WORSHIP SPACE ACOUSTICS

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PLANNING FOR GOOD ROOM ACOUSTICS

7.1 INTRODUCTION

The objective of room acoustics planning and design is to provide rooms that allow good communication for speech and music between speakers, singers, and instruments and the congregants/listeners. In the worship space, congregants participate as sound sources, communicating also with one another by prayer and song, therefore, the send-receive situation is different from that of a theater, concert hall, or similar space.

Room acoustics planning also includes the control of acoustical defects such as noise, echo, and rattle. Noise control is discussed in Chapter 8 and echo and other acoustical problems are discussed later in this chapter.

Background noise levels must be sufficiently low to allow good communication. In rooms intended for worship, low levels of background noise are needed because the contrast between the sound level of the spoken and musical message and the silence during pauses enhances drama. Low background noise also will allow worshippers to hear the full, dynamic range and spatial qualities of the reverberation. The sound quality of background noise will vary, depending on individual preference and on whether the noise is due to heating, ventilation, air conditioning (usually called HVAC noise), to other activities in the building, to traffic, or to neighboring industry. This leads to different noise criteria being necessary, depending on the noise and the use of the room.
For worship spaces, the placement of the worshippers' seating, the choir, and the organ are of special interest. Speakers, singers, instrumentalists, and worshippers may have conflicting requirements regarding suitable acoustics. Individual preference may be substantially different. Solo performers such as speakers and singers will usually want to sense the acoustic response of the auditorium, whereas choirs, musicians playing in groups, or orchestras will put more emphasis on the way the room allows the members to interact. Organ players typically want the room to enhance the size of the instruments. Without reverberation, the sound quality of speech and music would be dependent on the directivity of the sound source and would lose beauty and emotional power as well.

The way sound is distributed in the room is not only expressed by sound level and sound level distributions but also by timbre and temporal characteristics. The temporal characteristics are a result of the room size and shape as well as the way the audience and other sound absorbing and scattering areas are distributed over the room's boundaries. Acoustic planning and design must be introduced in the early sketching stage when developing a new worship space, therefore, cooperation between the architect and acoustician is necessary for effective acoustics. If a pipe organ or large electronic instruments are to be installed, the builder of those instruments should also be involved from the beginning of the design process.

The possibilities of changing the general acoustics of a room without building a new interior shell or implementing other drastic changes, such as suspending sound-reflecting panels and installing sound-diffusing or absorbing wall surfaces, are limited once the room exists physically. For rooms that already exist, sound systems that enhance clarity or reverberation, as described in Chapter 10, may be the most cost-effective way to improve acoustics.

The quality of room acoustics is difficult to measure. Chapter 5 discusses some metrics for room acoustics quality. Among these, reverberation time (RT) and Clarity are the most important. Room acoustic metrics often require considerable experience and expertise to be applied correctly. Frequently, listening (hearing, itself, is an important measurement device) and subjective judgment by experts is the only way to assess the room acoustics quality.

During the planning of the worship space, it is important that acoustic faults such as noise and echo are eliminated and that the desired balance between direct, envelopmental, and reverberant sound is achieved for clarity and reverberation. This can be accomplished both by passive and by active means. Passive means include: (1) choice of seating area size and arrangement, (2) design of room shape (size, plans, and sections), (3) choice of ceiling height (i.e., room volume), and (4) choice of sound-absorbing and scattering properties of walls, ceiling, floor, and seating area. Active means include sound reinforcement and reverberation enhancement systems. Whereas the influence of all of these factors are interdependent, one can say that room shape and seating primarily determine direct sound and early-reflected
sound for the worshippers, and that room volume, absorptive and scattering properties of room surfaces primarily determine the reverberant sound.

### 7.2 PSYCHOACOUSTICS: THE PRECEDENCE EFFECT AND BINAURAL UNMASKING

Without the signal processing provided by our hearing that creates the so-called precedence effect, we would have difficulties communicating in rooms. The precedence effect makes it possible for us to hear the direction of the location of the sound source from the arrival characteristics of the direct sound. The precedence effect, sometimes referred to as the law of the first wave front, usually works quite well in rooms, auditoria, etc., but in some cases, such as when the sound source is obscured or when there are focusing surfaces, the directional impression can shift in an undesirable way.

Experience has shown that a somewhat later arriving sound due to a reflection (for example, delayed by 20 ms corresponding to an additional 6 m of travel) can be up to 10 dB stronger than the direct sound without affecting the apparent direction of the sound source.

The precedence effect can be beneficial in many sound-system applications in which enhanced clarity is desired in worship spaces. By introducing a small delay in the amplified signal, the directional impression of the sound source will remain unchanged, at the chazzan, priest, or imam.

Binaural unmasking makes it possible for us to separate direct from reverberant sound and makes the sound more clear. It is easy to convince oneself of this effect by simply listening with one ear blocked by a finger in a reverberant room.

### 7.3 SEATING AREA

Note that there is no worshippers’ seating in mosques and some Greek Orthodox churches; in this text, the term seating area has been retained for all denominations to describe the area in which congregants assemble to worship.

Most traditional churches and mosques will require the worshippers to be on a horizontal, plane floor. Evangelical churches will often have a sloped seating area. Synagogues will often feature a horizontal main floor seating area and galleries with sloped seating areas, although many synagogues also have sloped seating on the main floor.

Direct sound is the sound that propagates the shortest route from the sound source to the listener without any blockage such as a barrier or a corner. The strength of the direct sound will be higher the closer the worshippers are to the sound-source (see Chapter 1).
In practice, the first 5 ms of sound to reach the listeners are considered to make up the direct sound that will also include early-reflected sound (arriving within 5 ms of the direct sound) from the floor on which a speaker is standing, from nearby objects, and from the seating and worshippers themselves as shown in Figure 7.1. The latter sound, reflected at a shallow angle, is called grazing reflected sound and cannot be separated from the true direct sound because of the temporal masking in our hearing. The interaction between the true direct and the grazing sound leads to a timbre change in the direct sound, causing it to be thinner and less full-bodied. A measurement of the acoustical effect on the spectrum of the direct sound is illustrated in Figure 7.2.

