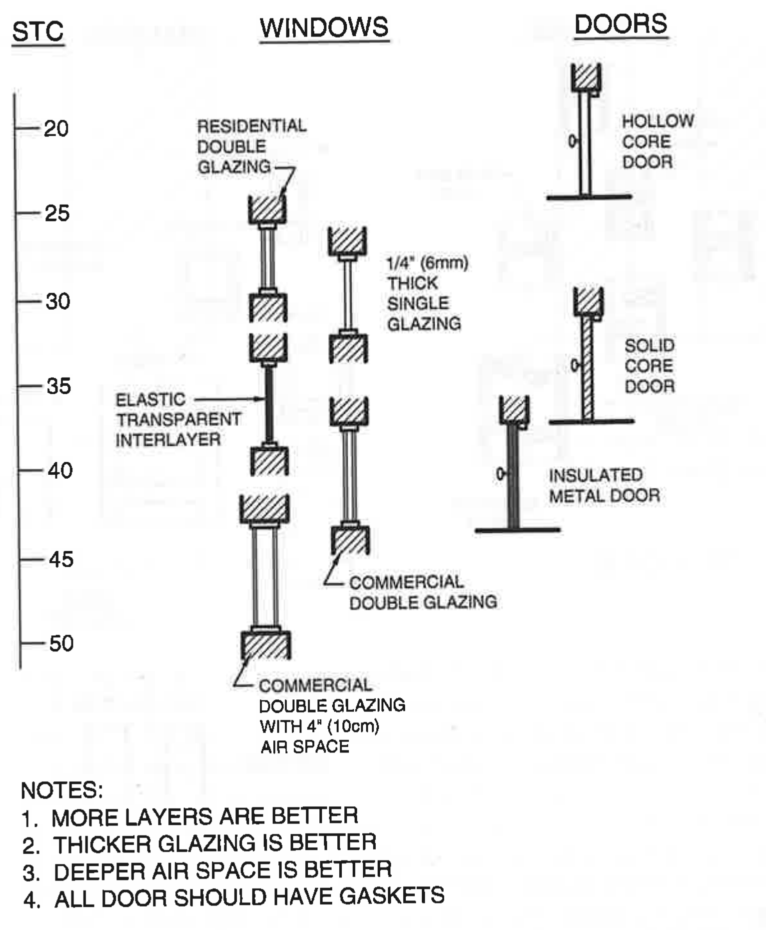


Fig. 5.10d The STC ratings for these windows and doors can be compared with the STC ratings of walls in Fig. 5.10c. Because the composite value of a whole wall with windows and doors will be much closer to the lower STC component, the specified window and door STC ratings should be close to the wall STC.

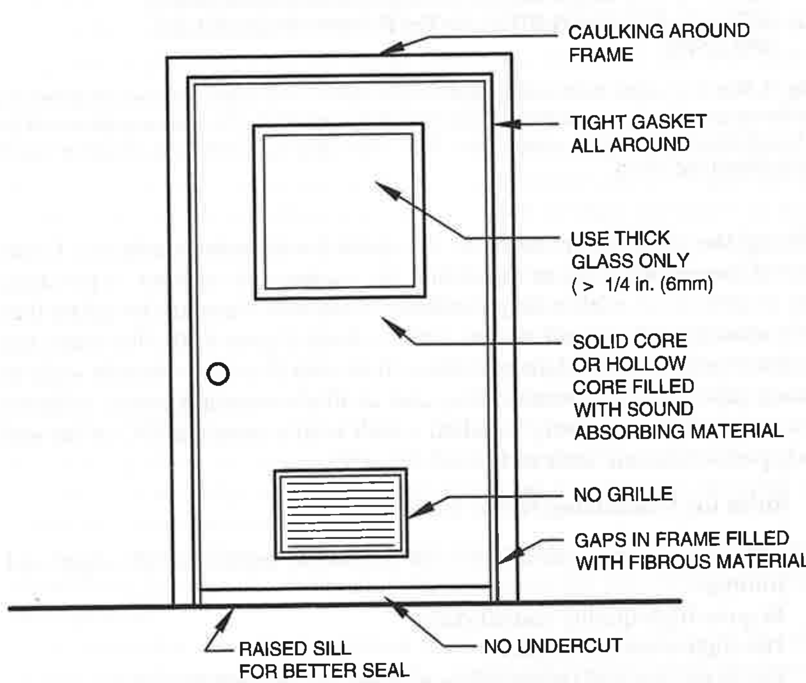


Fig. 5.10e Because doors are potential weak areas in preventing sound transmission through a wall, they have to be carefully designed, specified, and constructed.

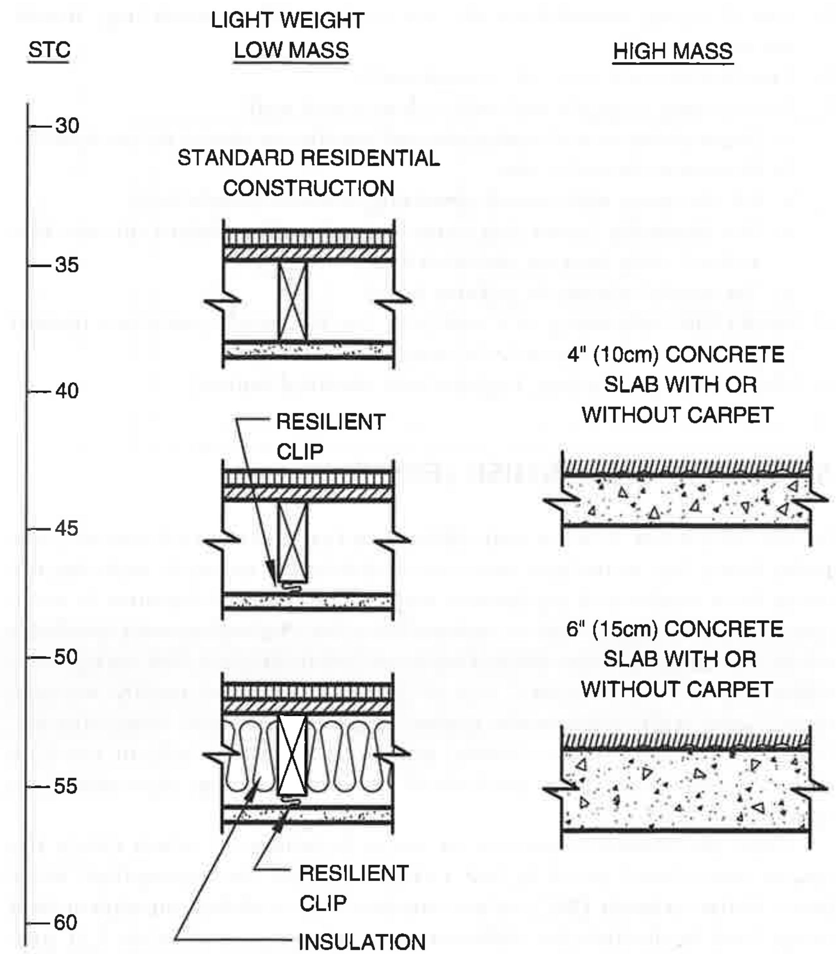


Fig. 5.10f The STC ratings for common floor systems are shown.

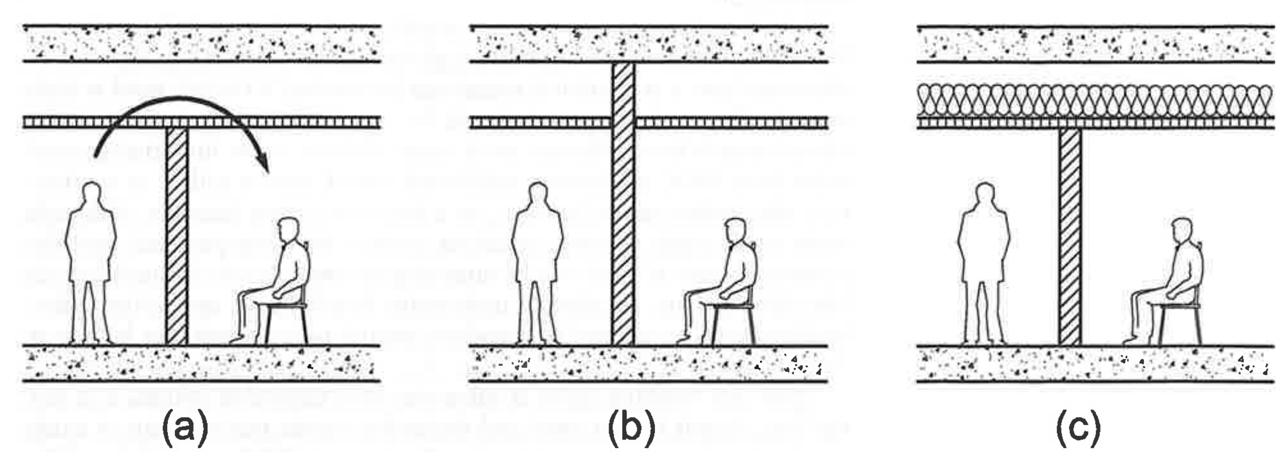


Fig. 5.10g When partitions only reach the suspended ceiling as shown in (a), noise short-circuiting will occur. If the partition cannot extend to the structural slab as shown in (b), then a large amount of sound-absorbing material is required (c).

