Architectural Acoustics

Lecture 16: Acoustical Criteria and Space Design

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Learning Objective

- Precedence effect
- Signal to noise ratio
- Room design for speech
  - Classroom design

Precedence effect

When a sound is reflected off a wall or other solid surface, the returning sound waves reinforce the original sound and the phenomena is called the precedence effect or Haas effect (1951)

First established by scientist, Joseph Henry in 1940

The precedence effect or the Haas effect is of considerable importance in architectural acoustics both for the natural reinforcement of live sounds and sound from reflecting surfaces

If a reinforcing sound (even from loudspeaker) if is within the below mentioned time of the initial sound, then a clear understanding can be expected

For speech, a delay of 25 msec
For music, a delay of 35 msec
For romantic music, delays as high as 50 msec

Signal-to-Noise Ratio

The degree to which noise inhibits intelligibility is dependent on the *signal-to-noise ratio*, which is simply the signal level minus the noise level in dB.

Ainger and Strutt (1935) coined the ratio *impression (Q metric)*

$$Q = E_d + E_e \;/\; E_l + E_n$$

Desired Q>1

where E_d = direct field energy (N m)
E_e = early part of the reflected energy (N m)
E_l = late portion of the reflected energy (N m)
E_n = constant noise energy (N m)

Early-reflected sounds with the direct sound increases the apparent strength of the whole

When Direct and early sound = Noise and reverberant sound (Q= 1)

Ainger and Strutt had set the dividing line between early and late reflections at 1/16 second (62.5 ms) and set a lower limit of 1 for a satisfactory value of *Q*.

Signal-to-Noise Ratio

One of the earliest attempts of Thiele (published in 1953) at relating early to total sound energy ratio to intelligibility, which he called the definition, D.

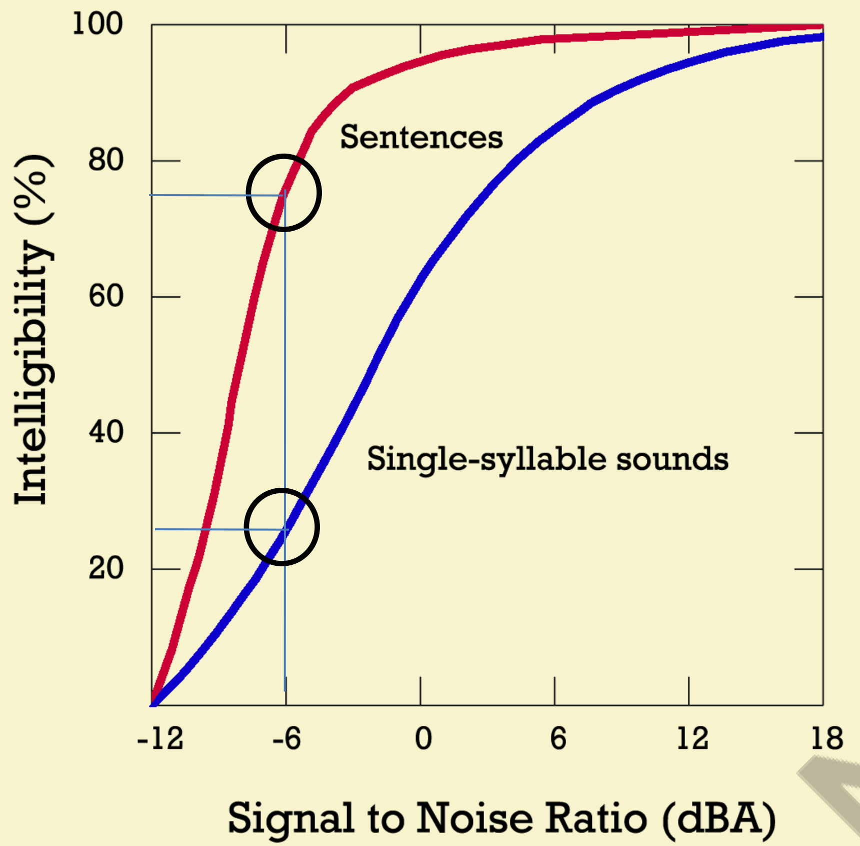
Definition 'D'

He considered the useful energy = the direct energy + the reflected energy that arrives within 50 msec of the direct sound.

Definition did not account for the contribution of the background noise.

Bradley (1986) established that signal-to-noise ratios significantly less than 15 dB yield very satisfactory intelligibility.

Signal-to-Noise Ratio



Percent of words and sentences correctly identified in the presence of background noise (Kinsler et al., 1982)

For sentences higher is the intelligibility than single syllable sounds under same S/N ratio

Background noise levels in small classrooms and lecture halls are designed to an NC 30 (35 dBA) larger auditoria to an NC 25 (30 dBA)

Bradley (1986) hold that a 10–15 dB margin is a reasonable choice for intelligibility.

Signal-to-Noise Ratio

	when added	when subtracted
two decibel values with difference as below	increase in higher of the level (dB)	decrease from higher of the levels (dB)
0 or 1dB	3dB	10dB (least)
2 or 3dB	2dB	4.3 – 3dB
4 to 8dB	1dB	2.2dB to 0.7dB
9dB or more	0 dB	0.5dB

70 dB (SIGNAL) +70dB(SIGNAL) = 73dB, 78dB + 84dB = 85dB

70 dB (SIGNAL) – 70 dB (NOISE) = 60dB, 85dB – 78dB = 84dB

Fundamental requirements in designing rooms for speech (Doelle, 1972)

1. There must be adequate loudness - high direct field level.
2. The sound level must be relatively uniform.
3. The reverberation characteristics of the room must be appropriate.
4. There must be a high signal-to-noise ratio.
5. Background noise levels must be low enough to not interfere with the listening environment.
6. The room must be free from acoustical defects such as long delayed reflections, flutter echoes, focusing, and resonance.

Beyond 30 to 40 feet it is difficult to understand unreinforced speech

Optimum volume per seat should be 110 cu ft (3.1 cu m) (80 – 150 cuft)
Less volume increases loudness and decreases RT for same area of absorption

Acoustic requirement for classroom design

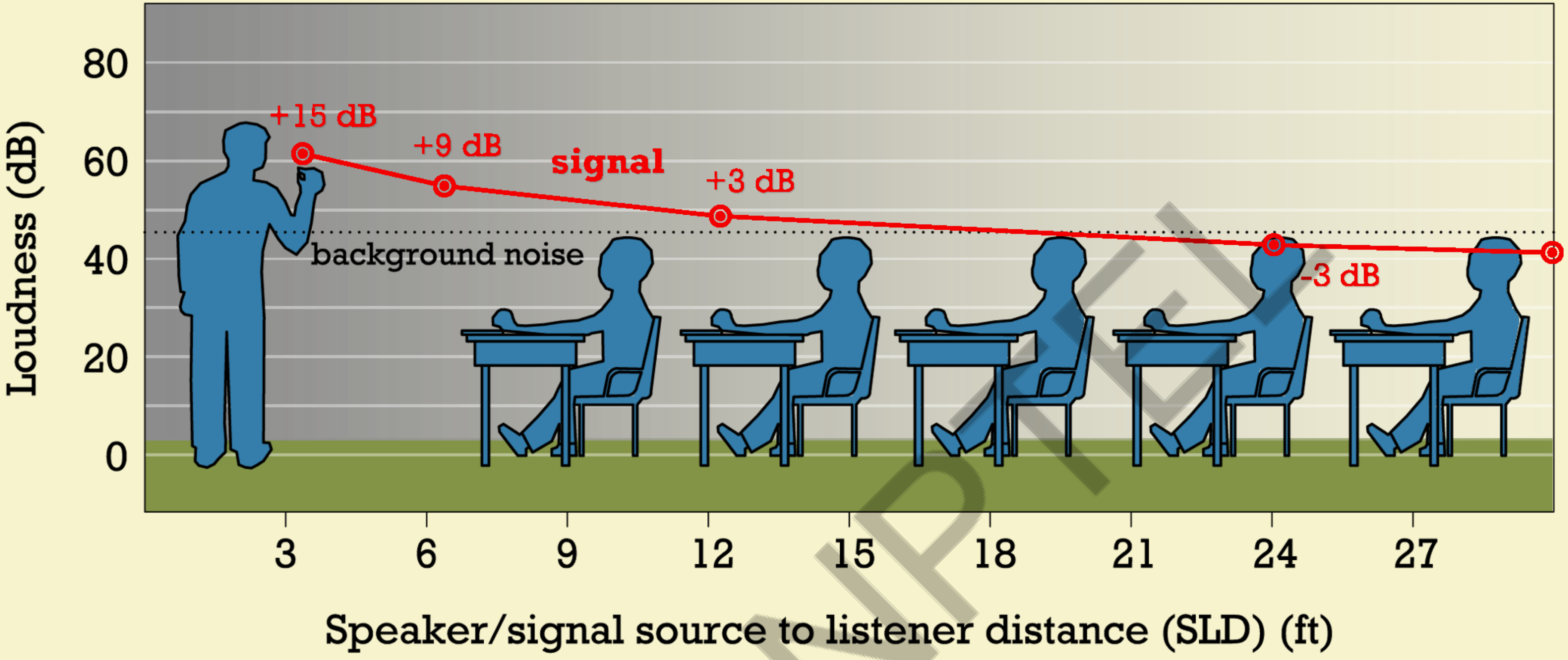
For children specially primary section 100% intelligibility is desired.

Children should also be heard to the teacher.

