

# ACOUSTICS DESIGN IN AUDITORIA: THE CASE OF THE LRC AT CUEA

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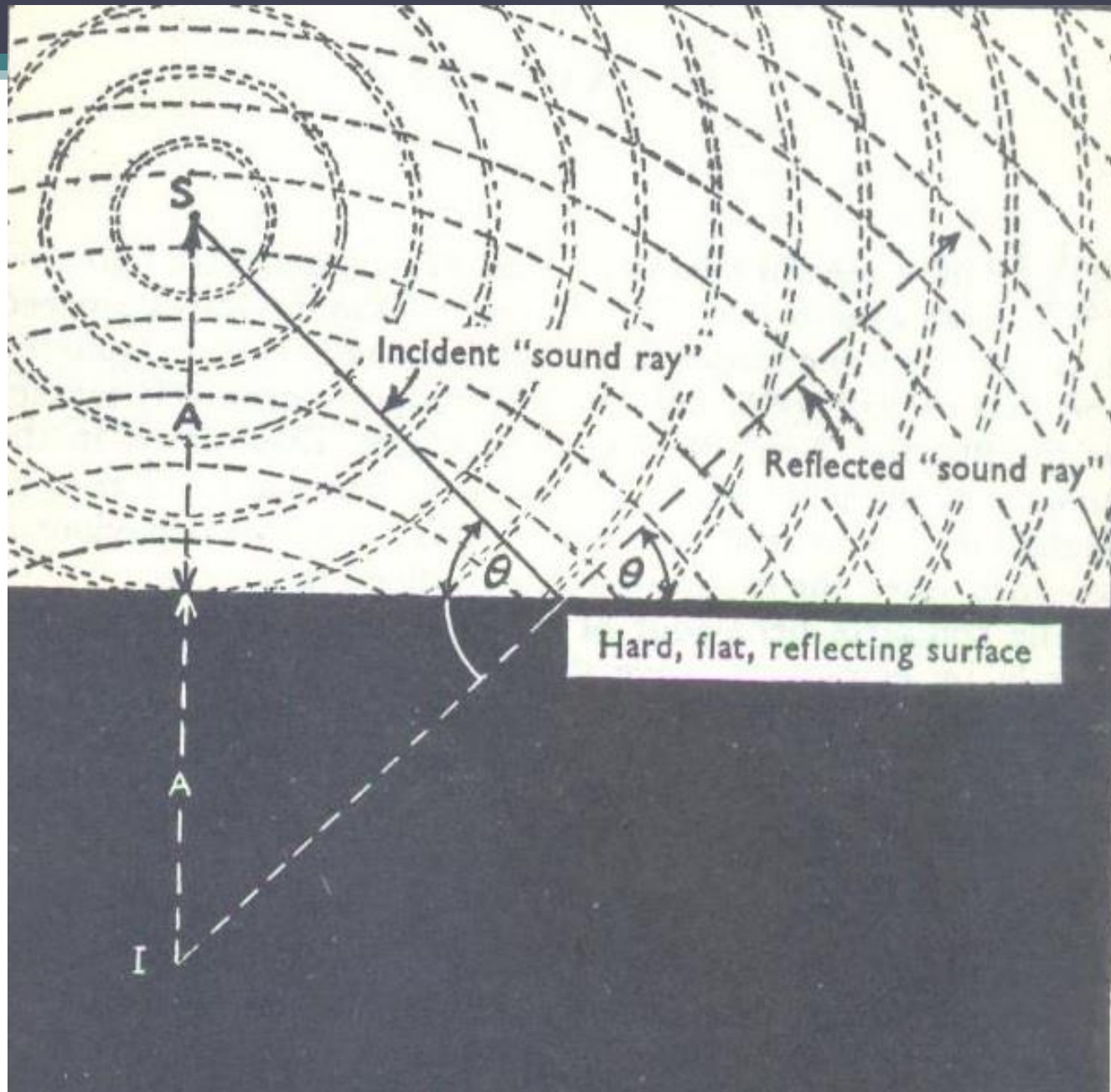
# **1.0 Introduction**

If one examines acoustic qualities of large gathering spaces in Kenya, nothing seems to work. A visit to most churches, lecture halls and conference facilities including those in 5-star hotels will attest to this. This paper explores the different architectural design strategies that are required to achieve quality acoustics' environment in these spaces.

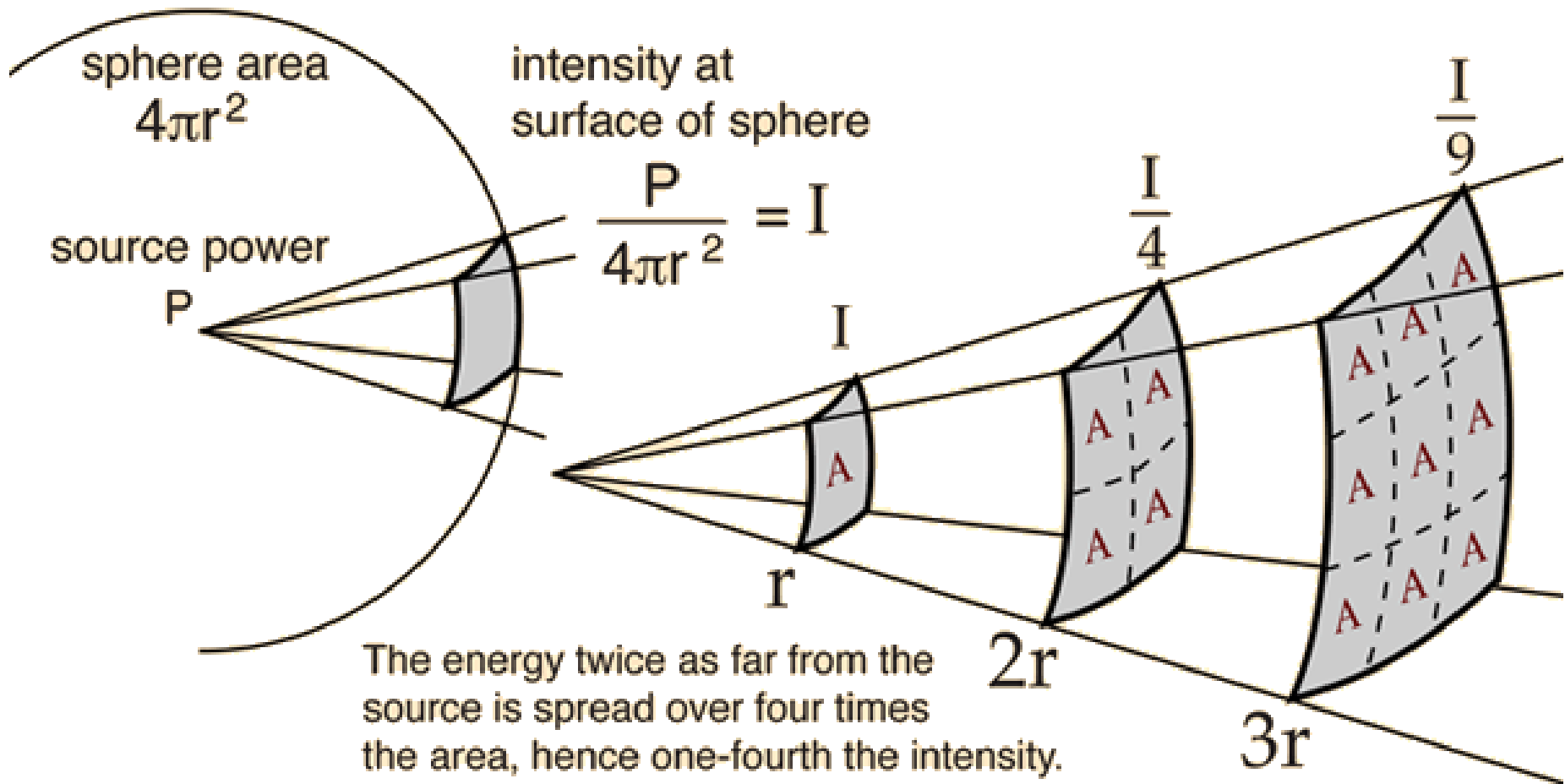
## **2.0 Behaviour of sound in rooms**

When sound is originated from a point source in air, a series of sound waves proceed outwards from the source in an ever-increasing concentric spheres, and the sound energy at any point becomes progressively weaker as the distance from the source increases.

Thus, the sound intensity from a point source of sound will obey the inverse square law if there are no reflections.

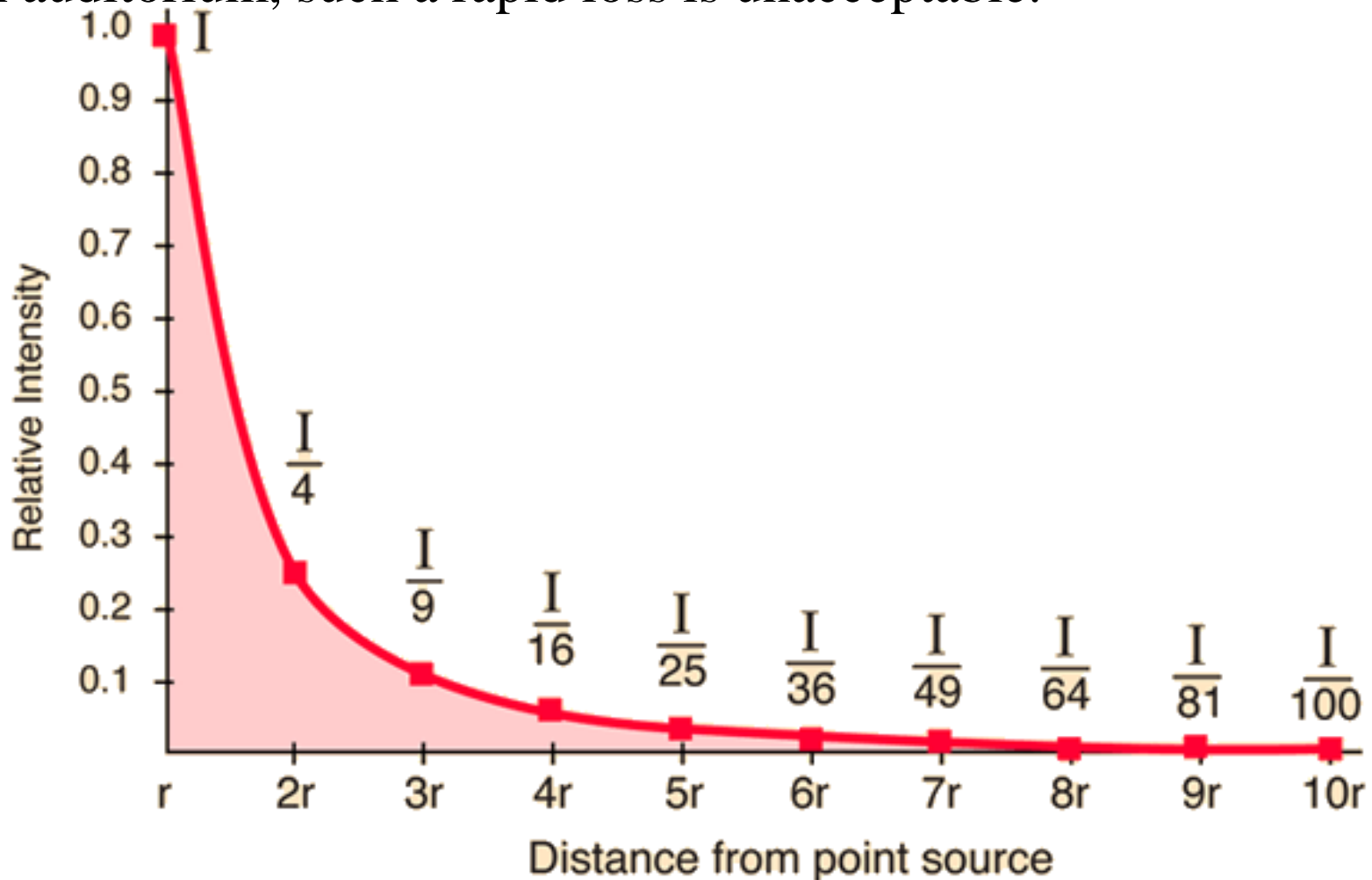


**Reflection from a Plane surface**



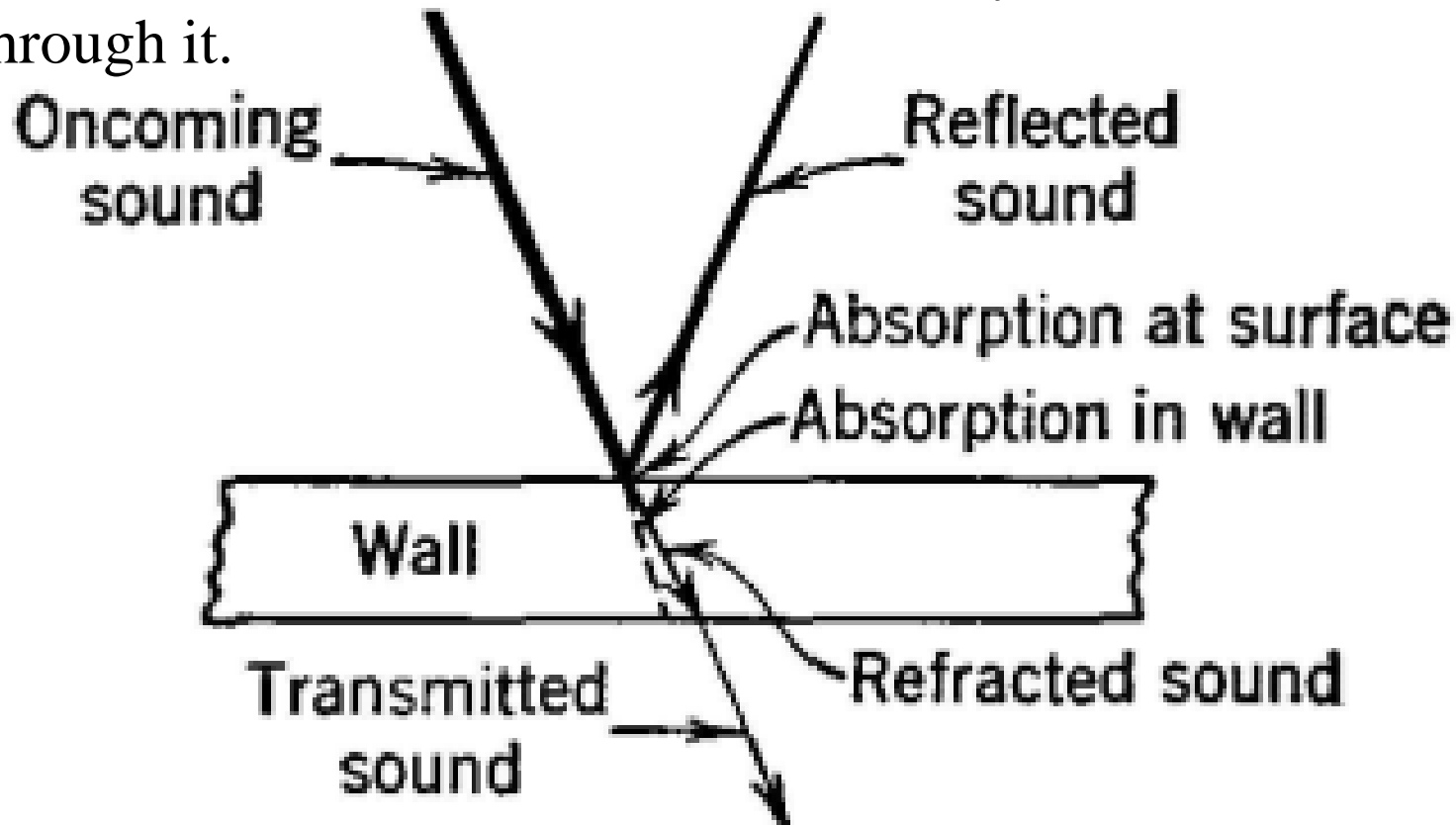
## Inverse Square Law, Sound

A graph of the drop of sound intensity according to the inverse square law emphasizes the rapid loss associated with the inverse square law. In an auditorium, such a rapid loss is unacceptable.



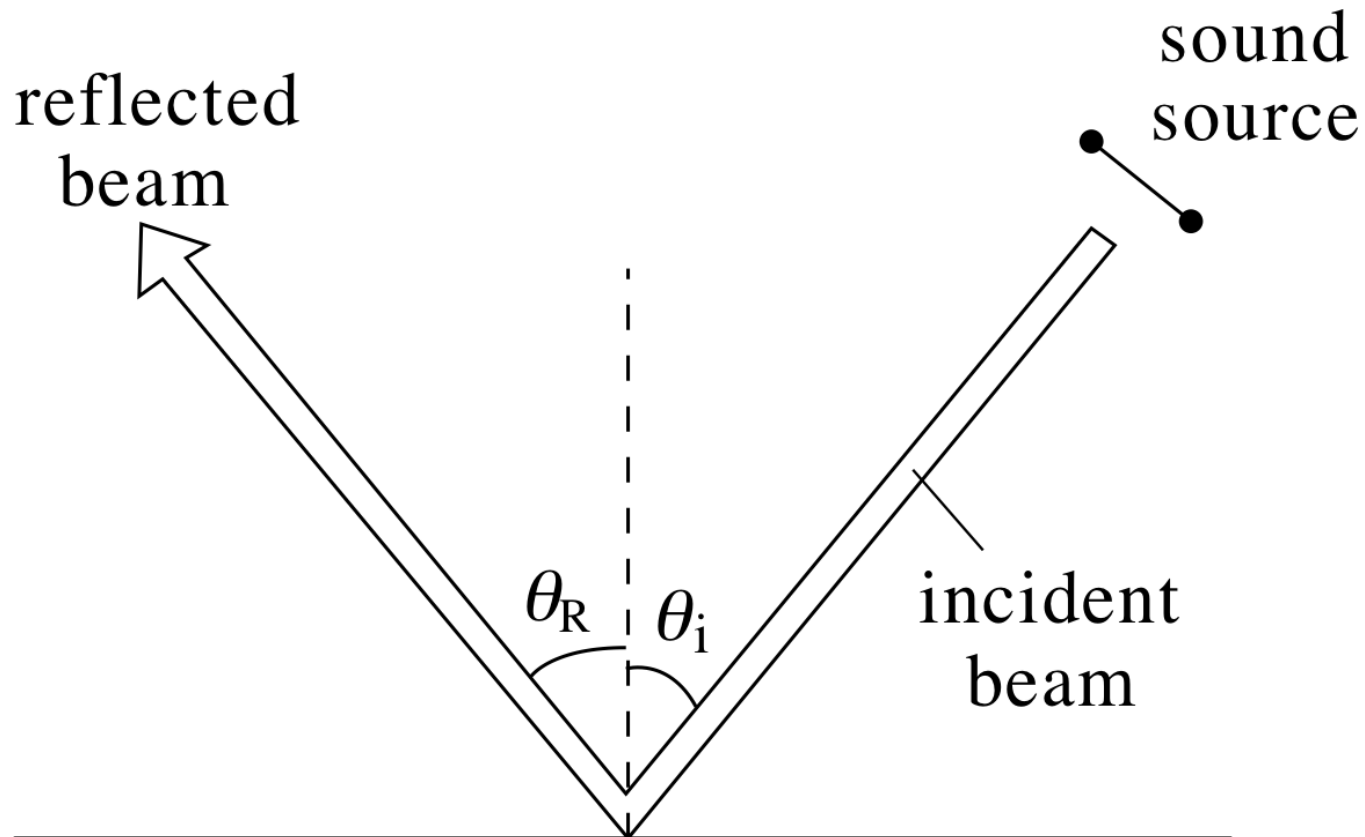
**Graph showing the Inverse Square Law**

The analysis of the paths of the sound waves can be used to find out the path of the direct sound and what kind of distribution the first few reflections of sound will have. When sound waves strike one of the room boundaries or surfaces, some of the sound energy is reflected from the surface, some is absorbed by it and some is transmitted through it.