![Figure 7.1](image)

**Figure 7.1** Grazing sound reflection is due to sound being reflected by seating and worshippers themselves when the sound source is approximately the same height as the listeners’ heads. The dashed lines indicate incident sound at grazing angle and the solid line indicates reflected sound. Interference between the two sounds results in the seat-dip effect at seats distanced from the source (see Figure 7.2).

![Figure 7.2](image)

**Figure 7.2** Measured early-sound SPLs (in a concert hall) just above audience seating minus calculated SPLs based on spherical divergence of true direct sound. Some reinforcement due to grazing-reflected sound gives a positive difference but the seat-dip phenomenon gives a negative difference, adapted from Reference 7.1.
By introducing a sloped seating arrangement, particularly one with an increasing slope, this effect may be minimized because the angle at which sound is reflected by the listeners is less grazing. The effect is also minimized by raising the sound source above the plane of the listeners’ heads, as indicated in Figure 7.3, and it is typically absent at the front seats of balconies, which contributes to the excellent sound quality there. For most church organ installations, the effect is also absent because the organ is typically mounted high over the plane of the worshippers as discussed later in this chapter.

### 7.4 FLOOR PLANS

Is there a preferred floor plan? Also, venues other than worship spaces such as theaters and rooms for music need to be optimized in regard to speech and music sound quality and clarity. Some common theater designs are the proscenium, thrust-stage, and in-the-round designs. Acoustically, worship spaces may be thought of analogously.

An untrained speaker typically has insufficient sound power to reach distances greater than 20 m (60 ft) even in quiet and nonreverberant spaces. One can regard this as the farthest distance from a listener to a speaker in a worship space. Figure 7.4 shows various distributions of the worshippers seating area assuming a maximum distance of 25 m (80 ft) between the center of the wall at the sending end and the farthest point in the seating area.

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**Figure 7.3** Reduction of the seat-dip effect can be achieved by sloping the seating area and by lifting the sound source relative to the plane of worshippers. Case A should be avoided, cases B and C offer improvement. Combination as shown in D offers even greater improvement.
Many traditional churches and cathedrals have a basilica or cruciform floor plan. A cruciform worship space with seating in the transepts also (see Figure 7.5) can be thought of as a variation on the theater thrust-stage, allowing more worshippers to come closer to the speaker, choir, and organ (unless the organ is placed at the back of the nave). For maximum speech intelligibility, each transept may need its own loudspeaker system in addition to the nave's sound system.

The fan-shaped seating plan provides the shortest average distance and the largest seating area within a limited radius from the sound source. However, the directivity of the human voice needs to be taken into account. The voice directivity will lead to less speech consonant power being radiated to the sides. The maximum direction to the sides can be illustrated by the polar diagram shown in Figure 1.10. At $\pm 60^\circ$ the response at 2 kHz has dropped by approximately 3 dB relative to the front direction. This corresponds to a drop in the distance limit mentioned from approximately 20 m to 14 m (65 ft to 45 ft). Because of this directivity, a large fan-shape plan only works with amplification.

Another important effect is that much of the intelligibility of speech is carried by the visual information obtained by watching the speaker's mouth movement, particularly for consonants such as $p$, $b$, and $d$. Lip-reading is much more difficult when watching a speaker from the side rather than from the front.

One must also note that the fan-shaped plan results in echoes from the back wall unless that wall is treated by sound-absorptive or diffusive covering (similar to that in circular, octagonal, and hexagonal spaces discussed below). Both treatments result in shorter reverberation times, more so for absorption (which is
frequently a result because of the medium- or low-ceiling height commonly used with this plan). In the fan-shape seating plan situation, sound reinforcement will be necessary both to overcome the effects of great distance and voice directivity. The same applies to the rhomboid seating plan in which the main sound source is at one of the corners of a square.

In small in-the-round spaces, the average listener will not be more than 7 m (20 ft) away from the speaker, and the direct sound to behind the speaker may be supplemented by useful reflections from the facing wall (see Reference 7.5).

Because of the greater time delays involved, medium-sized and larger spaces having in-the-round plans will suffer unwanted echo and undesired sound concentration because of the wall facing the speaker as shown in Figure 7.6a. An
example of how a medium-sized in-the-round worship space (seating less than 600 persons) may be designed is illustrated in Figure 7.6b. The perimeter walls will need sound-absorbing treatment to reduce echo and reverberation and the ceiling should back reflect to enhance clarity for those listeners not facing the speaker. The ceiling should not be more than 7 m (22 ft) above the center floor or
the sound reflections returned to the worshippers behind the speakers back will be delayed excessively (see Reference 7.5).

A large circular space is notoriously difficult unless an expertly designed and sound-absorptive treatment is used on focusing areas such as the perimeter walls. It will need sound reinforcement (see Figure 7.6c). Such a design was used for the 48 m diameter 6000 seat circular Church of God of Prophecy, Cleveland, TN. Six central clusters with directional loudspeaker systems provided coverage for all the seats, and a supplementary ceiling loudspeaker system was used for the 24 m diameter stage.

7.5 LENGTHWISE SECTIONS

Both lengthwise and crosswise sections are of interest because they define the room and, thus, how sound will be reflected by the walls and other surfaces. The voice power radiated to the back and the top of the speaker is lost unless reflecting surfaces, which have been carefully chosen, redirect this power for enhanced clarity and speech intelligibility.

In a rectangular plan room with a plane ceiling, the sound incident on it at the middle and back will be reflected to the rear wall. However, reflected a second time by the rear wall, the sound will be late in arriving and contribute detrimentally toward echo and reverberation. Figure 7.7 shows how an overhead reflector can improve distribution of early-reflected sound and how a sound-diffusive rear wall will help avoid echo. Figure 7.8 illustrates the sound-scattering real wall in St. Peter’s Episcopal Church, Bay Shore, Long Island, New York, as an example of this approach to control echo and still retain reverberation.

Reflected sound that is delayed no more than 50 ms—has travelled less than 17 m (50 ft) relative to the direct sound—will be useful in contributing to clarity and intelligibility. The choice of speaker platform, rear wall, and reflector geometry will determine the early-sound reflections. In worship spaces primarily intended for orthodox Jewish, Muslim, and modern Christian worship, high clarity and short reverberation times will be strived for. Here ceiling reflections should be directed down toward the congregants so that the direct and early-reflected to reverberant sound energy ratio is maximized (considering reverberation as a form of noise).