Low noise level or low reverberation or both is desired

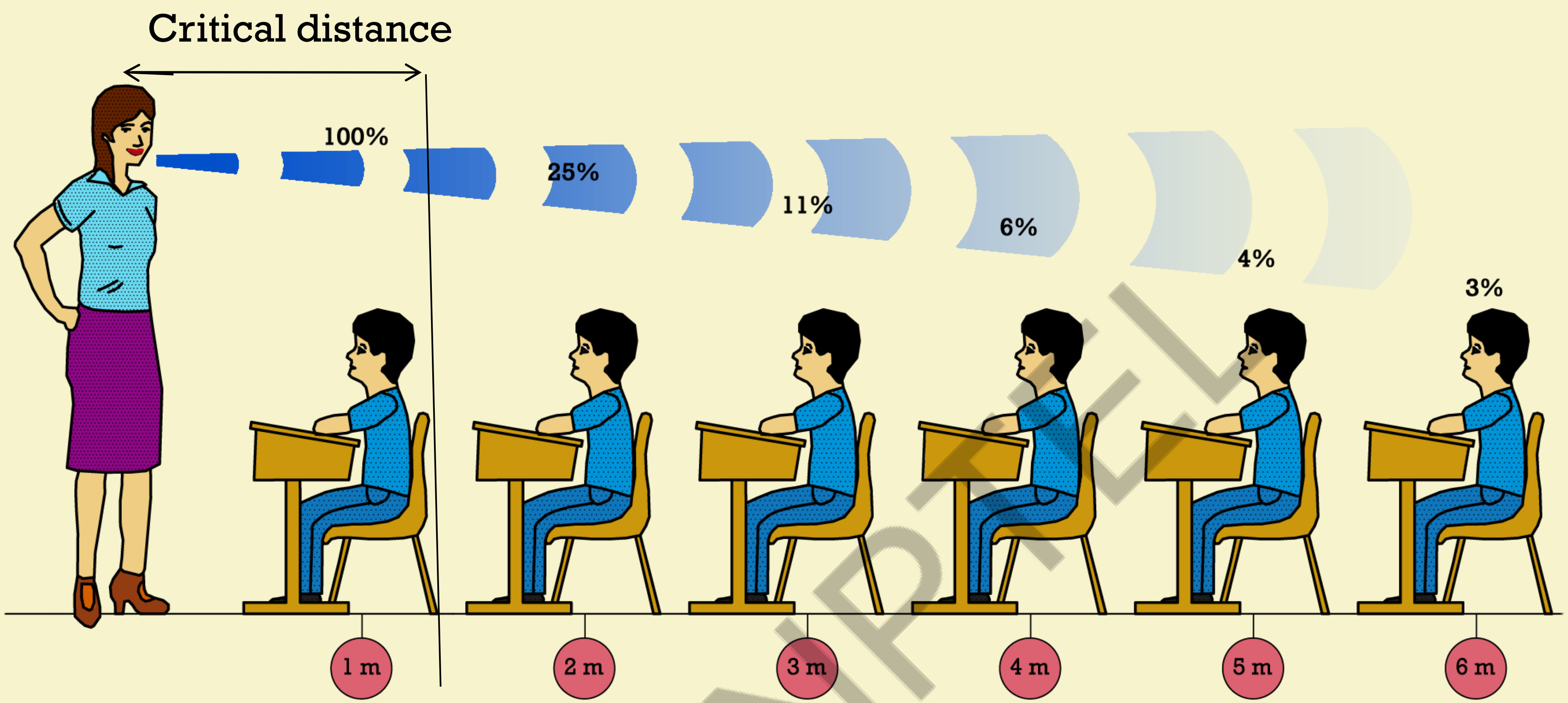
Additional aid for students with hearing or language disability

Avoid sources of noise – HVAC ducts, waste water lines



Inverse square law: pressure reduces with increased distance

Sound pressure decreases by 6dB for every doubling of distance

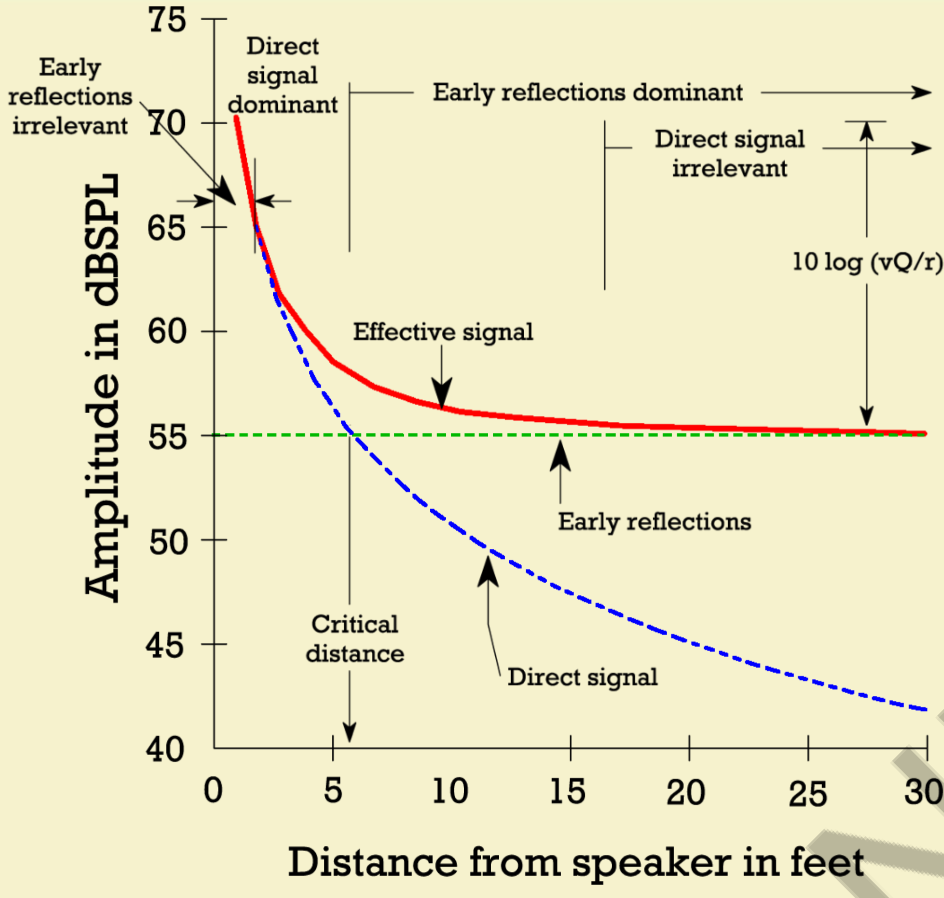


Source sound level drop in a classroom

Reflected sound support from the walls / ceiling provides sufficient loudness

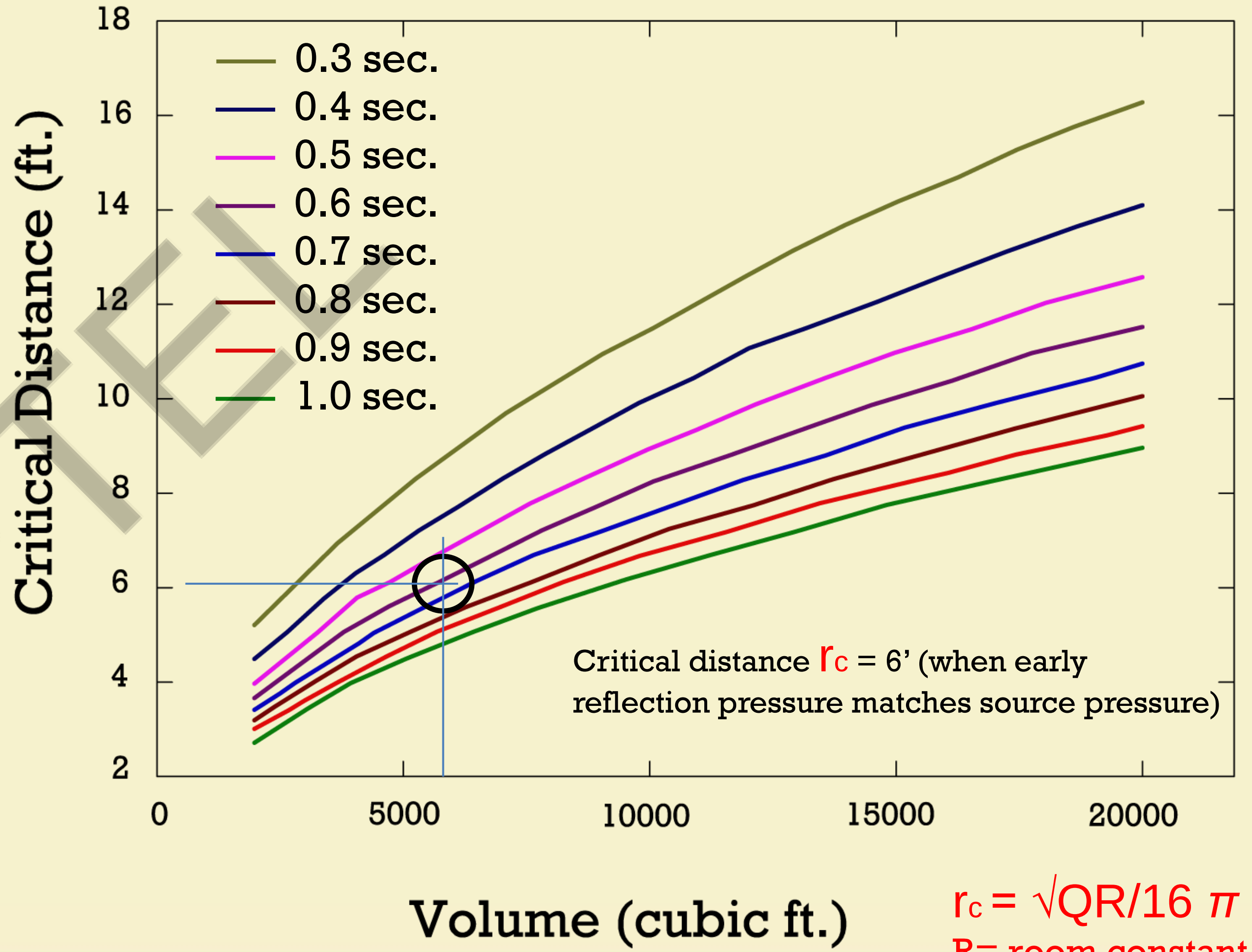
The orientation of a reflective element is determined by the required coverage

Critical distance



Estimates of the direct, early-reflected, and combined (effective) speech signal as functions of distance in a room measuring 30 x 20 x 10 feet ($v=6000$ ft^3) with a reverberation time (r) of 600 milliseconds. Talker Q is assumed to be 4. Average speech level at 1 foot = 72 dBSPL.

