Sound in Enclosed Spaces

Sound absorption
Sound reflection
Sound transmission

SOUND ABSORPTION

$$\alpha = \frac{I_a}{I_i} \qquad (18.1)$$

where

I_a = sound power density (intensity) absorbed by the material, W/cm^2

I_i = intensity impinging on the material, W/cm^2

α = absorption coefficient, with no units since it represents a ratio

$$A = S\alpha \qquad (18.2)$$

where

A = total absorption, sabins

S = surface area, square feet or square meters

α = coefficient of absorption

$$\sum S\alpha = S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n$$

or

$$\sum A = A_1 + A_2 + \ldots + An \qquad (18.3)$$

where

$\Sigma S\alpha$ = total absorption in the room, sabins

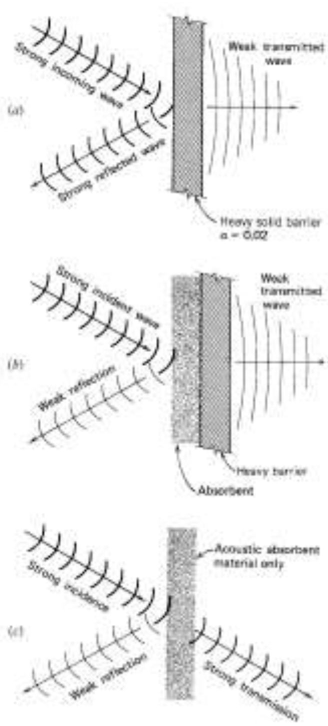
S_1, S_2, etc. = surface area of each material

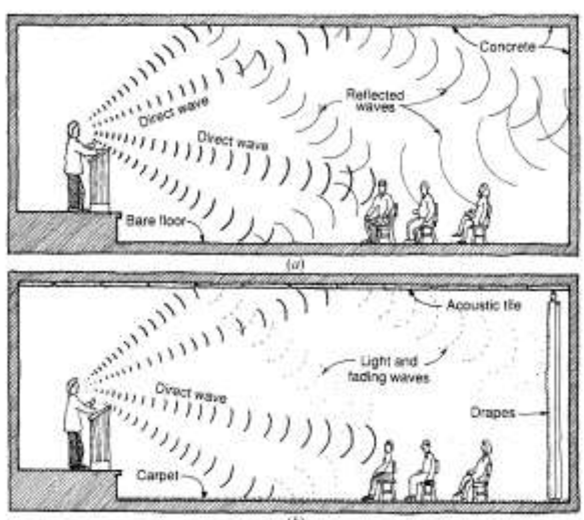
α_1, α_2, etc. = absorption coefficient of each material

A_1, A_2, etc. = total absorption of each material

	Absorption Coefficients (α)						
General Building Materials and Furnishings[b]	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC[c]
Brick, unglazed	0.03	0.03	0.03	0.04	0.05	0.07	0.005
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03	0.00
Carpet, heavy, on concrete	0.02	0.06	0.14	0.37	0.60	0.65	0.29
Carpet, heavy, on 40-oz (1.1 kg) hairfelt or foam rubber	0.08	0.24	0.57	0.69	0.71	0.73	0.55
Concrete block, coarse	0.36	0.44	0.31	0.29	0.39	0.25	0.35
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08	0.05
Fabrics							
Light velour, 10 oz/yd², hung straight, in contact with wall	0.03	0.04	0.11	0.17	0.24	0.35	0.15
Medium velour, 14 oz/yd², draped to half area	0.07	0.31	0.49	0.75	0.70	0.60	0.55
Heavy velour, 18 oz/yd², draped to half area	0.14	0.35	0.55	0.72	0.70	0.65	0.60
Floors							
Concrete or terrazzo	0.01	0.01	0.015	0.02	0.02	0.02	0.00
Linoleum, asphalt, rubber, or cork tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02	0.05
Wood	0.15	0.11	0.10	0.07	0.06	0.07	0.10
Glass							
Large panes of heavy plate glass	0.18	0.06	0.04	0.03	0.02	0.02	0.05
Ordinary window glass	0.35	0.25	0.18	0.12	0.07	0.04	0.15
Gypsum board, ½ in. nailed to 2 × 4's 16 in. o.c.	0.10	0.08	0.05	0.03	0.03	0.03	0.05
Marble or glazed tile	0.01	0.01	0.01	0.01	0.02	0.02	0.00
Openings							
Stage, depending on furnishings				0.25–0.75			
Deep balcony, upholstered seats				0.50–1.00			
Grilles, ventilating				0.15–0.50			
Plaster, gypsum or lime, smooth finish on tile or brick	0.013	0.015	0.02	0.03	0.04	0.05	0.05
Plaster, gypsum or lime, on lath	0.14	0.10	0.06	0.05	0.04	0.03	0.05
Plywood paneling, ⅜ in. (9 mm) thick	0.28	0.22	0.17	0.09	0.10	0.11	0.15
Rough wood, as tongue-and-groove cedar	0.24	0.19	0.14	0.08	0.13	0.10	0.14
Slightly vibrating surface (e.g., hollow core door)	0.02	0.02	0.03	0.03	0.04	0.05	0.03
Readily vibrating surface (e.g., thin wood paneling on 16-in. [406 mm] studs)	0.10	0.07	0.05	0.04	0.04	0.05	0.05
Water surface, as in a swimming pool	0.008	0.008	0.013	0.015	0.020	0.025	0.00

