Basic Acoustics in Concert Hall Architecture

Think of the concert hall as if it were instrument played by the sounds produced by musicians. For a successful instrument, an acoustician or architect needs to design space with paramount respect to the sound waves that will perform within it.

To understand how architects and acousticians design concert halls, one must understand some basic acoustics. The central function of acoustic architecture is to create a space that uses the natural properties of sound to distribute a source sound to audiences and performers in the most accurate and undisturbed way possible. Sound goes through three phases before a person can experience it in a concert hall: a sound originates at a source, travels through the air, and is received by a listener. Most of the following acoustic phenomena were known before the beginning of acoustic architecture in 1900, yet many of them only began to be considered directly in acoustic architecture in the recent past.

Phase 1: the sound source

The first important element of good acoustics is good sound production, which begins with the musician’s technique, projection, and instrument. The acoustician plays
an important role in sound production. The acoustics of a performance space will determine what the musician can hear on stage, and that has an impact on his or her comfort and confidence. Ashley Goodall, a consultant with Artec acoustic consultants, wrote that “the first rule of acoustics is that, however good the room, you’re only going to hear as good a performance as is given.”¹ In this sense, it is the acoustician’s priority to give performers the best possible environment in which to hear themselves and others in the ensemble. Because of the sound-absorptive qualities a full audience has, halls tend to sound significantly different with an audience than without; acousticians try, as well as physics allows, to create a consistency of sound for both empty rehearsal conditions and full-hall concert settings.

![Figure 1: Longitudinal wave (left) and transverse wave (right). In the longitudinal wave high-density areas are in compression and low-density areas are in rarefaction.](image)

Beyond the musician, acousticians need to be aware of the general properties of sound. Whether beautiful music or garbage trucks, sound is the movement of energy through a medium. For simplicity’s sake, we visualize this movement as a wave moving through air and building materials. In a sound wave,² energy makes particles vacillate in wave motion, creating areas of high-density compression and low-density rarefaction in

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² *Italics* indicates a common term used in acoustics or architecture.
the form of a longitudinal wave (figure 1, left).

Although sound travels as a longitudinal wave, we almost always visualize sound waves as transverse waves (figure 1, right) like those seen on oscilloscopes or waveform displays.

Waves move energy over distances, and the distance a disturbance travels during a complete vibration of a particle is known as the wavelength. The wavelength is also the distance between identical parts of consecutive waves. Acousticians need to consider wavelengths specifically when working with interference and resonance, to be discussed below.

Wavelength relates directly to the quality of sound people perceive: frequency. The frequency of a sound wave is calculated by dividing the speed of sound by the wavelength, thereby giving the number of cycles or wave peaks that pass during a time period. Most frequency measurements are given in Hertz (Hz), where one Hz = one cycle per second. For simple musical sounds, frequency is mapped onto pitch.

For a sense of the relationship between frequency and wavelength, imagine waves passing through room temperature air. A 100 Hz wave (about G2) has a wavelength just over eleven feet while a 500 Hz wave (a sharp B4) is only about two-feet-three-inches long.

Not only may sounds differ in frequency, but they may also differ in timbre. Timbre refers to the combined qualities of a sound that distinguish it from other sounds of the same pitch. This quality is most often associated with complex sounds.

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5 On a transverse wave, this could mean the distance between two consecutive peaks.
6 For example, we perceive a sine wave at 440 Hz as the pitch A.
7 G2 refers to the second lowest G on the piano (or the twenty-third key counting from the left). In this notation, C4 is middle C (261.63 Hz).
Part I, Chapter 2

complex sounds, frequency does not easily map to pitch because multiple frequencies occur within the same sound. If these multiple frequencies follow the overtone series\(^9\), we still perceive the sounds as pitched, but if these frequencies do not fit into this structure we perceive them as *noise*. Flutes, trumpets, and garbage trucks all sound different to us because each has a different mixture of multiple frequencies, thereby resulting in our perception of different timbres. Acousticians are aware of timbre because it is essential for a concert hall to accurately represent the complex sounds of all instruments.