Estimates of critical distances as a function of room size and reverberation time



$r_c = \sqrt{QR/16\,\pi}$

R= room constant

R = The total absorption in a room, including the air absorption in metric Sabin

Tasks

Try out some decibel addition and subtraction
Find the critical distance using the curves with different Reverberation times for different dimension classrooms/ small lecture rooms

Referred Books:

Concepts in Architectural Acoustics, M. David Egan

Architectural Acoustics by M. Long

Room Acoustics by Heinrich Kuttruff

Boothroyd, A. (2004). Room acoustics and speech reception: a model and some implications. *ACCESS: Achieving clear communication employing sound solutions*, 207-216. https://bit.ly/2HSQ8mz

Atcherson, S. R., Franklin, C. A., & Smith-Olinde, L. (2015). *Hearing assistive and access technology*. Plural Publishing.**(in turn, adapted from Boothroyd's original 1986 book)**

Architectural Acoustics

Lecture 17: Acoustical Criteria and Space Design

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Learning Objective

- Class room design details
- Privacy
- Sound masking
- Open space design
  - Open offices, Restaurants, Cocktail party effect

Classroom design details

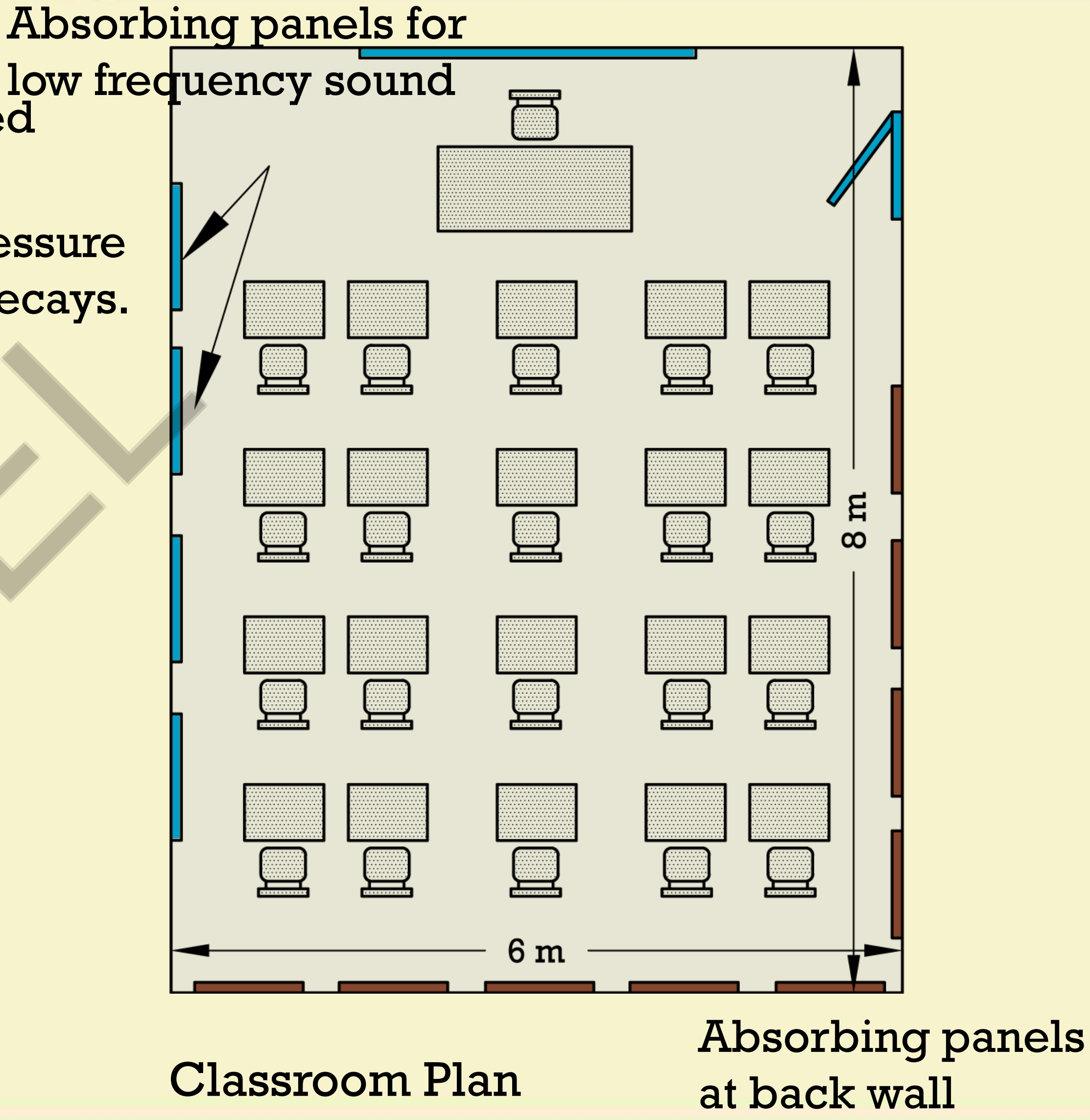
For a flat floor : Grazing attenuation of direct sound is observed

Critical distance is the distance at which the source sound pressure equals the reflected sound pressure and then source sound decays.

Critical distance depends on
- Volume of room
- Reverberation time

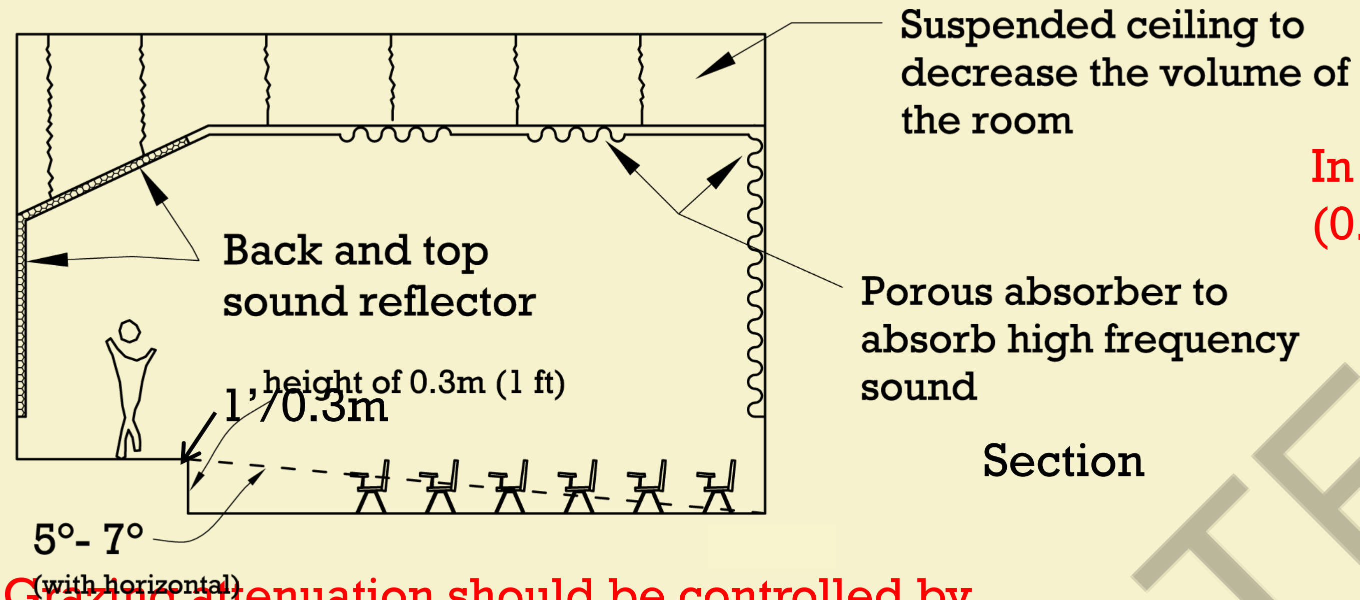
Beneficial reflections, preferably from overhead, should be designed

Frequency of human voice is 600Hz to 4000Hz Human voice so absorbers should be porous in nature.



Classroom Plan

Classroom design details

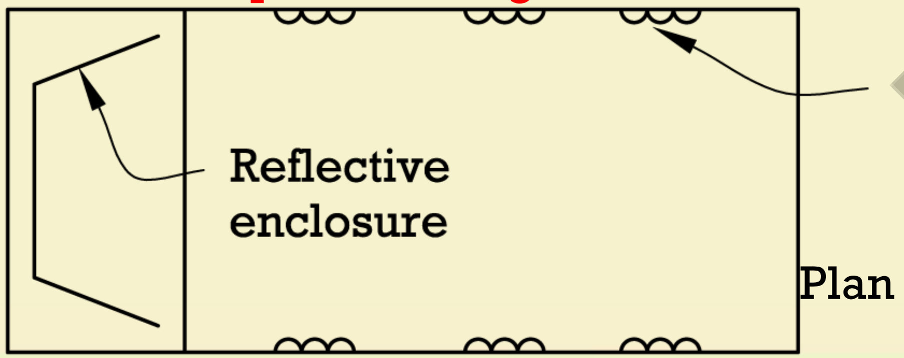


In a large flat-floored classroom, a platform of 1 ft (0.3 m) height can improve the sight lines significantly.

RT = Height of ceiling (in feet) / 20α
(α= absorption coefficient)

(mid-frequency reverberation time can be considered)

Grazing attenuation should be controlled by raising the talker height and/or by sloping the floor (5^0 -7^0) can also improve the sight lines



for RT = 0.6 sec and ceiling height is 10 feet, then desired α = 0.83

Conclusion for classroom

Typical classrooms size 8 m wide by 10 m deep accommodates 30 to 40 students.

