Architectural Acoustics

Among the primary considerations for a performing arts facility are the acoustical properties of the performance hall. Listener enjoyment almost always requires a room that has no noise infiltration from outside, nearly silent mechanical systems, and a carefully controlled balance between the direct sound from the performers, sound reflections from nearby surfaces, and overall sound reverberation. The contemporary professional field of architectural acoustics involves engineering design principles that must be placed in the context of multiple and often conflicting constraints.

Historical Notes

Dramatic theater dating from the edge of recorded history required spoken word audibility for an audience of several hundred to over a thousand. Acoustical engineering principles were not yet applied in any systematic manner. Roofless amphitheater designs, such as The Globe Theatre in London, appear to have utilized multilevel galleries to bring the audience relatively close to the stage. Performances in such open spaces required the actors to use exaggerated vocal effort and dramatic gestures to convey meaning.

Large cathedrals and other worship spaces from the 9th and 10th centuries had interior surfaces of stone, tile, and hard wood. Such surfaces are efficient at reflecting sound waves, resulting in highly reverberant acoustical properties. Music composed for such reverberant spaces had to exploit the acoustical environment, resulting in styles such as Gregorian chant and other choral works through the late Renaissance (e.g., Palestrina), that favored vowel sounds over enunciation for choral music. The musical composition style of major organ works for use in highly reverberant cathedrals also had to reflect the sonic properties. The pipe organ provided sufficient acoustical power and sustained sound production to fill the space, but reverberation limited the composers' use of rhythmic complexity and subtlety.

Baroque solo works, and also the chamber music of Haydn, Mozart, and others, utilized a small number of musicians performing music for small gatherings in a home or some other secular setting. The small "chamber" setting came with minimal reverberation. Composers took advantage of the intimate performance qualities to use rhythmic and harmonic intricacy that were not feasible in a highly reverberant space.

By the 18th century, the loudness and versatility of orchestral instruments improved significantly, and the manner in which composers were employed shifted from private patronage to public/popular support. The size of concert performance audiences increased, and this led to construction of larger concert halls and opera houses. Large orchestras in reverberant spaces required conductors to keep the ensembles together. Faced with the trend for big orchestras, large audiences, and halls seating thousands, composers developed new techniques in tone color and harmony, replacing the prior emphasis on melody and intricate counterpoint with increasingly expressive and romantic styles.

Engineering Acoustics: the Sabine Era

Up to nearly the end of the 19th century, performance halls were still being designed by trial and error. Various practices developed in an apprenticeship manner, much like the trial-and-error evolution of common musical instruments. There was no "engineering" in the sense of designing attributes to meet specific needs, but instead there were practices passed from one generation of builders to the next, with helpful features retained and unhelpful features deleted.

Harvard University's Fogg Art Museum, built in 1894, had a lecture hall notorious for its bad acoustical properties. At that time, no scientific field of architectural acoustics had yet been established, so there was no confidence to know what caused the acoustical deficiencies and what might be done to remedy the problems. Harvard's President, Charles Eliot, decided to task a young assistant professor of physics, Wallace Clement Sabine, to figure out why the Fogg lecture hall was acoustically so poor, and to determine what might be done to correct its flaws.

In that era long before electronic instrumentation and computers, Sabine's clever physical insight was to recognize that the air in a hall stores energy for a period of time in the form of acoustical waves traveling diffusely through the room to-and-fro at the speed of sound, reflecting from the floor, walls, and ceiling at a statistically predictable rate as the traveling sound waves encountered the various surfaces.

Sabine expressed his theory and experimental results by specifying the *reverberation time*: the time interval required for a loud sound in the hall to die away. Sabine's ability to measure sound levels was rather rudimentary, but he chose a decay of 60 decibels to designate the time interval. The reverberation time (RT) in seconds is still expressed today using Sabine's 60-decibel decay specification, so the time interval is abbreviated as T_{60}, or RT60.

Although not perfect, Sabine's work was practical and extremely effective in guiding assessment of the new field of "room acoustics." Sabine's reputation led to him being designated as the acoustical consultant for the design of Boston's new Symphony Hall in 1899. Sabine used his newly discovered principles to suggest several of the characteristic architectural features of Boston Symphony Hall that make it among the best symphony performances spaces in the world.

Reverberation time

Sabine's work developed an understanding that the reverberation time in a room is proportional to the ratio of the room's volume (cubic meters) to the room's total surface sound absorption.

$$T_{60} \propto \frac{Room\,Volume}{Surface\,Absorption}$$

Sabine determined that Fogg Lecture Hall required additional sound absorbing surfaces to reduce the reverberation time from over 2 seconds to be under 1 second. This helped the speech intelligibility in that hall.

Studies of performance spaces and audience preferences gives the following general guidelines for reverberation time

Purpose (unamplified)	***T_{60} (125-500 Hz)***
Lecture hall (spoken word)	0.5 - 0.8 seconds
Playhouse (spoken word)	0.9 – 1.0 seconds
Opera Hall	1.0 – 1.4 seconds
Concert Hall, classical and baroque styles	1.0 – 1.4 seconds
Concert Hall, 19th century romantic styles	2.0 – 2.5 seconds

Example Halls	***T_{60} @ 125 Hz***	***T_{60} @ 500 Hz***
Boston Symphony Hall	2.2 seconds	1.8 seconds
Musikvereinssaal, Vienna	2.4 seconds	2.1 seconds
Neues Gewandhaus, Leipzig	1.5 seconds	1.55 seconds
Metropolitan Opera House, New York	1.8 seconds	1.3 seconds
Reynolds Recital Hall, Bozeman	1.75 seconds	1.37 seconds

When architects give an indication of how well a particular hall will suit the needs of particular performance types, the T_{60} is often one of the key indicators.