Traditional Christian liturgical music (organ and classical orchestra) requires relatively long reverberation time for optimal listening conditions, whereas speech and modern evangelical music sound better with much shorter reverberation times.

By shaping the ceiling and walls appropriately, it is possible to combine clarity with reverberation so that this is a useful design for large traditional churches and nonorthodox synagogues that should be designed for optimal music acoustics.
The same approach may be used in orthodox synagogues in which there will be two main sound source locations. Because the five books of Moses are read from a central platform—the bimah—in orthodox synagogues, the back-reflecting ceiling approach is suitable there as well (see Figure 7.9).
Looking at the crosswise sections, we find that the sound reflected by the ceiling can be directed to reach the listeners directly, to be scattered, or to be reflected to reach the walls and then the listeners. Some alternative ceiling designs are shown in Figure 7.10.

Figure 7.9 Both a sound reflector and a back-reflecting ceiling are useful in orthodox synagogues to improve speech intelligibility at distant seats.

7.6 CROSSWISE SECTIONS

Looking at the crosswise sections, we find that the sound reflected by the ceiling can be directed to reach the listeners directly, to be scattered, or to be reflected to reach the walls and then the listeners. Some alternative ceiling designs are shown in Figure 7.10.

Figure 7.10 Some crosswise ceiling profiles useful to achieve higher sound-diffusion in rooms for music.
In rooms intended for music, the ceiling is sometimes designed to be scattered and to send the sound toward the walls; it is then redirected toward the audience. This makes the sound source appear greater. It also helps blend the sound from the various musical instruments. Usually, this effect is not desired in worship spaces in which the congregants expect the sound to come from the speaker or the singer. In some worship spaces, however, in which there is a choir balcony or gallery and an organ to the back of the congregation, such blending is greatly desired.

By using the curved or diffusive ceiling designs (see Figures 7.10a and 7.10b), incident sound will be redirected to the side walls. Early-reflected sound from the walls will enhance the auditory source width—the perceived width of the sound source.

In some churches and synagogues, the ceiling apex angle is less than 90° (acute angle peak). Sound then will be repeatedly reflected by the ceiling before reaching the worshippers (see Figure 7.10c). Because some sound energy is always scattered at any reflection, this leads to primarily diffused sound reaching the worshippers, resulting in excellent acoustics for music (see Reference 7.6).

Figure 7.11 Interior of Hitchcock Presbyterian Church, Scarsdale, NY, that has a ceiling angle less than 90°, resulting in excellent diffusion and acoustics (photo: David L. Klepper. Sound System Design: Larry S. King. Room Acoustics and Noise Control: L. Gerald Marshall).
An example of such a reverse-V ceiling design is found in the Hitchcock Presbyterian Church, Scarsdale, New York (see Figure 7.11). If the upper part of the side walls is angled inward more early-reflected sound will reach the listeners. This is one way of controlling the direct and early to reverberant sound ratio. The First Presbyterian Church, Stamford, Connecticut (see Figure 7.12), is an excellent example of this design that combines a small ceiling apex angle with tilted side walls (see Reference 7.7).

If plane ceiling surfaces are made diffusive by decorative elements of sufficient depth such as coffers, cupolas, or arches, the sound will, to a large extent, be scattered and reach the worshippers as early reverberant sound. In many churches, the ceiling is made up of small domes that normally has the center of curvature well above the worshippers and will act as sound scatterers, as discussed later in this chapter.

### 7.7 PREFERRED REVERBERATION TIME

Experience has shown that the reverberation time suitable for various uses and sizes of rooms can be approximated as illustrated in Figure 7.13.

Generally, one strives to achieve control of the reverberation time to an interval of $\pm 0.1$ s at midrange frequencies. Figure 7.14 shows the average ability to sense a certain change in reverberation time. The common range for reverberation time is 1 to 3 s, in which a reverberation time change of less than 5% can be noticed.
Figure 7.13  Suggested reverberation times for speech and music in worship spaces.
The reverberation time in churches in which organ music is played should increase somewhat at low frequencies from 250 Hz and downward; the reverberation time in the 63 Hz octave band may be approximately 50% higher than in the 1 kHz octave band.

Since the reverberation time requirement for speech is that one should not have any reverberation time increase at low frequencies, the combination of good acoustics for both speech and music may be difficult to achieve unless a reflector or sound system is used for speakers. Excessively sound-absorptive pew cushions or seating will tend to result in dull acoustics.

A platform may need to be installed for performances played in the crossing of a church. In mosques, the worshippers are generally sitting on the floor which means that the imam and musicians will be above the worshippers listening plane, improving communication. In large synagogues, the rabbi and chazzan will be on a platform that also helps communication, typically 0.5 to 1 m (1.5 to 3 ft) high.

### 7.8 COLORATION

Coloration is the term used to describe timbre changes. There are two important types of coloration: one due to the lack of binaural information and one due to the presence of only strong sidewall reflections in the sound field. Two types of reflection patterns leading to coloration are shown in Figure 7.15.
Figure 7.15 (a) Examples of impulse responses $h(t)$ causing coloration and their associated frequency responses. Direct sound and a single strong reflection. (b) Repetitive reflection pattern.
The first kind of coloration (see Figure 7.15a) will generally occur when there is a lack of sound from the sides, for example, when listening to mono sound recordings over headphones. The figure shows how repetitive frequency response variations are introduced by the presence of a strong reflection in the symmetry plane of the head. The precedence effect will be put out of play for a much delayed strong reflection, leading to a shift in the apparent direction of the sound source. For delays longer than 50 ms, echo will occur if the reflected energy is large enough and if there are no reflections filling in between the early sound and the late reflection.

The second, and more serious, type of coloration occurs when one has two highly reflective parallel walls dominating the sound field in a room. This leads to the reflection pattern shown in Figure 7.15b. The acoustic effect is, in this case, called a **flutter echo** or **comb filter effect**. This effect occurs when one has two plane opposing walls, the time delays are small, and there is a lack of other reflected sound. If present, one hears flutter echo easily when clapping one’s hands. If the ceiling and wall in a wide room are hard and smooth, one can have the same type of reflection pattern, but in the vertical direction, causing coloration of the first kind.