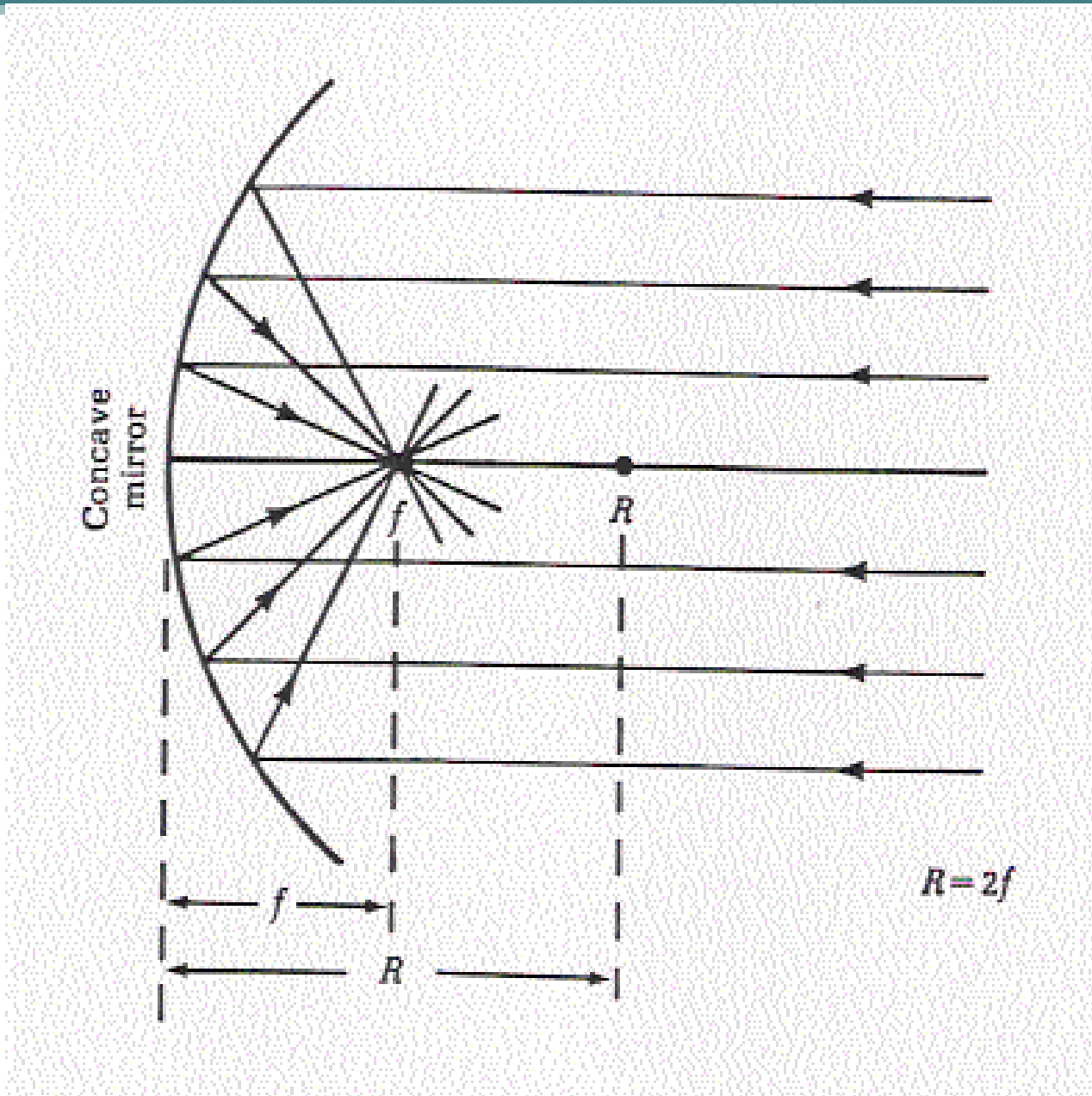


**Phenomena occurring when a sound wave strikes a rigid wall**

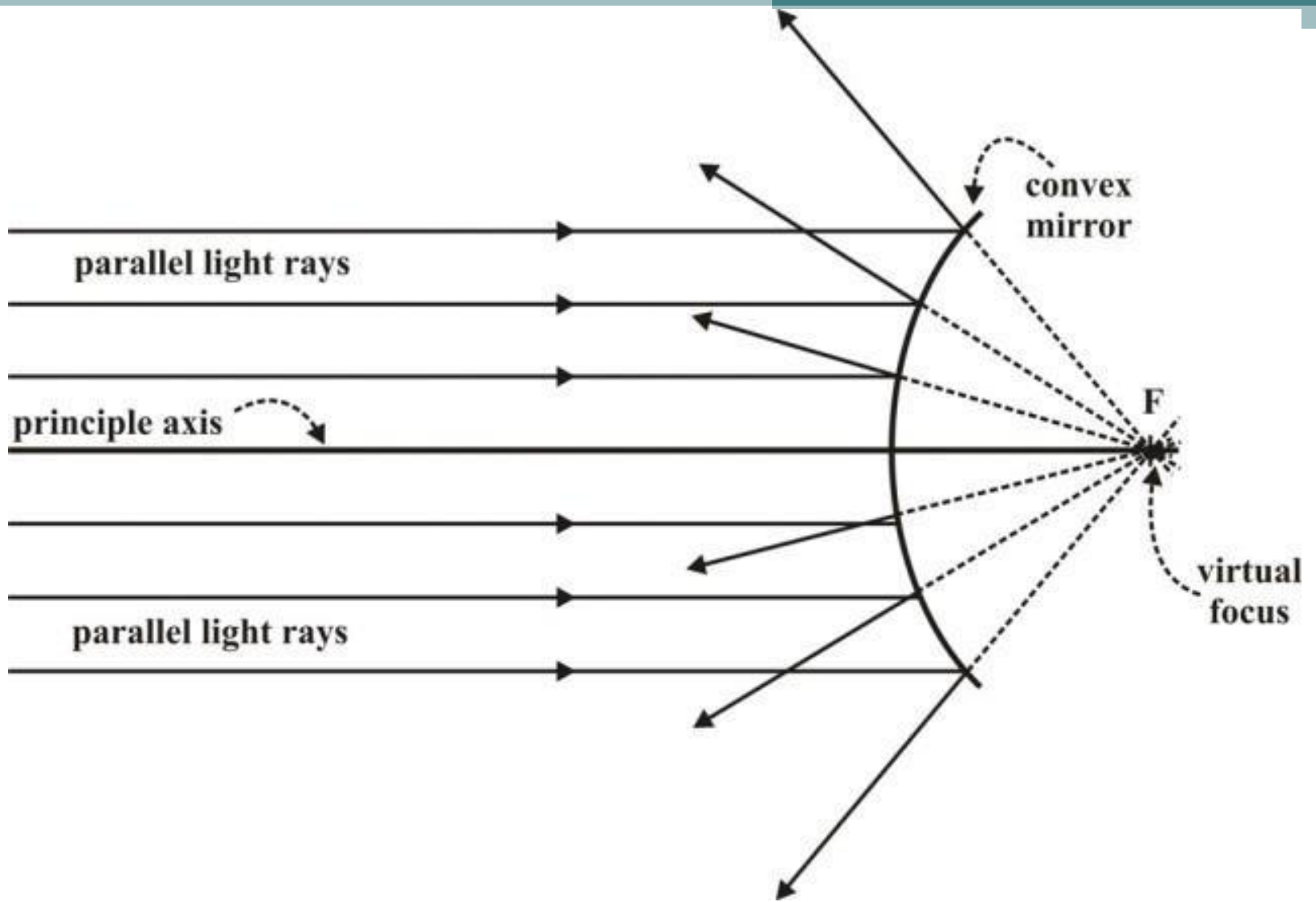
For a hard flat reflecting surface, the angle of reflection in all cases equals the angle of incidence. Reflected sound waves from curved surfaces are such that those from a convex surface disperse whereas those from a concave surface converge.



Reflection of sound from a flat surface.



**Reflection of sound from a spherical concave mirror**



**Reflection of sound from a spherical convex mirror**

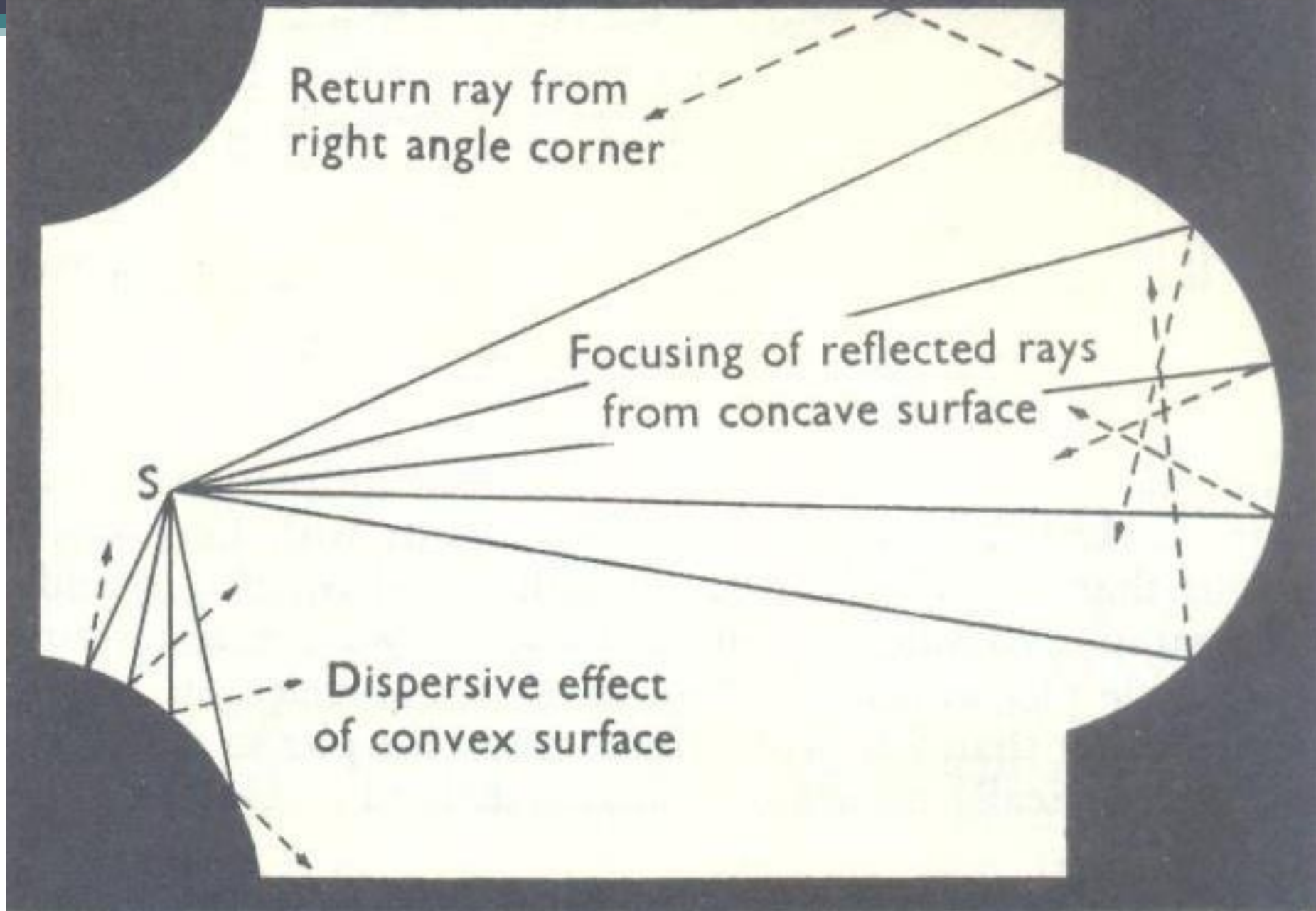
Return ray from  
right angle corner


Focusing of reflected rays  
from concave surface

Dispersive effect  
of convex surface

S

**Reflections from curved surfaces and corners**





The nature of the surfaces on which the sound waves falls determines how much will be absorbed. Broadly, hard rigid non-porous surfaces provide the least absorption (or are thus the best reflectors), while soft porous surfaces and those which can vibrate absorb more of the sound. When sound energy is absorbed, it is converted into heat energy, although the amount of heat is very small.

The efficiency of the absorption process is rated by a number, the **ABSORPTION COEFFICIENT** of the material, varying from zero to one. If no sound at all is absorbed, the coefficient would be 0 and if all sound is absorbed, the coefficient is 1.0

# Absorption Coefficients

**Table 8-3** Average Absorption Coefficients for Several Types of Building Materials at Octave Frequency Intervals

Material	Frequency (Hz)					
	125	250	500	1000	2000	4000
Concrete, bricks	0.01	0.01	0.02	0.02	0.02	0.03
Glass	0.19	0.08	0.06	0.04	0.03	0.02
Plasterboard	0.20	0.15	0.10	0.08	0.04	0.02
Plywood	0.45	0.25	0.13	0.11	0.10	0.09
Carpet	0.10	0.20	0.30	0.35	0.50	0.60
Curtains	0.05	0.12	0.25	0.35	0.40	0.45
Acoustical board	0.25	0.45	0.80	0.90	0.90	0.90

**Table 8-4** Average Absorption in Sabins at Octave Frequency Intervals of Seats and a Person

	Frequency (Hz)				
	125	250	500	1000	2000
Unupholstered seat	0.15	0.22	0.25	0.28	0.50
Upholstered seat	3.0	3.1	3.1	3.2	3.4
Adult person	2.5	3.5	4.2	4.6	5.0
Adult in upholstered seat	3.0	3.8	4.5	5.0	5.2

# Reverberation time

Each time sound waves meet the boundary surfaces of a room, some of their energy is absorbed, while the remainder is represented by the waves reflected from the surface. The reflected waves eventually meet a boundary and again part of their energy is absorbed and the other part is re-reflected and so on. In the lack of continuous replacement of the original sound energy, we would therefore expect any sound produced in a room to die away slowly to inaudibility, rather than to cease abruptly when the supplying energy is turned off. **How long this dying away process takes depends on two factors, namely how much absorption occurs when the waves meet the boundaries and how often they do so.**

- i) The first factor is the sum of the product of the areas of the different types of internal surfaces and their absorption efficiency or coefficient. The sound decay time will be less when the absorption is great.

$$A = \alpha \cdot S = \text{equivalent absorption surface or area in m}^2$$

ii) The second factor depends on the size or volume of the room because sound travels at a fixed speed, and the greater the volume, the less often the waves meet the wall absorbing surfaces and thus the longer will be the decay time.

This relationship was first put into quantitative form by W.C. Sabine (1868 - 1919) towards the end of the nineteenth century, in 1898. This relationship is called the reverberation time formula. The now well-known Sabine formula states that the time required for sound to decay by 60 decibels (reverberation time) and is found from the equation:

$$RT_{60} = k \cdot V / A = 0.161 \cdot V / A \quad (\text{V and A in metres})$$

$$\text{with } k = (24 \times \ln 10) / c_{20} = 0.161 \text{ (meter)}$$

$$RT_{60} = \text{reverberation time in seconds (reverb time)}$$

RT is expressed in seconds.

$V$  = room volume in  $\text{m}^3$

$A = \alpha \cdot S$  = equivalent absorption surface or area in  $\text{m}^2$

$\alpha_1 \dots \alpha_n$  = **absorption coefficients** or attenuation coefficients

The terms "attenuation coefficient" and "absorption coefficient" are used interchangeably

$S_1 \dots S_n$  = absorbing surface areas in  $\text{m}^2$

$A = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \dots$

$c_{20}$  = **speed of sound** is 343 m/s at  $20^\circ\text{C}$

Sound engineers and sound designers ("ear people") mostly use the usual sound field quantity. They therefore state:

$RT_{60}$  is the reverberation time, it takes for the **sound pressure level**  $L_p$  (SPL) to decrease by 60 dB.

Acousticians and sound protectors ("noise fighters") seem to like more the sound energy quantity. They express this differently:

$RT_{60}$  is the reverberation time, it takes for the **sound intensity level  $L_1$**  to decrease by 60 dB.

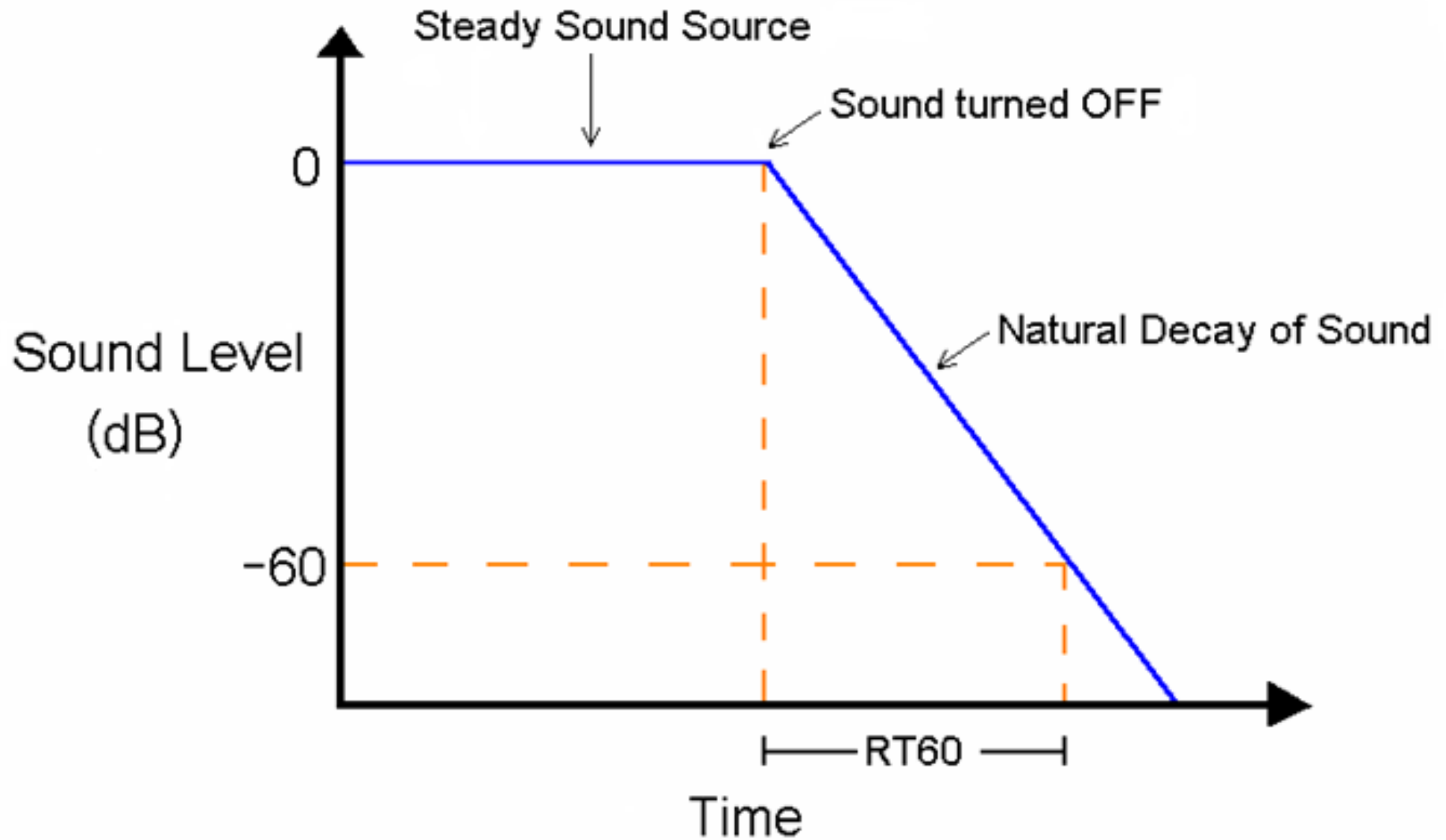
Sometimes you may hear the statement:

$RT_{60}$  is the reverberation time, it takes for the **sound level  $L$**  to drop by 60 dB.

Whatever the user wants to tell us so accurately. **Level is level or dB is dB.**

**Reverberation time ( $RT$ )** is a measure of the amount of reverberation in a space and equal to the time required for the level of a steady sound to decay by 60 dB after the sound has stopped.

The **decay rate** depends on the amount of **sound absorption** in a room, the room geometry, and the frequency of the sound.



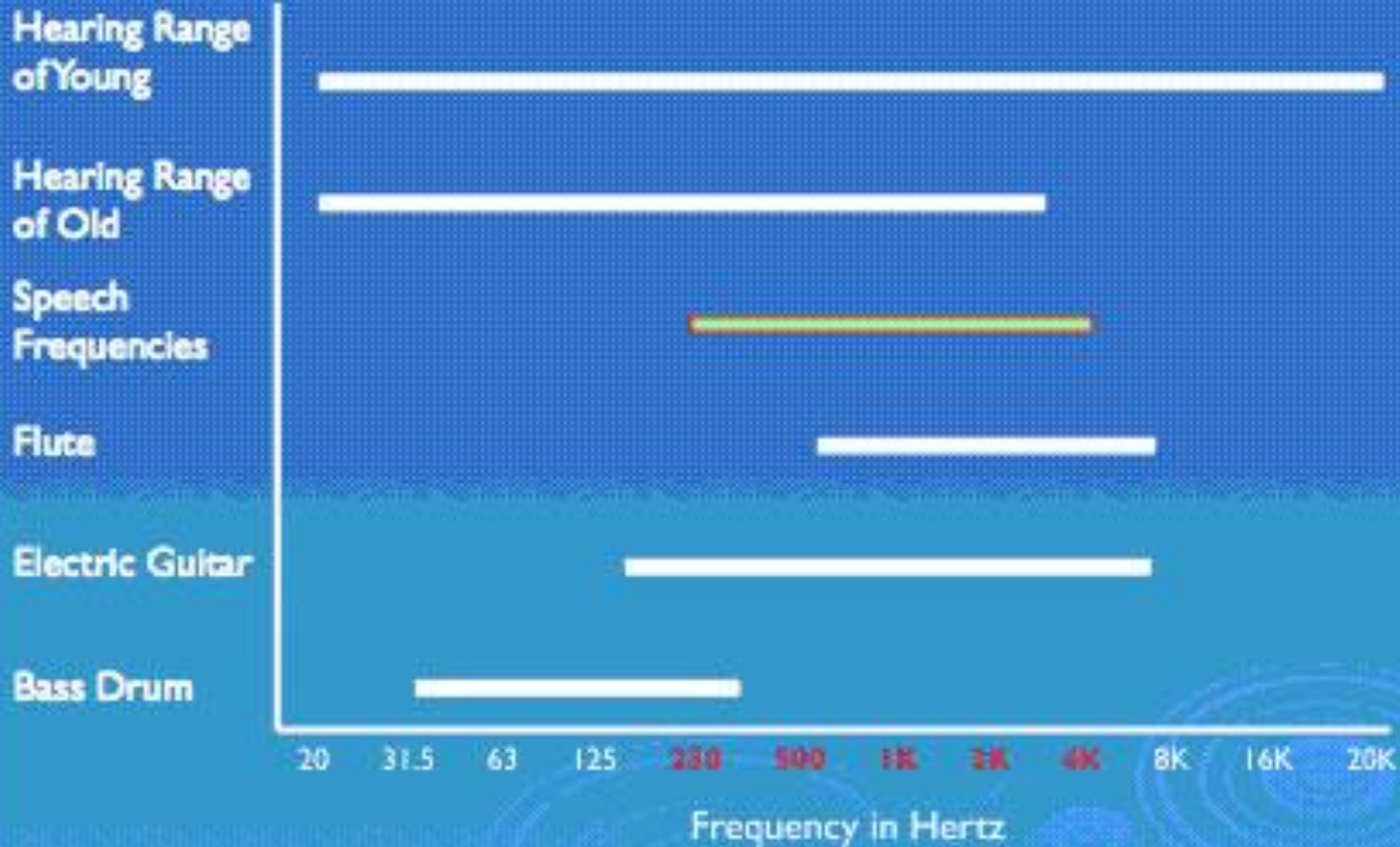
Steady sound decay by 60 dB after the sound has stopped= Reverberation Time

The total sound level any room is made up of two parts, namely:

- i. The sound produced by the direct path of the waves from the sound source to the listener and
- ii. The sound produced by reflections from walls and other surfaces.

The two parts are known as the direct sound and the reverberant sound respectively. The first part depends only on the strength of the source, whereas the second part depends on the amount of absorption in the room.