5. Use damping materials on the rear of thin stiff materials (e.g., mastic on sheet metal).
6. Use double walls instead of single walls.
7. When using a double leaf wall such as a stud wall:
   a. Decouple layers with springlike resilient clips or special rubber spacers.
   b. Maximize the cavity size.
   c. Fill the cavity with sound-absorbing material (insulation).
   d. Use dissimilar leaves (e.g., one layer of gypsum board on one side and a double layer on the other side).
   e. Use special acoustical gypsum board.
8. Avoid the outflanking of a wall (e.g., use full-height partitions instead of partitions reaching only the suspended ceiling.
9. Avoid weak points (e.g., back-to-back electrical outlets).

5.11 ACCEPTABLE NOISE LEVELS

In most situations, it is not only difficult and expensive to achieve very low noise levels, but sometimes not even desirable. For example, reducing the noise from mechanical equipment may not be desirable because in some spaces, such as those with an open-office plan, the background mechanical noise can make more distracting noise less noticeable. The background noise can effectively "mask" the distracting sounds of nearby workers, since noise with information content (speech) is much more distracting than non-information-content noise (e.g. constant uniform machine noise). Fortunately, noisy mechanical equipment is less expensive than quiet equipment.

Thus, the common practice in many buildings is to not create the lowest noise level possible, but rather to create the appropriate noise level. **Noise criteria (NC)** values are one way to define an appropriate noise level in decibels for different types of spaces, and Table 5.11 provides recommended NC values for common types of spaces. Note that the NC number represents a curve defining the noise level at certain frequencies. The NC curves only apply to constant noise that the brain can learn to ignore, and they are not applicable for sudden noises, which the brain cannot ignore because they may represent a threat or important information.

It is often less expensive to use masking noise than to build walls and floors that will have a sufficiently high transmission loss (TL). Figure 5.11 illustrates how a transmitted sound can be masked if the NC level is high enough. The masking sound should be 3 to 5 dB louder than the transmitted speech from adjacent work areas. If there is too little background noise from HVAC equipment, additional sounds can be added. In a restaurant, the options might be music or a decorative water fountain. Although often used, music can be a problem because it is very personal, and the particular music played may be annoying to some people. Natural sounds like falling water are almost universally loved. In an open-plan office, loudspeakers can be used to broadcast neutral noise, sometimes known as "white noise."

Although masking noise is often the least expensive option, it is not the best. People have a need and desire for a quiet environment. A study by the American Society of Interior Designers (ASID) revealed that 70%

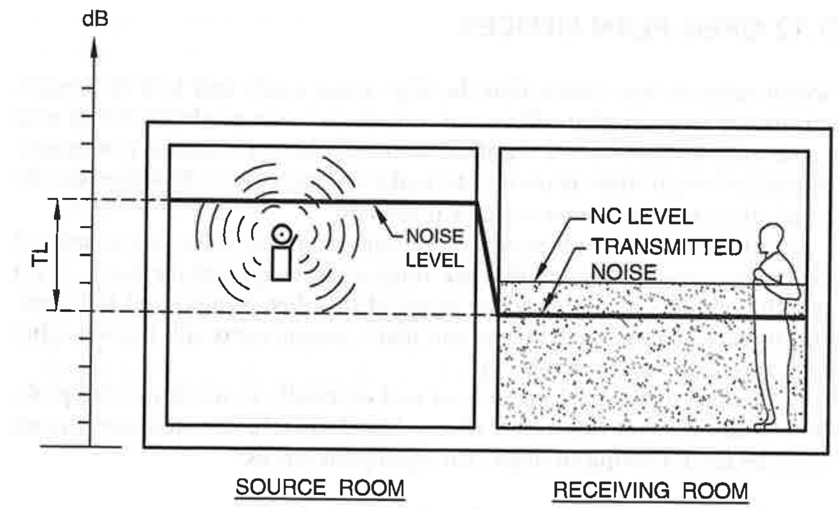


Fig. 5.11 After the transmission loss (TL), the reduced noise level in the receiving room is shown by the dB curve. If the noise criteria (NC) level is at least 5 dB higher, the transmitted noise will be "masked" by the noise in the receiving room. In that case, the transmitted noise will be less annoying and distracting.

TABLE 5.11 Noise Criteria (NC) Recommendations

Type of Space	Listening Requirements	NC	Perception
Large concert halls, auditoriums, churches	Extremely high	<20	Very quiet
Small auditoriums, theaters, churches, conference rooms	Very high	20-30	Quiet
Bedrooms, hotels, hospitals	Quite high	25-35	Quiet
classrooms, libraries, offices	High	30-35	Moderately quiet
Open-plan offices, retail shops, restaurants	Moderately high	35-40	Somewhat noisy
Lobbies, repair shops	Moderately low	40-45	Moderately noisy
Kitchens, industrial shops	Low	45-55	Noisy

*Mechanical engineers used the NC curves in the past to design duct air speed, diffusers, and other HVAC equipment to provide the desired background noise. They now prefer to use the closely related **room criteria (RC)** curves instead.

of office workers believe that workplace noise reduces their productivity. Since open-office plans create difficult acoustical problems, they will be discussed in more detail in the next section.

Another study revealed that noise from neighbors was the primary complaint of 60% of people living in multifamily housing. Noise is one of the reasons that people seek detached houses in the suburbs. Consequently, from a sustainable development perspective, it is important to reduce the noise level in cities and to reduce sound transmission between apartments.

5.12 OPEN-PLAN OFFICES

Recent research has shown that the high noise levels and lack of acoustical privacy in open-plan offices not only yield lower productivity but also cause high levels of stress, conflict, and high blood pressure (Oommen, 2008). Although there is no way to make an open-plan office acoustically good, there are many ways to make it less bad.

As always, the first objective is to eliminate or minimize the sources of distracting noise. Activities that are noisy or have a need for quiet or for speech confidentiality should be grouped together. Similarly, it is important to enclose noisy activities where many people must talk to each other (e.g., meetings and conferences).

To reduce the general noise level and especially to minimize the problem of the content-rich noise of overheard speech, the designer should consider the following strategies for open-plan offices:

Rules of Thumb for Open-Plan Offices

1. Use a ceiling height of at least 12 ft (3.7 m) with an additional plenum space of 3 ft. (1 m).
2. Cubicle partitions should have the following characteristics: be as high as possible, reach the floor, have no gaps where they meet, and be of absorbent material, usually covered by a fabric.
3. Occupants of open-plan offices should be at least 12 ft. (4 m) apart unless occupants are in a sound shadow (Fig. 5.12a).
4. Ceilings should be covered with highly absorbent material, and they should contain a minimum number of sound-reflecting items such as large lighting fixtures. Task ambient (indirect) lighting would be very appropriate
5. Cover the floor with carpet to not only absorb sound but also to minimize sounds of chair movements and people walking.

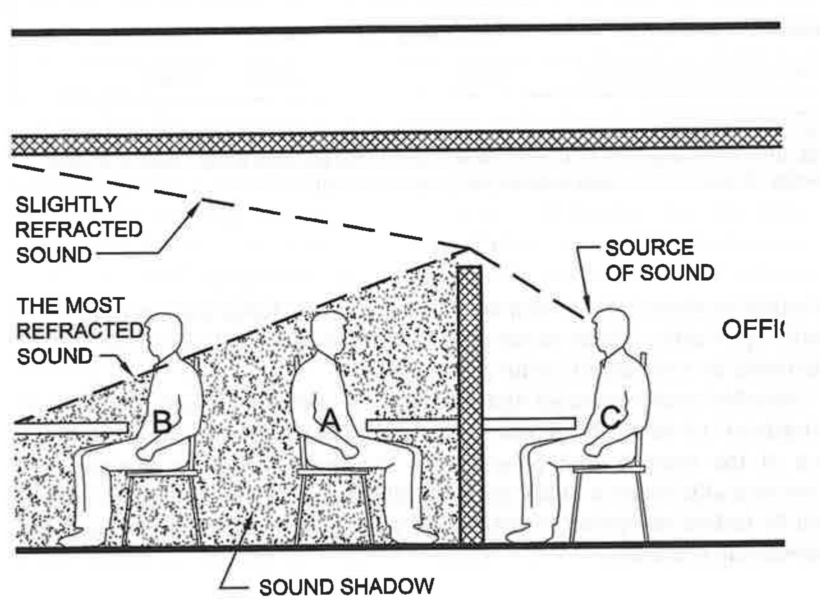


Fig. 5.12a Sound shadows are created when sounds refract over and around partitions. Consequently, the noise generated by occupant C will distract occupant A less than occupant B.

6. All perimeter walls should be covered with sound absorbent material (Fig. 5.12b).
7. Arrange cubicle openings so that direct sound cannot be transferred (Fig. 5.12b).
8. Use sound-absorbing partitions with glazing tops (Fig. 5.12c).
9. If necessary, use masking noise broadcast with loudspeakers above the suspended ceiling.

Open-plan offices will always have some problem with noise and overheard speech because some sound will always outflank the partitions. Open-plan offices are popular largely because they save money by reducing the required work area. However, since productivity and the health of workers is reduced, there may be small if any cost savings.