### 7.9 ECHO

If the time delay between direct sound and reflection(s) in Figures 7.6a and 7.7a is long enough, and the reflection strong enough, one will hear echo. The sensitivity of the ear to echo is illustrated in Figure 7.16.

![Figure 7.16](image)

**Figure 7.16** Percentage persons annoyed by echo in listening to a direct sound in combination with a delayed sound.
The more rapid the information in the sound, the more annoying the echo is. Slow, low-frequency flue pipe organ tones will not be affected by echo, but speech and fast trumpet passages will. Because of the characteristics of musical instruments and music, echoes are often more annoying at high frequencies than at low frequencies.

7.10 SOME SOUND-REFLECTION PROBLEMS

7.10.1 Domes and Other Curved Surfaces

For echoes to occur, the reflected sound must be fairly strong; this is the case when there are curved surfaces such as domes focusing the reflected sound. Since domes occur frequently in worship space architecture, it is important to know under which conditions echoes occur.

Figure 7.17 shows sound rays from a source at $S$ in a room having a circular plan. The numbers identify the points at which rays are reflected. A ray is reflected at the same angle as it is incident against the normal of the circle at that point. After some time, the resulting wave front is the oval shape to the right and focusing has occurred.

Circles, ellipses, and parabolas are the most common curve shapes in architecture and their reflection patterns are illustrated in Figure 7.18. Ellipses have two focal points and parabolas collect an incident plane wave to a focal point.

Domes are frequent architectural elements in worship spaces and can cause multiple reflections against a floor. Two instances of reflection focusing are shown.

![Figure 7.17](image_url)  
*Figure 7.17* Construction of the reflected wave front in a circular plan. All travel paths from the location of the source at $S$ are equally long.
in Figure 7.19. In both cases there is a spherical ceiling above a plane floor. The center of curvature is at C, the source at S, and the focal point at F. Domes having their center of curvature below the floor are quite common in orthodox churches. The question then becomes, how can one avoid disturbing focusing. There are several possibilities.

If the worship space is in the planning stage and architecture allows, the center of curvature should be kept well above the heads of the worshippers, because the focusing point will always be far away and not cause harm. The ray construction for this case is presented in Figure 7.20. One should also note that such domes actually scatter sound.

As a rule, to avoid any focusing problem, there should be neither a sound source nor receiver within the full circle formed by the spherical dome. Three
other possibilities are shown in Figure 7.21: (1) to treat the dome by sound-absorptive material, (2) to make the dome sufficiently diffusive, and (3) to make the dome acoustically transparent, for example, by making it out of perforated metal or other material.

The American church architect, Harold Wagoner, frequently employed a large radius that was three times the height of the laterally curved ceiling and transitioning directly to a small radius that was less than a quarter of the ceiling height at each side giving the appearance of a barrel-vault without its acoustical problems.

### 7.10.2 Whispering Galleries
The whispering gallery effect is due to high-frequency sound such as a whisper carried around by a curved surface with minimal sound absorption (see Figure 7.22).

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**Figure 7.21** Three possibilities for avoiding focusing by a dome.

**Figure 7.22** Rays will follow the curved wall of a circular plan space.
A classic example of a whispering gallery is found in the Statuary Hall in the United States Capitol, Washington, D.C., but the effect will be found in any room with hard, concave curved walls. It is an acoustical oddity, but it is seldom a problem because it requires both a sound source and a receiver close to the wall.

### 7.10.3 Pillars

Churches and mosques frequently have large arrays of pillars (see Figures C.9 or M.10). Whereas slim, single pillars will not affect sound appreciably as long as their cross section is small compared to wavelength, there are occasions when pillars cause unwanted acoustical blockage along with their sight blockage. When pillars have cross-section dimensions approximately 0.3 m (1 ft), that is, approximately one wavelength at 1 kHz, or larger, they start to cast a shadow and to reflect sound at frequencies important to speech. Repetitive reflections from a row of pillars may cause an effect similar to that generated by other repetitive sound reflections as discussed previously. Additionally, the reflections reduce speech intelligibility for the worshippers seated in the shadow zones unless suitable reflecting surfaces and/or a good sound system are provided.

At some angle the area behind the pillars will become invisible to the sound source. This is an indication that the direct acoustic path will also be absent for consonants which, of course, results in poor speech intelligibility.

The situation is not as bad for organ music as it is for speech because a small drop in clarity for organ music is not as serious as it is for speech intelligibility. Organ music relies heavily on the diffuse reflections of the room and the reverberation for its acoustic effect. Pipe organs, which are physically large instruments, are often placed at the far end or at the front of a church which means that there will always be numerous reflections both within the organ case and from the side walls surrounding the organ, as well as from the ceiling above the organ (see Section 7.18.2). The pillars virtually will have no influence on the reverberant sound but may still reduce clarity. With the proper design of nearby surfaces, the same effect can be provided for the choir.

### 7.11 ANNEXES AND DUAL-SLOPE REVERBERATION CURVES

Many churches have a cruciform floor shape which means that there are acoustically four different rooms that are coupled through the crossing (see Figure 7.5). In many churches and cathedrals there are also side chapels (see Figure C.2). This means that there will be many seats for which there are no sight lines, that is, there will be a lack of direct sound and associated early reflections. The rooms will have various early decay times because of the dissimilar geometry and sound difference. If the side rooms—transepts—are mainly used for overflow seating on holidays,
then the problem is minor. Otherwise, if the transepts are frequently used, sound systems may need to be utilized to obtain the desired speech intelligibility. Again, it is important to stress that the voice is directional and, thus, requires appropriate compensation.

Because of the differences in reverberation times, there may be dual slope reverberation slopes. The seriousness of this condition depends on subjective preference. From the viewpoint of combining clarity with long reverberation time, the dual slope reverberation may, in fact, be an advantage.

### 7.12 BALCONIES

Common elements in worship spaces are balconies and galleries. (In this text we will use the terms balcony and gallery interchangeably although architects reserve the term gallery for a worship space balcony that is supported by pillars.) There are many reasons for having balconies; in churches they may be used for added seating capacity and in synagogues and mosques they may provide separate seating for women and men. An extreme case is the mosque shown in Figure M.9 in which men and women worship on two separate floors coupled by way of an open space at the front of the mosque.