Ceilings in classrooms are low enough to add to early reflections

Low frequency sound is of no importance in speech and hence appropriate absorbers may be added

Reverberation times preferred between 0.4 to 0.8 seconds

Intelligibility should be maximum (at least 80%)

Reflective surfaces i.e. surfaces near source should not be covered.
Make the side walls reflective surfaces in order to increase the signal intensity.

Privacy

The inverse of intelligibility is privacy.

Articulation index is equally useful in the calculation of privacy as it was for intelligibility.

When articulation index is low privacy is high.

Source sound level – Attenuation – Masking of sound = Signal to noise ratio (Privacy)

1) Control the sound source 2) Increase the path attenuation 3) Raise the masking sound level

↓ Orienting sound source

↓ Absorbing sound

↓ Electronic sound

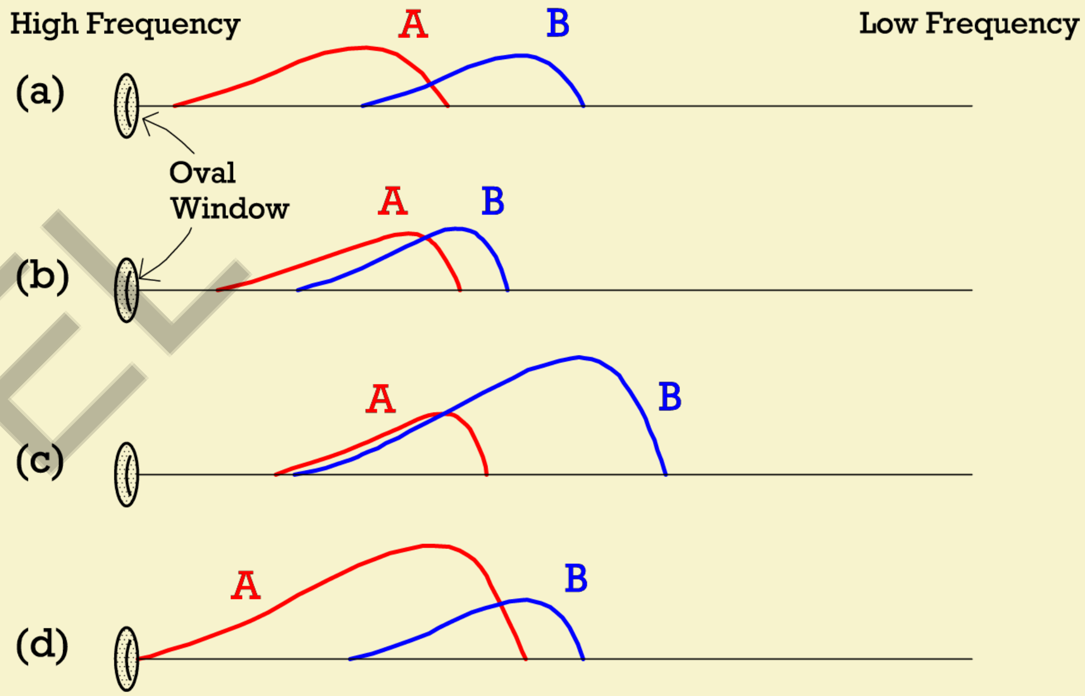
Masking of sound

The quieter sound is *masked* by the louder.

The louder the masking tone the wider the range of frequencies it can mask.

Tones close in frequency mask each other more than those that are widely separated.

Overlap of regions of the cochlea (Rossing, 1990)



Simplified response of the basilar membrane for two pure tones A and B:
(a) The excitations barely overlap, little masking occurs
(b) There is an appreciable overlap; Tone B masks tone A, and somewhat more than the reverse.
(c) The more intense tone B almost completely masks the higher-frequency tone A.
(d) The more intense tone A does not completely mask the lower-frequency tone B.

Masking of sound

Masking effect is most prominent when the sound is coming from same direction

Our hearing is more sensitive to reflections arriving from lateral directions than from front or rear

Reflections from ceilings can also get masked more effectively by the original sound

Hence early reflections from side walls are not equivalent to early reflections from the ceiling or from overhead reflectors.

If the total energy from lateral reflections is greater than the energy from overhead reflection, the hall takes a desirable "spatial impression."

Application:
Masking is useful to cover unwanted sound
Low music in background can mask human voice in restaurants

Open office design

Privacy in an open-office work environment can be achieved when

careful arrangement of the furniture orientation of both talkers and listeners

Partial height barriers of the correct type and correct height

highly absorbent ceiling and wall panels

masking sound should have the proper spectral content and level

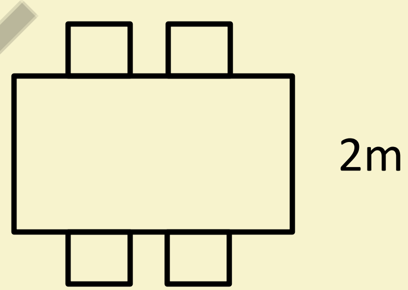
No reverberant field exists, particularly because of intervening barriers and highly absorptive ceilings.

Restaurant design

In restaurants or private homes, the noise may be generated by conversations other than those of interest.

Objective is to talk comfortably across a table (1.2 - 2m),
but conversations not to be overheard by someone at a neighboring table (say 3-4m away)

A normal conversational level = 70dB



hard-surfaced restaurants it is very difficult for hearing

addition of absorbing materials can control reverberant noise

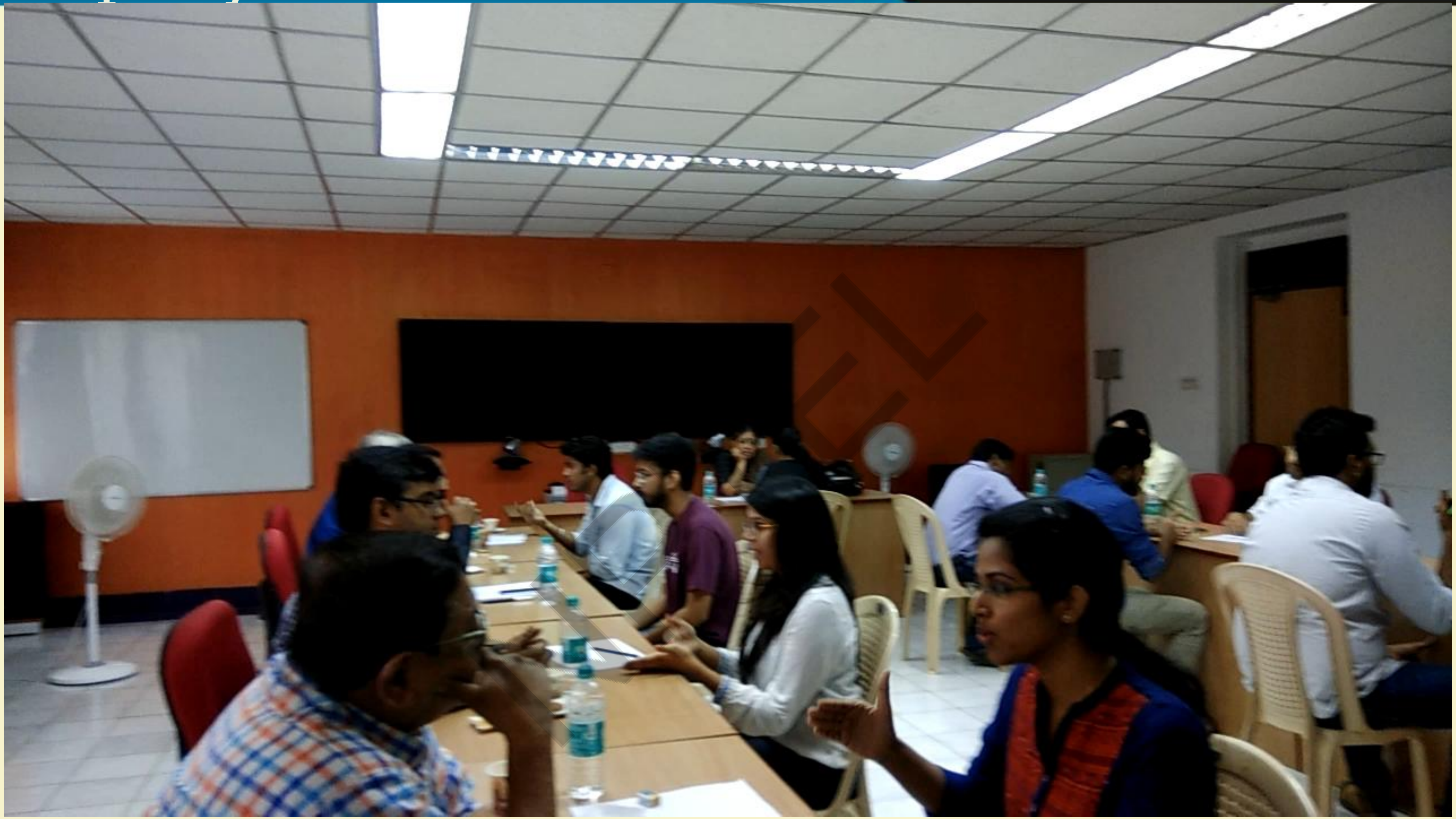
an area approximately equal to the restaurant ceiling area

Open office layout
[Source: *flickr.com*]

Carpet flooring

Restaurant layout
[Source: *pixabay.com*]

Cocktail party effect



Tasks

Find out the heights of classrooms of different capacity with different RT considering standard porous absorbers.

Referred Books:
Concepts in Architectural Acoustics, M. David Egan
Architectural Acoustics by M. Long
Room Acoustics by Heinrich Kuttruff

Perception of Direction

The perception of direction is controlled by two factors:
1) the interaural delay time between the ears
2) the level difference created by the interaction between the head and the ears.

The first ear receives sound a millisecond before the other ear

Shielding provided by the head helps brain differentiate the loudness and hence the direction is perceived

When two sounds arrive at a listener simultaneously, the louder sound determines the direction.