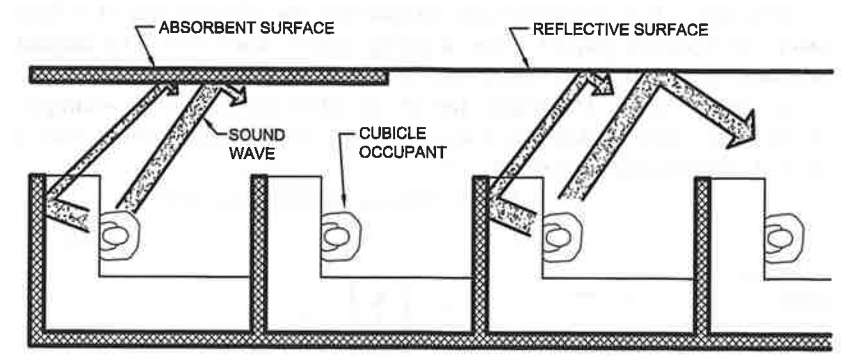


Fig. 5.12b PLAN VIEW In open-plan offices, the perimeter walls as well as the partitions need to be covered by sound-absorbing material.

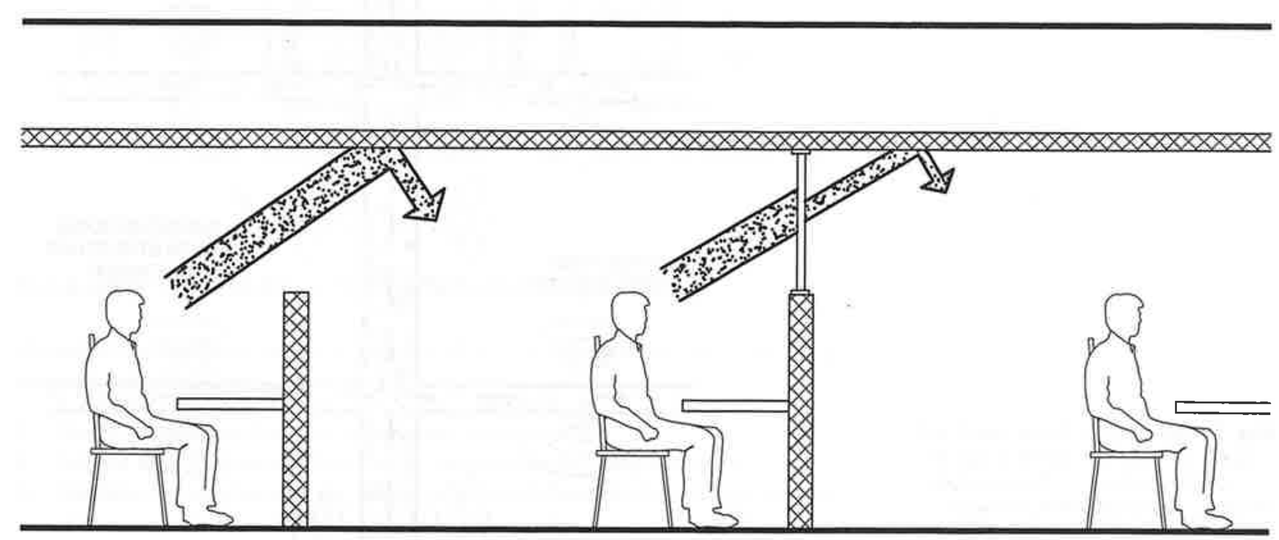


Fig. 5.12c Adding glazing to the top of cubicle partitions will increase acoustical privacy yet allow visual interconnection.

5.13 IMPACT NOISE

Hitting a table with a hammer will make a lot of airborne noise but will not be heard two rooms or floors away. On the other hand, hitting a structural column with a hammer will generate structure-borne sound that will be heard all over the building (Fig. 5.13a). Structure-borne noise has a high energy level and moves long distances with little attenuation.

In buildings, the most common source of structure-borne noise is the impact of hard shoes on a hard floor surface, and it is most severe for the room directly below hard floors. Fortunately, this problem can usually be avoided by using carpets or some other cushioning floor finish. However, when a hard surface is required, there are several strategies to minimize the impact noise. The best solution is to have a separate concrete slab floating on the structural slab by means of a cushioning material (Fig. 5.13b). If that is not an option, then use a suspended ceiling with sound-absorbing material and special spring hangers (Fig. 5.13b).

Although it is very problematic to quantify the effectiveness of a floor system in isolating impact noise, a rating system does exist. The **impact isolation class (IIC)** is a rating system for the ability of floor systems to isolate impact noise. The higher the IIC number, the better. For example, an exposed concrete slab has a value of 25, while a slab covered with a padded carpet has a value of 85.

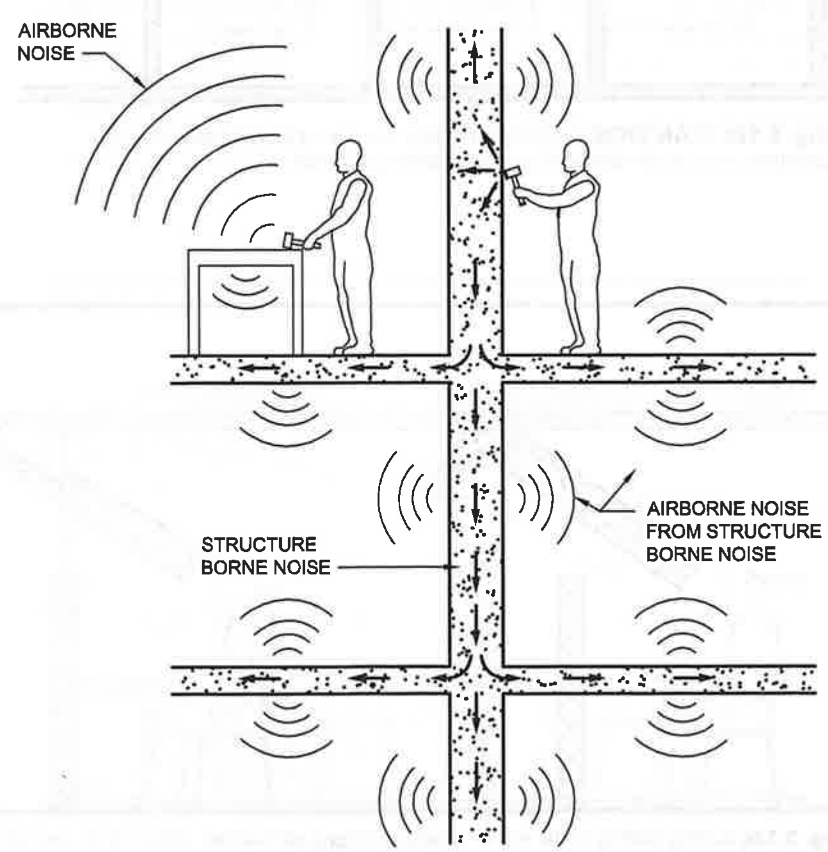


Fig. 5.13a Structure-borne sound will travel great distances within a rigid or monolithic structure. As the structure vibrates, it generates airborne noise far removed from where the noise was generated.

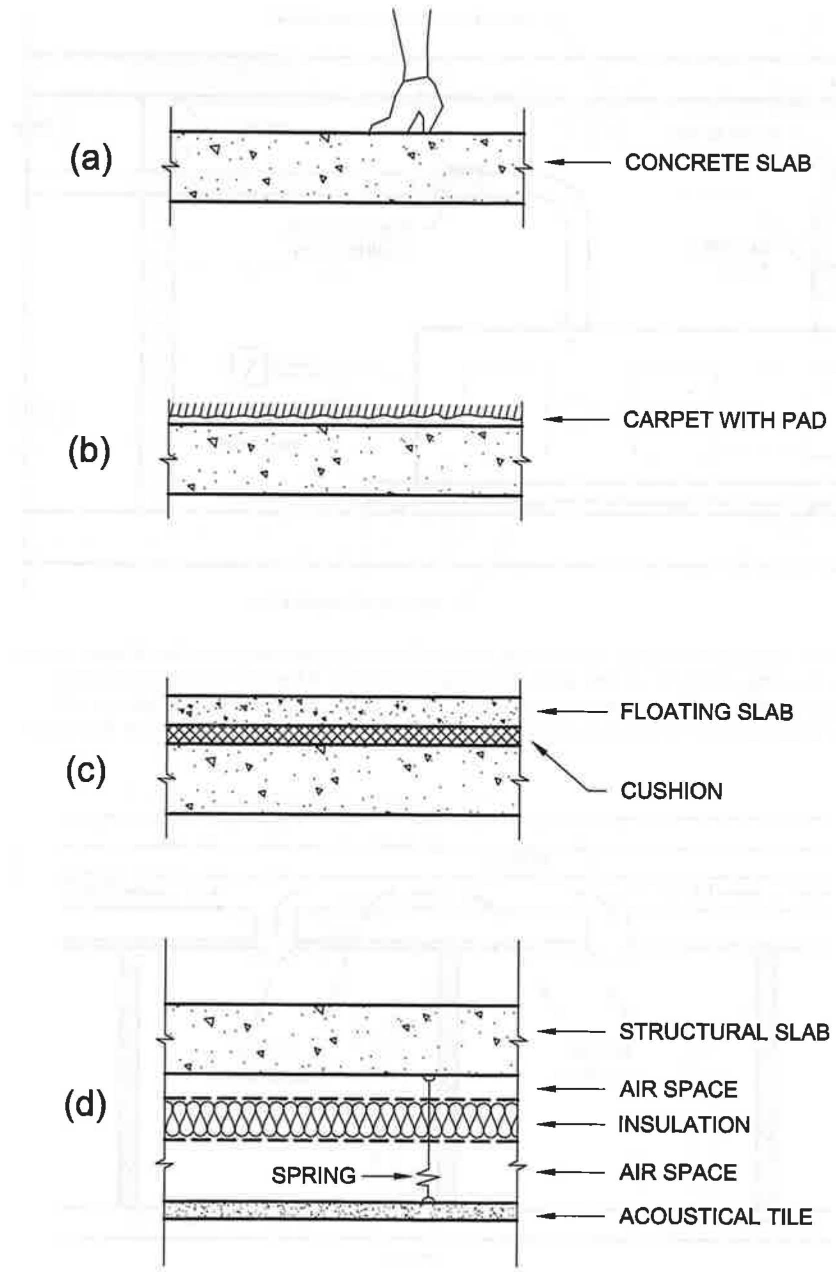


Fig. 5.13b Most structure-borne sounds in buildings come from the impact of shoes on a hard floor surface with the greatest impact on the space directly below the hard surface (a). The most common solution is to use carpeting or some other cushioning material (b). However, if a hard floor surface is required, a floating floor can be used, but it must be isolated not only from the structural slab underneath but also at the edges to prevent outflanking (c). If a floating floor is not an option, a sound-absorbing suspended ceiling will help the space below. However, the hangers must be of a type that will not transmit the noise (d).