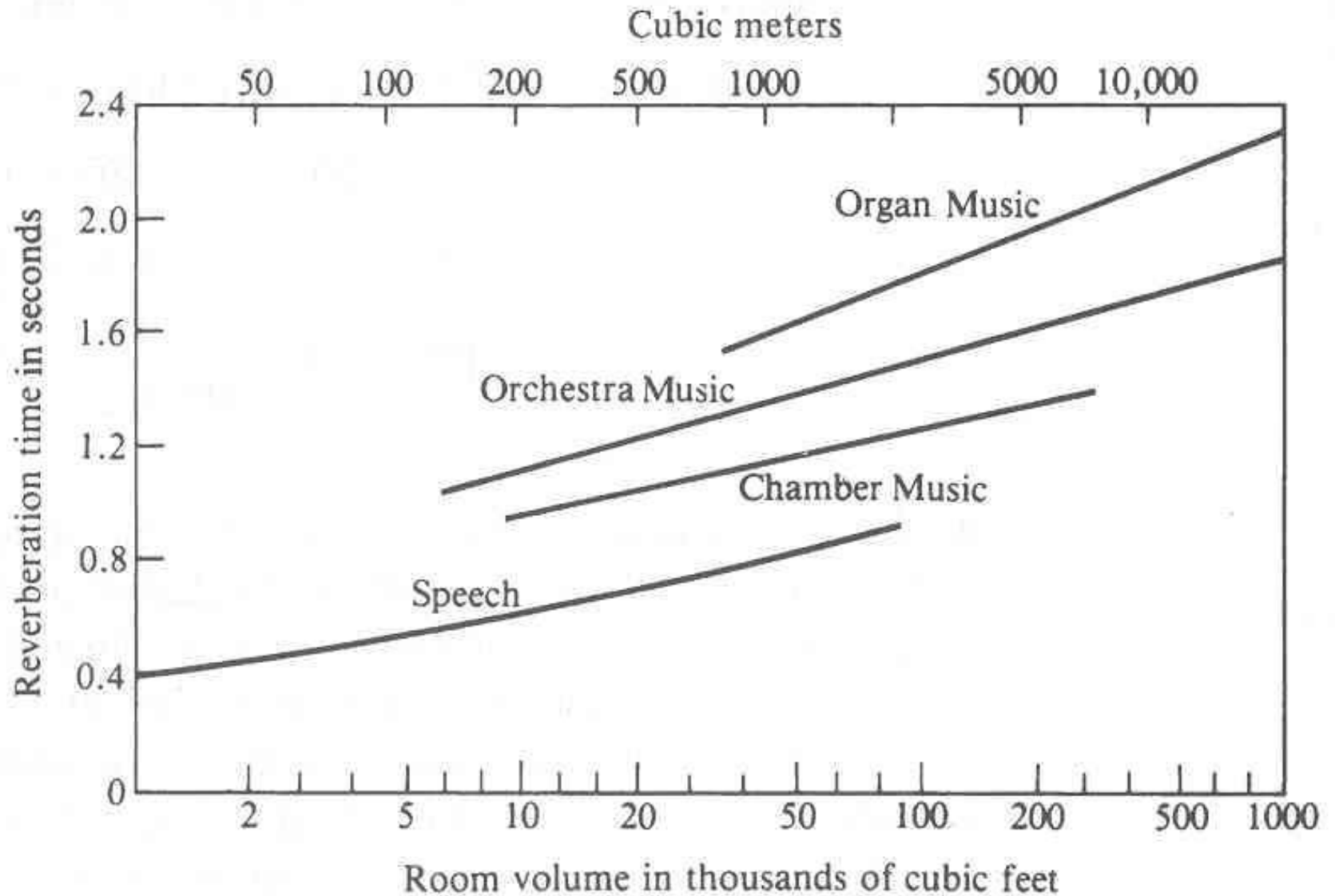
# Frequency Ranges



**Frequency range varies by source and is diminished with age**

Room Type	$T_{60}$ (sec)
Classrooms	0.6-0.7
Movie Theaters	0.9-1.2
Multipurpose Rooms	1.6-1.8
Concert Halls	1.7-2.2
Band Rooms	0.9-1.1
Choral Rooms	1.2-1.6

**Desired Reverberation time ( $T_{60}$ ) for different spaces**



**Appropriate values of Reverberation Time are presented in the table above**

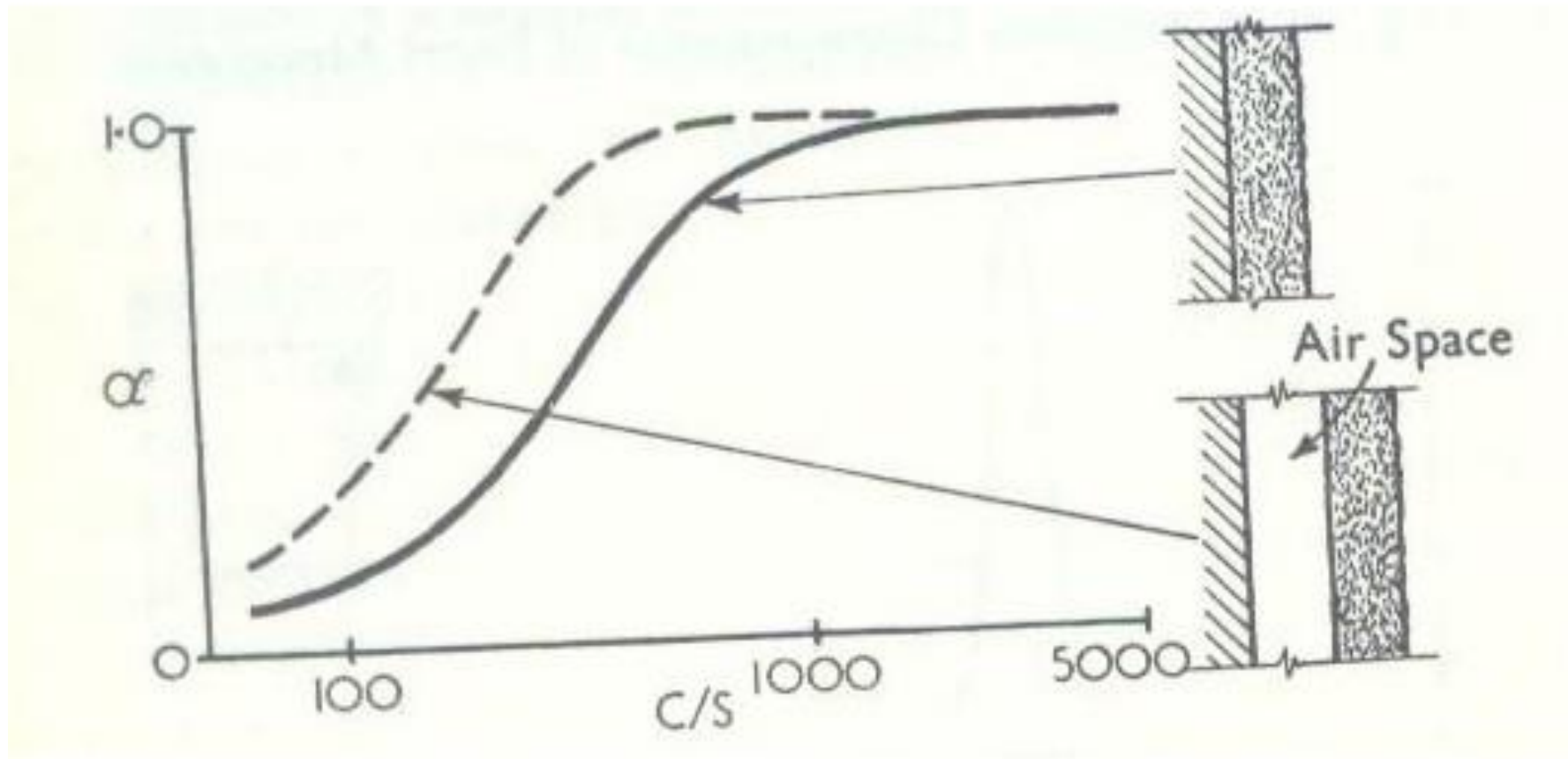
# Characteristics of Sound Absorbents

There are four basic types of absorbents, namely:

- 1. Porous absorbents:** These are best in the higher frequencies. Examples include, Mineral wool - Rock wool, slag wool and fibreglass etc.
- 2. Membrane absorbents:** This is best in low frequencies.
- 3. Resonant absorbers (Helmholtz resonators):** This can be ‘tuned’ to a very narrow band of any frequency.
- 4. Perforated panel absorbents:** These are a combination of resonant and porous absorbers and are best in medium frequencies. They can be ‘tuned’ to some extent by variation of hole size, shape and spacing and of backing material and space.



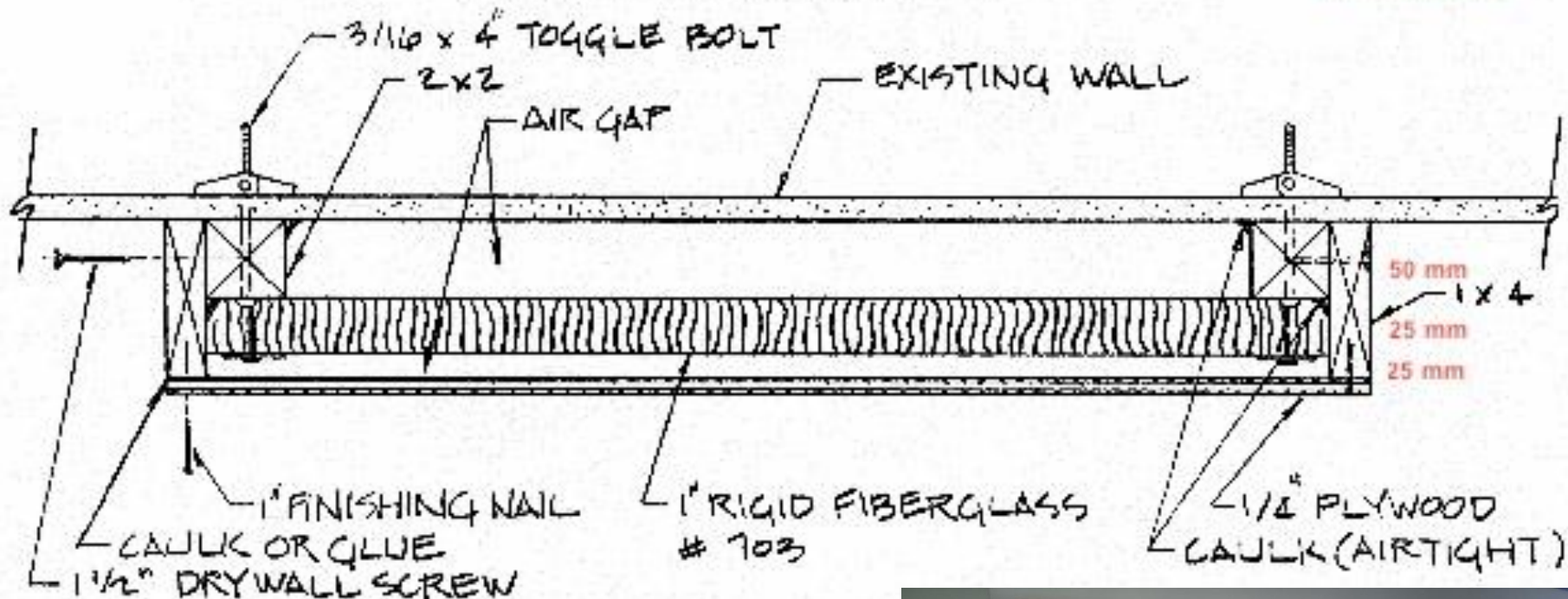
**Porous absorbent: Mineral wool**



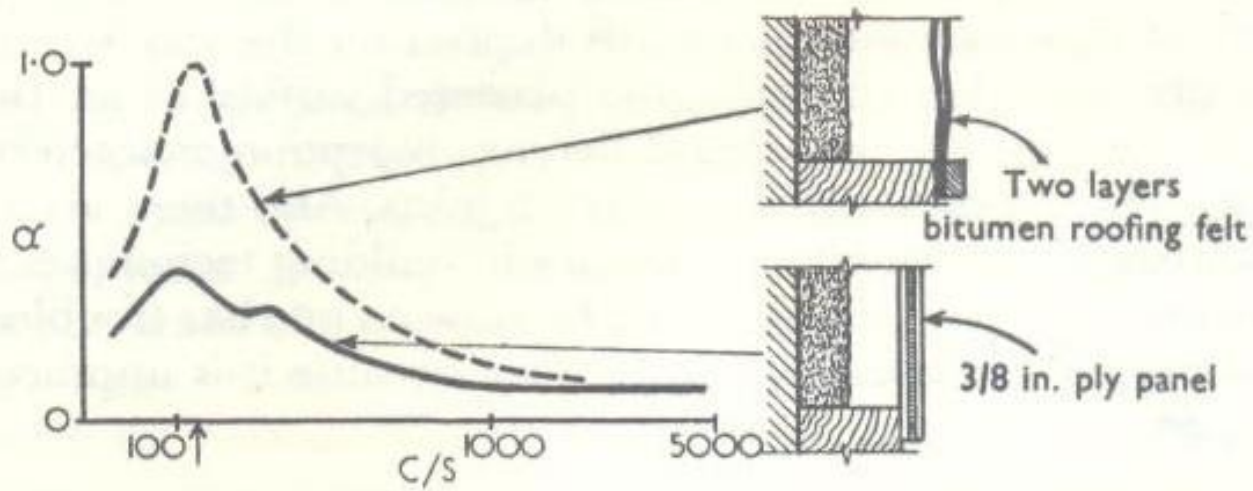
**Absorption characteristics of Porous Absorbents**

# DEEP-BASS TRAP

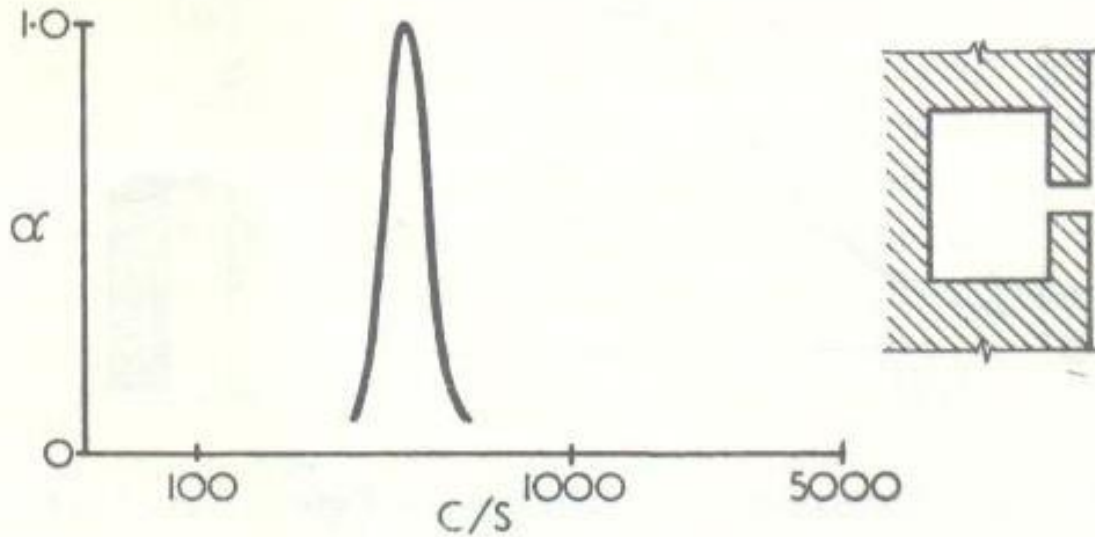
80 - 160 Hz



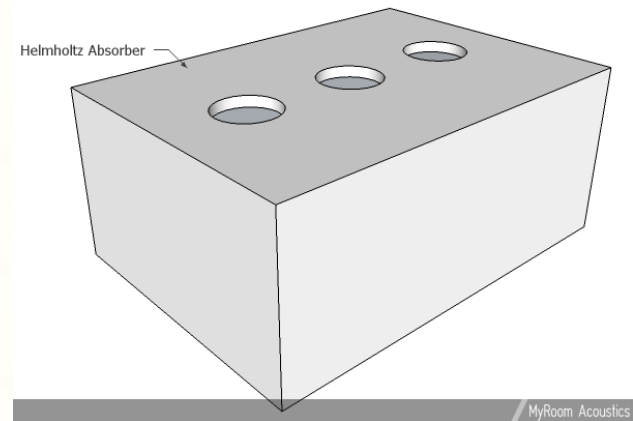
**Membrane absorbent**



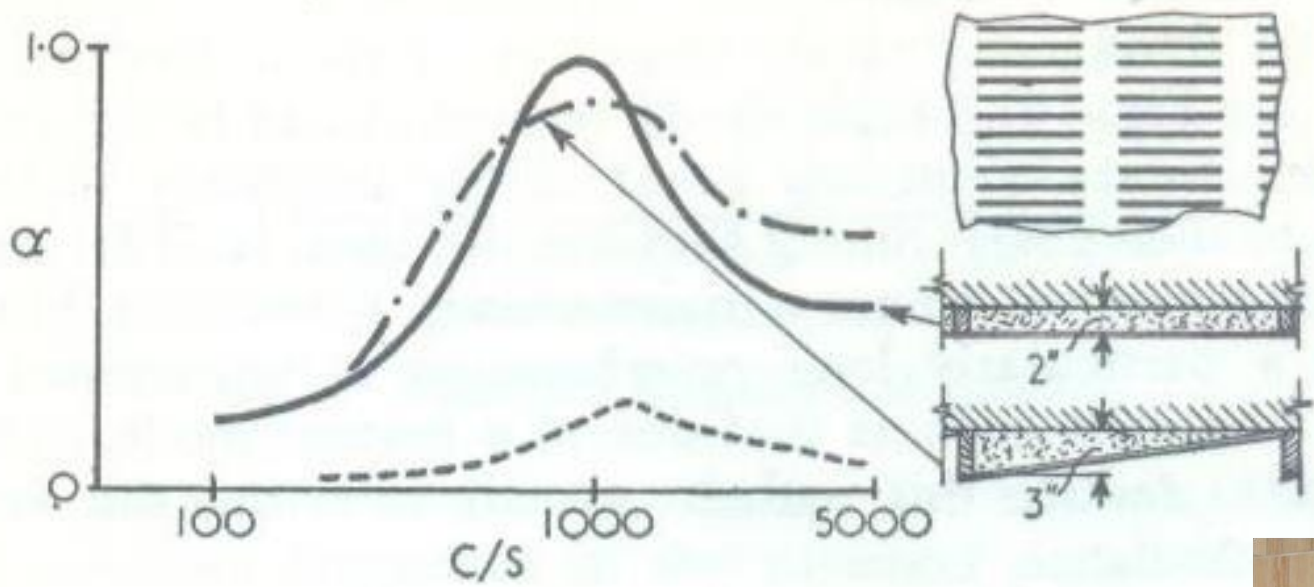
Absorption Characteristics of Panel Absorbents