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Architectural Acoustics

Lecture 18: Acoustical Criteria and Space Design

Conference rooms

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Learning Objective

Rooms for speech

- Conference rooms

Recapitulation

Clarity of speech is our objective

Three basic types of acoustical issues

- Isolation from outside sound
- Source sound and reflection
- Internal absorption
- Background noise

Signal to noise ratio - Single source, Multiple source

Direct sound can reach the audience further if the reverberation time is lower and the volume is lower

Critical distance

Beyond which the reflective sound plays an important role

Conference and board rooms

Comes under medium live room, reverberation time (0.8 – 0.9 sec)

Capacity determines the volume, architectural components of these rooms—size, shape is known.

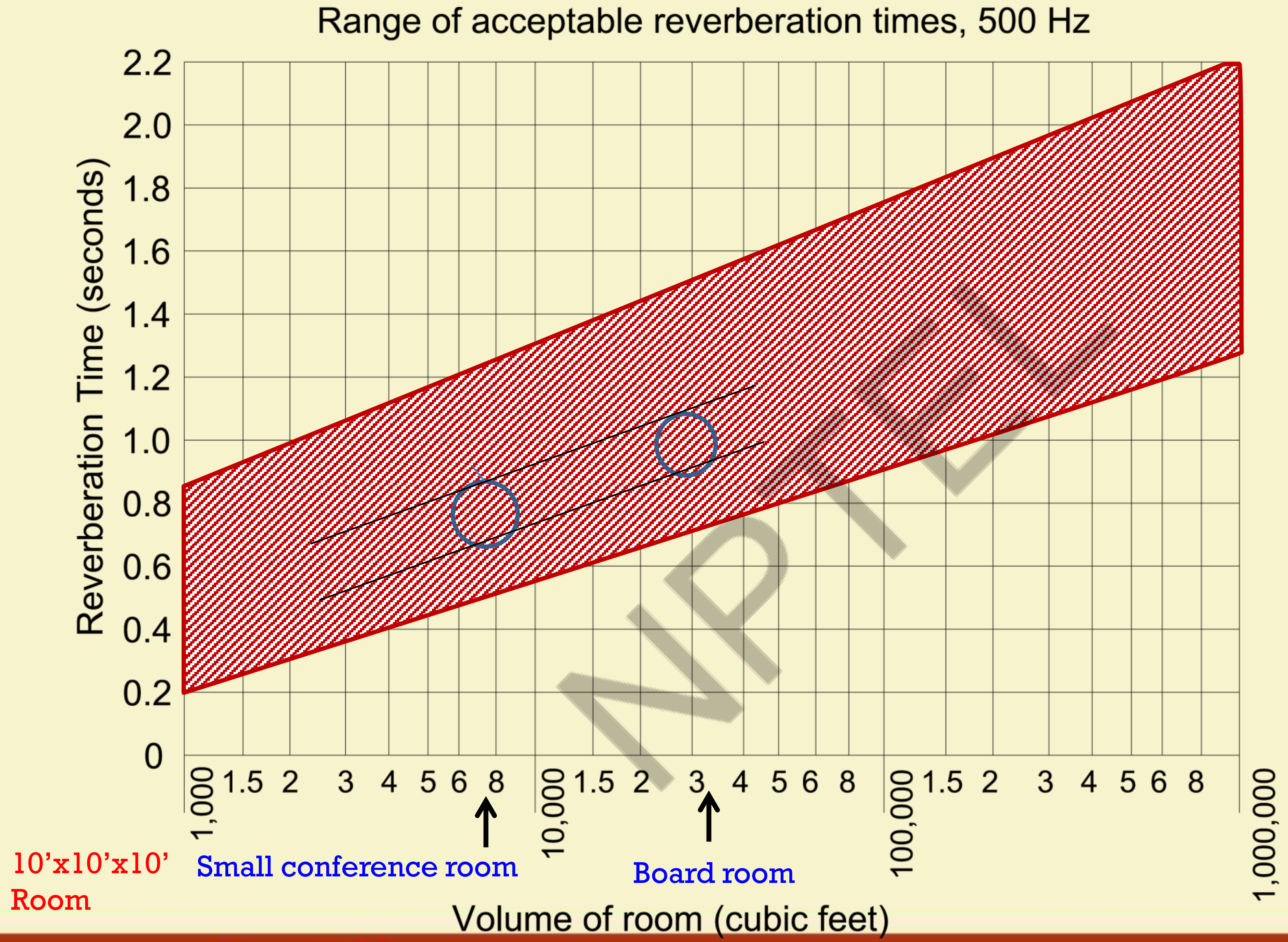
Seating arrangement determines the acoustical plan

Usually oval / rectangular seating with chairs around is desired, it allows discussion with each other.