5.14 MECHANICAL SYSTEMS NOISE CONTROL

To reduce noise from mechanical and electrical equipment, the following steps should be taken:

1. Noise prevention by specifying quiet equipment.
2. Locate the noisy equipment as far as possible from quiet areas.
3. Enclose the equipment in rooms with much sound-absorbing material and an enclosure with a low sound transmission.
4. The equipment should be isolated from the rest of the building by flexible connections to minimize structure-borne noise transmission (Fig. 5.14a).

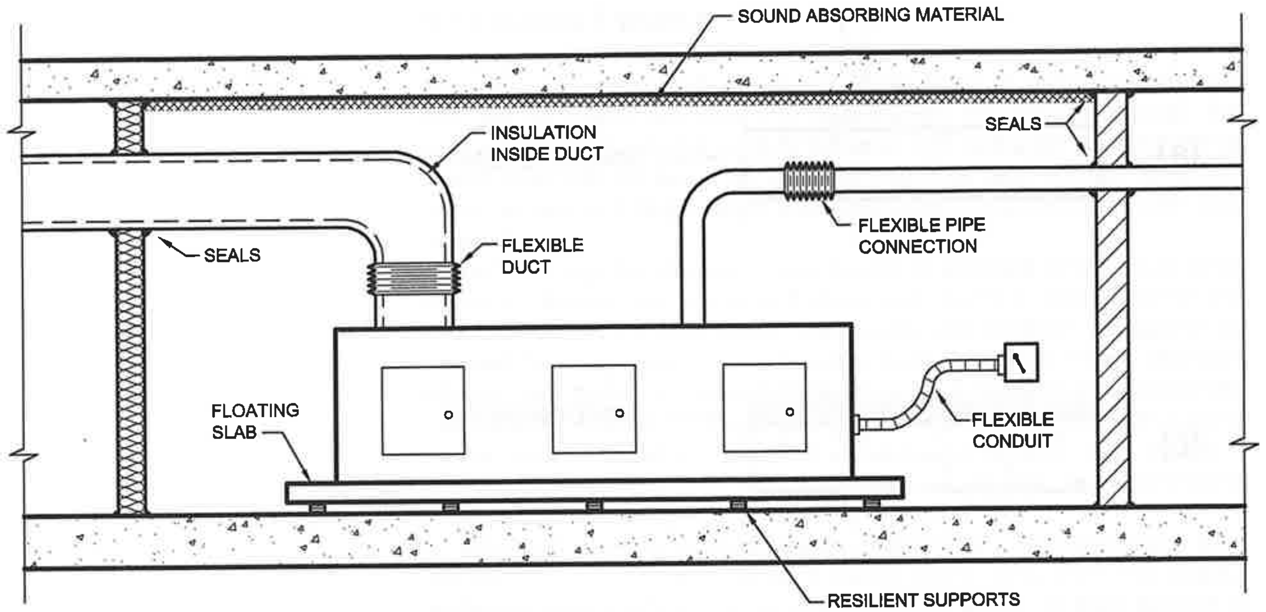


Fig. 5.14a Because even the least noisy mechanical equipment makes much noise, the mechanical equipment room should have sound-absorbing material on the ceiling and the walls. Also the ceiling, floor, and walls should be designed to have low sound transmission. Vibrating equipment is often mounted on a floating slab resting on a continuous cushion or on resilient supports such as springs. All ducts, pipes, and conduits must have a flexible section to prevent structure-borne sound transmission, and all penetrations of the room's envelope must be carefully sealed.

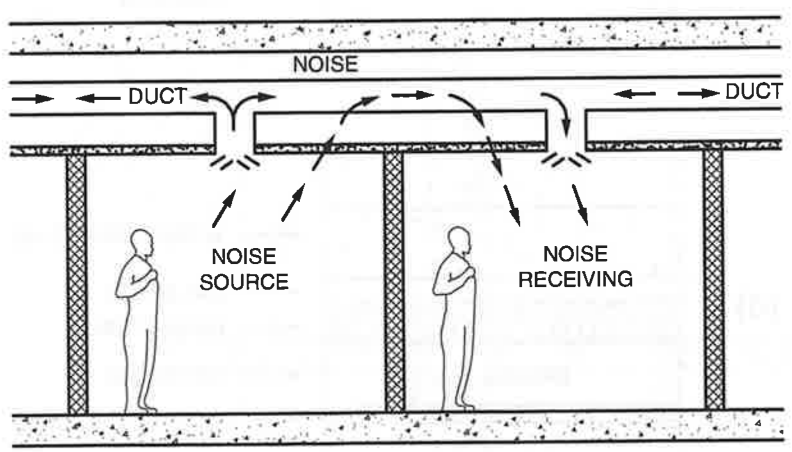


Fig. 5.14b To prevent noise from outflanking low-transmission walls through ducts, either have diffusers, registers, and grilles far apart or line the ductwork with sound-absorbing insulation. Note that all arrows in this diagram represent sound and not air flow.

Ducts are a major noise problem because they both transmit and generate noise. Structure-borne sound from the air handler can be effectively stopped by a small section of flexible duct (Fig. 5.14a). Ducts can also allow noise to outflank partitions (Fig. 5.14b). Airborne noise transmission can be minimized by either lining the ducts with sound-absorbing material or by the use of sound traps (Fig. 5.14c).

Besides transmitting noise, ducts also generate noise, if their design results in either a too high an air velocity or air turbulence. Thus, the duct system should be designed to have the lowest air velocity possible and to have gentle turns and smooth transitions (Fig. 5.14c). A duct system can either use small ducts at high velocity or large ducts at low velocity air flow. Although small ducts are initially less expensive, they require more energy