When there is a balcony situation, one must consider the sound quality both on the balcony and underneath it. Typically, the ceiling height under the balcony is 2 to 3 m which results in a home listening situation, that is, sound similar to that received from a stereo system and coming mainly from the front. The reverberation will also come from the front, as when listening to a stereo system in the home. This means that the desired spatial effect of the reverberation will be absent and, in particular, choir and organ music will suffer. For concert halls it is recommended that the balcony depth should be smaller than the opening height; this is also a good plan for worship spaces in which one strives for natural reverberant sound. For speech intelligibility and clarity, direct and early-reflected sound also should reach those listeners at the far end of the balcony, that is, minimally listeners on the balcony should have an unobstructed view of the speaker or musician.

Four different on top or underneath balcony situations are shown in Figure 7.23. The situation in both 7.23a and b is clearly unacceptable; minimal sound will come in because of the low ceiling height and incoming sound will be attenuated on its way to the far-back listeners. Interaction with congregants, except in close proximity, is also impaired. Because of the increased height of the opening on the balcony in 7.23c, the listeners on the balcony will have improved reverberant sound and early reflections. In 7.23d, the ratio between balcony depth and opening height, both on top and under the balcony, is about unity and will give good acoustical results and will provide visual intimacy as well.
The photo in Figure 7.24 shows an unusual situation in which a synagogue features two gallery levels. The upper balcony is virtually never used because of the poor speech intelligibility there, a result of the lack of both direct and early-reflected sound.

By having sloping balcony undersides, as shown in Figure 7.23d and Figure S.7a, direct sound, early reflections, and reverberant sound will still reach the congregants. Balcony undersides should be made sound reflective.

Another possibility to eliminate a poor, under-balcony situation is to fix an array of loudspeakers to the ceiling under the balcony. These loudspeakers can then be fed with signals that have been appropriately delayed and reverberated technically, using an electronic reverberation system, or by feeding sound picked up by microphones in more reverberant parts of the church. Obviously, the expense may not be justified if such seating is rarely used, but planning in advance, including conduit and loudspeaker back-boxes for such an installation, might save a great deal of money when the desire to implement such an installation arrives.

Balcony fronts are usually reflective and may need to be angled to avoid echo, or to diffuse incident sound as shown in Figure 7.28b.
Figure 7.24 Synagogue in German 1850s style with two levels of balconies in Gothenburg, Sweden (photo: Mendel Kleiner).

Figure 7.25 Small pulpit canopy reflector in the 17th century Morlanda church, Sweden (photo: Mendel Kleiner).
7.13 REFLECTORS

The beneficial effect of reflectors was discussed earlier. Reflectors are usually used to distribute the sound from a speaker or an orchestra to the audience, or to improve the acoustical conditions for musicians on stage. Reflectors can be planar or curved. Sometimes curved reflectors are used as diffusers.

Figure 7.25 shows a pulpit canopy reflector in a church. The acoustic advantages of such a reflector are small and, with the availability of modern sound systems, there is really no acoustical reason to use such a reflector because it is too small to be acoustically effective. The main positive effect of this canopy will be the added support given to the voice and felt by the priest.

In traditional, orthodox synagogues, the chazzan’s voice is directed toward the Aron Ha-Kodesh—in principle, away from most of the worshippers—as indicated in Figure 7.9. In this case, a reflector may be useful; an effective reflector can be made of laminated glass. Figure S.14 shows how the rabbi’s pulpit has been used to provide a reflector for the cantor’s voice in the synagogue shown in Figure 7.24.

For a reflector to be acoustically reflective, its surface must have dimensions much larger than the wavelength of sound. It must also cover a significant part of the solid angle as seen from the sound source. Additionally, it must have sufficient mass to prevent it from vibrating. Often the criterion is set that the mass per unit area should be at least 20 kg/m² (ca. 4 lb/ft²). To give an appreciable reflection of medium- and high-frequency voice sounds, the mass per unit area can be as low as 2 kg/m² and the dimensions 1 m by 1 m (3 ft by 3 ft).

Note that the angle of incidence affects the efficiency of the reflector and that groups of reflectors will show different behaviors from single reflectors. In addition, the reflection properties of reflectors will depend on whatever surface roughness they may have. The acrylic plastic ceiling reflectors shown at the top of the photo in Figure 7.26 are designed to be somewhat diffusive, as well as blocking a focused echo from the domed ceiling above.

Figure 7.26 The translucent plastic ceiling reflectors in the Rodef Shalom Synagogue, Pittsburgh, PA, are designed to be somewhat diffusive and eliminate a focused echo from the dome above (photo: David L. Klepper, Klepper Marshall King, consultants).
Because reflectors are usually relatively small, it is easy to do a provisional installation to convince oneself of the added benefit. Finally, it should be noted that technically the reflection properties of reflectors are best investigated using physical scale modeling.

7.14 BARRIERS AND MECHITZOT

In many cases it is necessary to subdivide a room into visually and acoustically separate volumes. A partial wall, or a barrier, can then be used to achieve a sound shadow. The effectiveness of a barrier is determined by its acoustic and mechanical properties plus the wavelength and the angle of incidence of sound.

For sound in the speech range, that is, 250 Hz to 4 kHz, the wavelengths are between 1.7 m to 0.08 m (6 ft to 3 in). If the barrier height is of the order of 2 m (7 ft), the result is poor shadow action at the lowest-voice frequencies because of diffraction of sound around the barrier.

A thin reflecting barrier will usually have more insertion loss than a thin absorptive barrier. A thick barrier usually results in better insertion loss than a thin barrier because the sound has to propagate over two edges.

It is important that the barrier has sufficient sound insulation so that sound is not transmitted through the barrier. This typically requires a mass per unit area more than 10 kg/m² (2 lb/ft²) for barriers of the type common in open plan offices.

Figure 7.27 A mechitzah is a divider separating men’s and women’s seating in an orthodox synagogue (photo: Eric M. Saperstein, Artisans of the Valley, Pennington, NJ).
A special type of barrier is the acoustically transparent *mechitza* that is used in mosques and orthodox synagogues to separate men from women in worship. In traditional orthodox synagogues, the mechitza (pl. mechitzot) needs to provide visual isolation and is normally around 2 m high. Figure 7.27 shows a mechitza in an orthodox synagogue. In modern orthodox synagogues, a mechitza need not be a visual barrier and can be as low as 1 m. Only a few conservative synagogues and no reform synagogues use a mechitza. More examples of mechitzot can be found in Part II in the chapter on synagogues.