Other Considerations

It is important to understand that different surface materials have different sound absorbing properties at different frequencies. For example, a heavy carpet on a solid floor absorbs 35% of the incident sound energy at 1,000 Hz frequency, but only absorbs 2% of the incident sound energy at 125 Hz. This means that high frequency sounds decay more quickly than low frequency sounds in a carpeted room due to being absorbed by the carpeted surface. In contrast, a wall made of gypsum wallboard (drywall) absorbs only 4% of the incident sound at 1,000 Hz, but the wall absorbs 30% of the sound at 125 Hz.

Surface absorptivity	**Frequency in Hz**					
Description	**125**	**250**	**500**	**1000**	**2000**	**4000**
Carpet, heavy on concrete	0.02	0.06	0.14	0.35	0.60	0.65
Gypsum, 1/2 in. on studs	0.30	0.10	0.05	0.04	0.07	0.09

Therefore, part of the task of the acoustical designer is to choose a balance between the size and absorbing properties of the various surfaces to achieve the desired T_{60} at the frequencies of interest.

In addition to the basic feature of reverberation time, musicians and audiences assess several other acoustical attributes of a performance space when making a subjective judgement about the hall's quality.

- In general, musicians and audiences prefer halls that have slightly longer reverberation time at 125 Hz compared to the reverberation time above 500 Hz. This subjective quality of longer low-frequency reverb is known as "warmth."
- Because sound travels about 1 foot per millisecond, performers and audiences notice time delays when the distances within the hall are more than 25-30 feet. In Willson Auditorium, for example, the Symphony uses a stage riser section that extends out into the hall, making the distance from the conductor to the percussion about 40 feet, and the distance from the far east edge of the violin section to the far west edge of the string bass section more than 50 feet. These distances affect the perception of *intimacy* because of a lack of time synchrony of sound from different parts of the orchestra. The distances also affect the relative arrival time of direct sound and the arrival of early reflections from surfaces near the stage, which also influences audience satisfaction.
- Audiences and performers desire a hall with excellent blend, diffusion, and ensemble. Designers often include surfaces near the performers, such as individual panels of various shapes, sizes, and orientations, to create complicated overlapping reflections that give a highly desirable diffuse and uniformly reverberant sound field.

Traditional orchestra concert halls provide a sense of warmth and presence by using a narrow and long hall shape, often referred to as a "shoebox" design. Boston Symphony Hall and the Große Musikvereinssaal in Vienna are shoebox halls, for example. Having the side walls relatively close to the performers and the audience gives desirable early lateral reflections and a strong sense of envelopment and intimacy.

However, the shoebox format places a relatively large fraction of the audience at a significant distance from the stage, which some audience members and concert promoters find unappealing from a visual standpoint. For this reason, there may be a demand by the facility developer to use a wider "fan-shaped" floorplan that puts more seats closer to the stage. This tradeoff for more close seats is often to the detriment of the hall's acoustical attributes by weakening and delaying the lateral reflections for much of the seating area.

Hall Types

--An **opera** or a **ballet** theater needs a stagehouse with fly space for sets and lighting fixtures, side wings with off-stage space, a proscenium curtain and stage front, a "pit" for the orchestra, and a moderately-sized auditorium—organized like a playhouse—with precise acoustics and a relatively short reverberation time (perhaps 1 to 1.5 seconds).

Theatrical lighting instruments are required, as is a computerized lighting control system. The space requires a modern and flexible sound reinforcement system (wireless and wired microphones, amplifiers, loudspeakers).

Such a performance hall would also work for **conventional stage plays and operettas** (e.g., "Death of a Salesman" or "Oklahoma").

If the feasibility analysis indicates sufficient support, the hall could potentially be big enough to host **touring Broadway groups**, assuming that truck access, a suitable loading dock, and exterior doors were provided for load-in and load-out.

--A **symphony orchestra or symphonic choir**, on the other hand, needs a stagehouse *without* fly space, *no* wings, and *no* pit. The stagehouse is acoustically part of the auditorium: the orchestra is in the "same room" as the audience. A suitable orchestra hall is larger and narrower than a playhouse, with a longer reverberation time (1.5-2.0 seconds) and provision for early lateral reflections for good envelopment. Theatrical-style lighting instruments and controllers are not essential, and a good quality public address (PA) system for spoken announcements would be fully adequate.

--**Chamber music, acoustic soloists, and Baroque recitals** need a smaller stage, no pit, no curtain, no wings, etc., but a more intimate seating and a shorter reverberation time.

--Providing plenty of **additional space for rehearsals, storing stage equipment and risers, fabricating and storing sets, holding costumes, etc.**, is also essential. Having to move essential equipment, risers, costumes, pianos, tympani, etc., in and out of storage somewhere across town may be unavoidable, but some thought needs to go into minimizing the need for such effort.

--An **experimental theater** ("black box") with flexible seating, lighting, and staging is desirable for unconventional productions.