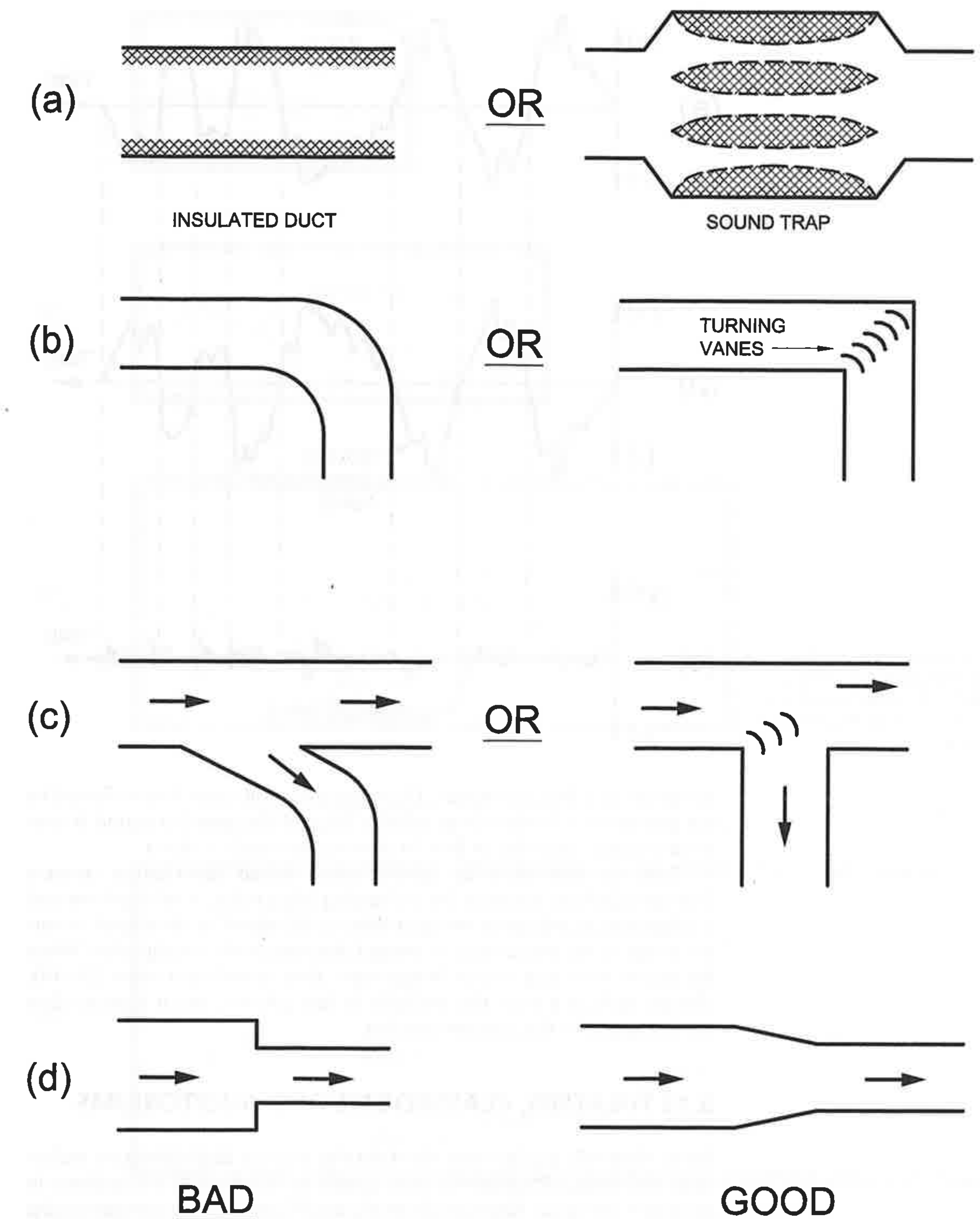


Fig. 5.14c To minimize duct noise, use the lowest velocity air flow possible. Also, line the ducts with sound-absorbing material or use noise traps (a). Since turbulence generates noise, use curved ducts, turning vanes, or gradual transitions to maintain laminar air flow (b, c, and d).

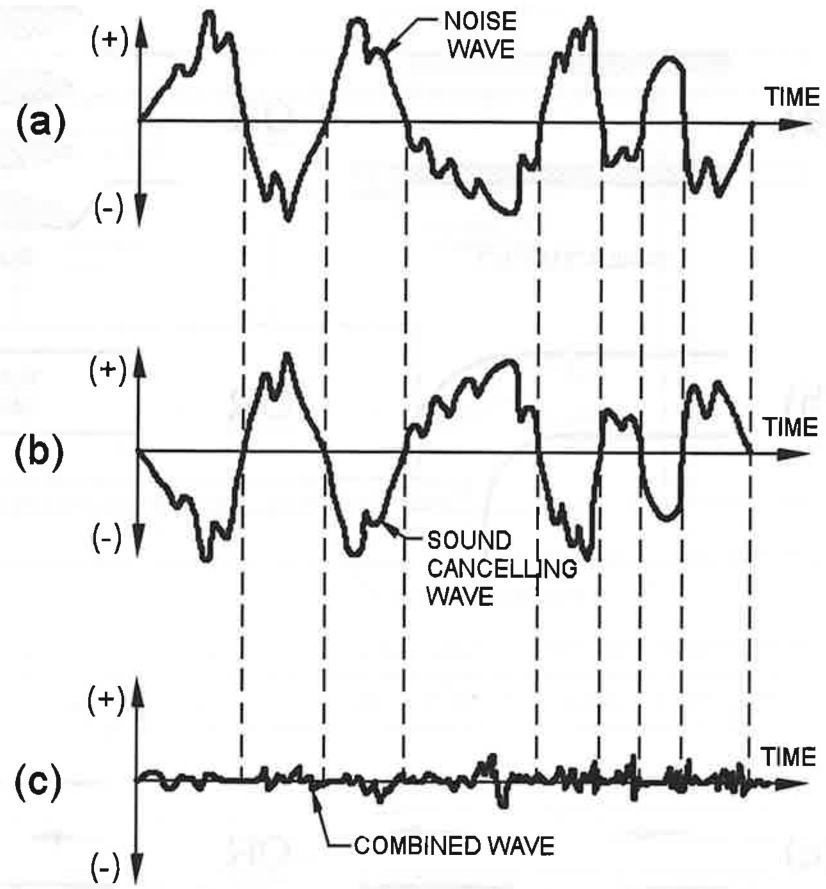


Fig. 5.14d Electronic noise canceling technology generates a mirror image of the noise wave. When the noise (a) and mirror image (b) waves meet, they mostly cancel each other out (c).

to operate and they are noisier. The transmission of noise is not affected by the direction of air flow or its velocity because the speed of sound is over 30 times faster than the air flow in ducts or the wind outdoors.

There are now electronic devices called **sound cancellation systems** that can eliminate some of the air handler (fan) noise. A microphone and loudspeaker are placed in the duct close to the source of the sound. A mirror image of the sound wave is created and sent to the loudspeaker. When the sound wave and mirror image meet, they cancel each other (5.14d). This technology is now also available in headphones, and it is most often used in airplanes for auditory comfort.

5.15 THEATERS, CLASSROOMS AND AUDITORIUMS

Before electronic amplification, the main challenge for large classroom, auditorium, and theater designers was creating sufficient loudness for the audience in the rear of the space. Although electronic amplification is very common today, it is still desirable to hear some types of music acoustically. Consequently, it is still necessary to design some types of spaces so that sufficient sound energy reaches the audience in the rear of the space without amplification.

Many of the strategies used by the ancient Greeks and Romans still hold. Raked (sloped) seating creates not only good sight lines but also good hearing lines (Fig. 5.15a). A hard reflecting surface behind the

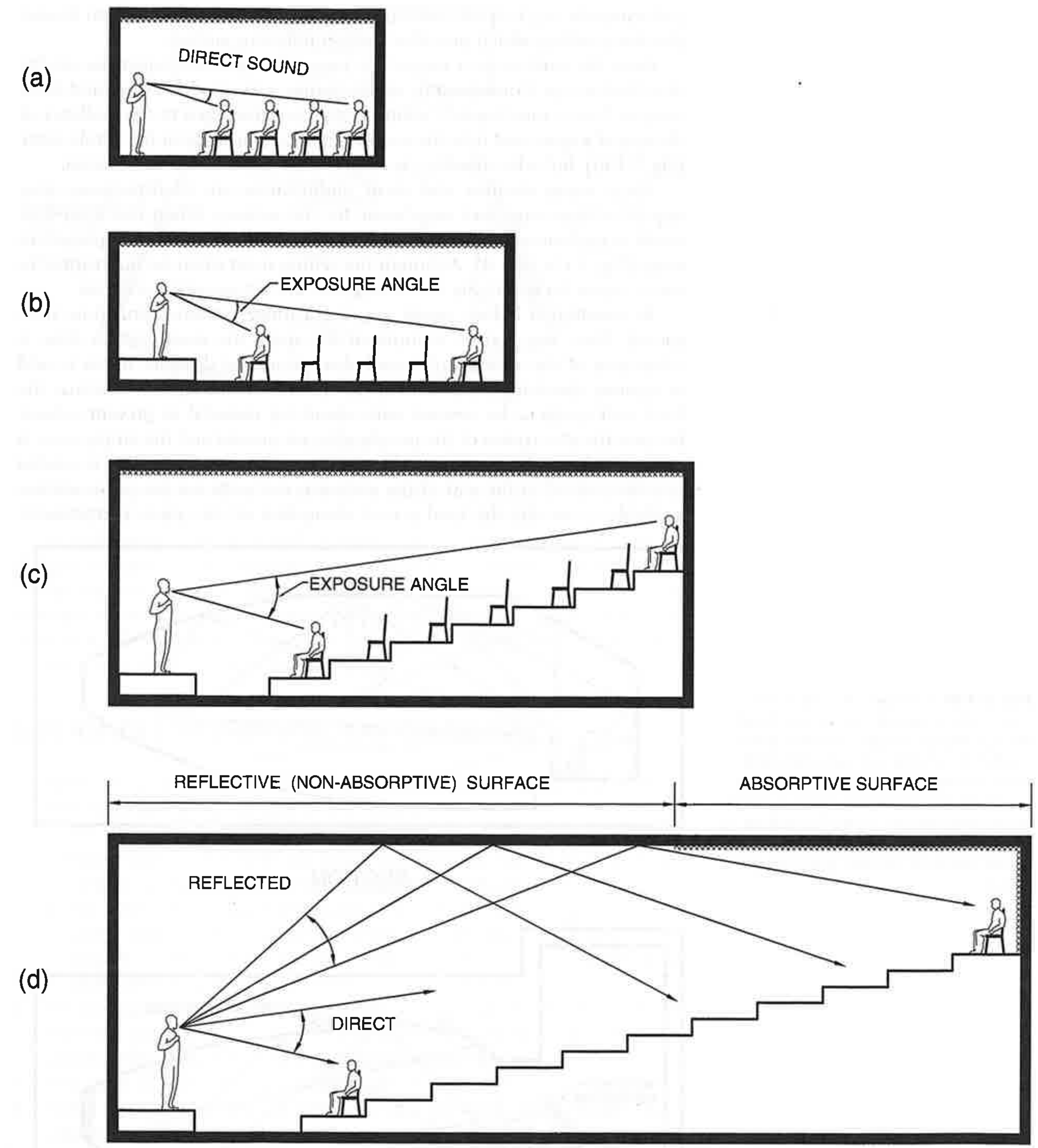


Fig. 5.15a As a room gets larger, not only is a given amount of sound energy spread over more people but also the people in the rear are further away (a and b). Thus, it is a challenge to supply enough sound to the rear of the audience. Stepping or sloping the floor not only improves the sight lines but also increases the exposure angle (c). In larger rooms, hard surfaces can be used to reflect more sound to the rear of the audience (d). To prevent echoes, the rear wall, and in very large rooms, the rear ceiling should be covered with sound-absorbing material.

performers is very helpful, and unlike the ancient theater, a modern theater also has a ceiling which provides another reflecting surface.