In the mosque the separation of men and women worshippers is usually achieved by having separate mosques, although, as previously discussed in connection with Figure M.9, some sects only separate men and women so they are out of sight of one another during worship. Liberal Muslims have fully integrated worship.

### 7.15 DIFFUSERS

A common desire for good room acoustics is to diffuse the sound reflections made by plane surfaces. In most rooms for music and speech, a suitable amount of diffuse reflection will prevent flutter echo and enhance the *smoothness* of sound. For a diffuser to work properly, it needs surface irregularities of approximately a quarter wavelength or larger, but even small surface unevenness is advantageous. Niches about 0.3 to 0.4 m deep (1 to 1.5 ft) are usually sufficient for good results. The irregularities should be randomized for optimum effect, but this is often not possible for architectural reasons. Figure 7.28 shows several types of irregular surfaces that may be used to scatter sound. Nearly any extended roughness deeper than 10 cm (3 in) will add beneficial diffusion.

An acoustic effect of diffusion is that the diffusive surface seems to *disappear*, but that the room still sounds reverberant. Diffusers are common building elements in recording and monitoring studios. Before installing a quadratic residue diffuser (QRD), or other mathematically defined diffusers, one should discuss the possibility of designing custom with the architect—architecturally pleasing unevenness on walls and ceiling.

### 7.16 TEMPORARY STRUCTURES AND TENTS

Occasionally it will be necessary to set up a temporary structure to be used as a worship space. This may be when a venue not intended for worship is to be used or when one wants to conduct religious worship out of doors. Zoning regulations may also prevent a conventional building. In dry climates, one can make do with
Figure 7.28  (a) Use of polycylindrical diffusors in the organ recital hall at the Gothenburg School of Music, Sweden (Photo: Mendel Kleiner). (b) Use of QRD diffusors on the balcony front of the Clear Lake United Methodist Church, Clear Lake, TX (Photo: David L. Klepper, Klepper Marshall King, consultants). (c) Use of rococo interior of the basilica in the Ottobeuren Benedictine abbey, located in Memmingen, Germany (photo: Johan Norrback, GOArt).
only a sound system; in places with rain, it may be necessary to add a tent or similar building. Figure 7.29 shows the interior of the Benedict Music Tent, Aspen, Colorado, which is a permanent outdoor structure used for summer concerts.

Tents and marquees offer both advantages and disadvantages from the viewpoint of acoustics. Because of the low mass per unit area of the canvas, the wall will have poor sound isolation, particularly at low frequencies. This may be of concern to the surroundings because if amplified speech and music are used in the tent, the sound levels can become high outside of the tent.

Typically, the canvas will be made of plastic or some water repellent synthetic cloth. Natural canvas will start to rot and leak after a few years, and modern tent structures are frequently made of Teflon-coated fiberglass. The structure shown in Figure 7.29 uses a canvas that has a surface mass of approximately 2 kg/m² (ca. 6 oz/ft²). The acoustic behavior of the fabric is determined by mass, tension, and damping. The mass will vary with precipitation. A wet fabric has higher mass per unit area. Rain on the fabric will cause considerable noise radiation from the canvas. Normally, the resonances of the fabric pieces are of minor acoustical interest because they are well damped by the air.

Looking at the room acoustics of the tent, one notices that most tents have surfaces that are convex (from the inside). This means that they are diffusive so early reflections will tend to be nondistinct and the reverberation sound will be well mixed; however, the acoustical properties of the floor or ground may be rather absorptive at medium and high frequencies. It is only in the case of the concrete or paved floor that it will be fully reflective.

Figure 7.29 The Benedict Music Tent, Aspen, CO, uses Teflon-coated fiberglass fabric. In addition, conventional reflectors are used to provide suitable early reflections (photo: Kirkegaard Associates, Chicago, IL).
Using the curves in Figure 4.3 one finds that, for a canvas having a mass per unit area of 2 kg/m² (6 oz/ft²), the sound-absorption coefficient is less than 0.2 only over 200 Hz. This means that amplification and loudspeaker systems would be needed to provide low-frequency sound. A mass per unit area of 10 kg/m² (2 lb/ft²) would essentially eliminate the problem and provide sufficiently full range sound reflection for most purposes.

### 7.17 ROOMS FOR SPEECH

Good speech intelligibility is not the same as naturally sounding speech. One can increase the intelligibility of amplified speech, particularly in noisy surroundings, by various types of signal processing such as spectral shaping and compression.

As discussed in Chapter 2, we can regard speech as a modulated signal (see Figure 2.5) with a complex tonal or noisy spectrum primarily covering the frequency range 0.25 to 4 kHz that is modulated by frequencies in the 0.2 to 8 Hz range. Reverberation and noise will decrease the modulation. A reduction in modulation results in a reduction of speech intelligibility. For speech modulation that does not affect the listener by reverberation, the reverberation time must be short and the ratio between direct and early-reflected sound to late-reverberant sound must be high.

There is, however, a practical limit to shortening the reverberation time. It is expensive to add sound absorbers to a room and it may be architecturally unacceptable. In addition, rooms are expected to have a certain reverberation time and level, determined by tradition and visual aspects (room purpose, shape, and volume, for example).

Speech intelligibility can be shown to increase with increasing reverberation time for short reverberation times in the range of up to 0.5 s. The reason is that sound absorption is coupled to both reverberation time and sound level. In addition, early-sound reflections by more reflective walls help to eliminate the influence of speaker sound radiation directivity on the sound pressure. The output of the human voice varies approximately 6 to 10 dB with angle in the frequency range most important for speech intelligibility.

These are some good rules for auditoria used primarily for the spoken word:

- Keep the travel paths of direct sound and important early reflections short. It is difficult for an untrained speaker to reach audiences with sufficient speech intelligibility at distances over 20 m (60 ft) without the use of amplification.
- There must be enough early reflections to provide sufficient sound at the listeners while at the same time not feeding sound energy into
the late part of the reverberant sound field. It is advantageous to strive for early-sound reflections to arrive close to the horizontal plane, rather than from above, to have good speech sound quality. However, sometimes it is necessary to make use of overhead sound reflectors as shown in Figure 7.24 or 7.25.