Absorption of Seats and Audience[d]		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC[c]
Audience, in upholstered seats, per ft² of floor area		0.60	0.74	0.88	0.96	0.93	0.85	—
Unoccupied cloth-upholstered seats, per ft² of floor area		0.49	0.66	0.80	0.88	0.82	0.70	—
Wooden pews, occupied, per ft² of floor area		0.57	0.61	0.75	0.86	0.91	0.86	—
Students in tablet-arm chairs, per ft² of floor area		0.30	0.42	0.50	0.85	0.85	0.84	
Acoustic Absorptive Materials	**Mtg[e]**	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**NRC[c]**
High-performance vinyl-faced fiberglass ceiling panels								
1 in. thick	E405	0.73	0.88	0.71	0.98	0.96	0.77	0.90
1.5 in. thick	E405	0.79	0.98	0.83	1.03	0.98	0.80	0.95
Painted nubby glass cloth panels								
¾ in. thick	E405	0.81	0.94	0.65	0.87	1.00	0.96	0.85
1 in. thick	E405	0.78	0.92	0.79	1.00	1.03	1.10	0.95
Random fissured ¾-in.-thick panels	E405	0.52	0.58	0.60	0.80	0.92	0.80	0.70
Perforated metal panel with infill 1 in. thick	E405	0.70	0.86	0.74	0.88	0.95	0.86	0.85
Typical averages, mineral fiber tiles and panels								
¾ in. fissured	E405	0.47	0.50	0.52	0.76	0.86	0.81	0.65
¾ in. textured	E405	0.49	0.55	0.53	0.80	0.94	0.83	0.70
⅝ in. fissured	E405	0.28	0.33	0.66	0.73	0.74	0.75	0.60
⅝ in. textured	E405	0.29	0.35	0.66	0.63	0.44	0.34	0.50
⅝ in. perforated	E405	0.27	0.29	0.55	0.78	0.69	0.53	0.60
3 in. thick × 16 in. square on 24-in. centers	A	0.40	0.61	1.92	2.54	2.62	2.60	





ROOM ACOUSTICS

REVERBERATION TIME

Reverberation is the persistence of sound after the sound source has ceased. Such persistence is a result of repeated reflections in an enclosed space.

Reverberation time (*TR*) is defined as the time required for the sound level to decrease 60 dB after the sound source has stopped producing sound

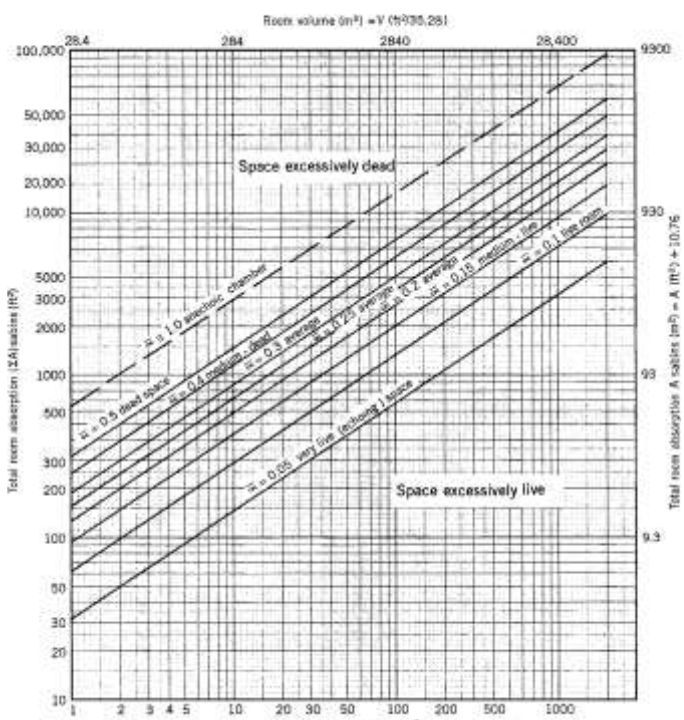
$$T_R = K \times \frac{V}{\sum A} \text{ seconds} \tag{18.4}$$

where

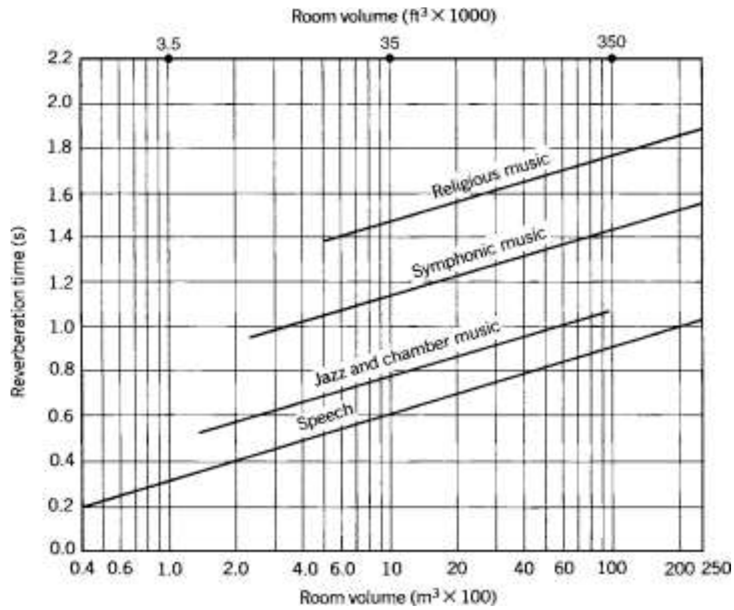
K = a constant, equal to 0.05 when measurements are in feet and 0.16 when in meters

V = room volume, ft^3 or m^3

$\sum A$ = total room absorption, sabins (ft^2 or m^2) at the frequency in question



Reverberation time for speech



$$T_R\,(\text{speech}) = 0.3 \log \frac{V}{10} \qquad (18.18)$$

where

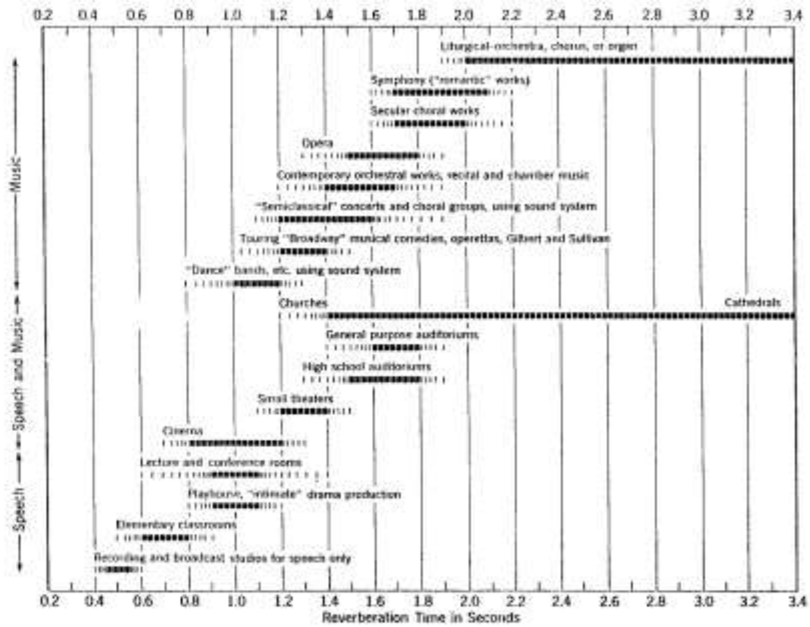
T_R (speech) = optimum reverberation time in seconds, for speech