Since the surfaces in a theater are large, most sound frequencies can be described as rays. Consequently, ray diagrams can be used to design and demonstrate how a maximum of sound energy is transmitted to the audience at the rear of a space and how the sound is diffused throughout the whole space (Fig. 5.15b). Rules for drawing ray diagrams are given in the next section.

Since many theaters and most auditoriums are multipurpose, they require a large stage and stagehouse for the scenery. When live acoustical music is performed in such theaters, movable reflectors are often placed on stage (Fig. 5.15c and d). Although the ceiling must often be interrupted to create access for spotlights, the ceiling can still act as a good reflector.

As mentioned before, music requires a longer reverberation time than speech. Since for a given volume of the space the reverberation time is a function of the amount of sound absorption, the designer needs to add or remove absorbing material to adjust the reverberation time. Because the back wall needs to be covered with absorbing material to prevent echoes, because the absorption of the people who are present and the empty seats is only partially under the designer's control, and because the ceiling is needed to reflect sound to the rear of the audience, the walls are the prime surface available to modify the total sound absorption of the space. Furthermore,

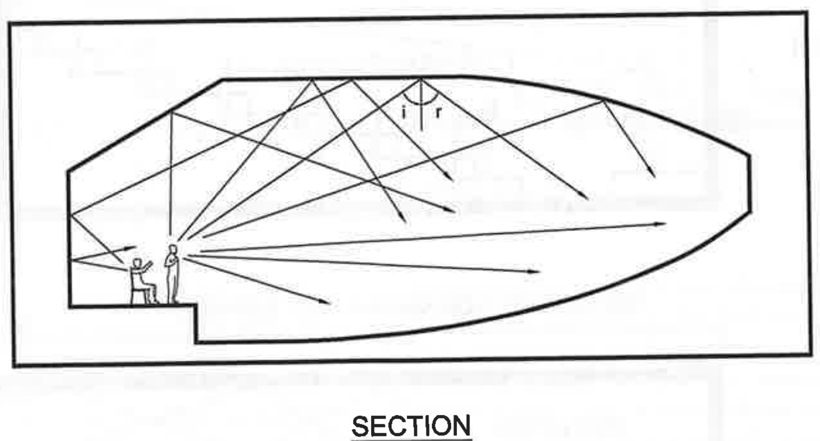


Fig. 5.15b The sound of speech and music can be represented as rays. To get enough sound energy to the rear of the theater, the ceiling and side walls need to be oriented in such a way that sound waves are reflected to the rear (i.e., angle of incidence equals angle of reflection). A graphical analysis using rays to represent sound waves can be used in the design process.

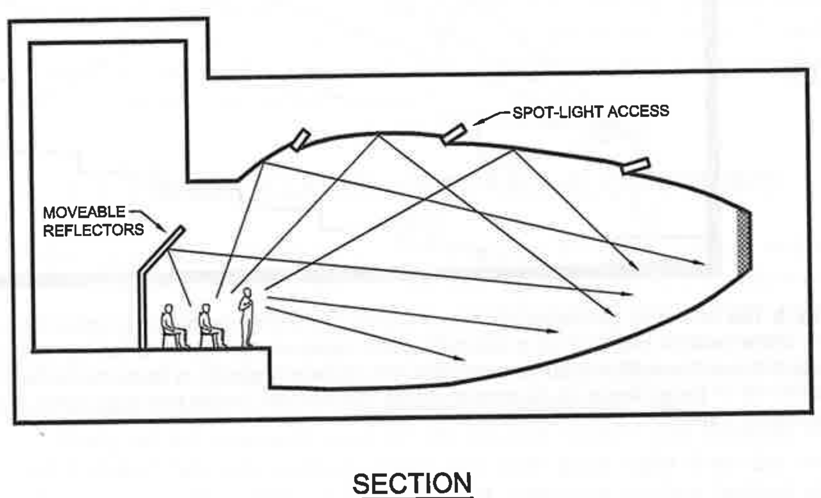


Fig. 5.15c Multipurpose theaters, with their large stages, often use movable reflectors because the stage wall is too far back to help when acoustic music is performed on stage. The ceiling design also gets more complicated because of the need for spotlights.

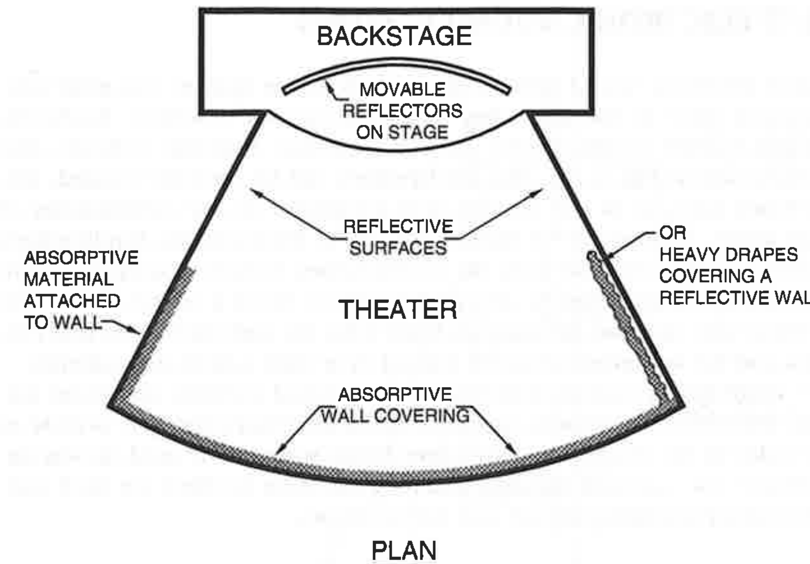


Fig. 5.15d To prevent echoes, the rear wall must be covered with absorbent material. Since the side walls near the stage are useful for reflecting sound to the rear of the audience, only the back portions of the side walls are available for sound-absorbing material to adjust the reverberation time.

only the rear of the side walls are usually available because the front of the side walls are also useful for reflecting sound toward the rear.

In multipurpose theaters and auditoriums the sound absorption can be designed to give a reverberation time somewhere between what is needed for speech and music. A more sophisticated solution is to have the wall's absorptivity be adjustable by such techniques as heavy movable drapes in front of a reflective wall, where open drapes increases the reflectivity, while closed drapes increase the absorptivity.

5.16 RULES FOR DRAWING RAY DIAGRAMS

1. Rays can only represent sound waves if the reflecting surface is large compared to the wavelength of the sound.
   a. *For speech* the longest wavelength is about 3 ft. (0.9 m) or 300 Hz. Since room dimensions are large compared to these very long wavelengths, speech sounds can always be represented by rays.
   b. *For music* the longest wavelength is about 15 ft. (4.4 m) or 70 Hz. Thus, rays can also represent music, except for the longer wavelengths when they reflect off small objects such as columns and small reflecting panels.
2. To keep speech and some types of music clear and crisp, the paths of reflected sounds should not be more than 33 ft. (10 m) longer than the direct paths. Otherwise echoes or partial echoes result.
3. The angle of reflection equals the angle of incidence.
4. Direct rays and rays after one reflection have the most sound energy. Thus, rays with multiple reflections should only be drawn to the second reflecting surface because the sound waves are then too weak to be important.
5. It is usually assumed that rays originate at a point. Since speakers and singers move and since music usually has more than one performer, several points of origin should be examined.
6. In a good design, the rays should not focus but should rather diffuse equally throughout the space.
7. Many rays should reach the rear of the space.

5.17 ELECTRONIC SOUND SYSTEMS

Since electronic sound systems are now of higher quality and more economical than in the past, they have become very common. Electronic sound systems consist of four parts: microphone, amplifier, controls, and loudspeakers (Fig. 5.17). The loudspeakers can be centrally located, distributed (usually in the ceiling), seat integrated, or any combination of the above. To prevent the horrible squeal of feedback, the loudspeakers must be sufficiently far from the microphones. Because loudspeakers are quite large, space must be allocated for them. Since it is critical that the person who operates the controls hears what the audience hears, that person and her equipment must be located in or right next to the audience.

Large spaces such as shopping malls, railroad stations, and some arenas with reflective surfaces must have many distributed speakers as close as possible to the listeners. If only a few distant speakers are used, as was traditional, the powerful speakers and long distances involved are ideal conditions for generating echoes and partial echoes.

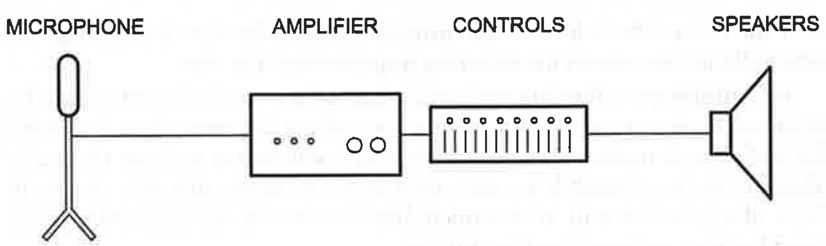


Fig. 5.17 An electronic sound system consists of four essential parts: microphone, amplifier, controls, and loudspeakers.