- Mirror-like (specular) reflections must not exceed the level of the reverberant sound if they arrive more than 30 ms after the arrival of the direct sound; such reflections may be perceived as echoes. As discussed previously, focusing by concave surfaces must be avoided.

- The human voice is directional. In small rooms, including classrooms and small auditoria having relatively hard walls, the speaker usually will be quite close to some sound-reflecting surfaces. This leads to strong early reflections that will add to the direct sound in such a way as to increase the speech intelligibility. In large auditoria such as worship spaces, assembly, and lecture halls, it is important to place the seating area within approximately a 120° arc from the speaker. The effective speech intelligibility will increase when the listeners can see the talker’s lip movements.

- For best speech quality, the reverberation time should be in the range of 0.6 to 1.0 seconds, increasing with the size of the room (see Figure 7.13). It is possible to combine this with the desire to have long reverberation time for music by using sound systems or designing the room in such a way that the reverberation curve has dual slopes. For speech the reverberation time should also be constant to within 10% over the 125 Hz to 8 kHz octave bands for small- and medium-sized rooms. The necessary room volume depends on the sound absorption by the audience. Typically, each person requires approximately 0.75 to 1 m² (7 to 9 ft²) of floor space. This results in a ceiling height in the range of 3 m (10 ft). Sound absorbers should be placed so that they do not interfere with the propagation of important early-sound reflections. This means that one should leave the central part of the ceiling non-absorptive in auditoria, classrooms, etc.

- For small studios and control rooms (such as those used at radio stations having volumes smaller than 25 m³ (750 ft³), it is common to reduce the reverberation time to the range 0.2 to 0.4 s for a neutral sound. It is sometimes also necessary to control the resonant modes at low frequencies using various types of tuned resonant sound absorbers, bass traps.
7.18 ROOMS FOR MUSIC

7.18.1 General Recommendations

The acoustics of worship spaces influence the way music is written and performed. Musical works are written for the reverberation characteristics of the places in which they are likely to be performed.

Organ music by César Franck sounds significantly better in large cathedrals than some of the smaller scale organ music by Buxtehude and Bach, which, on the other hand, excels in small churches.

Sound systems for reverberation enhancements, particularly those outdoors, can be used to effectively simulate many types of spaces.

Some general recommendations for rooms intended for performances and the enjoyment of music in the worship space are:

- The background noise sound pressure levels must be low.
- The sound level must be optimized; it should neither be too loud nor too low. The sound level depends on the particular piece of music, the size of the ensemble, the way the music is performed, and the sound absorption that is due primarily to the worshippers.
- The spatial and temporal distribution of the early reflections must be good.
- The ratio between direct & early-reflected to reverberant sound must be appropriate to the desired clarity for the music that will be played.
- The reverberation time must be appropriate for the music that will be played.

The optimal reverberation time depends on the size of the room as well as on the type of performance that is expected to dominate the use of the room (see Figure 7.13 that shows some target values for various room volumes).

The worship space possibly can be designed to have variable acoustics by passive or by active means. Passive variation can be achieved using variable absorption. Sound systems can be used to adjust clarity and/or reverberation by active means.

A worship space that has a short reverberation time will be considered dry and clinical and acoustically uninteresting. Churches will typically require a ceiling height of approximately 10 to 15 m (30 to 45 ft) to obtain a sufficiently long reverberation time. One often strives for a frequency independent reverberation time within ±5% in the octave bands from 250 Hz to 4 kHz.

Generally the sound absorption by common building constructions and surfaces is fairly low in the octave bands at 125 and below. Frequently, windows and poor floor constructions are the main sound absorbers at these low frequencies. It is common to allow an increase of reverberation time down to the 63 Hz octave...
band of approximately 50% over the value at 1 kHz. This practice results in good bass response and a warm-sounding reverberation.

The time gaps between the various components such as direct sound and major early reflections, are important and should be irregular and limited to a maximum of approximately 20 ms. The early reflections should be wideband, that is, not have a limited frequency range. One should avoid strong overhead reflections appearing in the same vertical plane as the direct sound. Because hearing cannot differentiate between signals having the same interaural delay time, such overhead reflections will cause comb filter effects unless masked by other reflections coming from the sides.

The spatial distribution of the early-reflected sound is important. Two effects are important, the *apparent source width* (ASW) and the *envelopment*, that is, the feeling of being immersed in reverberation arriving from all directions.

The apparent width of the sound source is determined by the way the early reflections reach the listener. The reflection angles should be close to the horizontal plane to maximize the advantages of our binaural hearing. One should also strive for many reflection incidence angles because this also contributes to the feeling of diffuseness in the sound field. It is advantageous if the directional distribution of the early reflections are such that when listening the sound field appears to be symmetrical. All of these requirements are easily fulfilled in conventional worship spaces such as in churches having cruciform or basilica floor plans.

To obtain good subjective diffusivity, the reflections in and close to the median plane should be minimized relative to the lateral reflections. The side walls should be somewhat scattering, for example by using shelves, balconies, unevenly placed sound-absorbing patches, objects, etc., having sizes in the range of 0.5 to 0.05 m (1.5 ft to 2 in). Typically, windows, pillars, and other decorations such as large religious symbols (crucifixes, for example) will provide the diffusivity.

One phenomenon of particular importance in long worship spaces is that of cancellation of direct sound on the main floor by the first reflection of sound off the audience in the frequency range between 125 Hz to 1 kHz—the *seat dip effect* discussed in conjunction with Figure 7.2. The cancellation will result in coloration of the sound, that is, the direct sound will sound weaker and thinner.

Because of the precedence effect, the direct sound determines our perception of the timbre of the sound source. Consequently, it is important to design the worship space so that coloration is minimized. This requires that speakers and performers are raised above the plane of the worshippers, that there are good sight lines for all worshippers, and that there are reflecting surfaces to fill in for some reduction in direct sound—if possible from the sides but if necessary from overhead.