Because sound waves are changes in particle density that result from an infusion of energy, the more energy one adds to the system, the greater the change in particle density. These changes in density constitute the sound pressure, *amplitude*, or *level* of your sound wave. The unit typically used for sound level is the *decibel* (dB). A dB is one-tenth of a bel, the unit named after Alexander Graham Bell that corresponds to a multiple of ten of the threshold of hearing.\(^10\) The decibel scale is logarithmic, meaning that a ten dB increase in sound pressure will double the perceived intensity, and likewise, a twenty dB increase results in a quadrupling of intensity. *Sound intensity* is another way of categorizing pressure; it is a relative description of sound level defined as the pressure difference between the rarefied and compressed air.\(^11\)

\(^9\) A series of tones whose frequencies are integral multiples of a *fundamental* frequency (the frequency a listener perceives). It is also known as a *harmonic series* or individually as *harmonics*.


The dB is defined mathematically as a sound pressure level (SPL):

\[
\text{SPL} = 20 \times \log(\frac{P}{\text{Pref}}) \text{ dB}
\]

Where \(P\) is the measured acoustic pressure and \(\text{Pref}\) is the reference pressure of \(2 \times 10^{-5}\) Pascals (Pa)\(^10\)


The acoustician and architect play key roles in concert hall performance before the sound even leaves the musician. A designer needs to be aware of the simple properties of sound to use them to create a good acoustic hall.

**Phase 2: the transmission path**

Once the sound energy has left the source, it travels through the air and building materials in the architectural space. The speed it travels at is related to the elasticity and density of the medium it travels through.\(^\text{12}\) For the purposes of architecture, we are most concerned with the speed of sound in air at room temperature (around twenty degrees Celsius). This speed is 343 meters per second (m/s) or 1,125 feet per second.\(^\text{13}\)

As sound travels away from its source, it spreads into the medium. This *diffusion* is both a blessing and a curse for acoustic architecture. Diffusing musical sound within a room blends to create a desired *ensemble* sound. However, the *inverse square law*, which states that each time the distance sound travels doubles, the sound level decreases by six dB,\(^\text{14}\) puts a limit on how far an audience member can be from the stage and still hear enough of the direct (un-reflected) sound.

Although the simplification is not perfect, sound wave movement is easiest to visualize geometrically with each wave as a directional vector. Within this paradigm, you may treat sound waves as you would light waves, and there are many analogies.

First, as with light, all surfaces *reflect* sound to some degree. When the sound reflects, the angle of reflection equals the angle of incidence. Reflections are essential to

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\(^\text{12}\) Floyd Rowe Watson, *Acoustics of Buildings; including acoustics of auditoriums and sound-proofing of rooms*, 3rd ed. (New York, 1941), p. 4


\(^\text{14}\) Op. cit., p. 11
indoor (and many outdoor) listening experiences. As sounds reflect around a space, they reach the listener at different times from different places, thus creating reverberation and other effects that give each space its own sound signature.

Figure 2: Concave surfaces (left) focus sound while convex surfaces (right) diffuse sound.

Acousticians must take wavelengths into consideration when dealing with reflective surfaces because the smallest dimension of a reflective surface must be at least the size of a frequency’s wavelength for that frequency to be reflected. To diffuse a frequency, the reflecting surface must be convex (figure 2, right) and longer in the curved dimension than one-half the wavelength of that frequency. Reflections from concave (figure 2, left) surfaces focus to a point like a radar dish; this effect creates acoustic hot-spots and dead-spots in concert halls. For this reason, acousticians use reflections to diffuse the sound as much as possible rather than focus it.