Sound source: A network of conversations

Source sound and critical distance – help of early reflection

Reverberation time

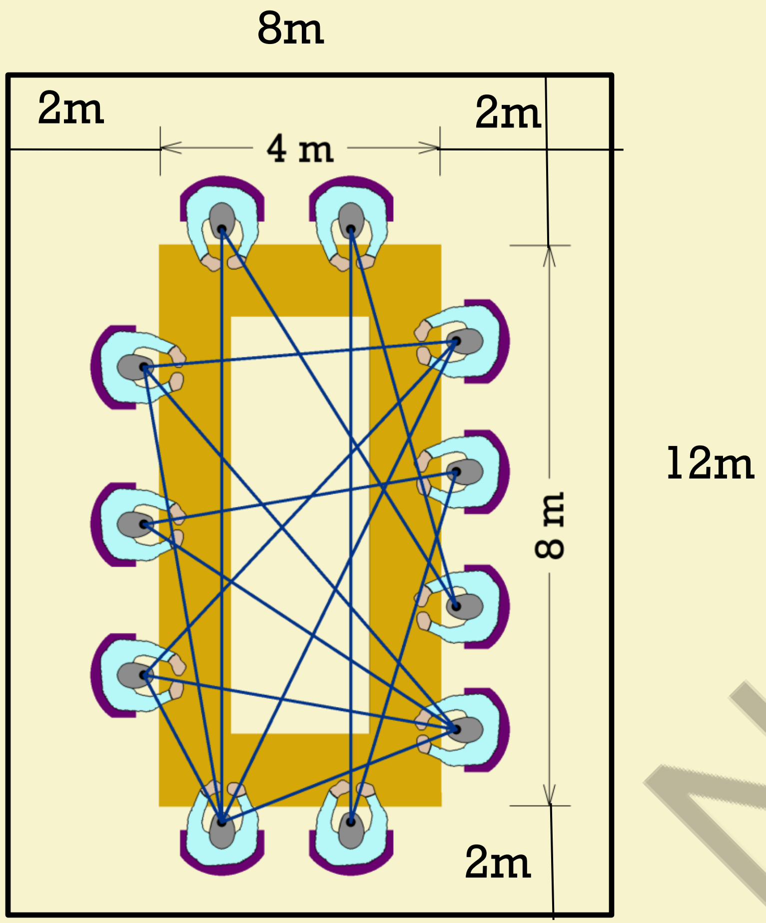


Bigger volume spaces can have larger reverberation time

$$RT=0.16V/A$$

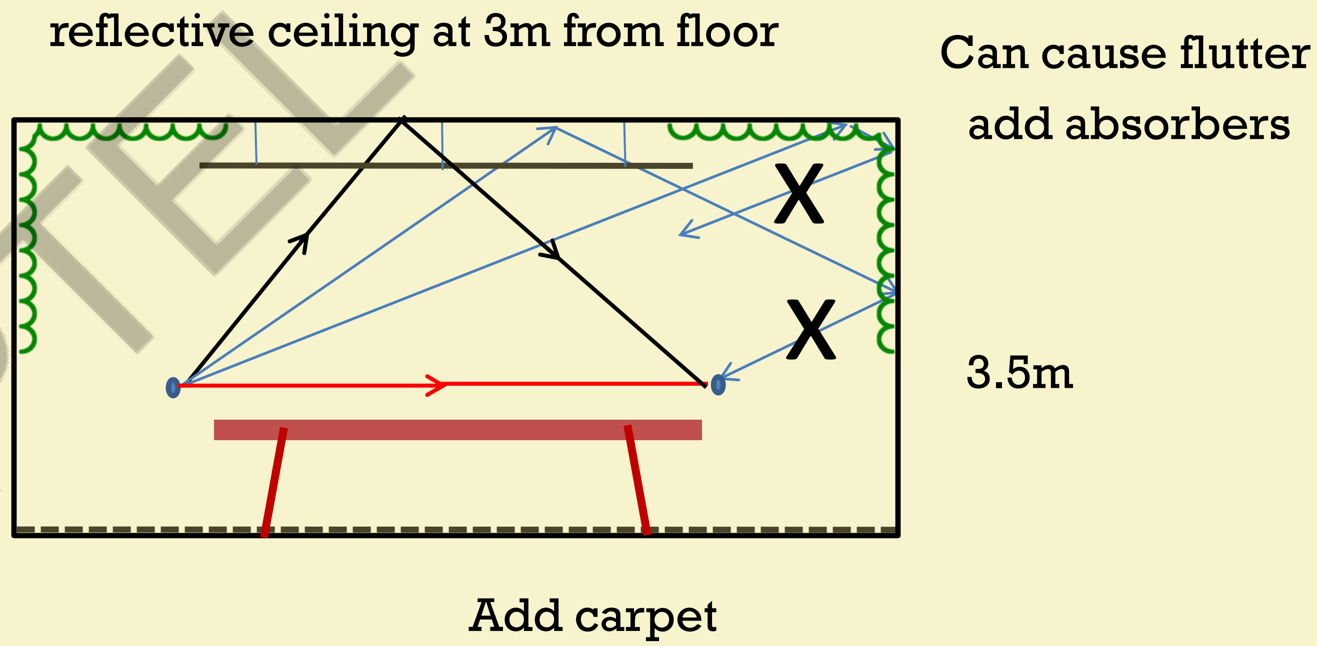
V= Volume of room
A= $\sum$ **s α**

Conference and board rooms

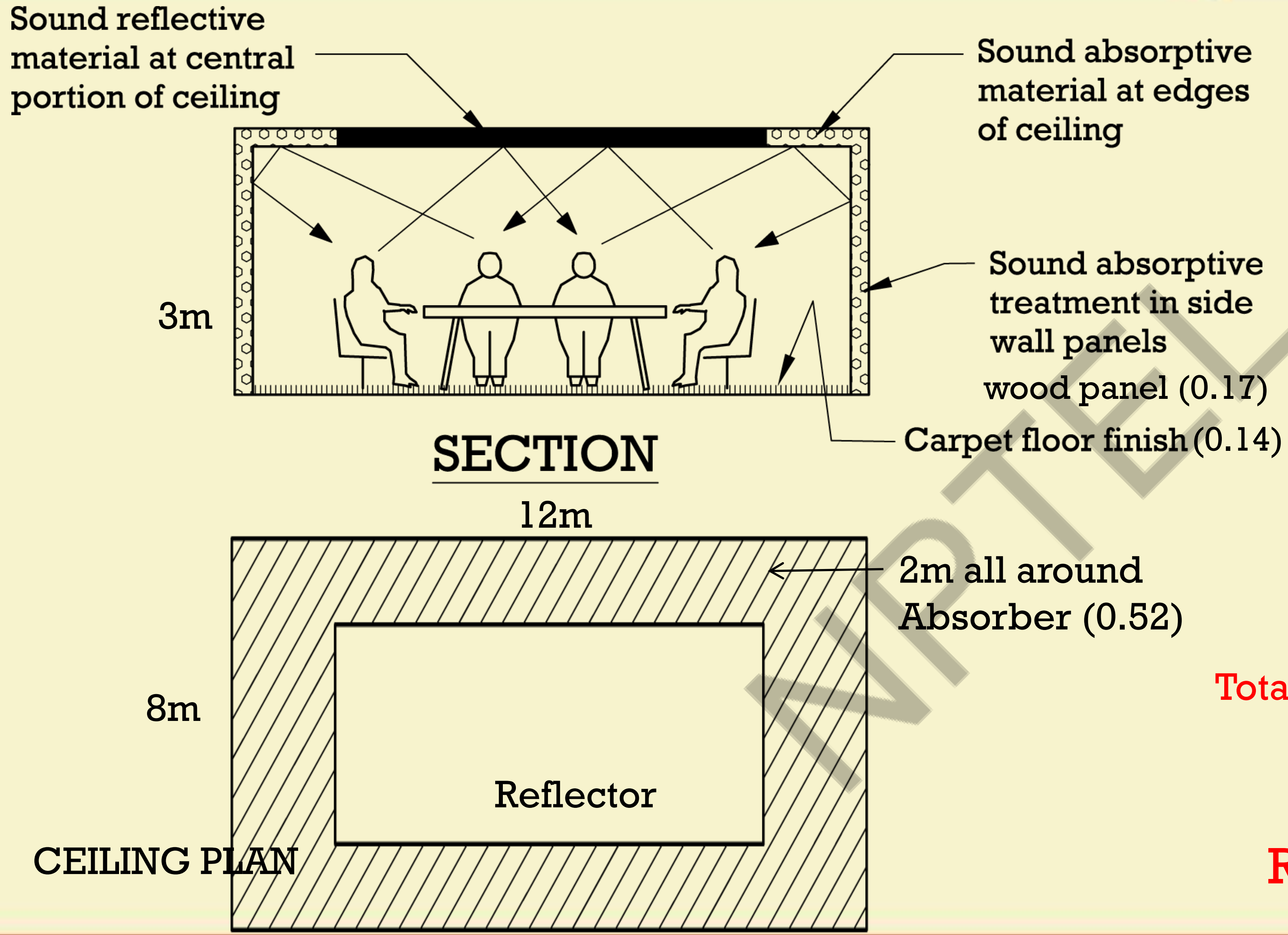


Typical layout plan of a conference room

Unreinforced speech is heard over distances up to about 35 ft or 12 m



Conference and board rooms



Volume of room = 288cum
3m x 8m x 12m

Area of ceiling absorber
8x12 - 4x8 =64 sqm

Area of wall absorber
2x3m x (8m+12m) = 120sqm

Area of exposed carpet
64sqm

Total absorption = 0.52x64+0.17x120+0.14x64
=62.64 sabine

RT = 0.16x288/62.64 = 0.735 sec

Conference and board rooms

Suggested acoustical measures

Reflective ceiling preferably at 3m height or lower for the central part

Absorptive ceiling preferably at the edges of the ceiling to reduce reverberation time

Sound absorptive treatment in side walls at least upto 50% of wall surface area

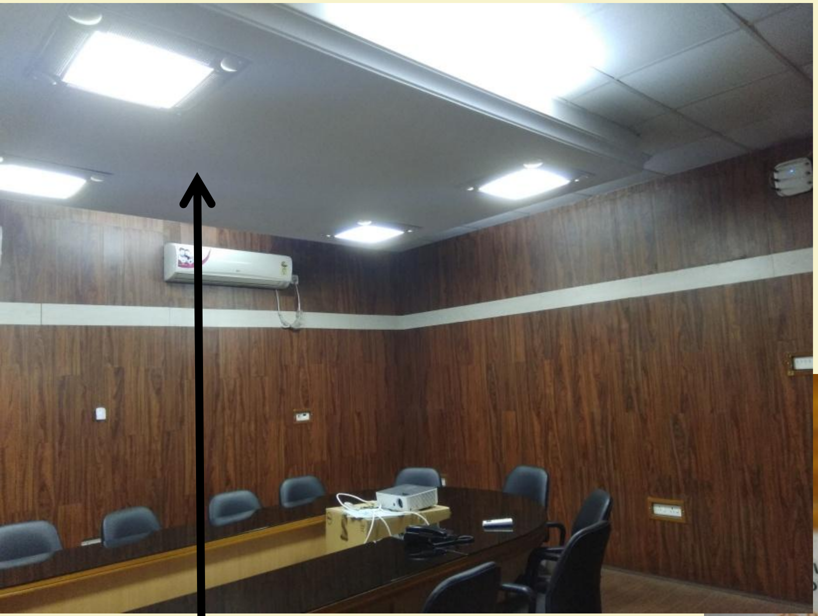
Cloth-wrapped panels, preferably with dense fiberglass or cork infill – porous absorber

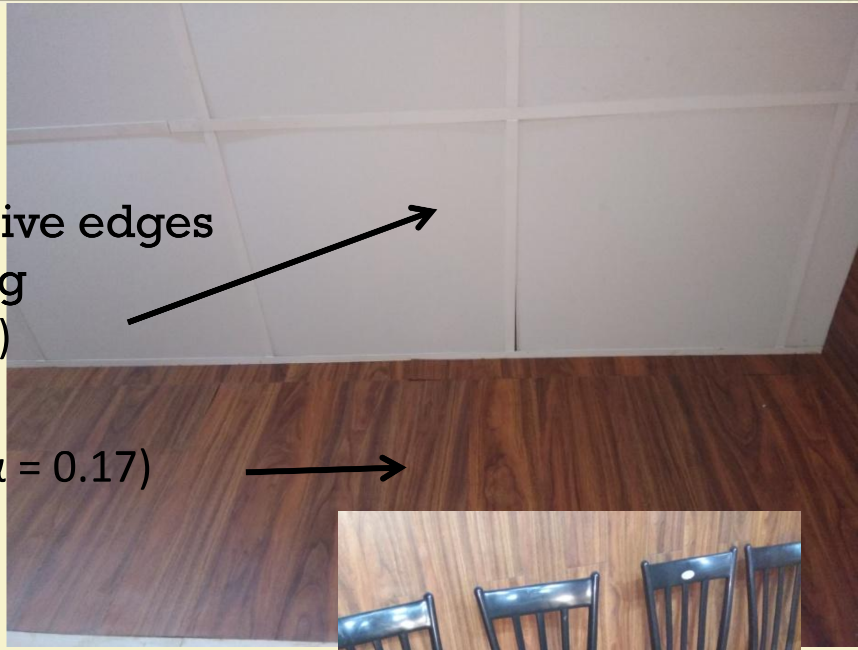
The chairs, curtains and human beings –act as absorbers

Avoiding mechanical noise from fans, ducts that can mask useful sound

Carpet as floor finish to stop foot sound

Small conference room





Absorptive edges
in ceiling
(α = 0.52)

Wall paneling (α = 0.17)