Absorption Characteristics of a single Helmholtz Resonator

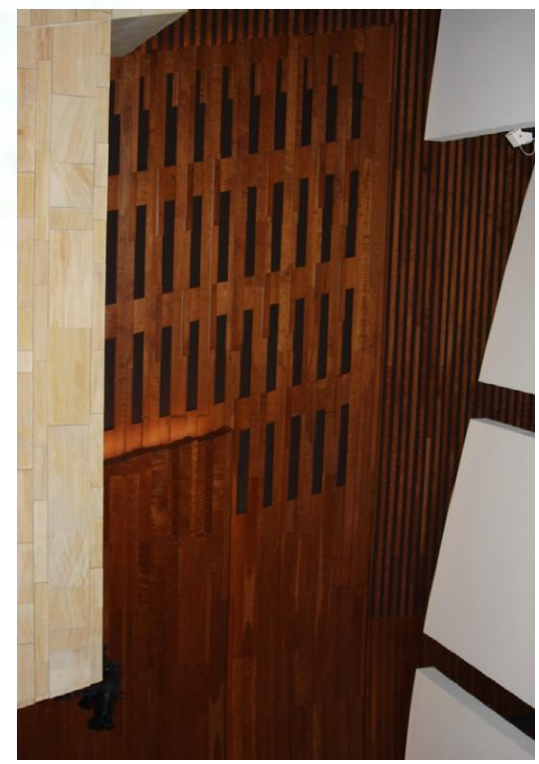


# Absorption Characteristics of Panel Absorbents & Helmholtz Absorbents

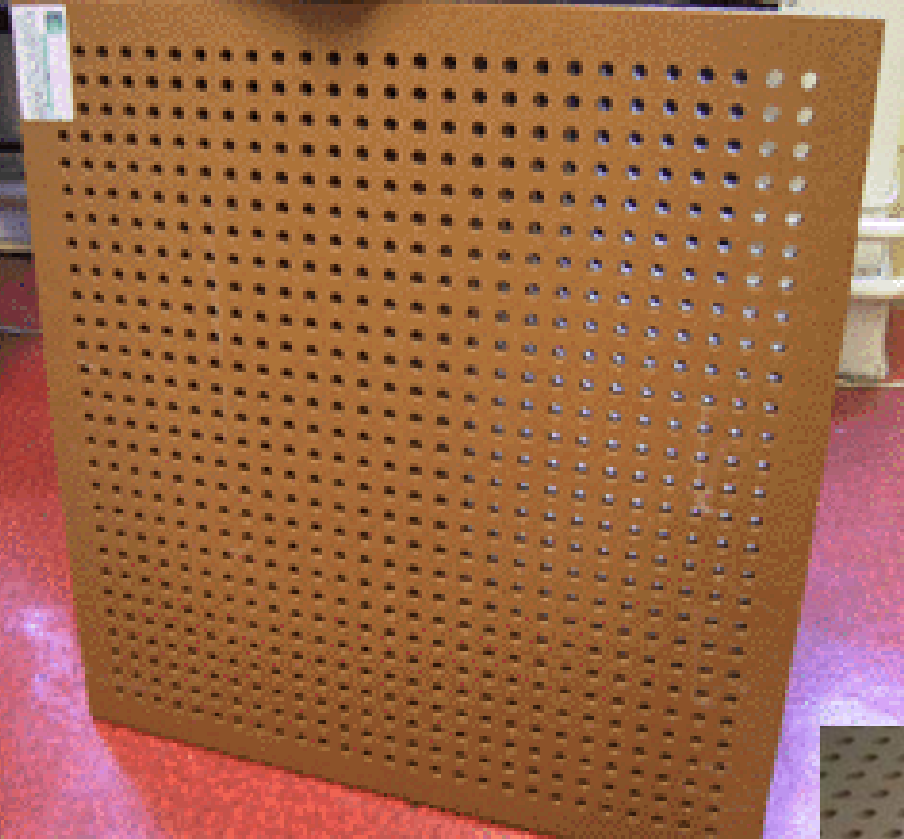


Absorption Characteristics of a Multiple Helmholtz Resonator Absorbent

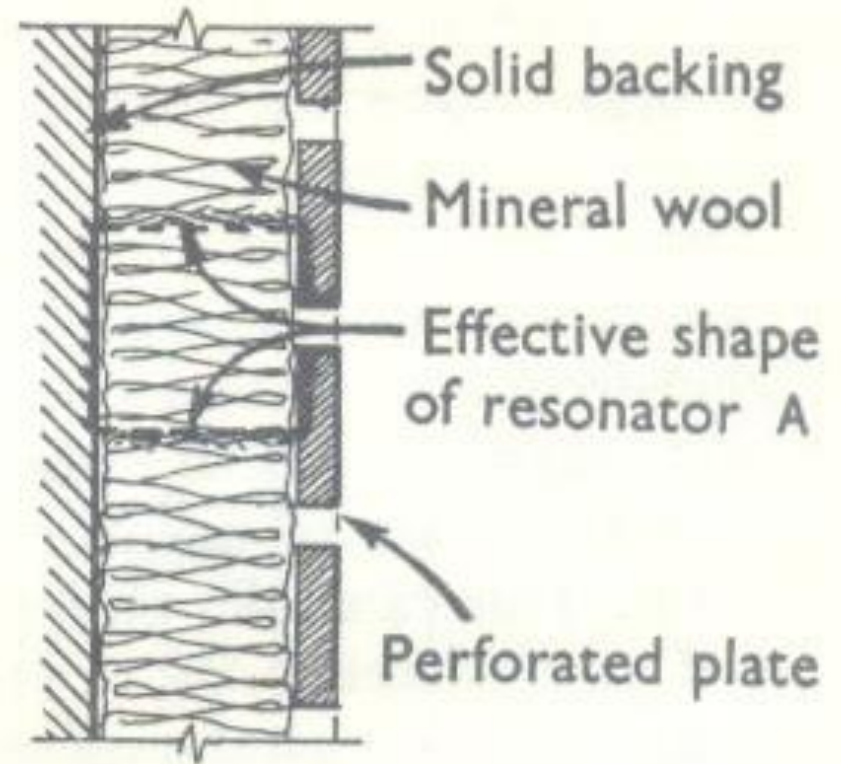
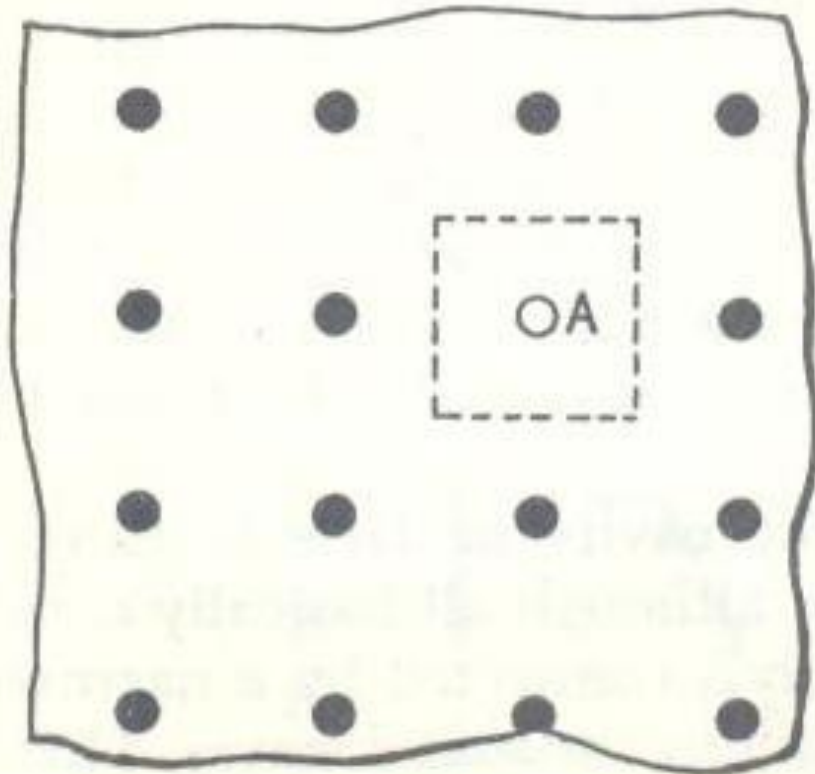
*Slotted Helmholtz Resonators*



**Helmholtz Resonator Absorbent**



**Round hole perforated panel**



Multiple Helmholtz Resonator Absorbent

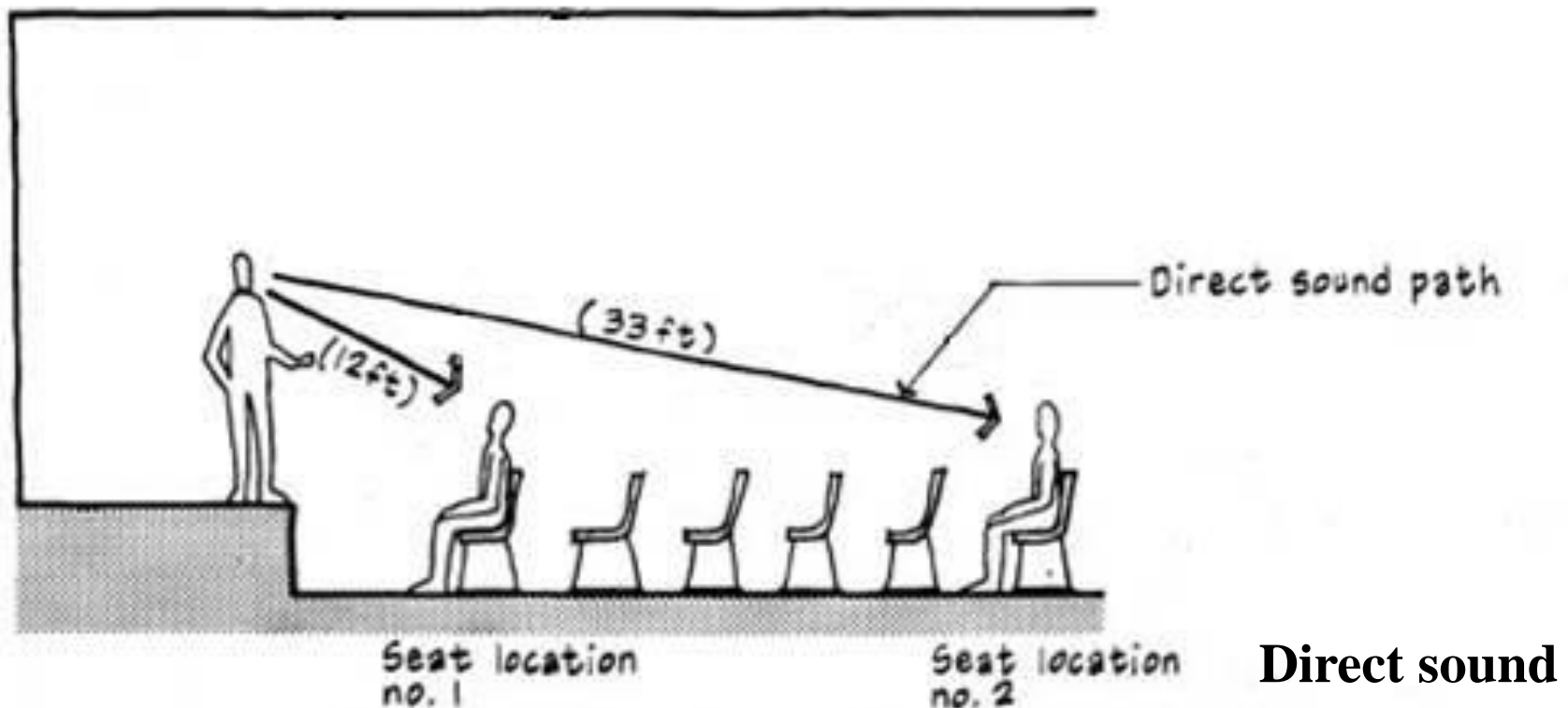
## Multiple Helmholtz Resonator Absorbents

The main aim in designing rooms for speech is to ensure that every member of the audience can clearly hear what the speaker says, in other words the problem is essentially that of intelligibility. A secondary aim is to preserve the natural qualities of a speaker's voice to ensure that each member of the audience can appreciate the nuances and dramatic effect being sought by the speaker.

If every member of an audience is to hear well, it is obvious that the sound at each audience seat must be loud enough. If the person speaking is to rely on the unaided power of his voice and not using speech amplification, then it is essential that best use be made of acoustic design to propagate his speech to the audience. There should be absolutely minimal background noise such as that from traffic noise outside the building or even a ventilation plant since these tend to mask the wanted sound.

### 3. Basic acoustic requirements for large gathering spaces for speech

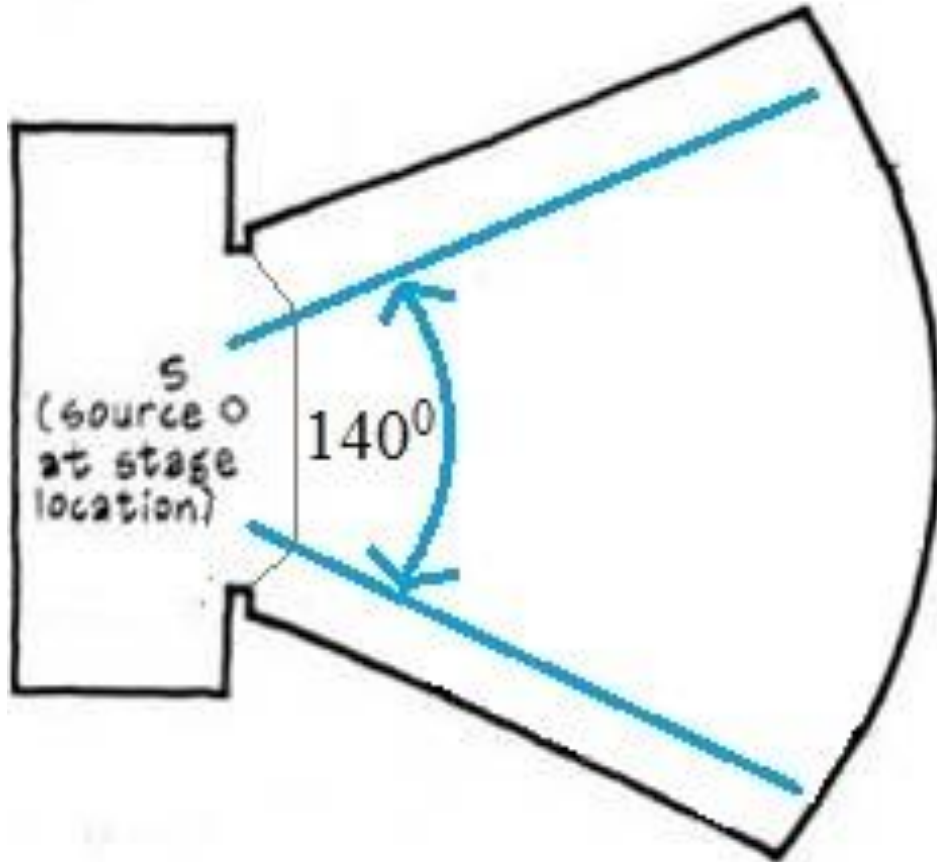
1. It is important that the direct sound i.e. sound proceeding directly from the source to the listener without having been reflected from the any room surface, be as strong as possible, thus the distance between the source and the listener should be kept as small as possible.



## 2. Shape of Hall

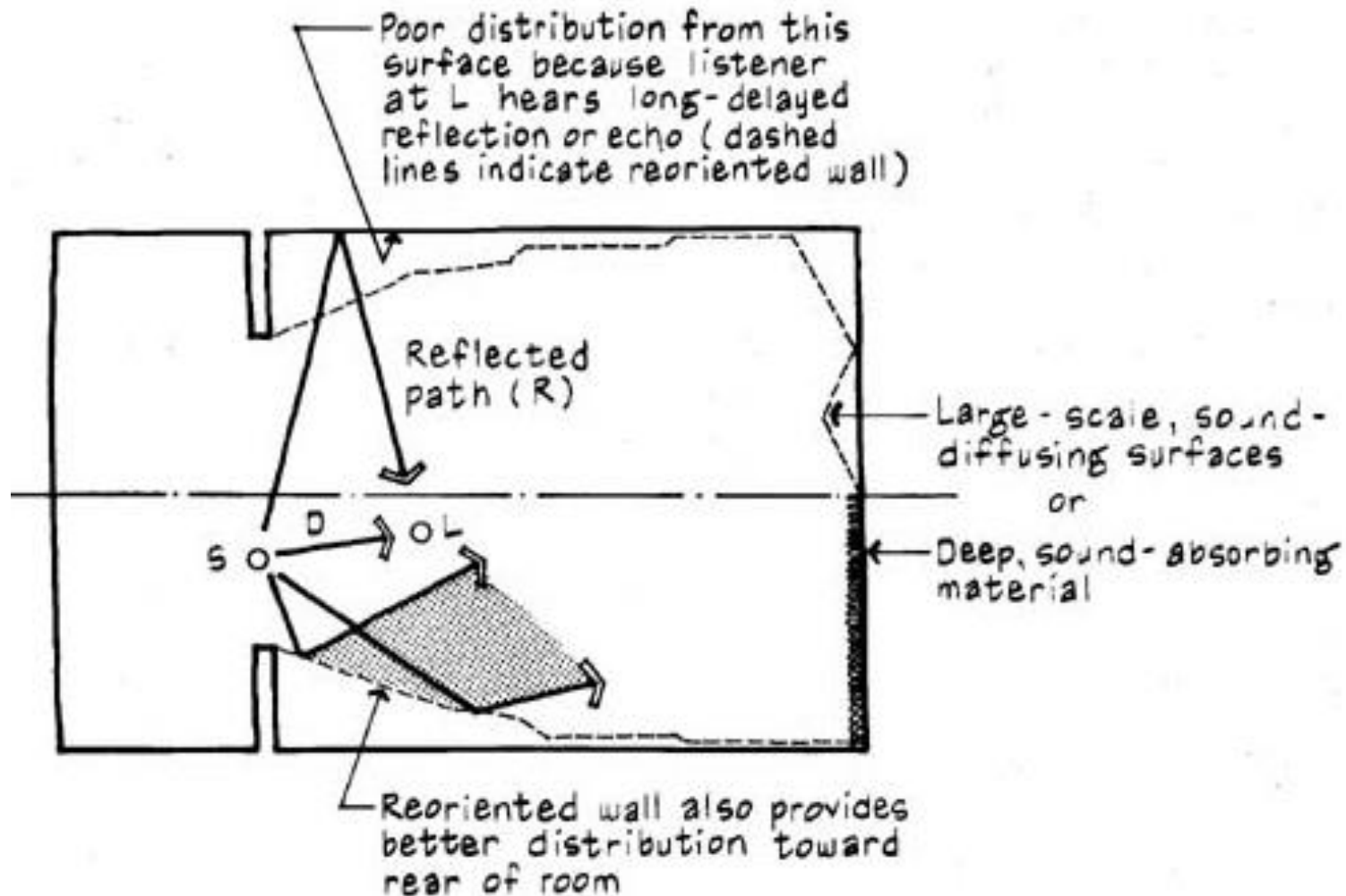
- Three basic plans are commonly used for large halls. These are Rectangular, Fan and Horse-Shoe shaped. As the size increases, there becomes a preference for the fan shape so that the audience is seated slightly closer to the sound source.
- Care must be taken to avoid concave rear wall for the hall.
- Lobby areas should be at least  $\frac{1}{3}$  of the total auditorium seating area.

3. In plan, the seats should be arranged so that none falls outside an angle of about  $140^\circ$  subtended at the position of the speaker. This is because speech is directional and the power of the higher frequencies on which intelligibility largely depends falls off fairly rapidly outside this angle.

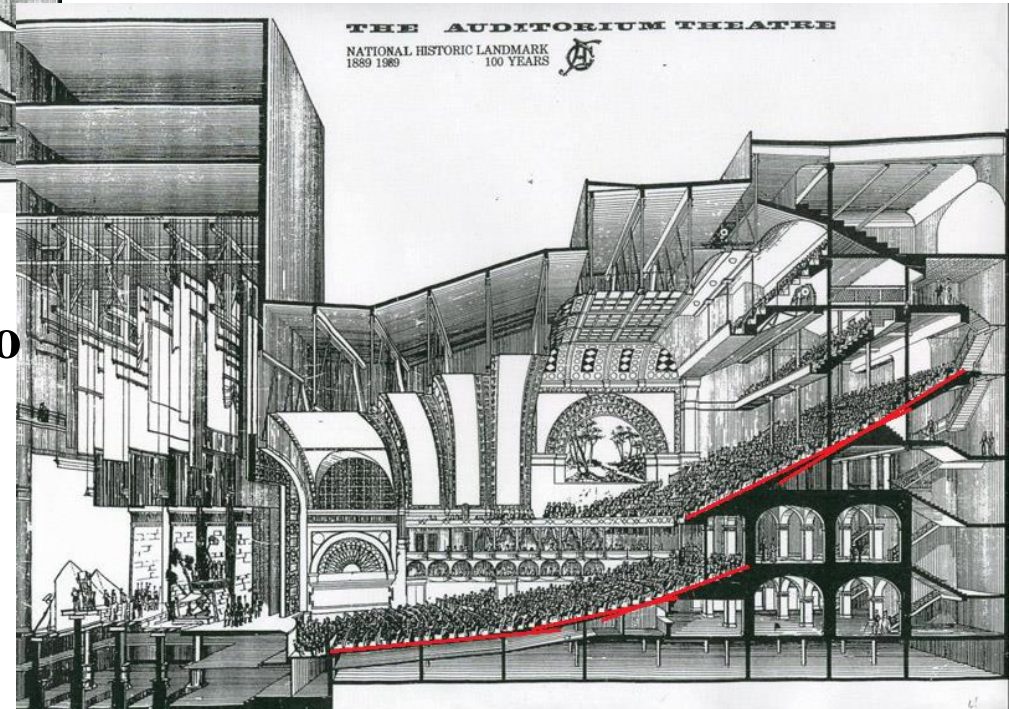
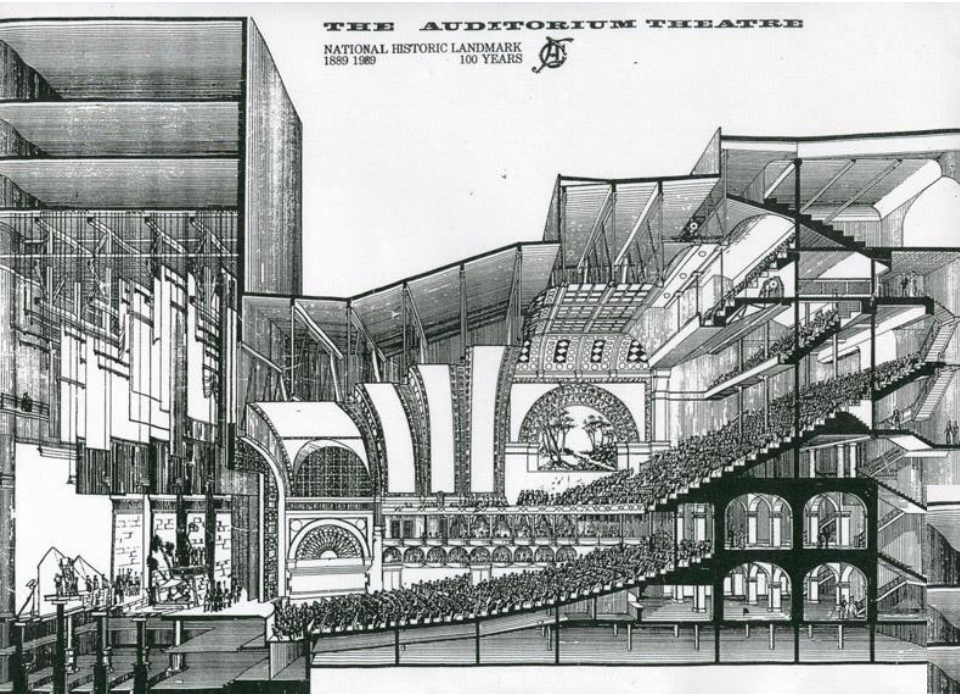


**$140^\circ$  seating subtended from the position of speaker**

4. The sidewalls of a small room may be parallel but are probably better converging on to the stage or platform, thus giving a fan-shaped plan. For large gathering spaces, it is recommended that the sidewalls should not be parallel. The same applies to the Floor and Ceiling.

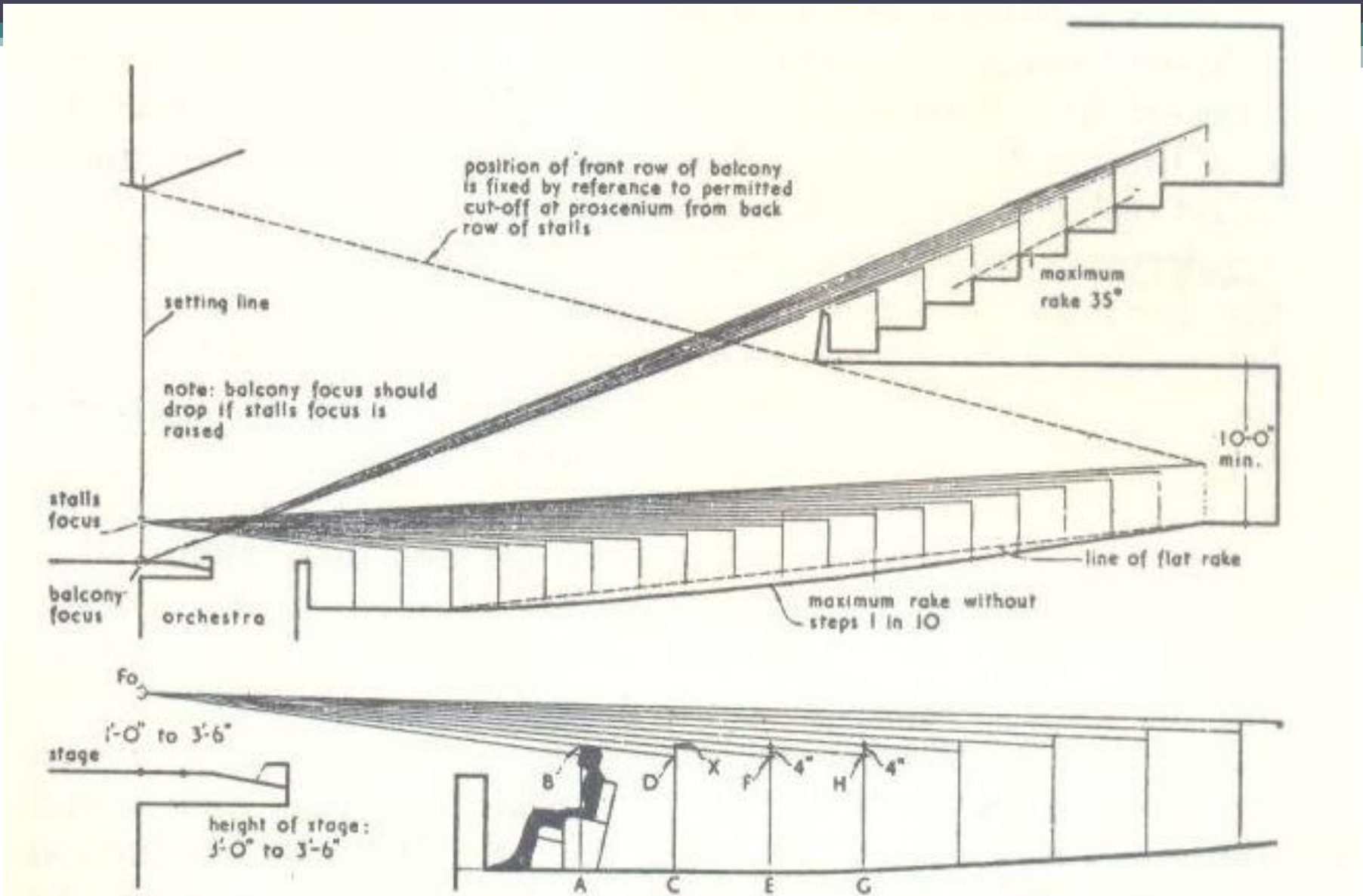


A curved raked seating helps to bring the audience closer to the person speaking on stage.