5.18 NOISE OUTDOORS

Cars and trucks are the main sources of noise outdoors, and that noise is generated in four different ways: engine/exhaust, tires, air motion, and horns. Laws and ordinances can reduce noise significantly by the following measures: requiring good mufflers, limiting speeds in quiet neighborhoods, and limiting the use of the horn. For example, the City of Vienna, Austria forbids the use of a car horn except in a real emergency.

When these measures are not enough, the following strategies can be used: Locate the building as far as possible from a highway or busy street. Minimize the windows facing the source of noise. Avoid operable windows or facades facing the noise source. Avoid reflecting the noise into the windows as is common when buildings with balconies border a noisy street (Fig. 5.18a). In that case, cover the underside of the balconies with sound-absorbing material, and use concrete or glass parapets instead of open railings. If these measures are not available or relevant, create a sound barrier either close to the sound or to the receiver.

Noise barriers along highways have become quite common (Fig. 5.18b). These barriers are quite effective for high-frequency sounds, because such waves tend to diffract very little from a straight line and create a large sound shadow. Unfortunately, low-frequency sounds tend to diffract significantly over the barriers, creating small sound shadows. Thus barriers should be as high as possible, and they should be as close as possible to the source of the noise. Also they should not have gaps or holes through which sound can bypass the barrier. If the highway or exit ramps are narrow the noise can be

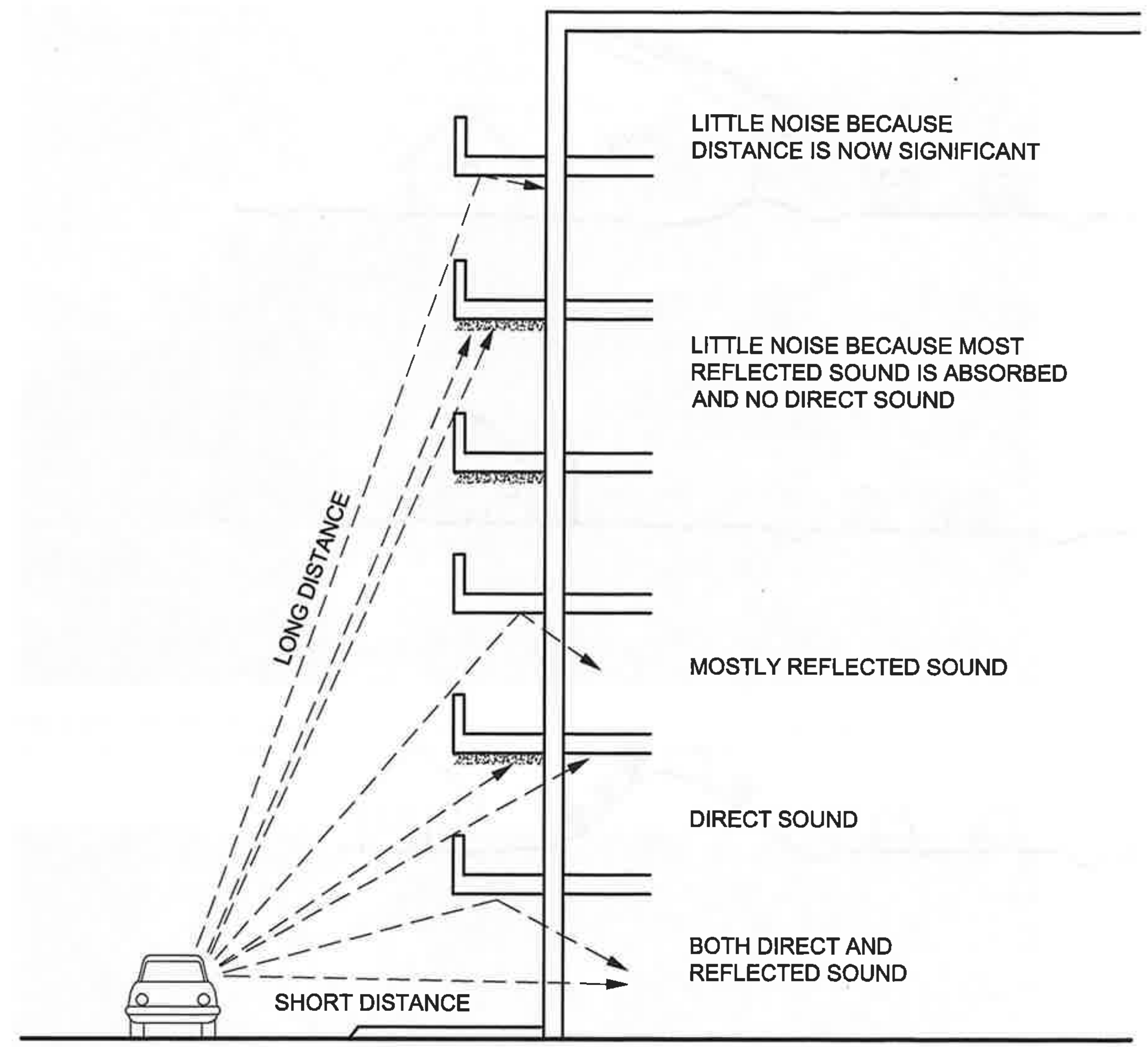


Fig. 5.18a Balconies both block and reflect noise into windows. Solid parapets and the addition of sound-absorbing material on the underside of the balconies are very helpful.

amplified by being reflected back and forth. Thus, in densely populated areas, sound-absorbing materials should be added to the barriers (Fig. 5.18c).

A noise barrier can also be made of high earth berms or a deep layer of trees. Although trees can block the view of the highway quite well, they are too porous to stop much sound. Thus, it takes about 100 ft. (30 m) of evergreen trees to reduce the noise level by 10 dB (Fig. 5.18b). One of the reasons for using earth sheltered architecture is the protection against noise. Thus, earth berms can also shelter buildings from noise, heat, cold, and storms (Fig. 5.18d). If none of the above techniques is available, then have the building face inward, as Frank Lloyd Wright did with his Larkin office building in Buffalo, New York. Since the building site was next to a noisy railyard, Wright decided to have the office spaces surround a large covered atrium (Fig. 5.18e). For small buildings, high garden walls are sometimes an alternative to atria.

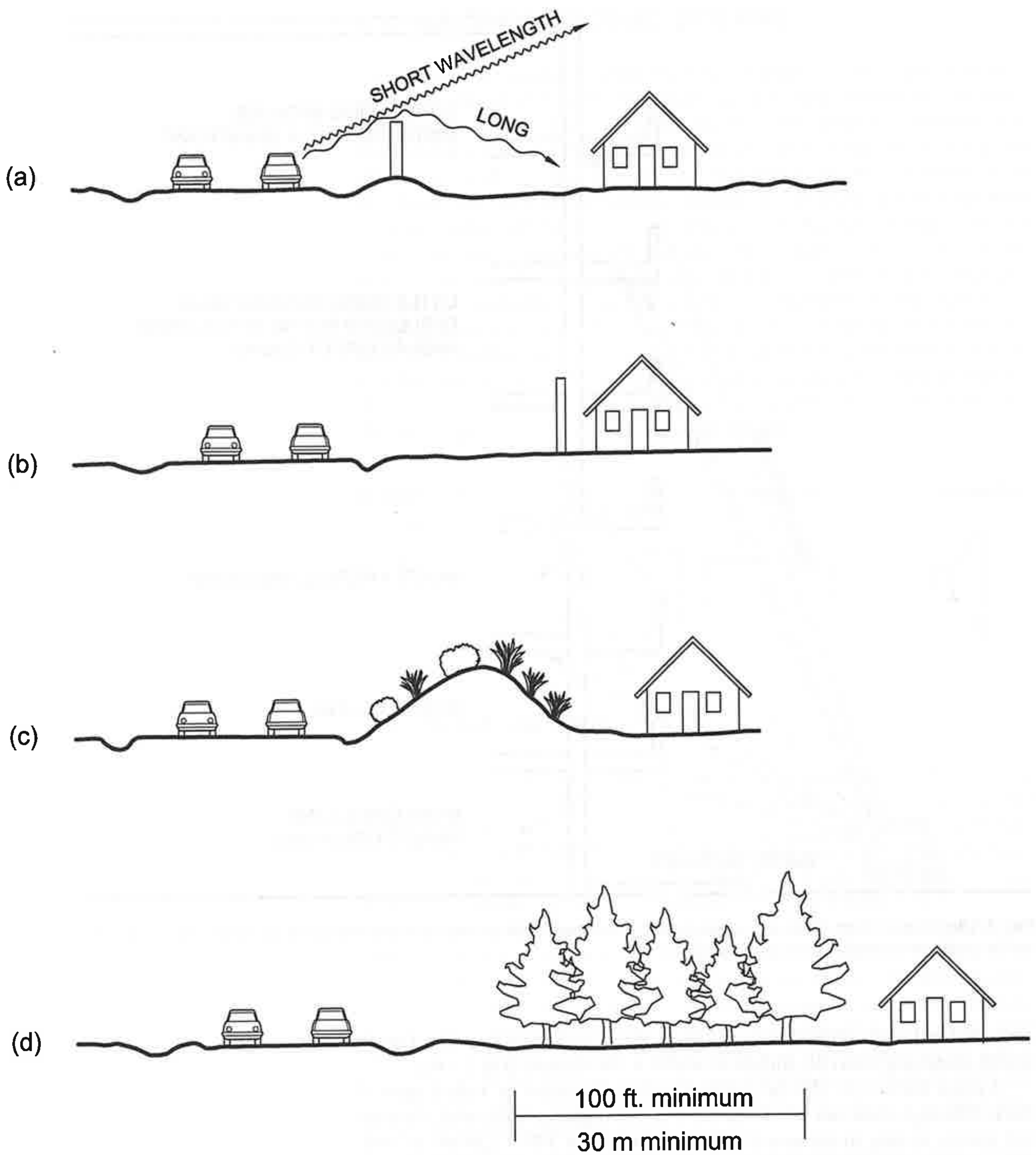


Fig. 5.18b Sound barriers along highways are becoming common in densely populated areas. The barrier is usually close to the source but could also be close to the receiver. When room permits, an earth berm is very effective. Trees can only be used in less populated areas, because it takes at least 100 ft. (30 m) to reduce the sound by one half.