It is also important that the acoustical conditions are such that they give musicians the possibility of hearing one another and give support for their own playing.
7.18.2 Organ Placement

Both the organ and the room in which it is placed are important for the quality of the organ sound. The size of the organ will depend on the desired organ loudness and that is determined by sound power, room volume, and room-sound absorption. The location will depend on visual and acoustical aspects and will involve balancing direct, early-reflected, and reverberant sound for desired clarity and reverberance (see Section 5.5). The Clarity metric $C_{80}$ is frequently used to estimate the subjectively perceived clarity as described previously. Suitable clarity is critical for sound quality. Differences of a few dBs in $C_{80}$ values may be easily heard. The desired clarity, and the associated values desired for $C_{80}$ will differ depending on music type.

For the start transients of the pipe sounds to be heard, the organ speech needs to be clear. Even though the fundamental and the first overtones of flue pipes have long start transients (particularly at low frequencies), higher overtones and other pipe sounds (for example speaking noise), will have short transient times. Pipes such as reed pipes will also have short, initial transient times.

Reverberation is essential, however, for the fullness and mixing of orchestral sound as well as envelopment. Even though some mixing of the organ sound takes place in the organ case, a fairly long reverberation time (up to 3 to 4 s) is necessary for most religious musical works. The reverberation also contributes strongly to the celestial and numinous qualities of organ sound.

The organ serves to support both choir and congregational singing. For congregational singing, it is essential that the organ sound is similar for all congregants. This typically requires the organ to be placed well above the floor. If the organ is placed at floor level, the audience attenuation of sound will result in a large variation in the strength at different places (See Section 7.3). Additionally, placing the organ well above floor level reduces the risk of echo in churches that have substantial ceiling heights. It also preserves the clarity of organ sound because attenuation of direct and early-reflected sound due to the congregants is avoided.

Some possibilities for the placement of a pipe organ in a church that has a cruciform floor plan are shown in Figure 7.30. Similar possibilities also exist in churches having a basilica plan. In most churches, large or small, positions B and A1 in the figure will be preferred for sound quality and uniformity and will provide excellent organ sound for congregational singing, and will be suitable for the choir. In both cases, the organ needs to be well above floor level. Position B offers good reverberation with the desired celestial sound characteristic. For position B, the organ will be placed on a gallery in the back of the room (see Christ Church [Episcopal], Rochester, New York, Figure 7.31). Unless the room has extreme width or height, the side walls or ceiling will provide desired early-reflected sound. In Reform Synagogues, the organ typically will be placed at position B also.
Position A1 has the advantage that it will give the best homogeneity of sound for the congregation, better than that of position B. The visual prominence may, however, be bothersome, and some prefer the organ not to be seen, but rather only heard as would be the case in position B.
Positions A2 and A3 are common in Episcopal and Anglican churches and are good for the choir and for reverberation. Sometimes, however, they result in insufficient clarity because of the design of the organ case and lack direct line-of-sight to the congregants.

Small churches are likely to have shorter reverberation times than large churches, but this should not influence the placement of the organ. In such churches, there may be excessive clarity of sound because the distances to the organ are small for all congregants and there is a lack of reverberant sound. But hiding the organ in a niche or transept (positions T, N2, and N3 in Figure 7.30) will greatly reduce its effectiveness in assisting the choir and the congregation. In small, nonreverberant churches, an electronic reverberation enhancement system may be used successfully (see discussion in Section 10.4.4).

Positions N2 and N3 are considered only for secondary organs, normally placed reasonably high for good sound distribution. They are useful positions when there is more than one organ or when the choir is in a nontypical position—seldom encountered in modern churches.

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**Figure 7.32** Suggested arrangement for organ and choir on top of gallery (adapted from Reference 7.8 and extended).
Typically, balcony fronts will be reflective, but when the organ is placed on a
gallery as in B, it is important that the gallery front is acoustically open (see Figure
7.33) so that the organ’s sound is not hampered by a barrier.

The wall against which the organ is placed should be heavy and act as an
efficient sound barrier in order to preserve the output power of the organ at low
frequencies. Note also that it is important to take care in placing the blower for the
organ so that its noise does not enter the worship space.

More information on organ placement can be found in Reference 7.10.

7.18.3 Organ and Choir Arrangements

In most churches music is frequently presented by the choir and organ together.
This may be the choir singing to the congregation or the choir leading the congre-
gation in singing. The most common arrangement is the choir at the front of the
organ with the console located so that the organist can conduct the choir from the
organ bench when a second musician is not present to conduct the choir. Such an
arrangement is shown in Figure 7.32 (see Reference 7.8).

The mouths of the lowest pipes in the organ should be at least 2 m (7 ft)
above the heads of the tallest choir members on the highest choir risers in order
to prevent these choir members suffering hearing loss and being unable to coordi-
nate with other choir members. At the same time, the organ sound should not
be blocked from the choir and certainly not from the organist at the console. The
rear gallery at the reform synagogue—North Shore Congregation Israel, Glencoe, Illinois shown in Figure 7.33 is a good example.

Here, the choir can be at the left or the right of the organ or one section on each side. They can hear the organ sufficiently for coordination, but not receive too high of organ sound pressure levels. The difficulty in that building is the location of the cantor, 30 meters away, at the front on the bimah, but a loudspeaker for coordination is provided in the cantor's lectern. Our understanding is that most cantors have preferred not to use it, but learn to anticipate sound from the choir and organ to keep synchronization for most of the congregation.

The stage of the Tanglewood Music Shed, Lenox, Massachusetts, presents still another possibility. Here, as shown in Figure 7.34, the organ is located above the reflective orchestral stage shell and can be heard in coordination with choir and the orchestra on the stage. The problem of coordination for stage musicians with the organ sound is solved by the openings in the stage ceiling that permit a moderate amount of organ sound energy to reach the stage musicians. The situation is similar at the Manhattan's Corpus Christi Roman Catholic Church, New York, New York, where the bottom surfaces of the organ's swell chamber and wind chests are among the actual overhead sound reflectors for the choir.

![Diagram](image_url)

**Figure 7.34** An example of how a choir and organ were coordinated at the stage of the Tanglewood Music Shed, Lenox, MA. It was the model for the solution at Corpus Christi Roman Catholic Church, New York, NY, near Columbia University, for the Holtkamp organ there. There the bottoms of the pipework wood air chests serve as the sound-reflecting panels with the open space between them allowing the right proportion of sound to reach the choir members' ears.