V = room volume, m^3

For instance, a typical classroom might have a volume of 150 m^3 (5300 ft^3). Optimum reverberation time is

$$T_R = 0.3 \log 15 = 0.35 \text{ s}$$

Reverberation time for music



1. Large-volume spaces require direct-path sound reinforcement by reflection.

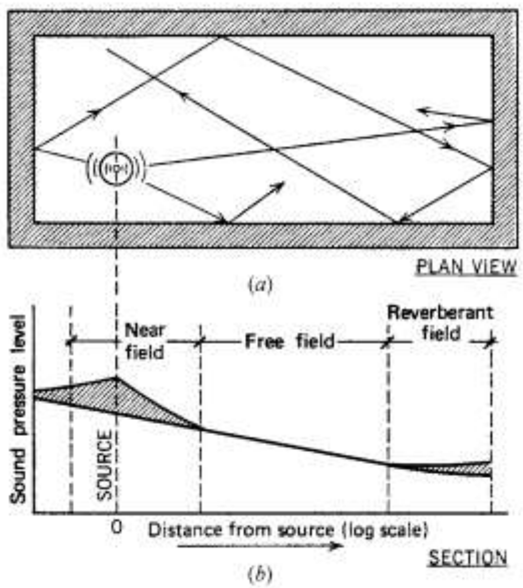
2. Relatively long reverberation time is needed to enhance the music—the exact amount depending upon the type of music. Designers should keep in mind that reverberation time recommendations vary as much as 100% among respected sources.

3. It is generally agreed that reverberation time should vary inversely with frequency (i.e., *TR* should be longer at lower frequencies [than the mid-frequency recommendation] and shorter at higher frequencies). The longer *TR* at low frequencies adds fullness to music and "body" to speech. Thus, *TR* at 100 Hz should be, according to most researchers, 35% to 75% longer than *TR* at the center frequencies.

4. Short *TR* at upper frequencies adds directivity to the music. With large ensembles, directivity gives the sense of depth and instrument location necessary for proper appreciation. This is often referred to as *clarity* or *definition* in music. With a solo instrument, this problem is diminished.

5. Brilliance of tone is primarily a function of high-frequency content. Since these frequencies are most readily absorbed, a good direct path must exist between sound source and listener. Since our eyes and ears are close together, a good sound path exists when a good vision path exists.

SOUND FIELDS IN AN ENCLOSED SPACE



I-P units:

$$SPL = PWL + 10 \log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) + 10.5 \quad (18.5)$$

SI units:

$$SPL = PWL + 10 \log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) + 0.2 \quad (18.6)$$

where

Q = a directivity constant

SPL = sound pressure level, dB

PWL = sound power level, dB

r = distance from source, ft (m)

R = room factor, ft² (m²)

The factor R can be calculated from

$$R = \frac{\Sigma S\,\overline{\alpha}}{1 - \overline{\alpha}}$$

where

ΣS = total room surface area, ft² (m$_2$)

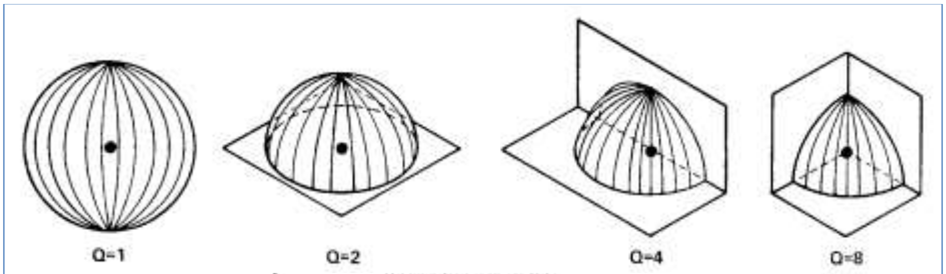
$\overline{\alpha}$ = average absorption coefficient of all materials in the room

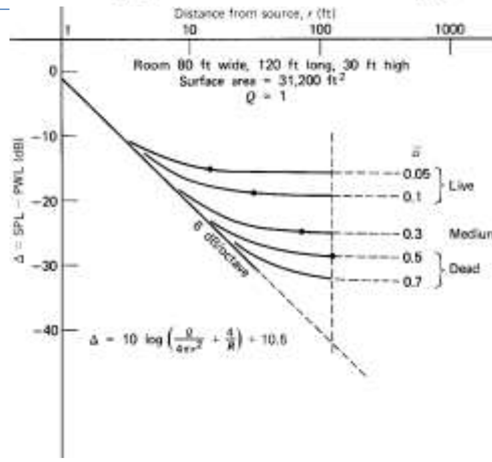
that is,

$$\overline{\alpha} = \frac{\Sigma A(\text{total room absorption})}{\Sigma S(\text{total room surface area})} \quad (18.7)$$

or

$$\overline{\alpha} = \frac{S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n}{S_1 + S_2 + \cdots + S_n} \quad (18.8)$$