**The Auditorium building in Chicago**

**5.** The seats should be arranged such that the heads of people seated on one row do not obstruct the direct sound paths to the people in the row behind. This is achieved by ensuring that a clearance of at least **75mm** is provided between the sight line from one row and the sight line from the next. A clearance of **100mm or more** is recommended. In this case, a **curving rake** is the ideal shape. This can be simplified into a straight rake, but this should not be done so that the clearance at any part of the seating is reduced below the desirable minimum. This arrangement also provides a good view for the audience. The audience should always see the person speaking.

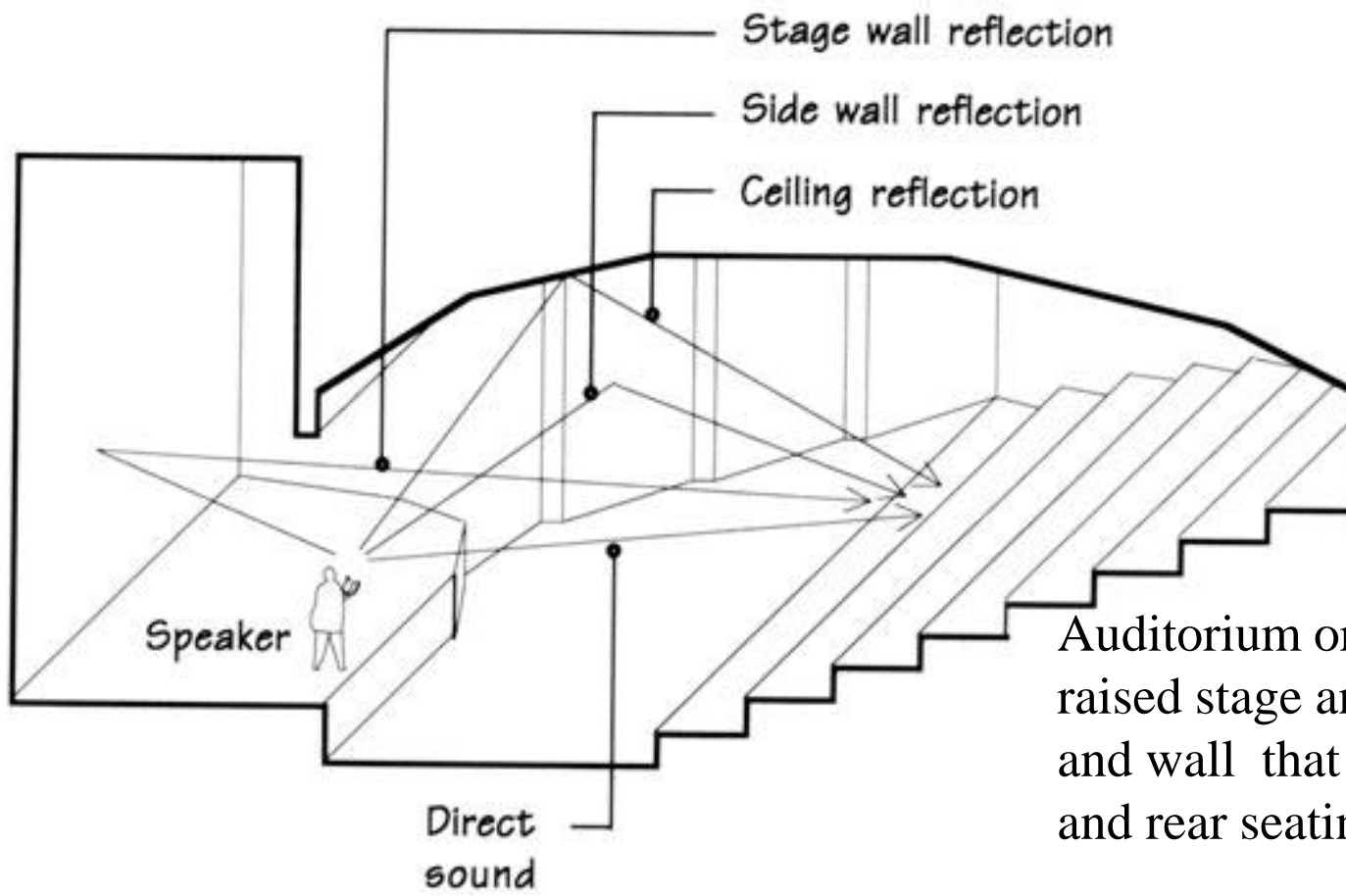


Arrange seats such that heads of audience seated on one row do not obstruct the direct sound paths to the people in the row behind



A curved ramped seating at Auditorium del Lingotto Torino, Italy

6. The speaker's platform or stage should be raised sufficiently high to ensure that the audience at the rear rows of the hall, especially if the hall has a flat floor, can see the person speaking on stage clearly. A stage height of approximately 1000mm is advisable.

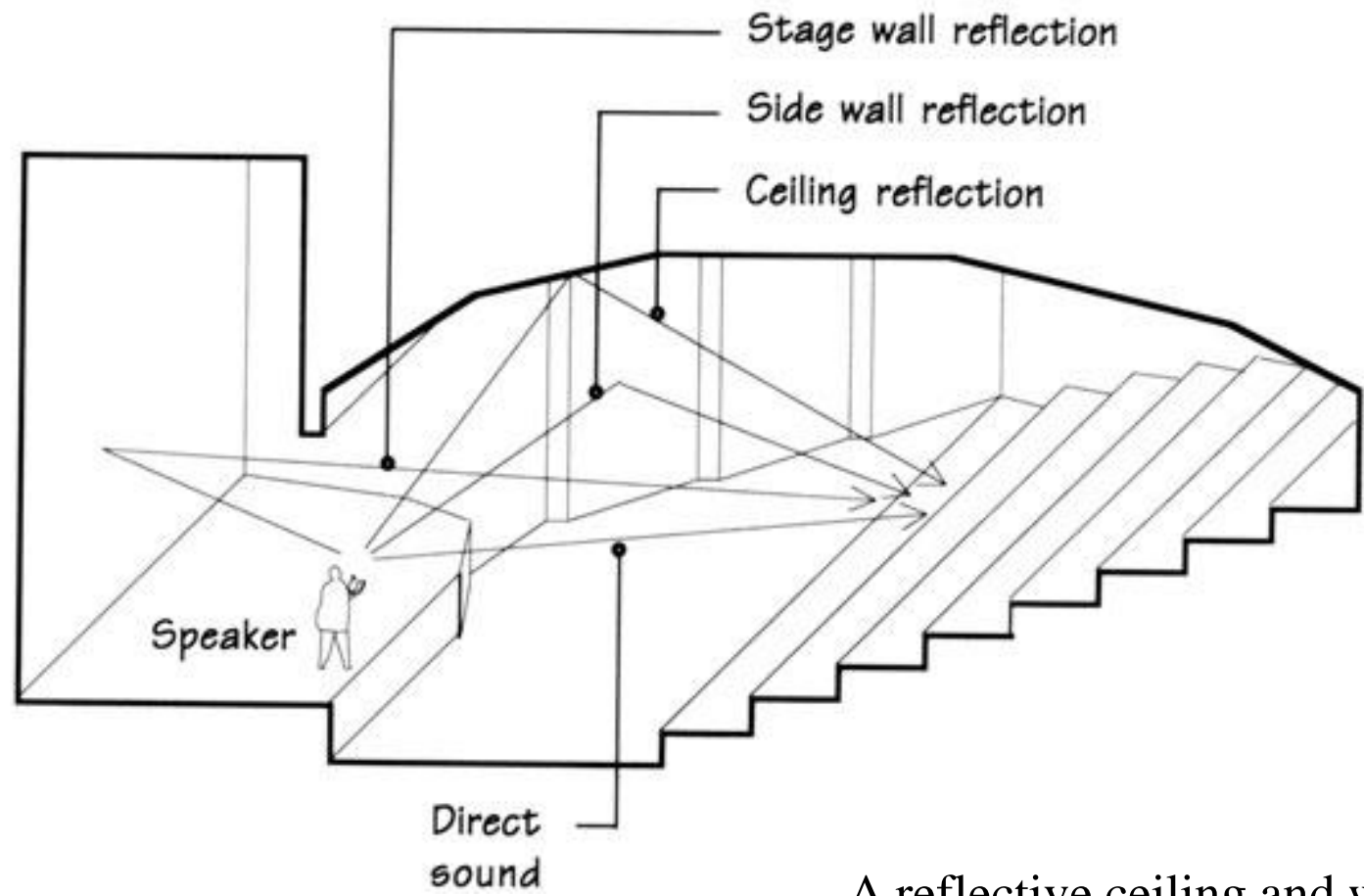


Auditorium or Lecture hall with a raised stage and a reflective ceiling and wall that directs sound to mid and rear seating areas

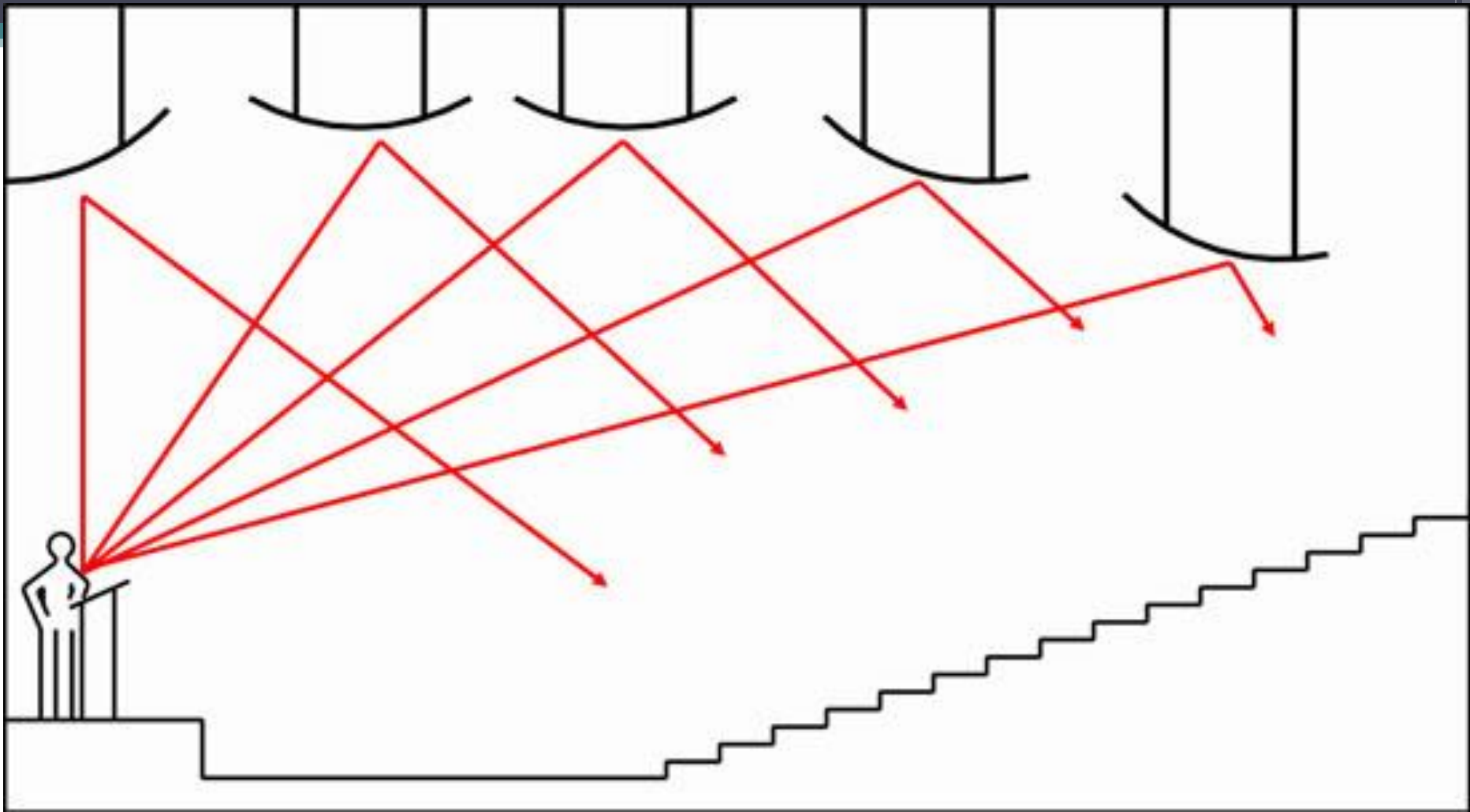


Hall with a raised stage and curved acoustical reflectors above the stage

7. Both the Ceiling and wall should be shaped so as to direct sound to mid and rear seating areas of the auditorium.



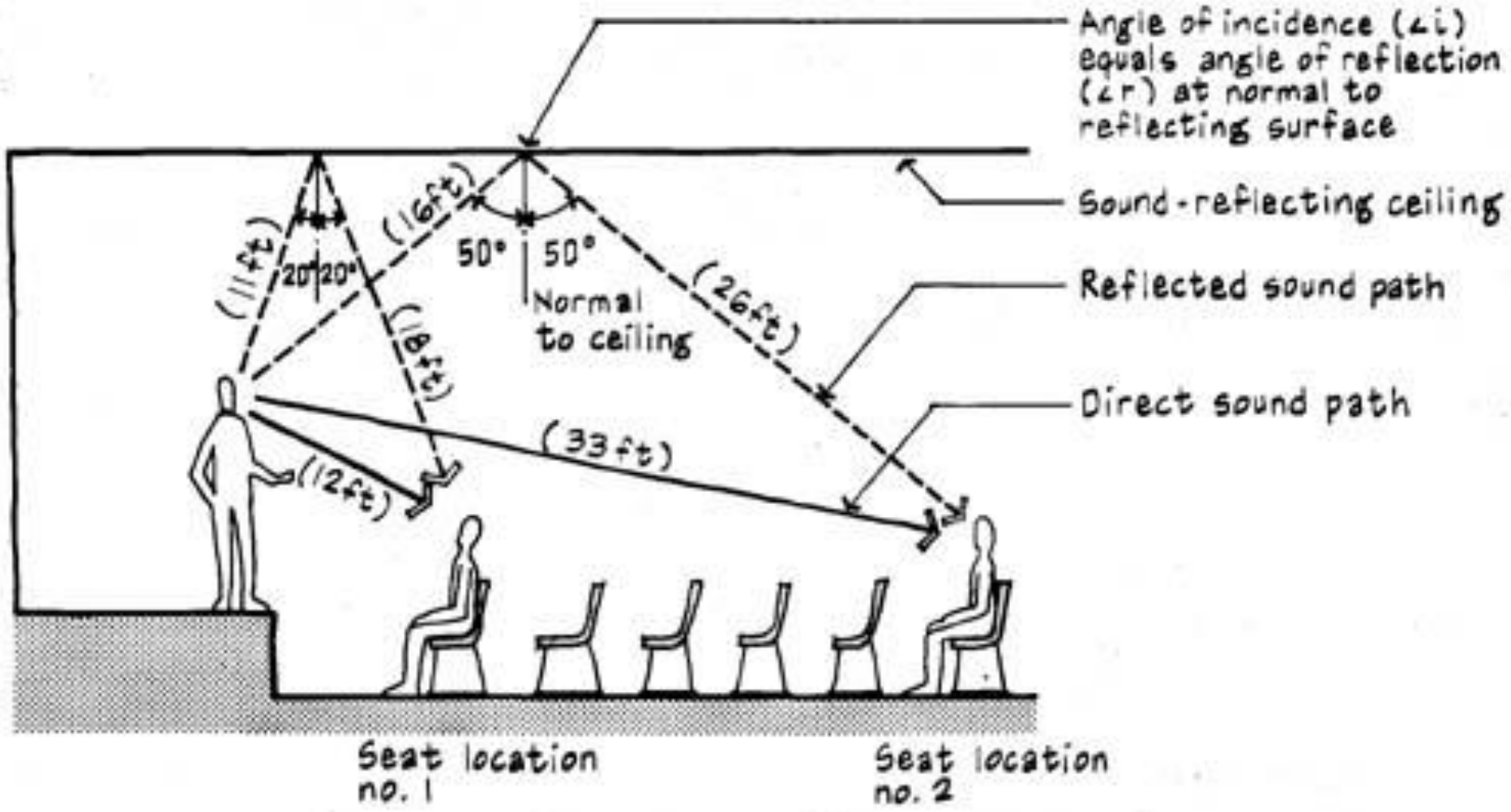
A reflective ceiling and wall that directs sound to mid and rear seating areas



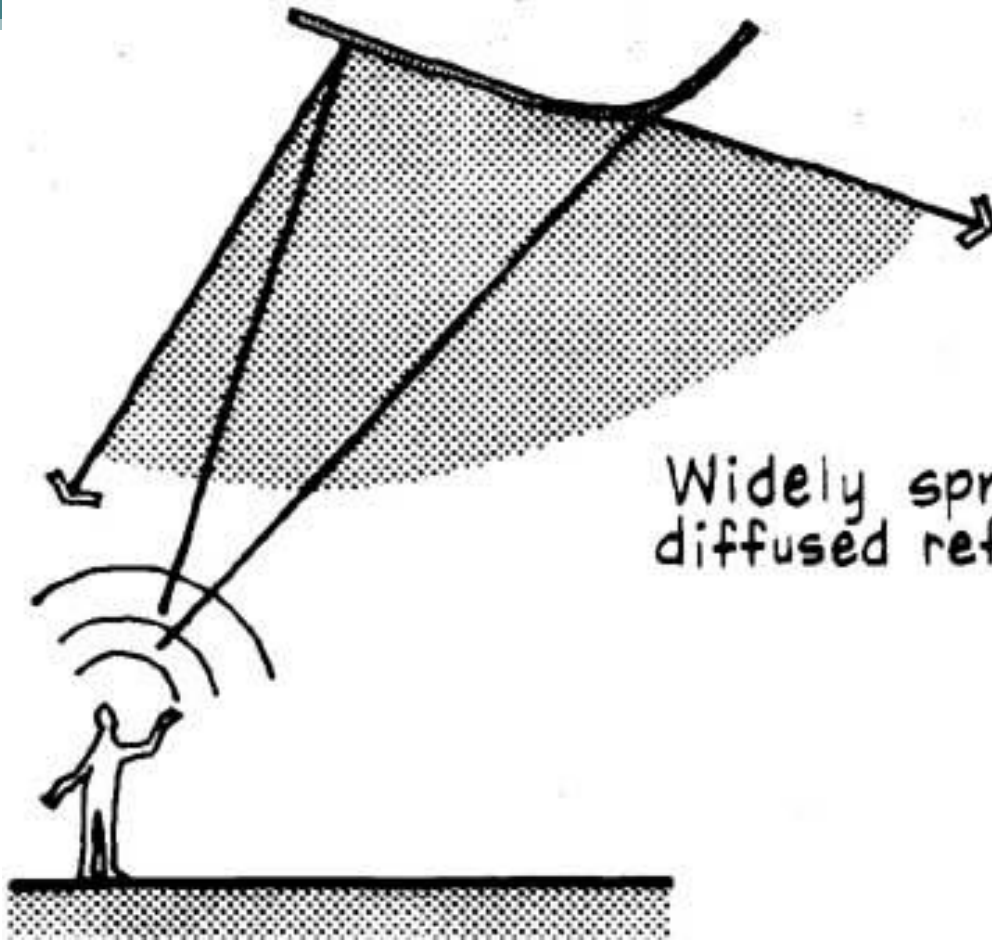
Curved acoustical reflectors direct and diffuse sound to the seating area of the auditorium

**8.** The first reflections arriving at a listener's ears very shortly after the arrival of the direct sound operate as a contribution to direct sound. In practice, having hard surfaces angled so that the reflected waves are directed towards the audience and preferentially towards those members who are most distant from the speaker is recommended. Sprayed surfaces above the stage or platform and at the sides are recommended. These should be studied geometrically in plan and in section and all reflected sound paths which are no greater than about 30 feet (10m) more than a direct sound path from the source to the part of the audience where the reflection arrives may be expected to provide a useful addition to the 'direct' sound.