Reflective ceiling

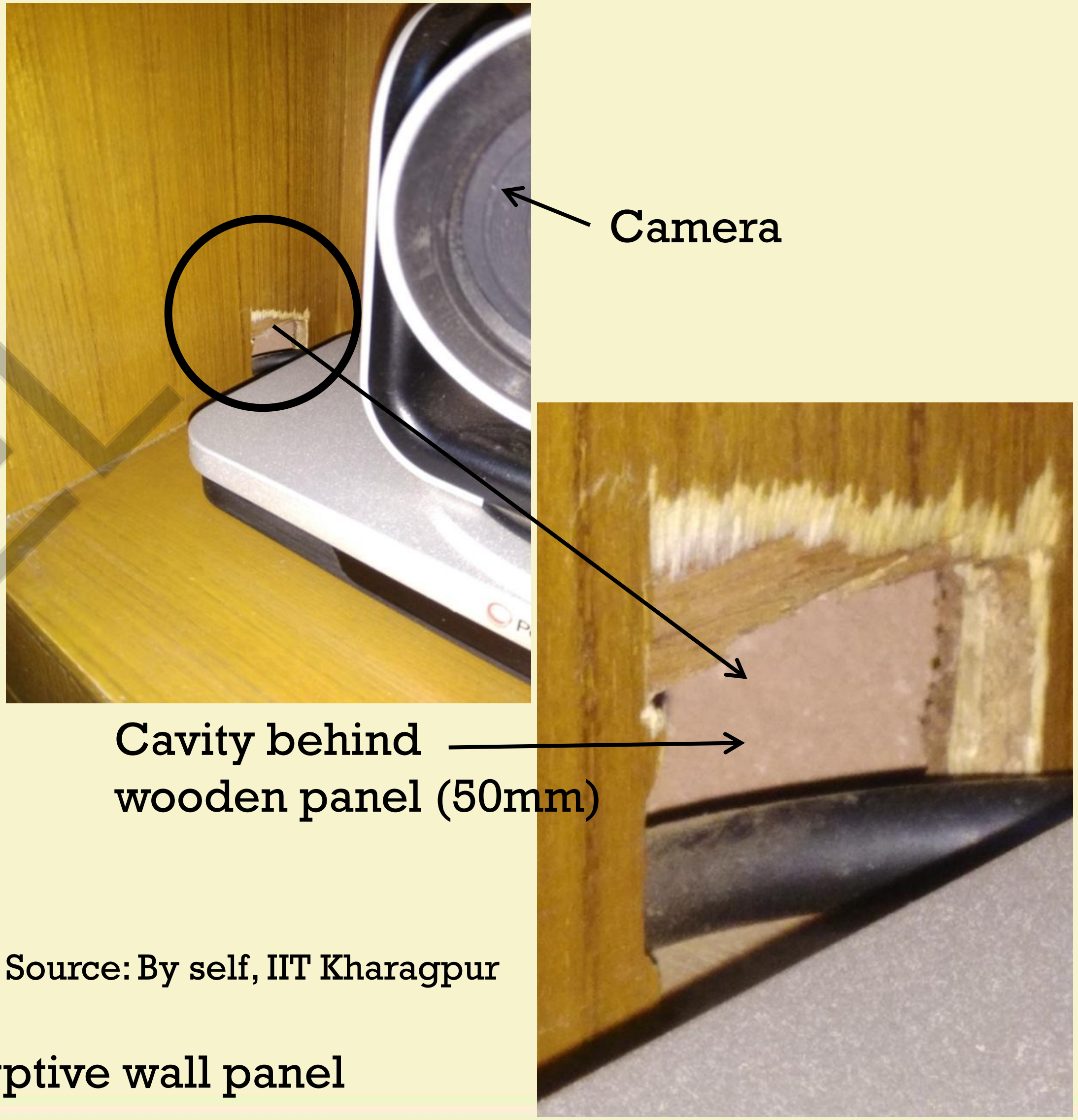
Cavity between wall panel
and structural wall (50mm)

Wooden finish
(no space between)

View: Small conference room

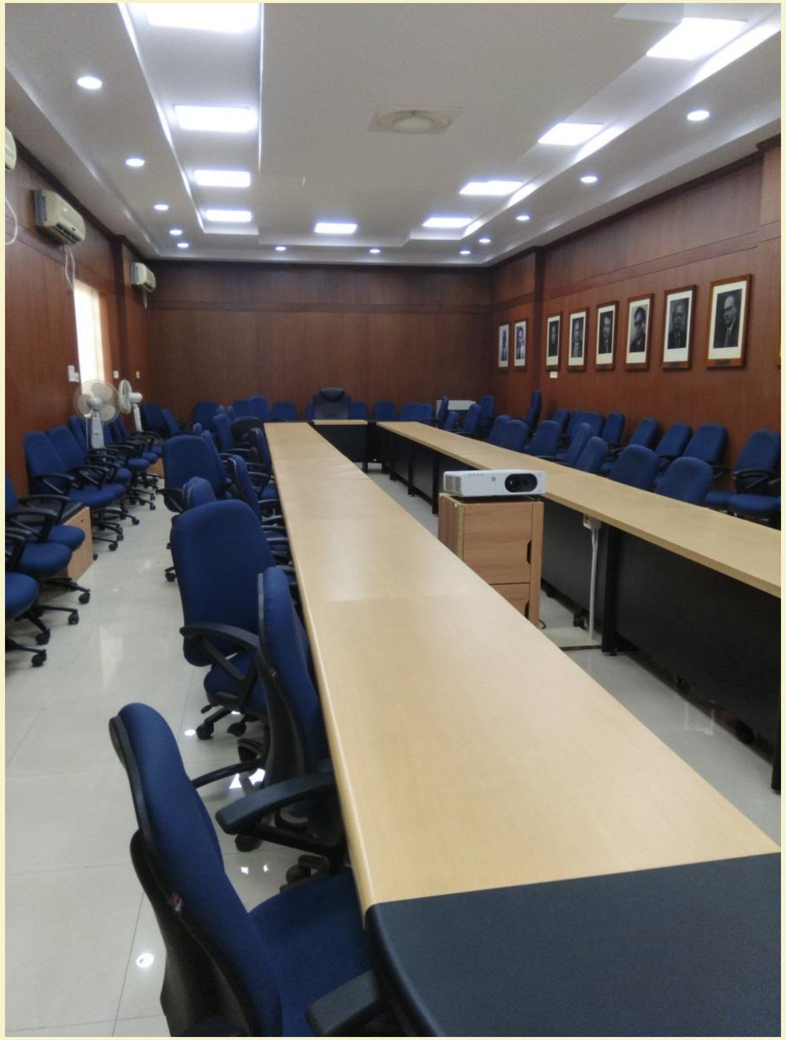
Source: By self, IIT Kharagpur

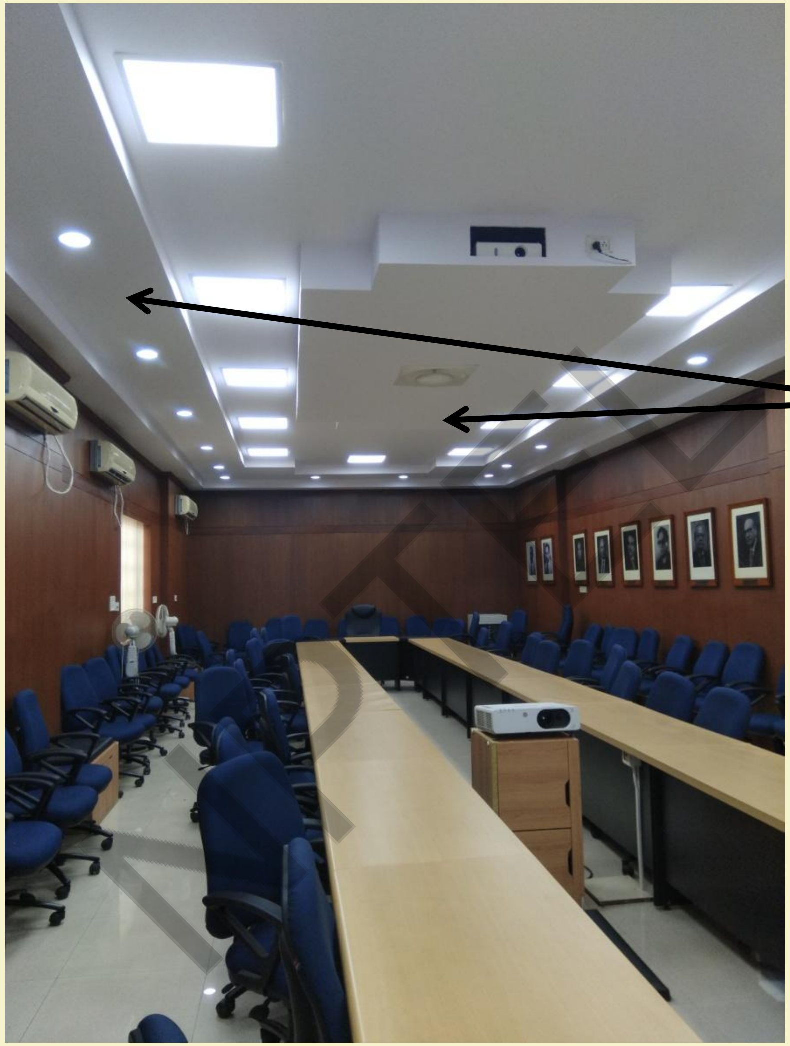
Small conference room with totally reflective ceiling and absorptive wall panel



Source: By self, IIT Kharagpur

Large conference Room





•Reflective ceiling at a lower height

•Absorptive wall with wood panels

•Tile flooring

Volume of Room: 900 cum
Seating length (approx) 14m
Width (approx) 5m
Projection system is present
Speakers are also used at times

View: Large conference room, Source: By self, IIT Kharagpur

Conclusion

Successful room acoustics is, thus, a combination of the geometry of the space and the absorptive and reflective properties of materials and its positioning depending on the sources and receivers.

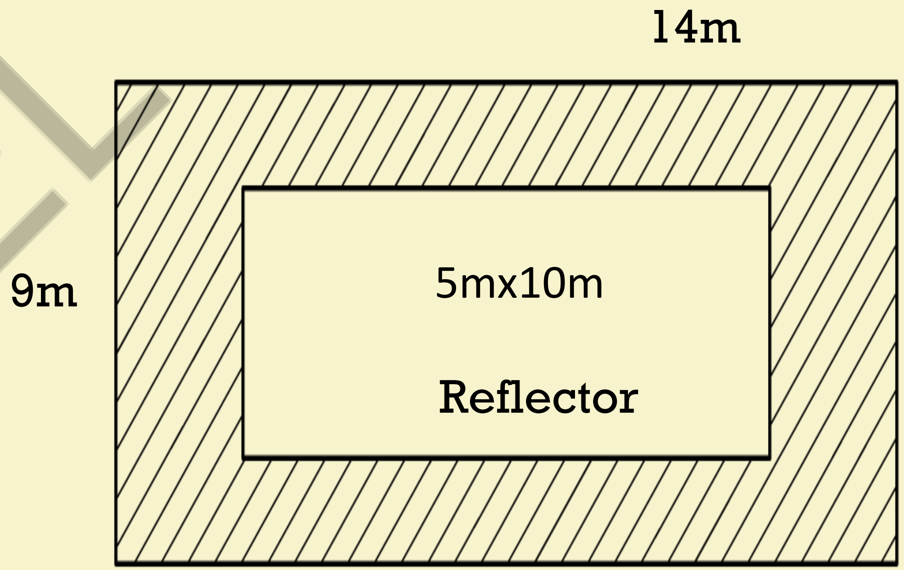
Room modes must be considered in the design
Proportion of room to be planned
Low frequency absorbers are advised

Task

Calculate the total absorption required in Sabine to get RT= 0.9 sec in a conference room of volume 3.7mx9m x14m. With 25mm fibreglass boards (0.65) beyond table in ceiling and with wood panel (0.17) in all walls from top is expected to provide sufficient absorption.