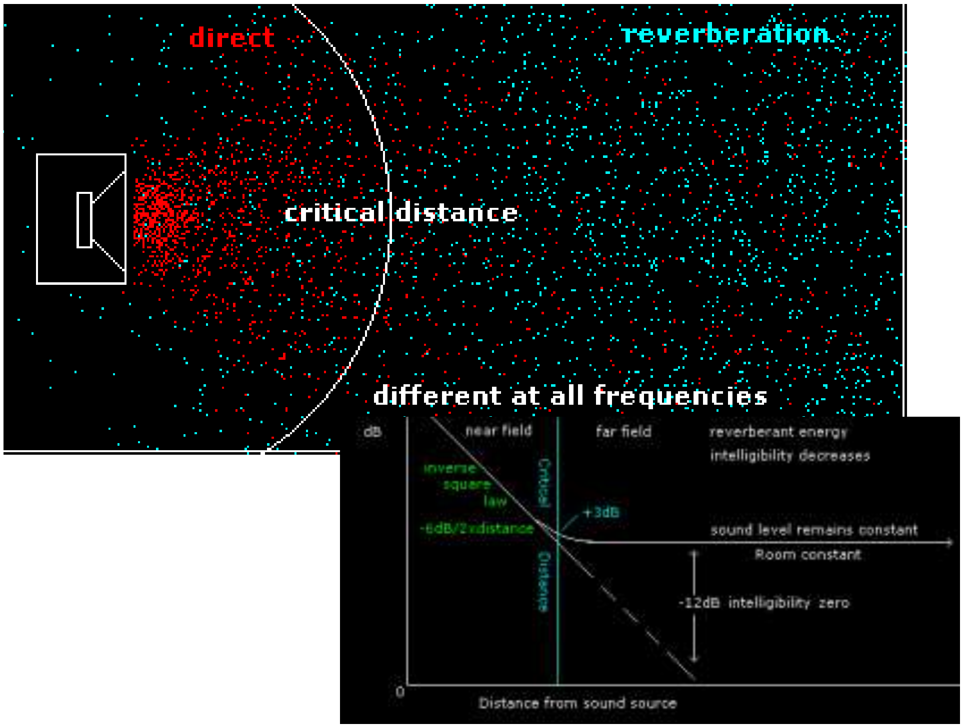
Critical distance

Critical distance is, (in audio physics),

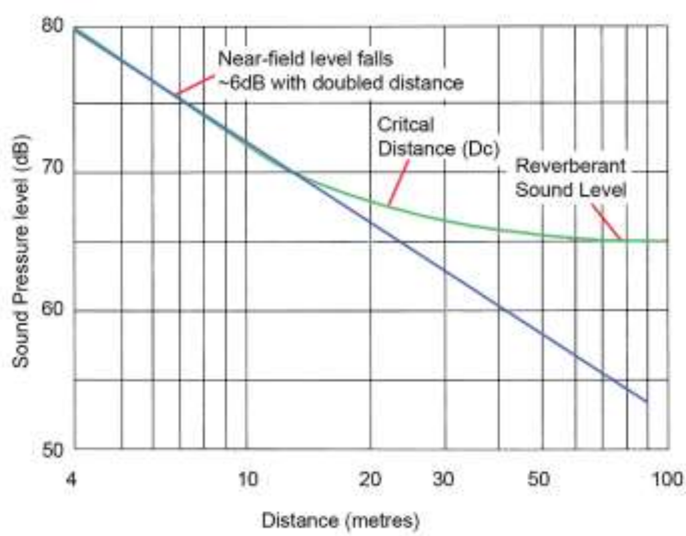
the distance at which the sound pressure level of the direct and the reverberant sound fields are equal.

In other words, the point in space where the amplitude of a reflected echo is the same as that of the source. This distance is dependent on the **geometry and absorption of the space, as well as the dimensions and shape of the sound source.**

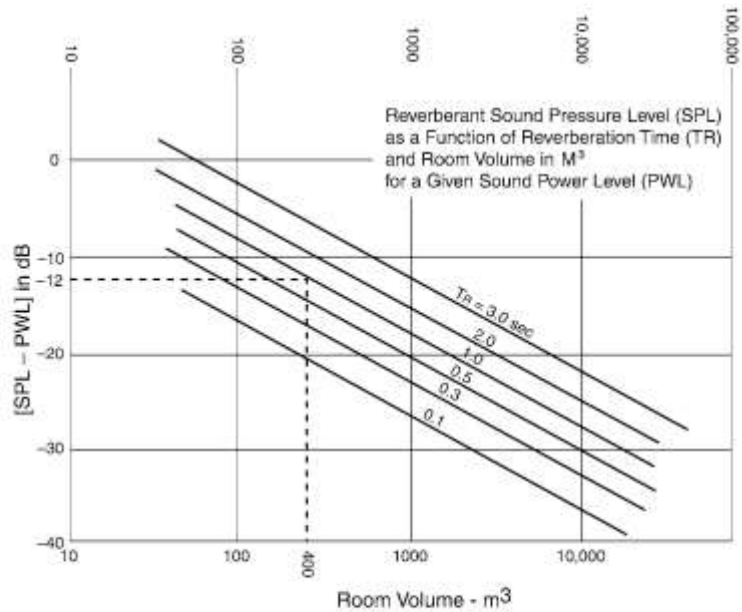
In a room within which a sound is generated, e.g. by a loudspeaker, every point is characterized by its own unique ratio of direct sound and sound reflected from the walls. The distance from the sound source at which the direct and reflected sound energies are equal is called the "critical distance".