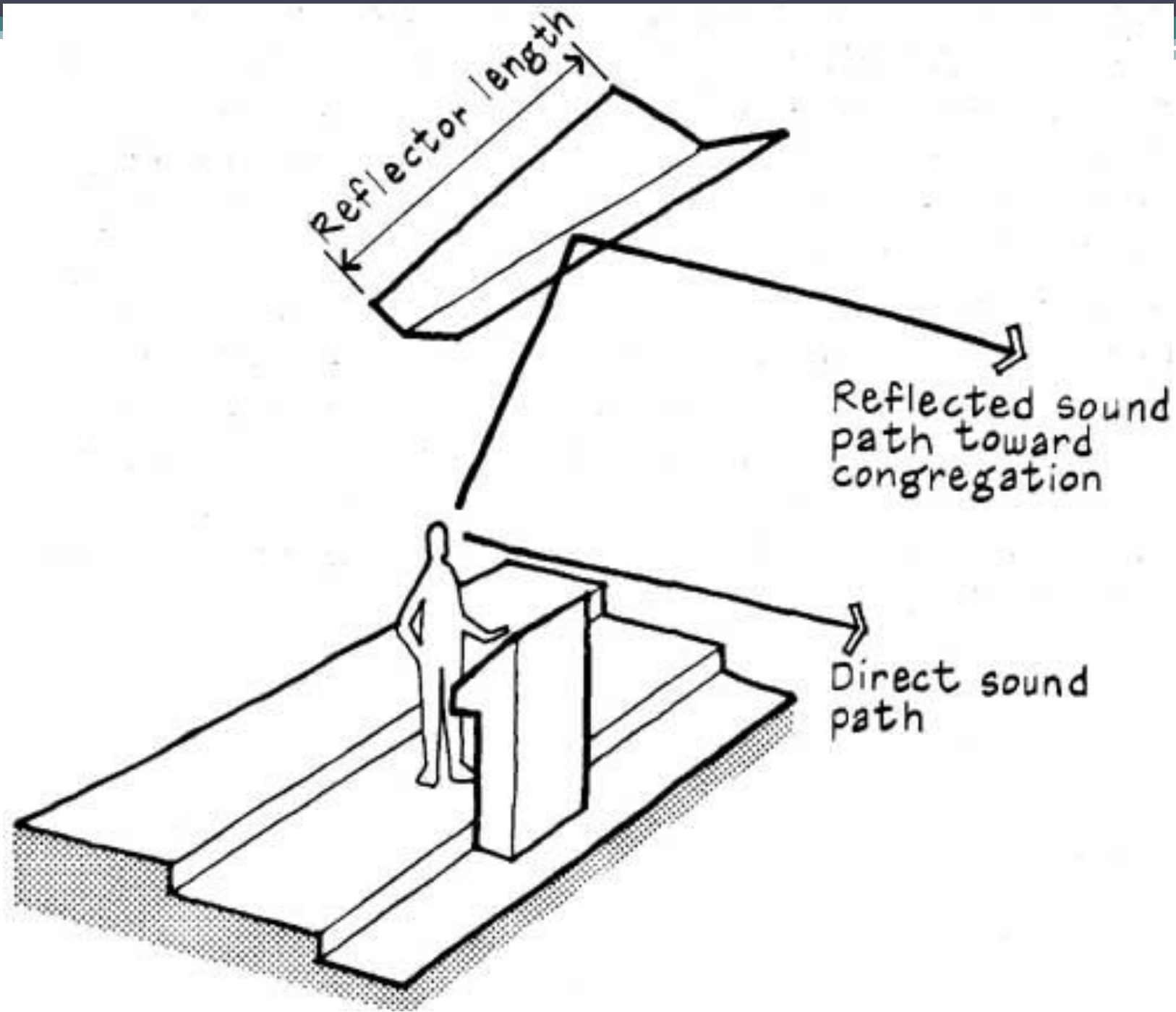
Reflected sound paths which are greater than 50 ft (16m) more than the direct sound path should be avoided because such sound waves can result in echoes being heard and a great reduction in intelligibility.

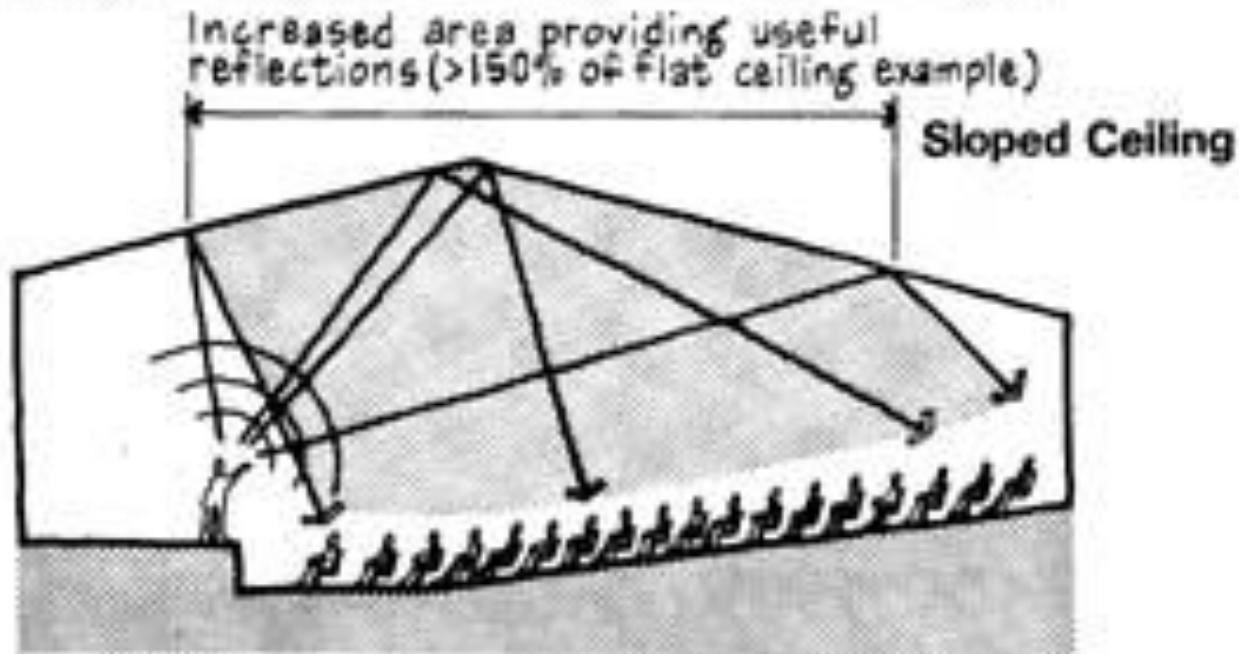
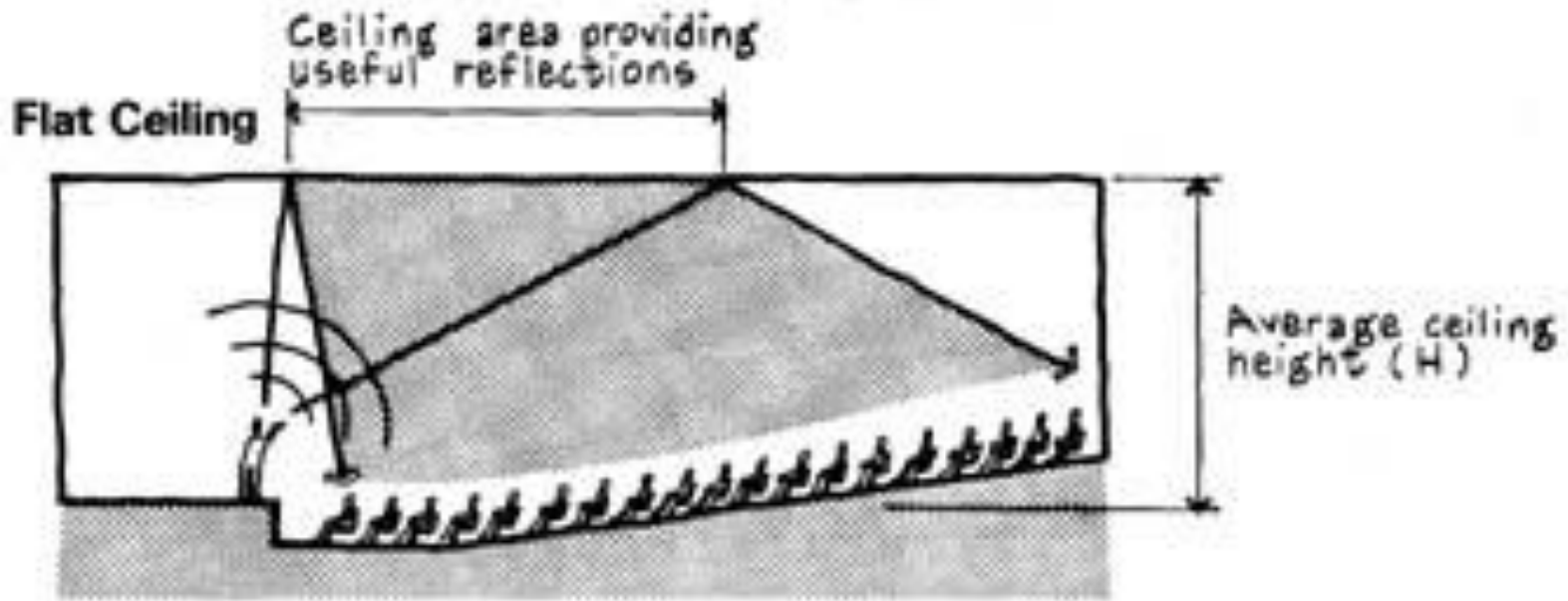


Curved acoustical reflectors direct and diffuse sound to the seating area of the auditorium



Widely spread or  
diffused reflected sound





Ceilings should be used to reflect sound towards the audience as illustrated in the second section.



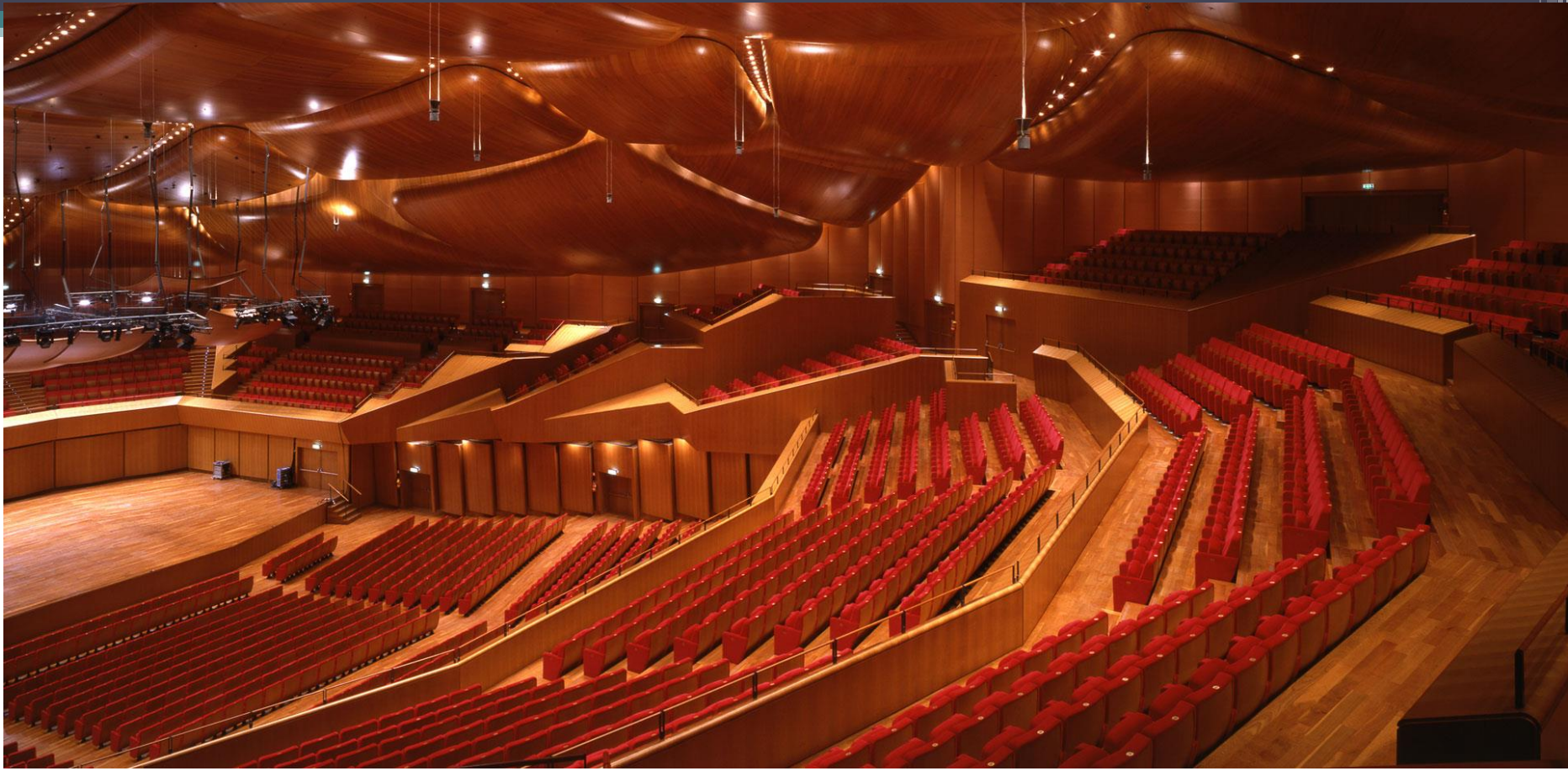
Auditorium del lingotto Torino, Italy. Notice the curved balcony sound reflectors



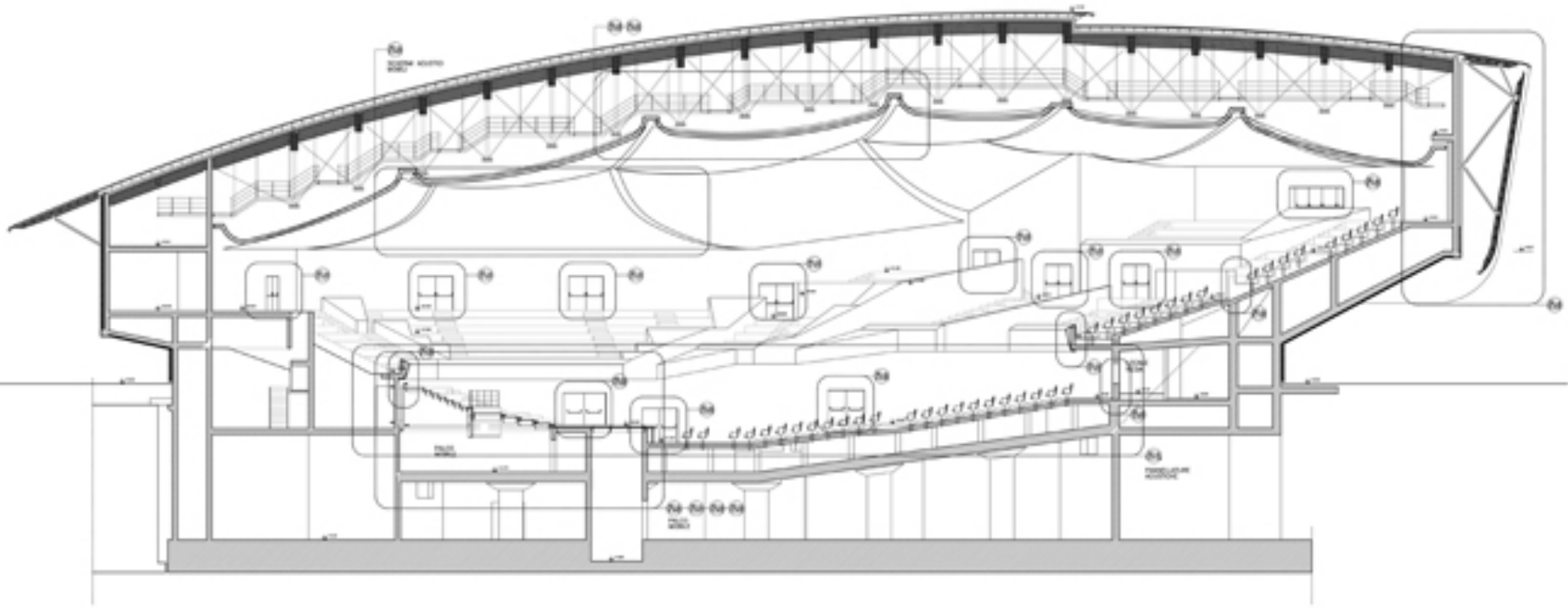
Auditorium del Lingotto Torino, Italy. Detail of the curved balcony sound reflectors



Finlandia hall by Alvar Aalto

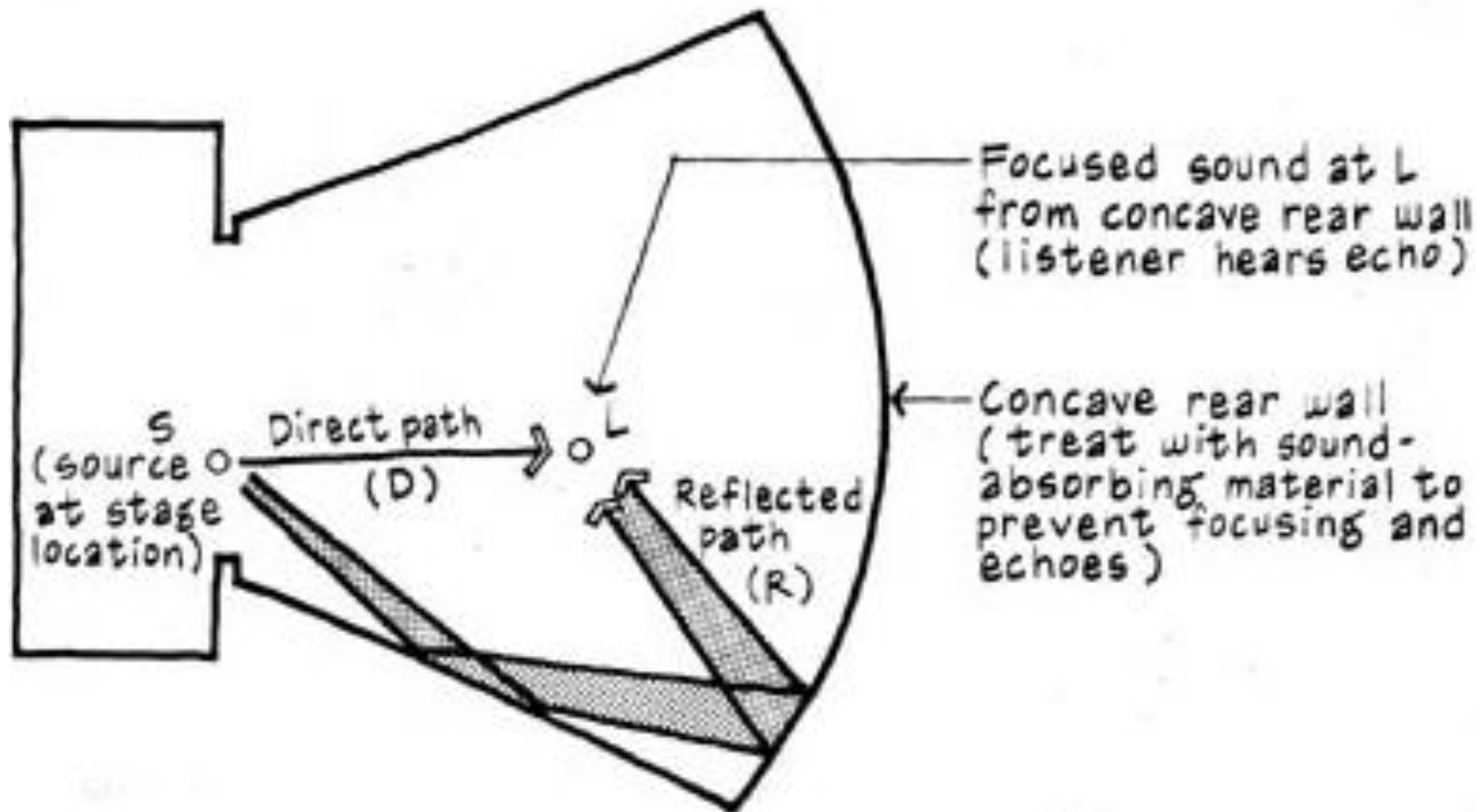


The floating curved ceiling at Parco della Musica by Renzo Piano helps in sound propagation

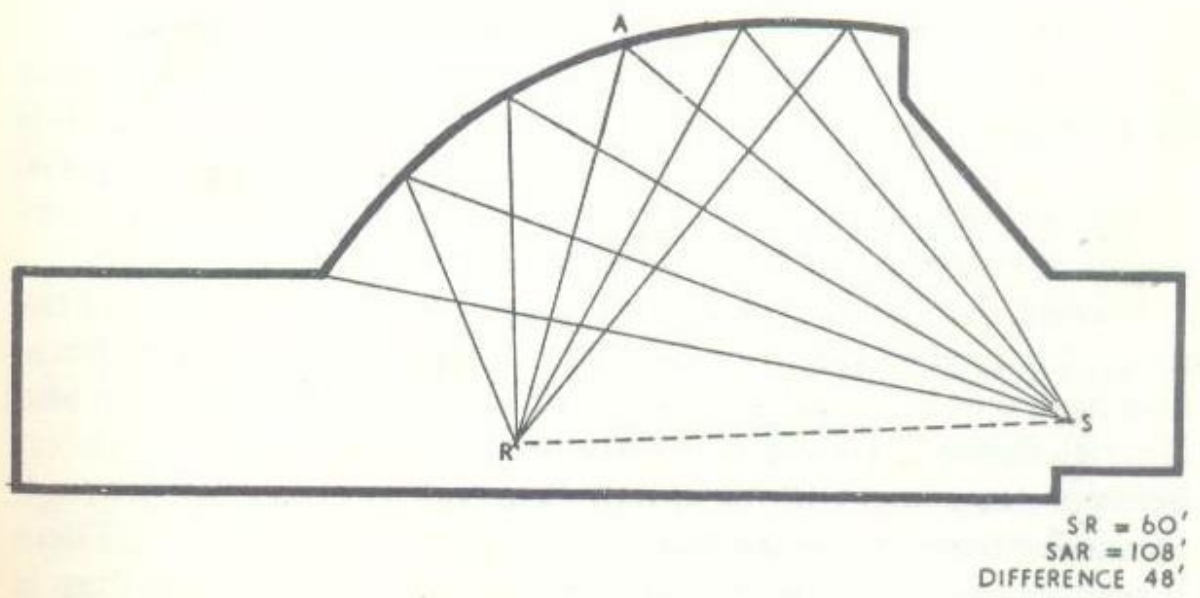
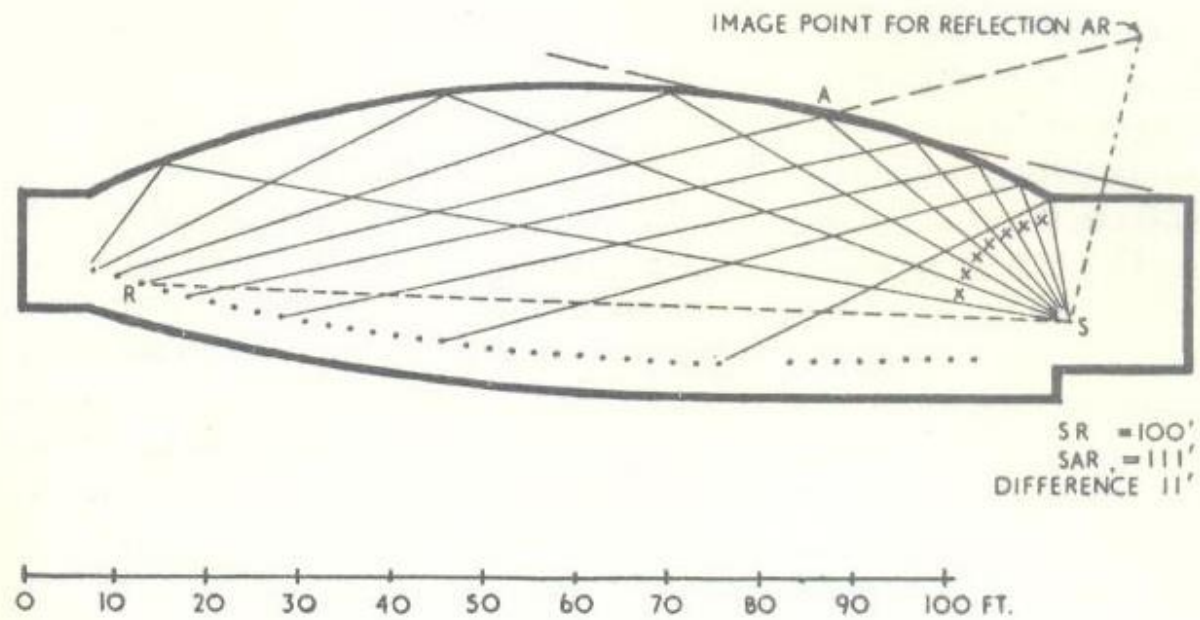


Section of the 2700-seater Concert Hall at Parco della Musica by Renzo Piano

9. Concave curved surfaces should be avoided, particularly if their geometry is such as to cause reflected waves having long path differences to be focused on part of the audience.