Not all of the sound wave reflects back into the space; a certain amount of absorption takes place when sound encounters a material. The interplay between sound reflections and absorption is the most basic consideration in architectural acoustics. The

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15 Burris-Meyer, loc. cit.
designer must be aware of three elements when composing a space with regard to reflection and absorption: the treatment of walls and surfaces, the contents of the room, and the transmission of the air itself in the space.\(^{16}\)

Wallace Clement Sabine (1868-1919) pioneered modern architectural acoustics with his study of the effects absorbent materials had on a room’s reverberation time. His work, published in 1900, was based on his experiences preparing for and acting as acoustic consultant for Boston Symphony Hall, completed in the same year; that hall stands as the first concert hall designed with respect to modern acoustic architecture.\(^{17}\)

Sabine’s earliest work centered around predicting the reverberant qualities of a space by analyzing the space’s size against its absorptive qualities. He determined the absorptive qualities of a room using the total surface area of a material and the absorptive quality of that material. After some experimentation, Sabine decided to measure material absorption in open window units (later to be called Sabins); the unit functions as a coefficient for the total surface area of a material. The product is then the area of open window (or 100% absorption) required to absorb the same amount of sound energy as the total surface area of the material. For example, wood-sheathing (hard pine) has absorptive value of 0.061 Sabins. If a hall contains forty square meters of wood-sheathing, its total absorption (A) would be: $A = 0.061 \text{ Sabins} \times 40 \text{ m}^2$, solved to: $A = 2.44 \text{ m}^2$ Sabins. In other words, the wood-sheathing has the equivalent absorption of 2.44 square meters of open window. Absorption plays a critical role in concert hall acoustics on every scale, from the structural materials of the building to the absorptive qualities of the audience members.

\(^{17}\) Emily Thompson, *The Soundscape of Modernity* (Cambridge, MA, 2002), pp. 13-57
Diffraction, as with light, is the phenomenon of sound waves apparently bending around partial barrier walls.\(^\text{18}\) Diffraction happens when the size of the wave is equal to or greater than the dimensions of the barrier surface; therefore, it is mostly a characteristic of middle and lower frequency sounds. Along with diffraction, refraction of sound works as it does with light; when a wave moves from one medium to another with a different density, the direction of the wave changes corresponding to the difference in density.

In “Reverberation,” Sabine groups interference and resonance as the second consideration of acoustic design: “the distortion of complex sounds.”\(^\text{19}\) The results of these properties have massive impacts on the acoustic experience in a space.

Because sound energy travels as a wave of compressed and rarefied particles in a medium, waves traveling in the same medium will either reinforce or oppose each other. When reflections are such that waves frequently map onto one another, it creates pockets of intensity and comparative silence known as constructive and destructive interference. Likewise, these effects may take place for only certain elements of the overtone series, creating changes in the timbre of a sound as your location in a space changes.\(^\text{20}\)

Although people often use resonance to refer to positive qualities within an acoustic space, most often an acoustician will have carefully worked to avoid resonances. Resonance happens when a frequency of sound matches the natural frequency of the space, causing sympathetic vibration and constructive interference. This results in those

\(^{18}\) Cowan, op. cit., p. 11
\(^{20}\) Op. cit., p. 5-9
natural frequencies to be more intense than other frequencies, causing masking,\textsuperscript{21} changes in timbre, and other unwanted acoustic distortions.

**Phase 3: receiving the sound**

Even the most perfect acoustic space needs a receiver to make all the effort worthwhile. People work well as recipients of sound energy, but they have specific attributes of which acousticians need to be aware. With perfect hearing, a person can hear waves between twenty and 20,000 Hz; frequencies below this threshold are called \textit{infrasonic}, those above it are called \textit{ultrasonic}. Our hearing works when the air pressure change is greater than $2\times10^{-5}$ Pa (zero dB) but below twenty Pa (the threshold of pain, 120 dB).\textsuperscript{22} We also have evolved to respond best to frequencies used in speech and baby cries. Therefore, the \textit{loudness} we perceive is not synonymous with the pressure or intensity of sound. This frequency range where waves of the same pressure sound the loudest is between 500 Hz and 6,000 Hz with the height of sensitivity between 3,000 and 4,000 Hz.\textsuperscript{23} Although there are many ambiguities in human neurology pertaining to sound, we currently believe our inner ears perform a Fourier analysis on the sounds that reach the tympanic membrane (eardrum) then sends that analyzed signal to our brain.\textsuperscript{24}