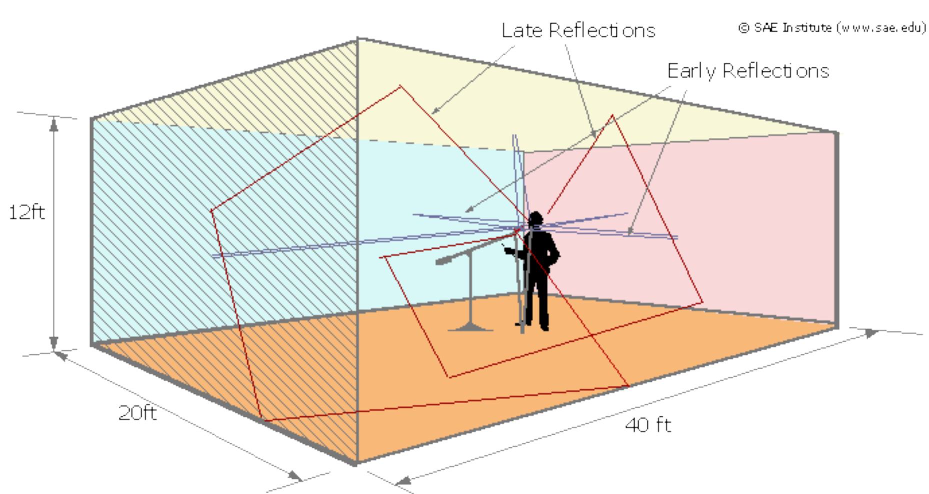
$$Dc = 0.14 \sqrt{Q*R}$$

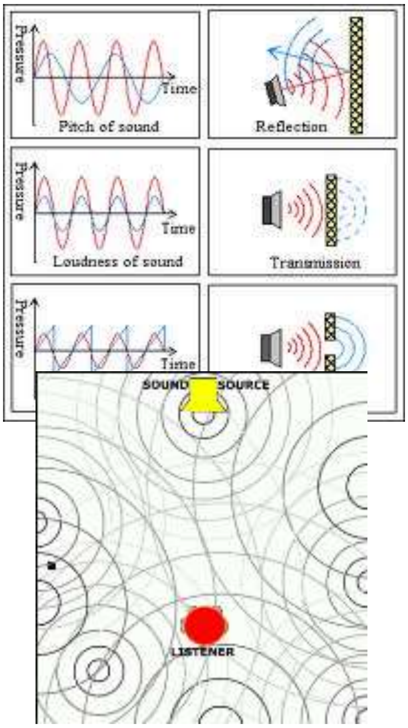


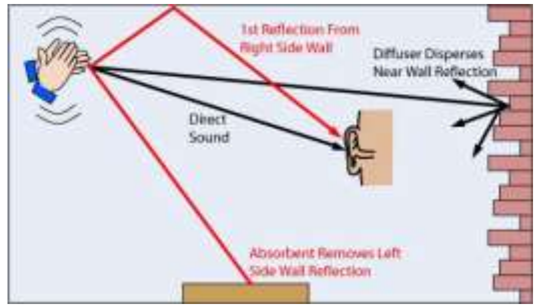
SPL and TR_{60}

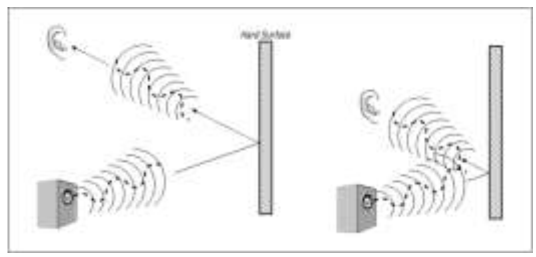


Sound Reflection

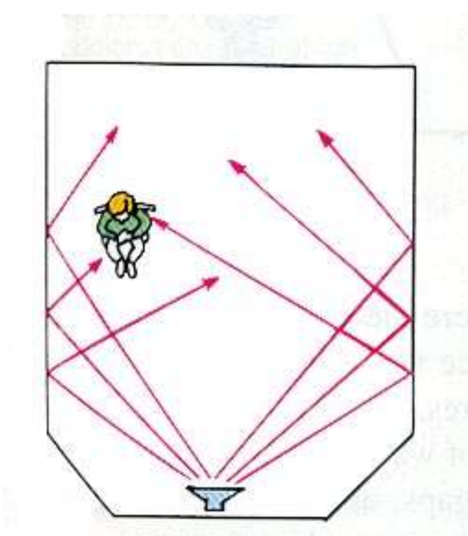


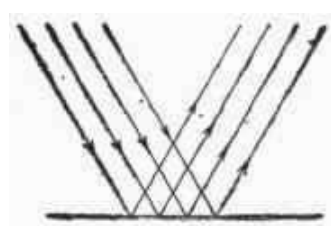


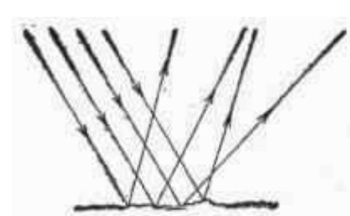




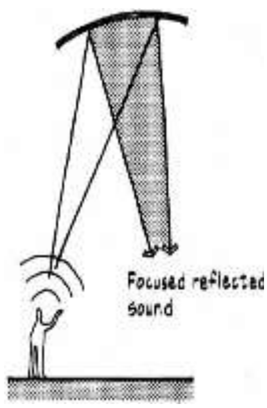
Reflection on surfaces

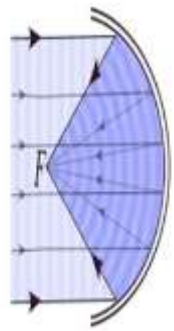