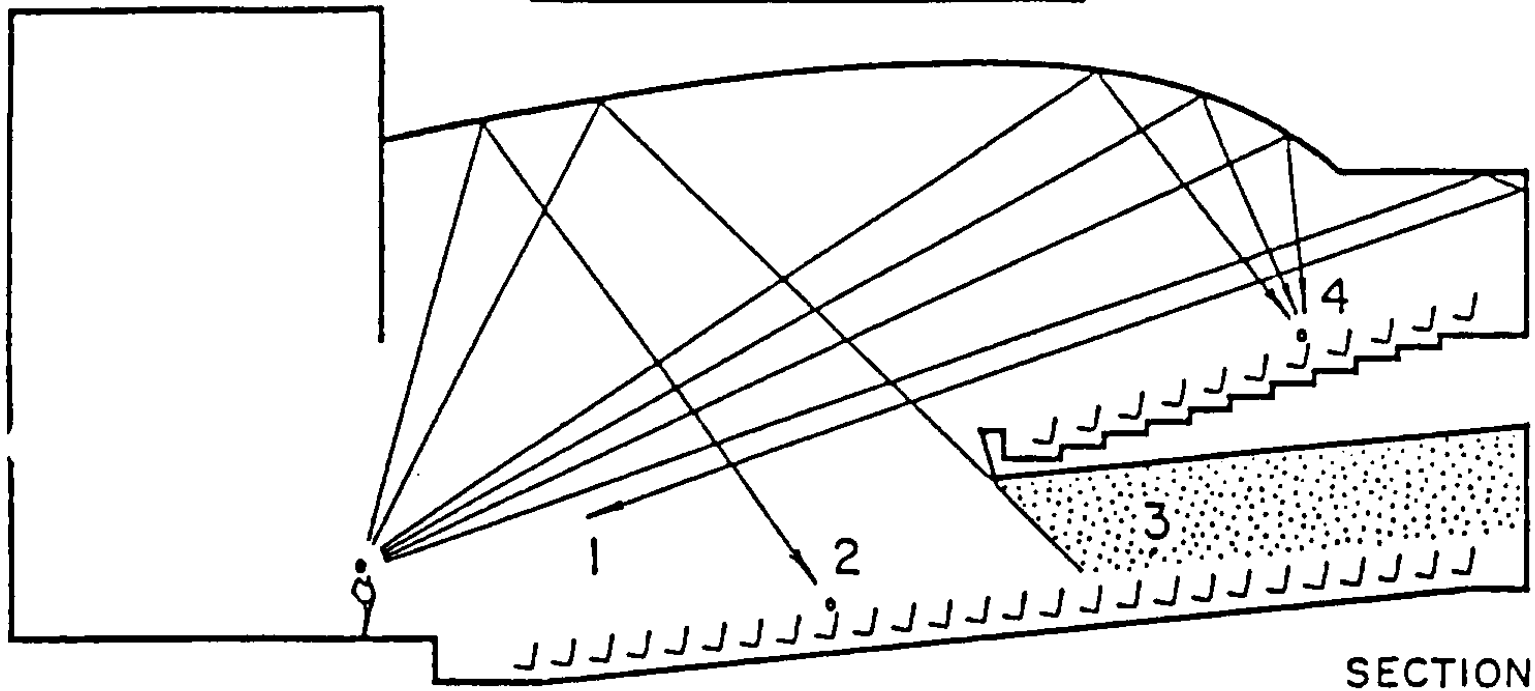


Concave curved surfaces should be avoided



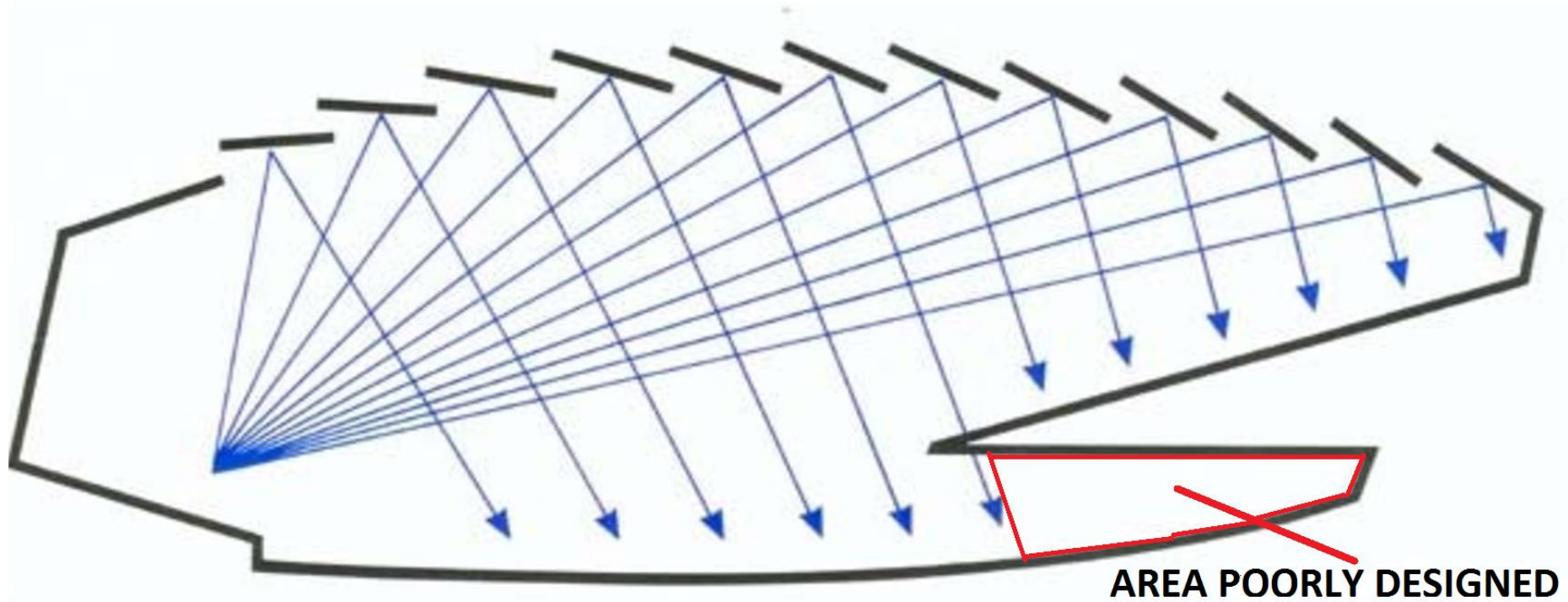
Two long sections of Halls (a) with useful reflecting ceiling surface (b) with ceiling which will cause echoes

Acoustical defects in an auditorium.  
(1) echo; (2) long-delayed reflection; (3) sound shadow;  
(4) sound concentration.

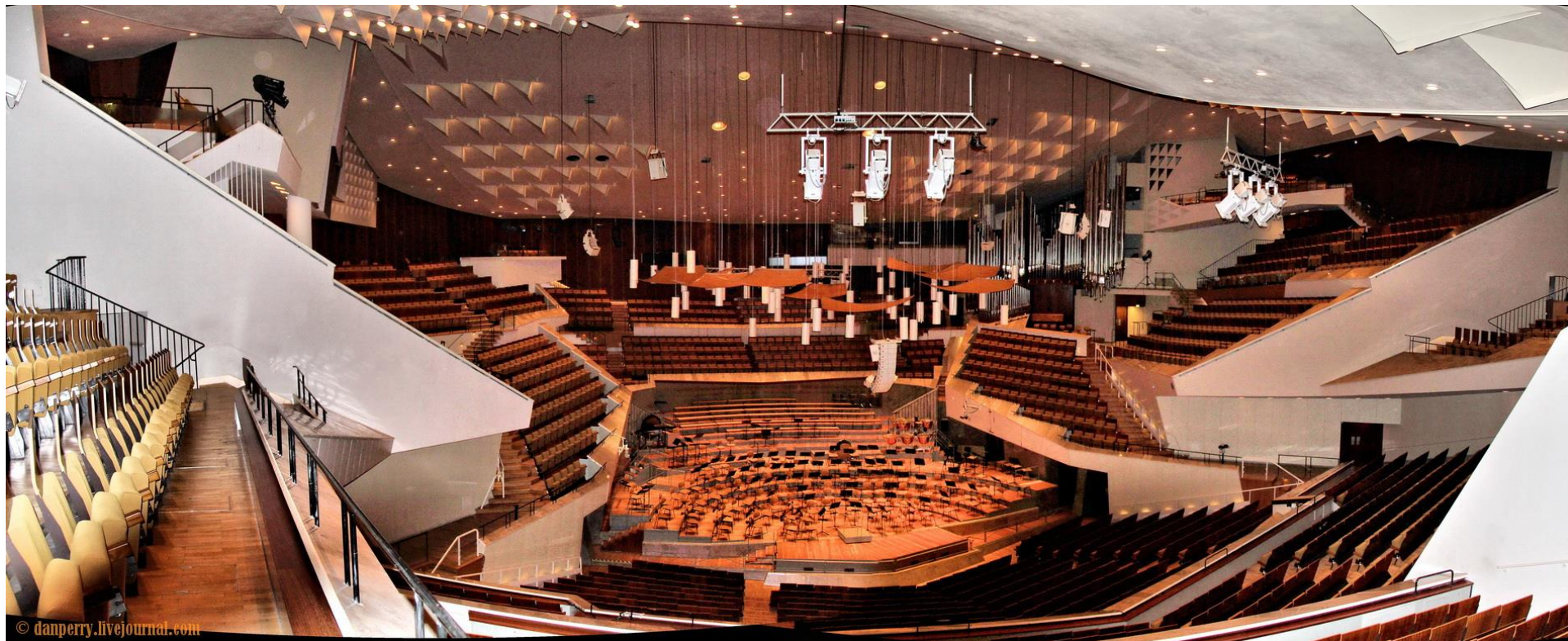


Acoustical defects in an auditorium:  
(1) Echo, (2) Long delayed reflection  
(3) Sound shadow (4) Sound concentration

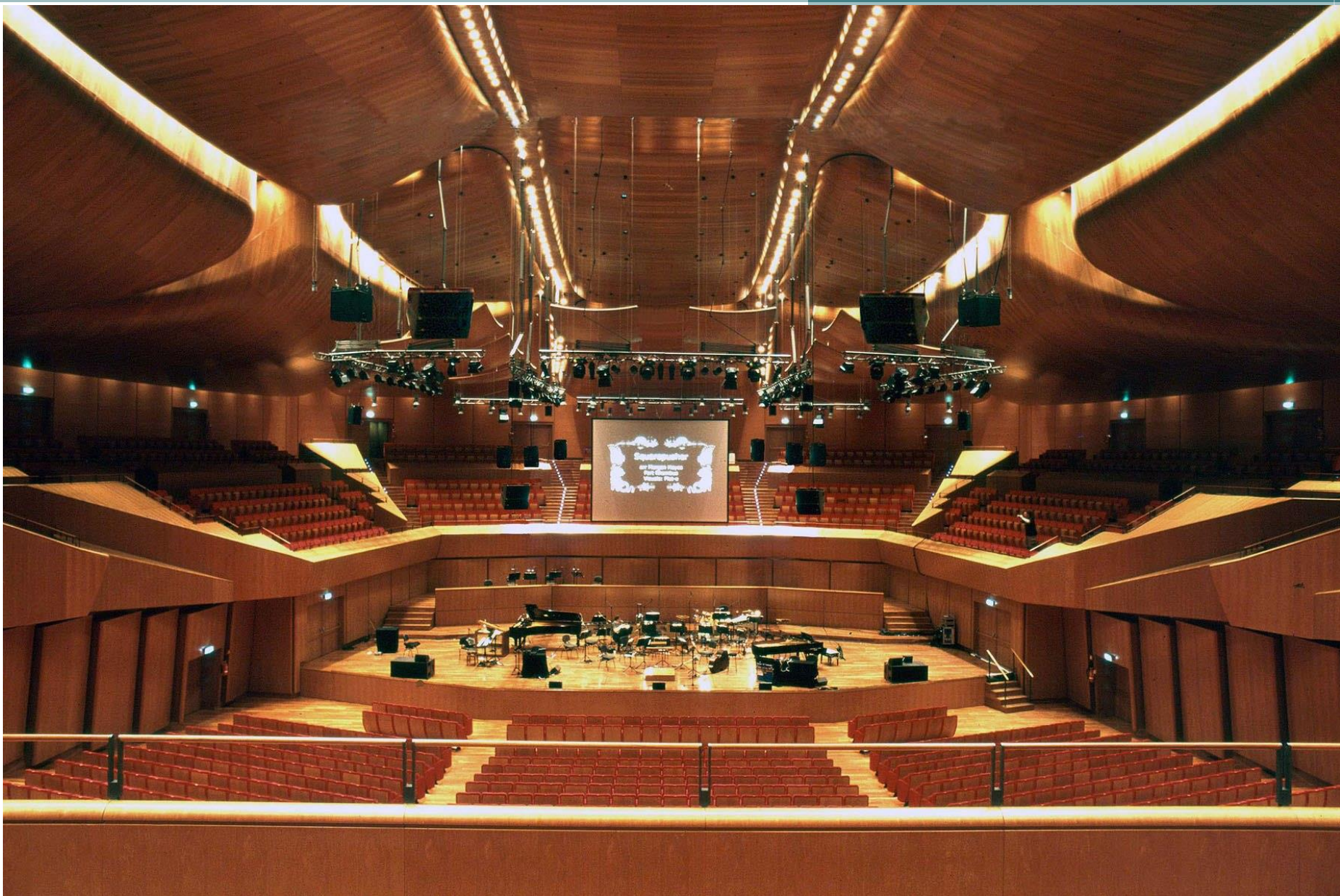
**10.** If galleries are required, the free height between the heads of the audience and the gallery ceiling/soffit should be made as great as possible, and the depth of the seating area under the gallery should not exceed twice this height. It is recommended that a Vineyard terracing arrangement be applied between the main seating area and the galleries, and thus no seating space beneath the galleries.



Auditorium Section showing sound shadow below balcony/gallery



Berlin Philamornie by Hans Sharoun - Vineyard terracing of galleries



Parco della musica by Renzo Piano - Vineyard terracing of galleries

## **11. Ceiling height**

The recommended ceiling height in auditoria design is between 8m and 12.5m for useful sound reflection by the ceiling.

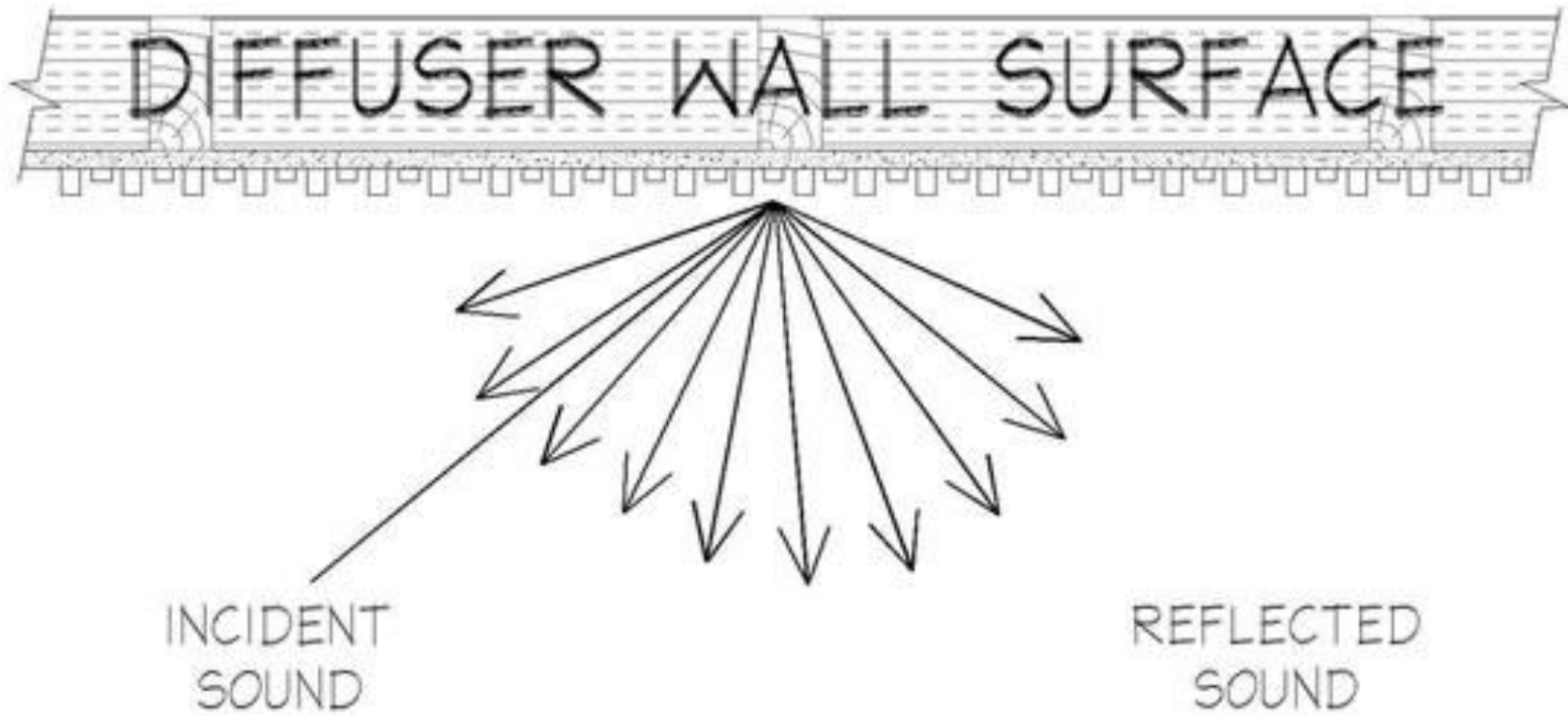
## **12. Finishes**

(a) The following should be sound absorbing:

- i. Proscenium walls
- ii. Gallery beam surfaces and columns if any
- iii. Auditorium back wall
- iv. Ceiling to side circulation aisles
- v. Doors
- vi. In areas where ceilings and walls meet, one or both of them should be sound absorbing to eliminate sound reflection from one of the surfaces to the other.
- vii. Floor finishes e.g. use of rubber polyurethane

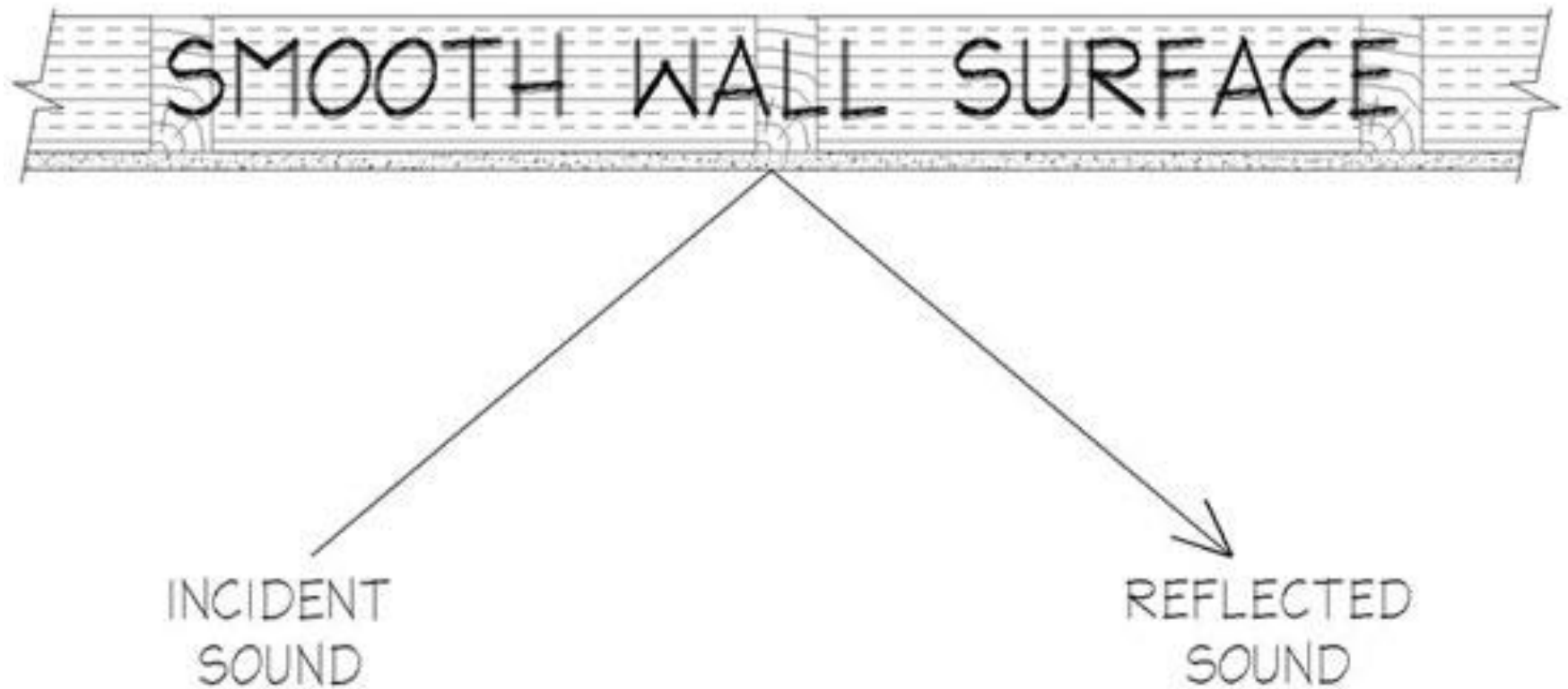
(b) Sound Reflecting surfaces

- i. Ceiling above central seating area
- ii. Curved acoustical reflectors above the stage