Another acoustic consideration of human hearing is our ability to discriminate sound locations on the horizontal plane through wave phase differences (\textit{interaural time})

\textsuperscript{21} Masking is “when one sound may get in the way of our perception of another. A very loud sound may prevent us from hearing quieter sounds. Loud sounds in particular frequency bands may prevent us from hearing those frequencies as constituents of another sound.” Trevor Wishart, \textit{On Sonic Art} (Amsterdam, 1998), p. 152
\textsuperscript{22} Cowan, op. cit., p. 30
\textsuperscript{24} Action potentials do not map directly to frequency neurologically because neurons cannot fire fast enough to represent higher frequencies (a single action potential takes nearly 2 milliseconds), so they use the \textit{volley principle} to share split the frequency between a population of neurons. Bear, op. cit., p. 295.
delay), *interaural intensity differences*, and the resonant qualities of our own pinna and ear canal.\textsuperscript{25} Because we are good sound locators, we feel uneasy when a sound does not come from where we expect, often caused by unexpected reflections.

Because of our keen sense of sound localization, it is important that each audience member in a concert hall receive direct sound from the performance. The simplest means of achieving that is by giving each seat an unobstructed view of the performers, thus allowing sound waves to have an uninterrupted journey to the listener. In consideration of direct sound, an acoustician needs to be aware of *sound shadows*, a phenomenon underneath long balconies that are not raised at least half the length of the balcony.\textsuperscript{26}

After a person has received the direct sound, he or she is bombarded with the sounds that have reflected off other surfaces in the hall. This results in the initial sound having a decaying tail known as *reverberation*. Reverberation is perhaps the most popular subject of acoustic architecture. It was the basis of Sabine’s pioneering article, and since then it has been the acoustician’s most reliable tool for forming sonic spaces. Reverberation is how people perceive reflected sounds in a space as the reflections’ energies decrease, and spaces that have no reverberation feel dead and unnatural. Reverberation is quantified by the amount of time it takes for a sound to decrease in sound pressure by sixty dB after production of the sound has stopped.\textsuperscript{27} In a room with good acoustics, the decay will be smooth.\textsuperscript{28}

Fortunately for acousticians, Sabine determined that reverberation decay time in a space is nearly constant in any location in the space, and regardless of where the sound

\begin{itemize}
\item \textsuperscript{25}Bear, op. cit., pp. 297-301
\item \textsuperscript{26}Doelle, op. cit., p. 61
\item \textsuperscript{27}Op. cit., p. 26
\item \textsuperscript{28}Fritz Ingerslev, *Acoustics in Modern Building Practice* (London, 1952), p. 38
\end{itemize}
originates. After that realization, he determined a formula to calculate, to a useful accuracy, the reverberation time of any space by using the space’s volume and its materials’ absorptive qualities:

\[ RT = \frac{(0.05V)}{(A+xV)} \]

Here, we see where Sabine’s absorption calculations come into play. The total absorption is calculated by finding the sum of all the individual surface materials’ absorptions:

\[ A = S_1 \cdot a_1 + S_2 \cdot a_2 + S_3 \cdot a_3 + \ldots + S_n \cdot a_n \]

Although there are many opinions on what reverberation times should be in spaces, most agree that concert halls should have longer reverberation times than rooms designed to be for speaking. Hope Bagenal suggests that through the above formula, the ideal reverberation time for a concert hall with a full audience should be between 1.6 and two seconds; however, opinions do vary.

*Echo* occurs in music when a minimum interval of one-tenth of a second passes between the perception of a direct and reflected sounds. Echo, along with interference, is considered one of the most serious acoustic distortions a space can have.

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29 W.C. Sabine, op. cit., pp. 17-18
30 RT=reverb time, sec; V=room vol., cu ft.; A=total absorption, sq ft sabins; x=air absorption coefficient
Metric: RT=(0.16V/(A+xV)
31 Hope Bagenal, *Practical acoustics and planning against noise* (Brooklyn, 1942), p. 90
32 Doelle, op. cit., p. 58