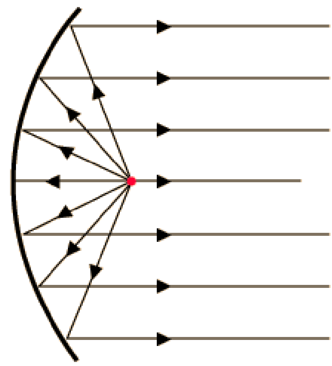


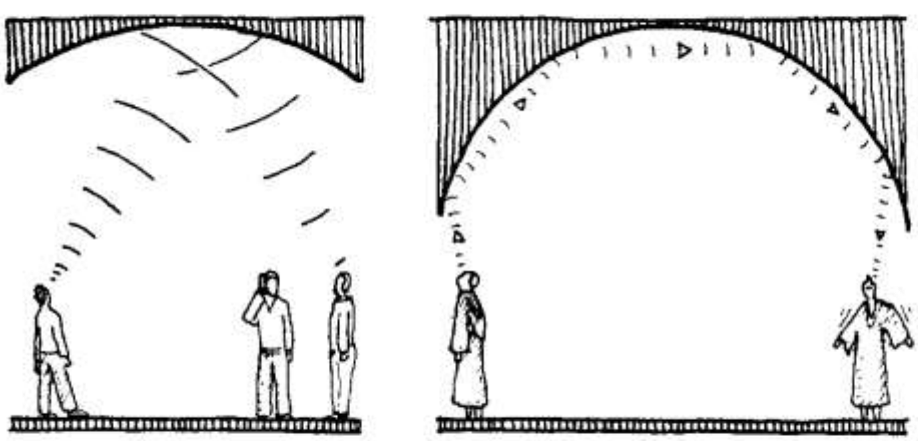


Curved surfaces



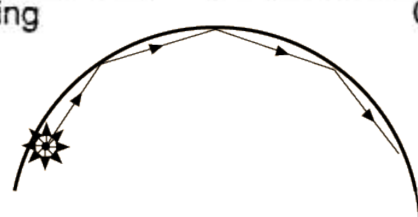




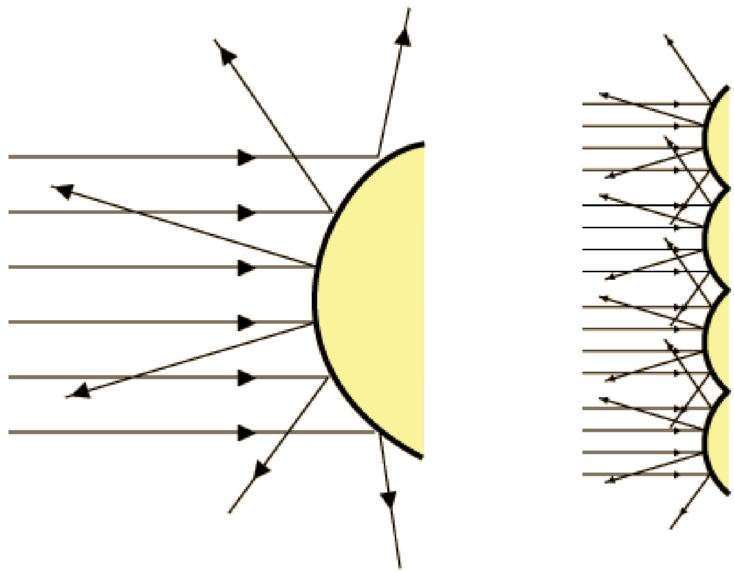


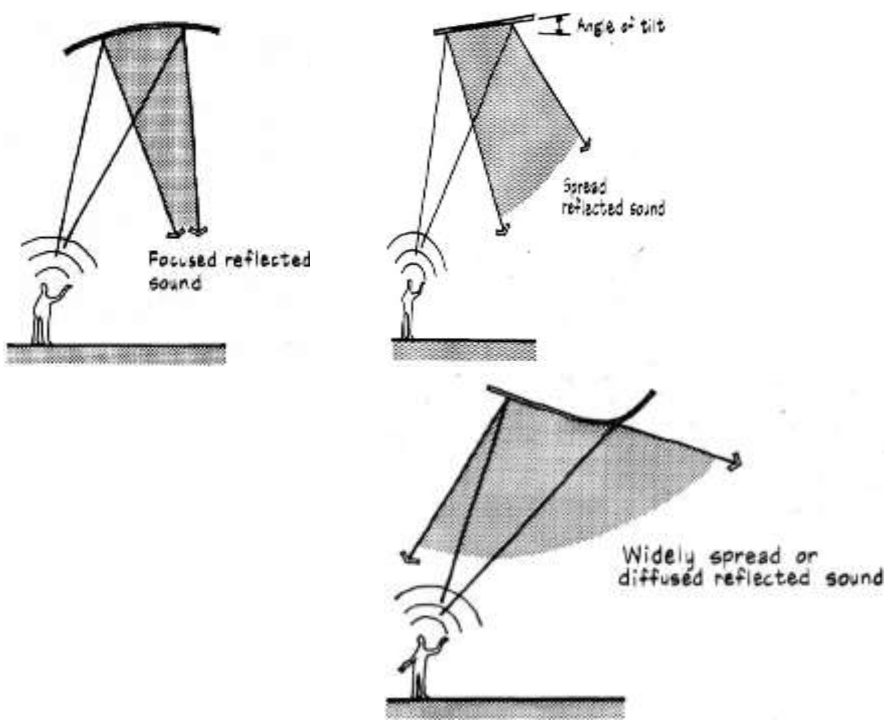
Focusing (a)

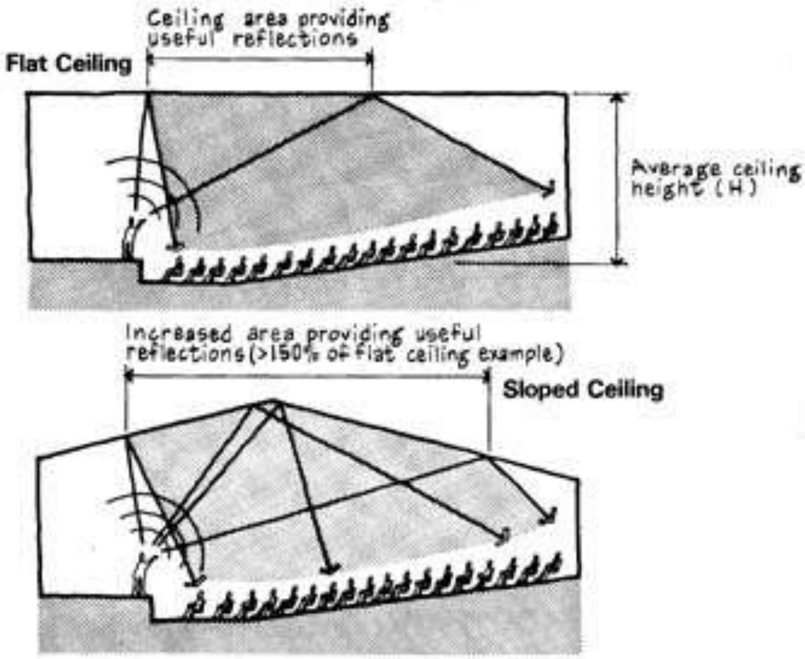
Creep (b)

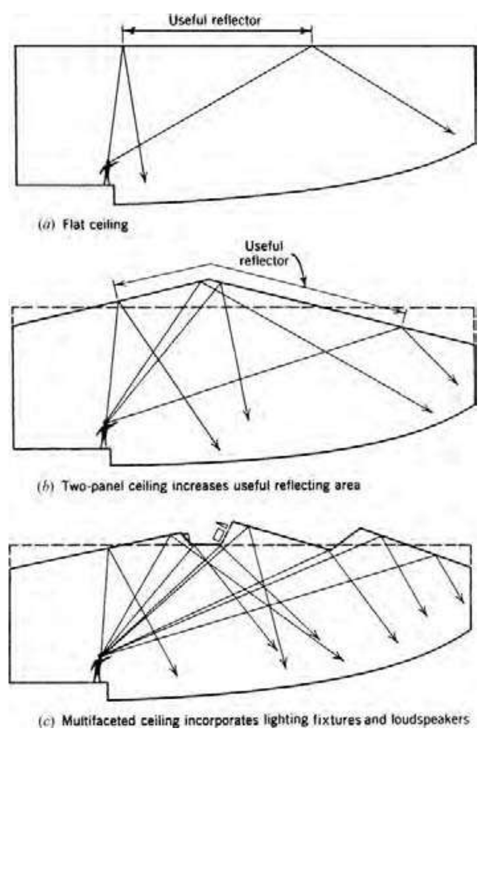


Diffuser




Focused reflected sound
Angle of tilt
Spread reflected sound
Widely spread or diffused reflected sound