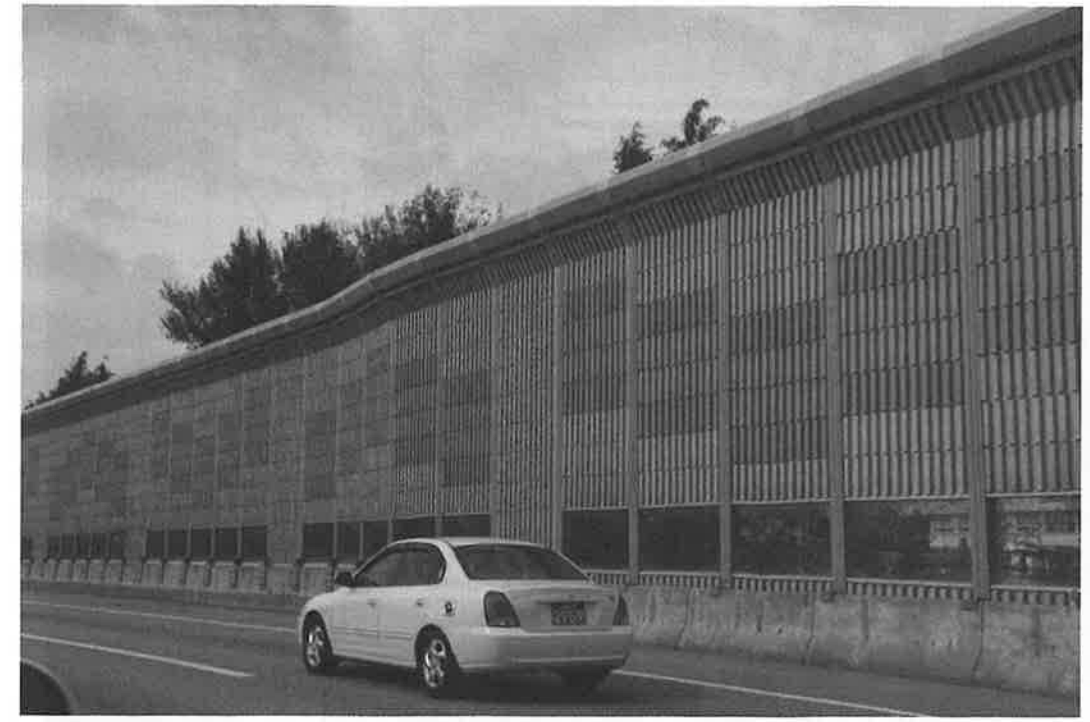


Fig. 5.18c In dense urban areas where reflected sound would be a problem, the noise barriers should be covered with sound-absorbing materials. Instead of being eyesores, barriers can be decorative as in this Korean example.

Fig. 5.18d Earth-sheltered buildings protect against extreme temperatures, extreme storms, and noise.

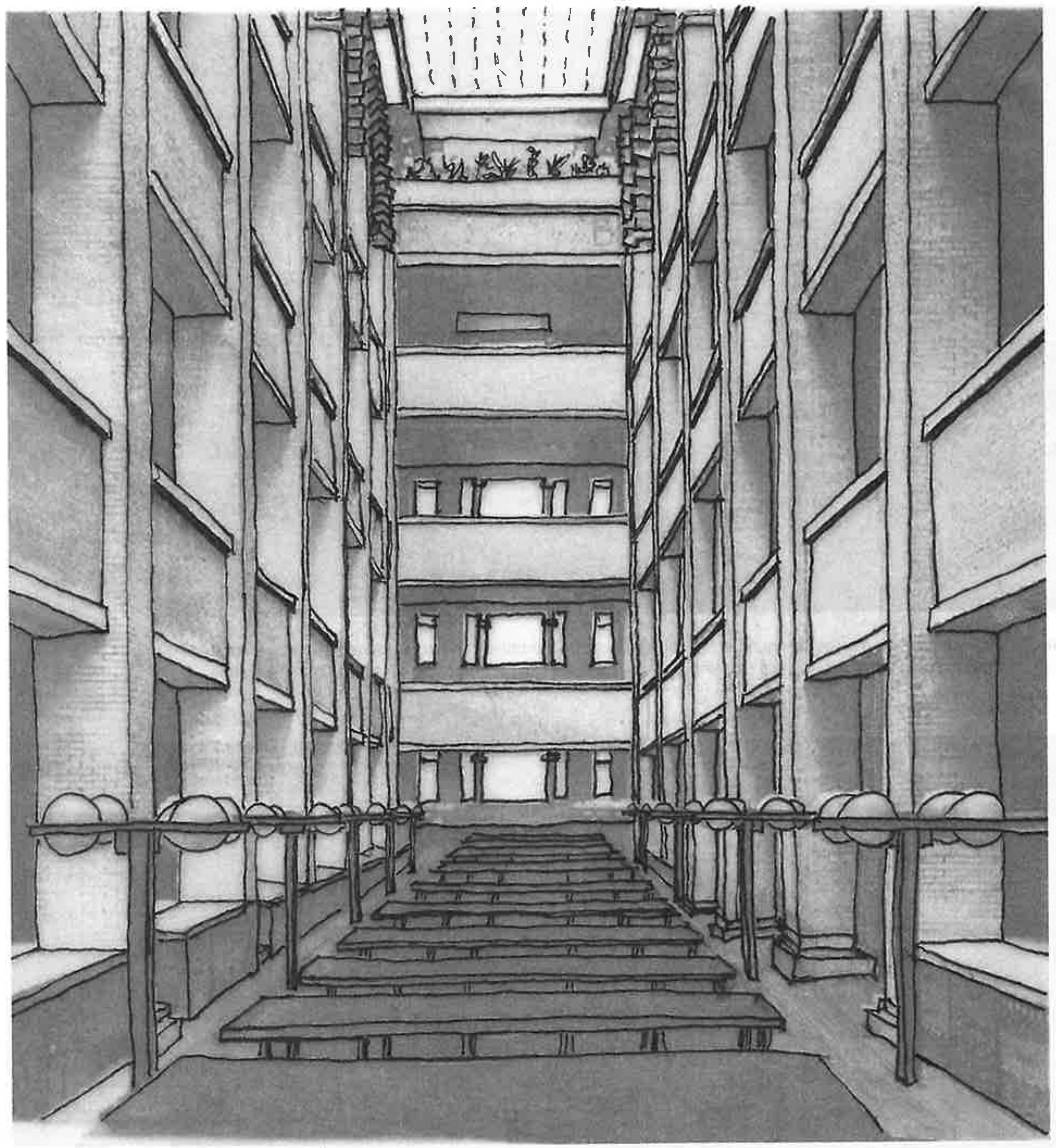


Fig. 5.18e Frank Lloyd Wright designed the Larkin Building in Buffalo to be inward looking because of the noisy location. All offices faced a full height atrium for views and daylighting.

5.19 CONCLUSION

Table 5.18 is a summary of both the acronyms explained in this chapter and a few additional ones in the field of architectural acoustics.

Table 5.18 Acoustical Rating Systems

Acronym	Name	Function
CAC	Ceiling Attenuation Class	For ceiling tiles and systems to minimize room to room noise outflanking through common plenum.
IIC	Impact Isolation Class	To minimize impact generated noise from passing through a floor/ceiling system to the room below.
NC	Noise Criteria	To define the appropriate noise level for various types of spaces.
NRC	Noise Reduction Coefficient	To rate the sound absorption ability of a material over a *range* of common frequencies. Thus, it is an average of SAC values.
OITC	Outdoor Indoor Transmission Class	To reduce noise transmission through building envelopes. Includes lower frequencies that are generated by planes, trains, trucks, and cars.
RC	Room Criteria	Improves on the noise criteria (NC) by including both higher and lower frequencies. Mechanical engineers prefer the RC over the NC.
SAC	Sound Absorption Coefficient	To rate the sound absorption ability of a material for a *specific* frequency.
SPP	Speech Privacy Potential	To predict the degree of privacy achieved from one area to another. It considers both the acceptable noise level and the transmitted noise.
STC	Sound Transmission Class	To rate the effectiveness of a wall or floor at reducing sound transmission over a *range* of common frequencies.
TL	Transmission Loss	To rate the effectiveness of a wall or floor at reducing sound transmission for a *specific* frequency.

Although acoustics is often the stepchild of architectural design, it deserves more attention than it usually gets. Sometimes the acoustics of a building are bad enough that the owner or occupants complain. More often bad acoustics reduce the efficiency and the enjoyment of a building. In either case, a basic knowledge of acoustics, as presented here, can ensure an acoustically successful design for ordinary spaces. Although the acoustical design of a theater may require an acoustical consultant, most buildings can be successfully designed by an informed architect.

Resources

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