In a diffuse sound field sound level is uniform in all locations and from all directions

Specular sound reflections off flat wall and ceiling surfaces often produce inconsistent poor acoustic quality throughout the listening space



## 4.0 Best Practice:

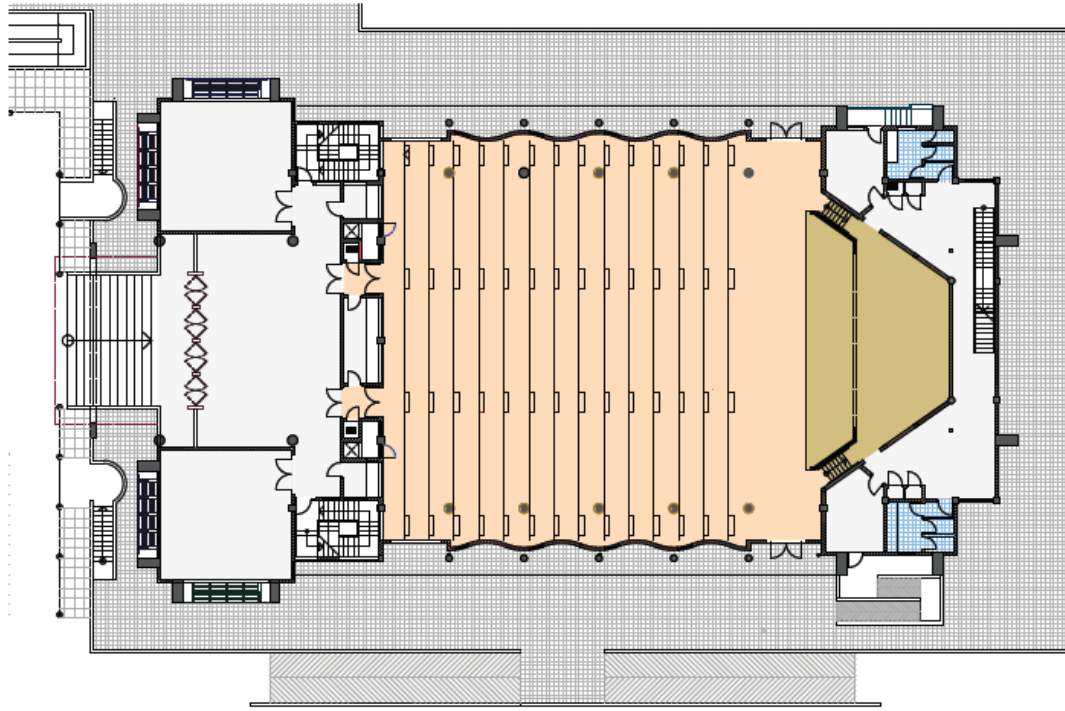
### **The LRC Conference Hall , Musau Kimeu**



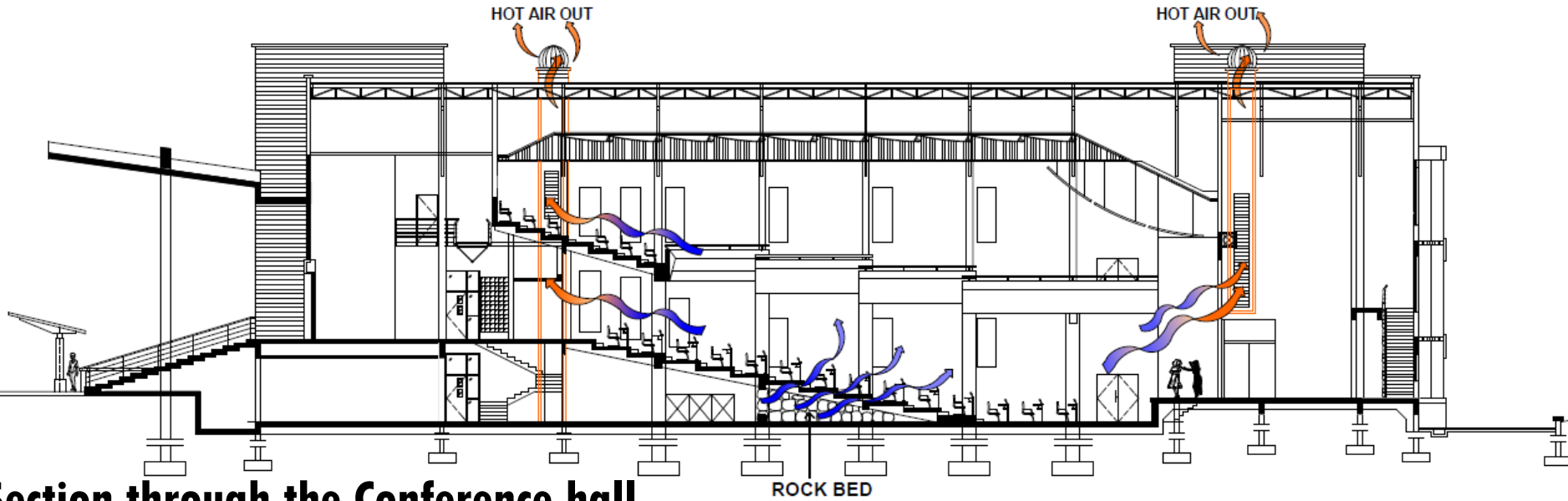
## **The LRC Conference Hall**

- **Originally envisaged to have a seating capacity of 600 persons, the conference hall currently seats 1200 people, 400 of whom sit in the 7 breakout rooms. Four of the discussion rooms have a seating capacity of 60 each, 2 others can seat 30 people each and the largest can seat 100 persons.**
- **This facility achieves several firsts, namely: it is arguably the largest conference hall in the region with excellent acoustic design. You better make time and visit the facility! The voice of a person speaking on stage is crystal clear to the audience seated at the rear row of seats in the gallery, 40m away and the person at the back of the balcony can clearly communicate with someone on stage without use of any public address system! Talk of going back to the basics in verbal communication. This has been achieved in this facility! The level of clarity is just amazing. In addition, the Conference hall is the second and the largest rock bed cooled naturally ventilated in Africa.**

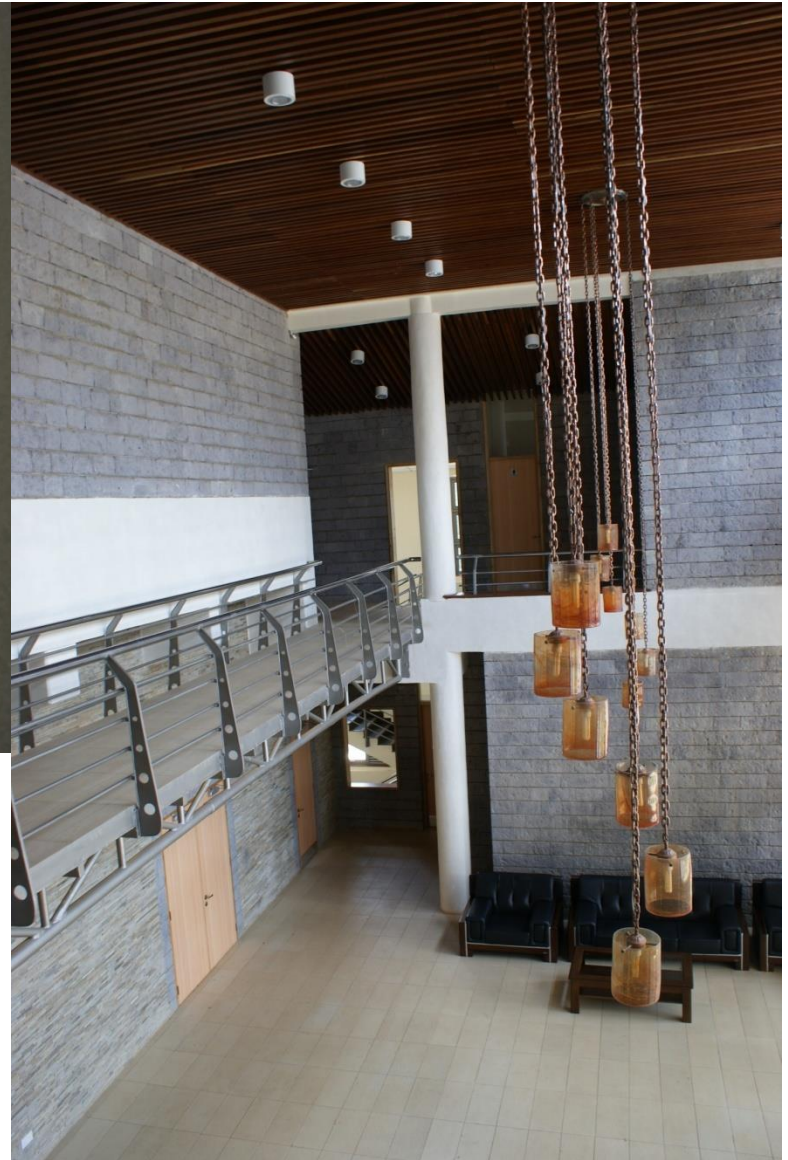
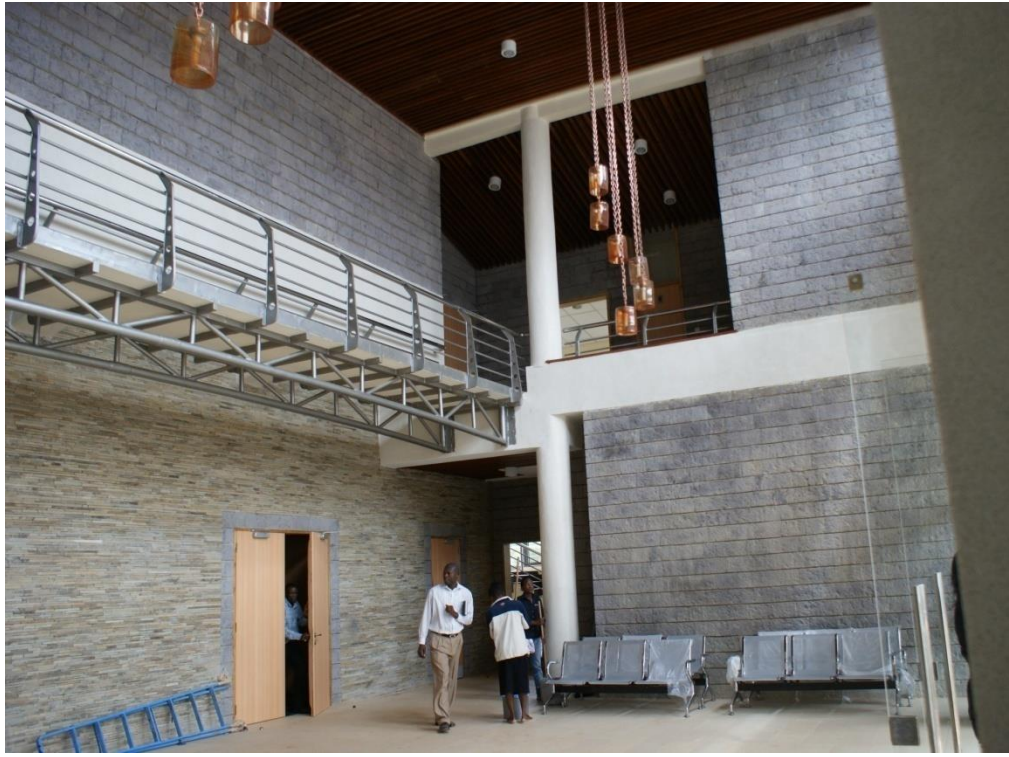
- **The hall's lofty double volume entrance lobby is elevated 2 metres above the main square. A flight of steps brings you to the lobby finished with cut mazeras and fine hand dressed Njiru blue stone. Hanging from the mvule timber joists' ceiling are two locally fabricated spiralling chandeliers and a floating steel bridge. To either side of the entrance are two of the 7 discussion rooms. From the lobby, one goes through a sound lock before getting into the hall. On either side of the sound lock is equipment and interpretation rooms.**
- **Wet areas are located on the lower ground floor beneath the raked seating and also on the first floor gallery level. Universal access especially for the physically challenged is provided for in the auditorium seating area and stage using ramps. From the gallery, one can walk out to the side balconies for a break.**



**Conference hall layout plan**



**Section through the Conference hall**



**Spiralling chandeliers hanging from mvule timber joists' ceiling and the floating steel bridge**



**Ramps are used to provide universal access especially for the physically challenged**

## **4.1 Acoustic Design**

### **i) Layout Planning**

- **CUEA wanted its new Conference hall to be world class, of a standard to enhance conferencing by the finest international standards for its use and also to be used to host local and international conferences. The brief also required the hall to house at least 5 Breakout or discussion rooms and language interpretation booths.**
- **For effective speech communication, a reverberation time of about 0.5 seconds is appropriate, However, for music a ‘live’ room with reverberation time of about 1.0 second is better. In designing the Conference hall, a reverberation time of about 0.5 seconds was used. For Conference halls, clarity of speech is key. Clarity comes from strong “early” reflections following the direct sound to the listener. In the design, this was ensured by placing sound reflectors above the stage area and the overall shape of the ceiling above the central seating area.**

- **The architect chose the 'horse shoe' balcony seating arrangement and a 'vineyard terracing' form for the relationship between the main seating area and the balconies, hence the balconies have the concept of breaking up the seating into blocks (like vineyard terraces). Part of the main balcony seats on top of the interpretation booths and equipment room i.e recessed away from the main seating area.**
- **The overall form of the hall was developed primarily from the desire to have quality acoustics and best practice. From an acoustics point of view, the end result is obviously pleasing and has set new acoustic design standards in conference halls in the region.**
- **The various acoustic considerations forced early decisions to be made on the type of lights and luminaries' to be used and thus due to the high ceiling of 12.5m above the finished floor level in front of the stage, LED general and concealed lighting at the ceiling was an obvious choice because of their long life. The special effects lighting including the stage lighting were also meticulously chosen with the overall effect and ambience in mind.**



**View of the Conference hall's main seating area and the 'horse shoe' balcony seating arrangement**



**The Conference hall in use**



**The special effects lighting directed towards the stage**



**The Conference hall in use**

## **a) Layout Plan**

- **Three basic layout plans are in common use for large halls. These are rectangular, fan, and horse-shoe shaped. Parallel surfaces must be avoided in auditorium design so as to minimise multiple reflections. A rectangular shape was chosen for the ground floor and a horse-shoe shaped layout for the galleries. To eliminate parallel side walls, sinusoidal walls were used. It is on the surfaces of these curved walls facing away from the stage that the glazed windows are located.**

## **b) Wall Surfaces, Columns, Beams & Doors**

- **Throughout the auditorium interior space, the principle of having 'perforated' cavity walls is used and thus whereas the external wall is blue, a hand dressed grey hard stone is used on the interiors with a cavity in-between. Mineral wool is sandwiched in between the cavity walls with no cement mortar on the vertical joints. In addition, the horizontal stone courses are laid such that every third course is recessed inwards by 50mm and all the cement mortar joints recessed in. Further, to avoid internal sound reflections, all internal columns, the main gallery beams and doors are padded with 50mm thick foam and covered with fire resistant vinyl padding.**



**To eliminate parallel side walls, 'perforated' sinusoidal (curved) cavity walls are used with windows facing away from the stage**

## c) Ceiling

- **Along the circulation aisles, the ceiling consists of mvule timber joists with perforated plywood and hessian cloth, 50mm thick mineral wool above the hessian cloth. A similar ceiling is used in the entrance lobby. In the central area of the auditorium, acoustic ceiling and purpose made sound reflecting profiled mdf ceiling is used. This also includes sound reflectors above the stage area. A high volume is strongly recommended for good acoustic qualities. In this case, the ceiling is 12.5m above the flat area in front of the stage.**



**Timber joists acoustic ceiling**





**View of the hall from the stage**



**Acoustic ceiling and sound absorbent vinyl covered balcony beams**

## **d) Flooring**

- **Flooring is done using “regupol” by the BSW (Berleburger Schaumstoff-Werk). It is a rubber-polyurethane composite, viscoplastic, which is friction enhancing. It is long lasting, resilient and can be recycled.**
- **Flooring on Stage is done using Mvule timber planks.**

## **e) The stage**

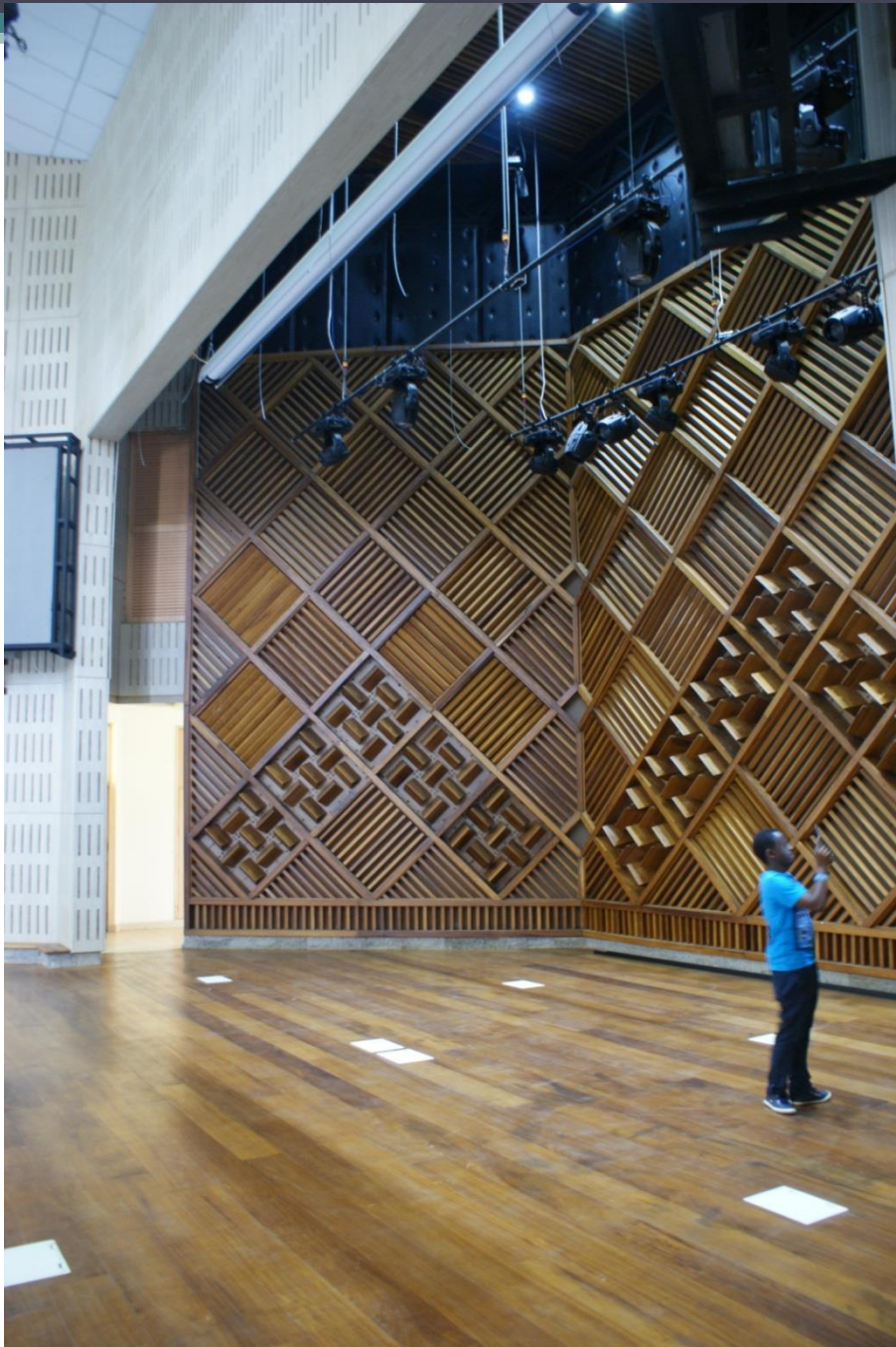
- **At the stage and the rear wall of the gallery, aesthetically designed acoustic timber panelling with adjustable panels gives the hall its signature identity. These panels are mounted on perforated MDF panels, creating a cavity with the rear masonry wall, within which mineral wool and hessian cloth are installed. The proscenium is padded with high sound absorbent vinyl covered panels for quality acoustics too.**



**View of the hall towards the stage**



**View of the hall from the stage**



- **The acoustic performance of LRC's Conference hall has outdone expectations and the hall has since its opening become the place of choice for most Conference Planners in Nairobi.**

**View of the stage showing acoustic timber panelling, high level sound absorbent vinyl covered panels and stage lighting**

## **5.0 Conclusion**

**Good acoustics are fundamental for effective communication, be it in conferences, speech delivery, musical performances or even in religious gatherings e.g. in churches. Sound intelligibility (clarity and strength) must always reach each member of the audience for the desired and enjoyable sound reception. The principles illustrated in this paper should go a long way in aiding the architect and acoustic specialist to achieve quality acoustics in large gathering spaces.**

**Thank you**