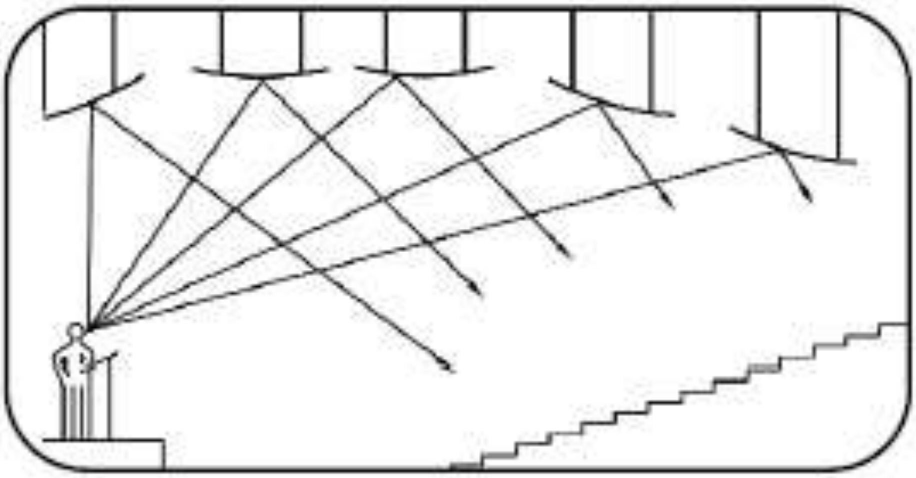


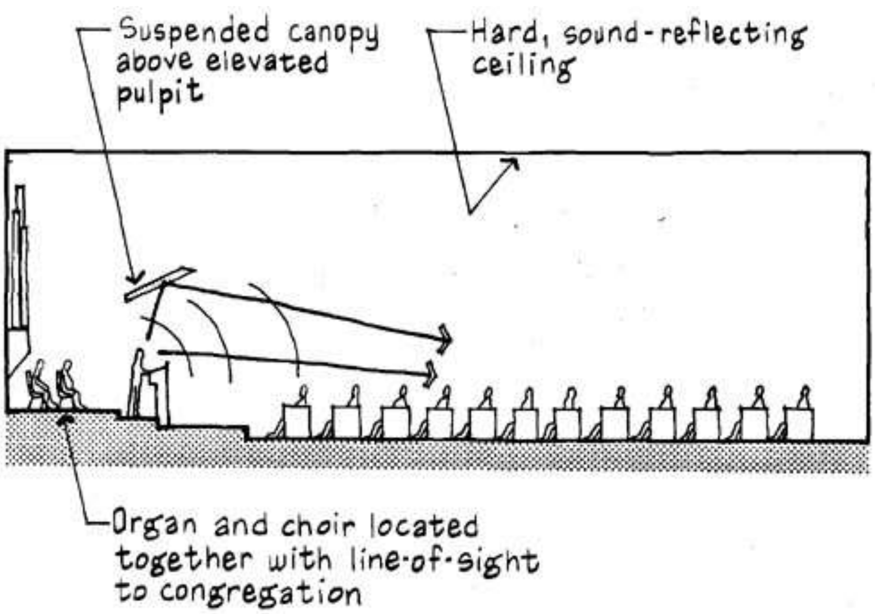


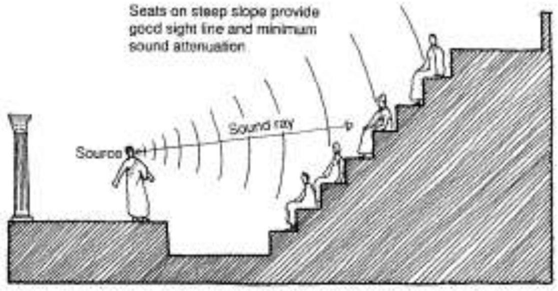
(a) Flat ceiling

(b) Two-panel ceiling increases useful reflecting area

(c) Multifaceted ceiling incorporates lighting fixtures and loudspeakers




Suspended canopy above elevated pulpit
Hard, sound-reflecting ceiling
Organ and choir located together with line-of-sight to congregation


Seats on steep slope provide good sight line and minimum sound attenuation
Sound ray
Source

(a)

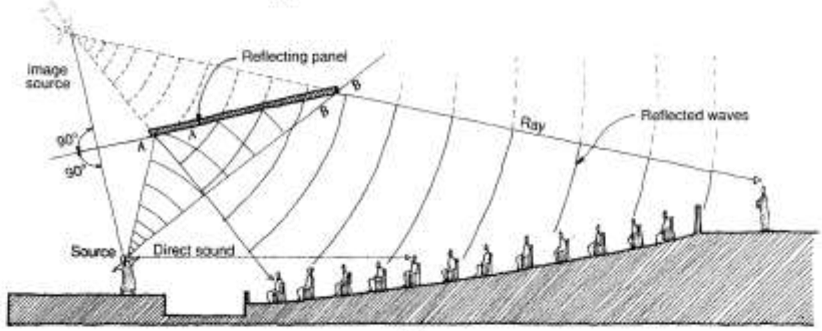
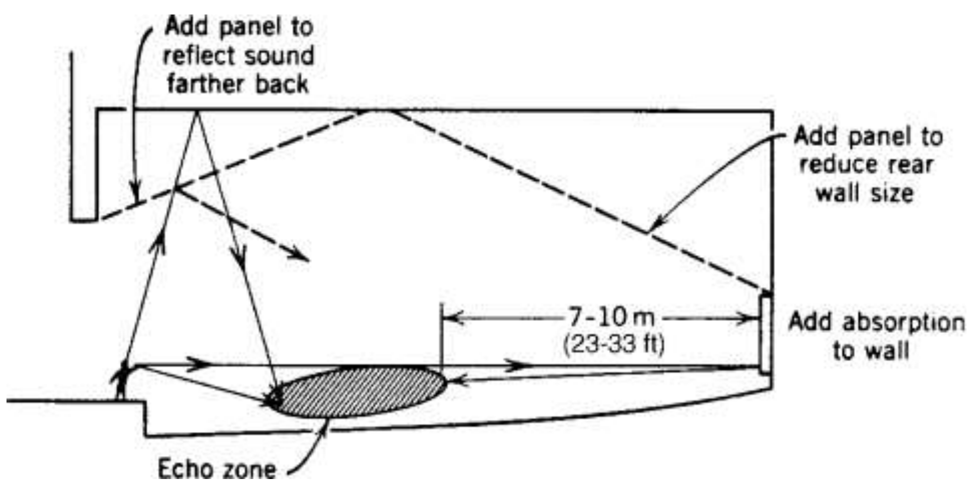
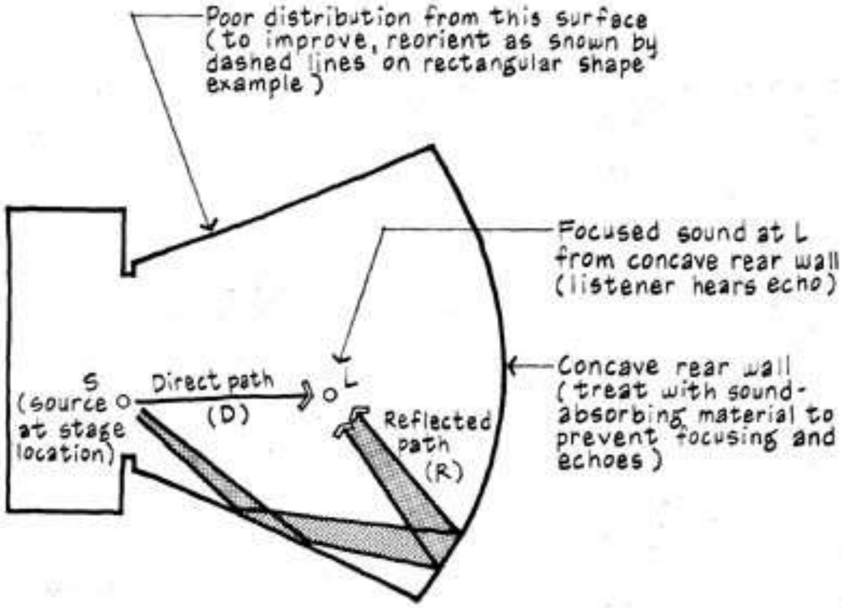
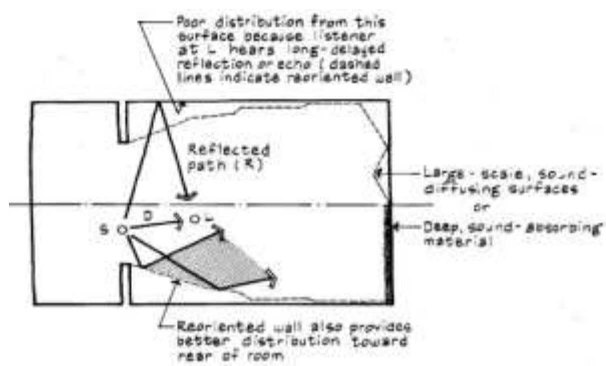


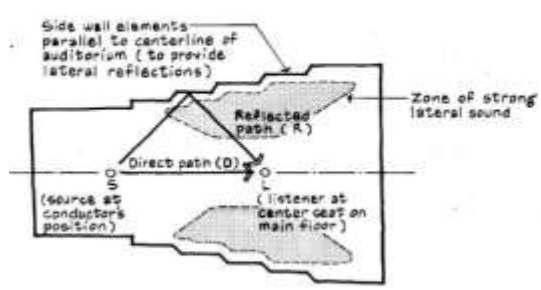
Image source
Reflecting panel
Reflected waves
Ray
90°
90°
A
B
Source
Direct sound

(b)

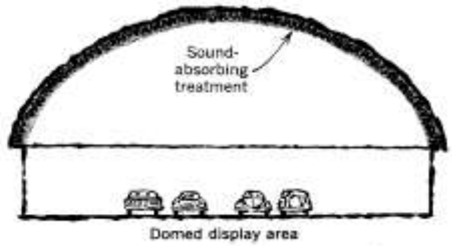

Add panel to reflect sound farther back
Add panel to reduce rear wall size
7-10 m
(23-33 ft)
Add absorption to wall
Echo zone

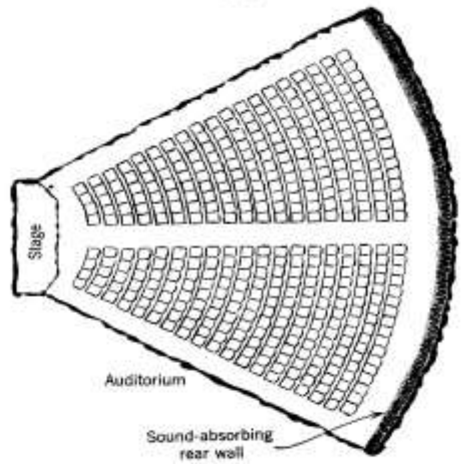

Poor distribution from this surface (to improve, reorient as shown by dashed lines on rectangular shape example)
Focused sound at L from concave rear wall (listener hears echo)
Concave rear wall (treat with sound-absorbing material to prevent focusing and echoes)
S (source at stage location)
Direct path (D)
L
Reflected path (R)

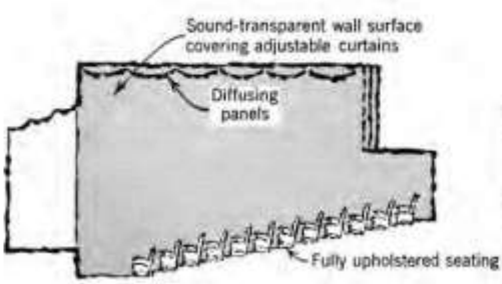

Poor distribution from this surface because listener at L hears long-delayed reflection or echo (dashed lines indicate reoriented wall)
Reflected path (R)
Large-scale, sound-diffusing surfaces
or
Deep, sound-absorbing material
S
D
L
Reoriented wall also provides better distribution toward rear of room


Side wall elements parallel to centerline of auditorium (to provide lateral reflections)
Zone of strong lateral sound
Reflected path (R)
Direct path (D)
S
(source at conductor's position)
L
(listener at center seat on main floor)

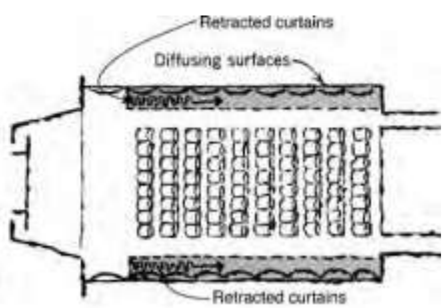
Absorption







Section



Plan

Echo and flattering