Show that the desired RT can be achieved. Refer to the plan for calculation.

Neglect absorption of flooring, chairs and users



CEILING PLAN

Referred Books:

Concepts in Architectural Acoustics, M. David Egan

Architectural Acoustics by M. Long

Room Acoustics by Heinrich Kuttruff

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Architectural Acoustics

Lecture 19: Acoustical Criteria and Space Design Lecture Halls

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Learning Objective

Acoustical Planning for Lecture Halls

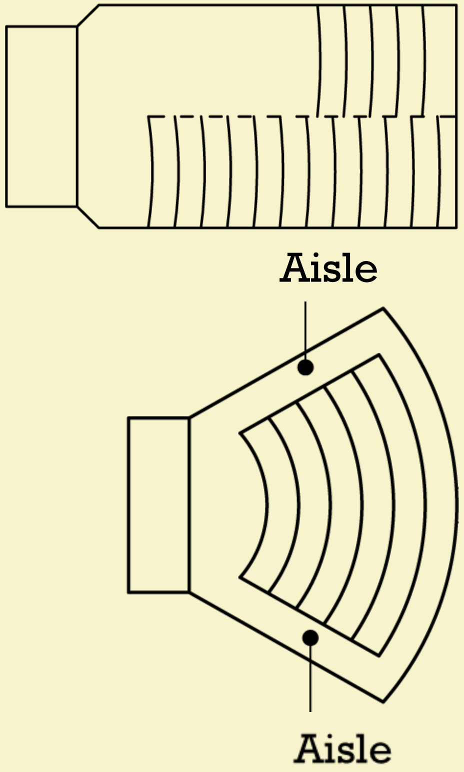
- Small Halls
- Big Halls

Large space design

Caution: echo, flutters

Capacity: 50 – 350 Area per person = 0.45 to 0.5 sqm Volume – 80 – 150cum / person

Choice of room shape



Rectilinear – provides better frontal view, drawback – flutter echo

Fan shape – brings audience closer, drawback – sound concentration
Appropriate use of absorbers

Fan shape configuration brings the audience close to the platform
seating layout should be contained within a 125^0

Rooms being large: the direct field should be augmented by
strong early reflections from hard surfaces (within 35ms).

Advantage of overhead reflections – source direction perceived same as actual
Disadvantage – can mask source sound

Raising the floor

Direct sound energy reaches the audience in different extent without any acoustical measure.

Increases the critical distance i.e. direct sound reaches further
Q increases ($r_c = \sqrt{QR/16\pi}$)

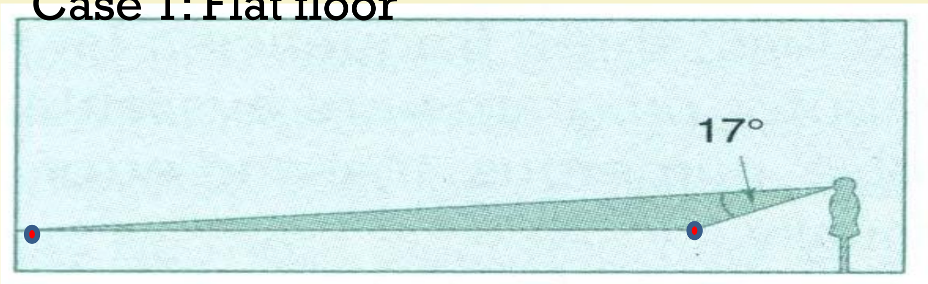
Raising floor (Case 3) also gives a better view to the audience

Case 2 and Case 3 helps
- useful reflections
- reduces grazing attenuation.

Slope of $18^0 - 22^0$
Suggested for bigger lecture halls

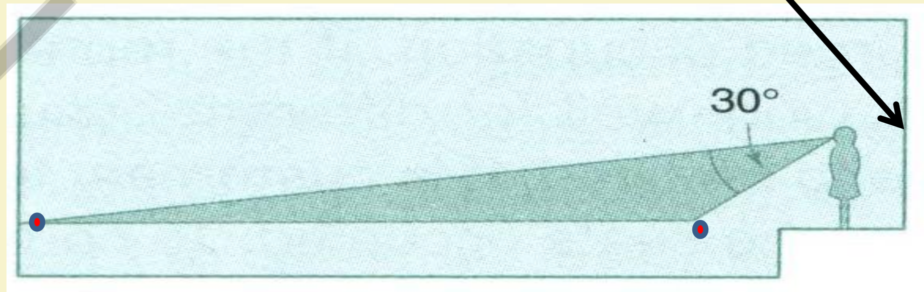
Halls beyond 25m: hard to hear

Case 1: Flat floor



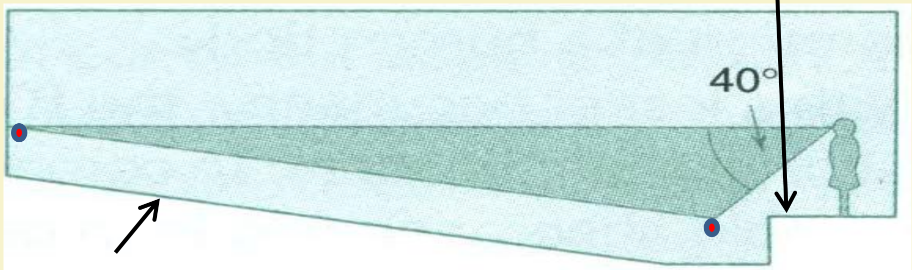
Case 2: Raised stage

Back reflective surface



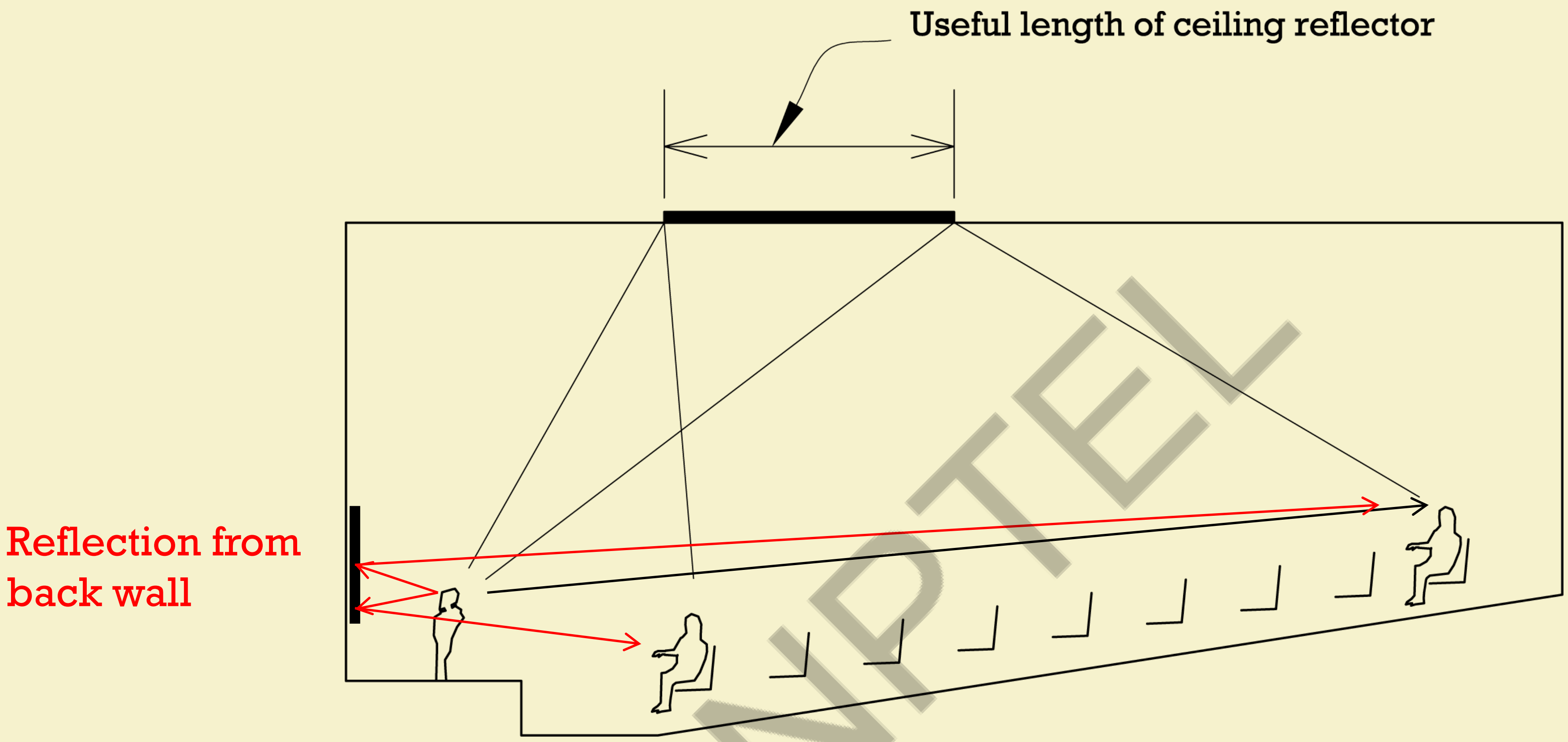
Case 3: Raised floor

a raised platform



A stepped or sloped floor

Utilising the ceiling

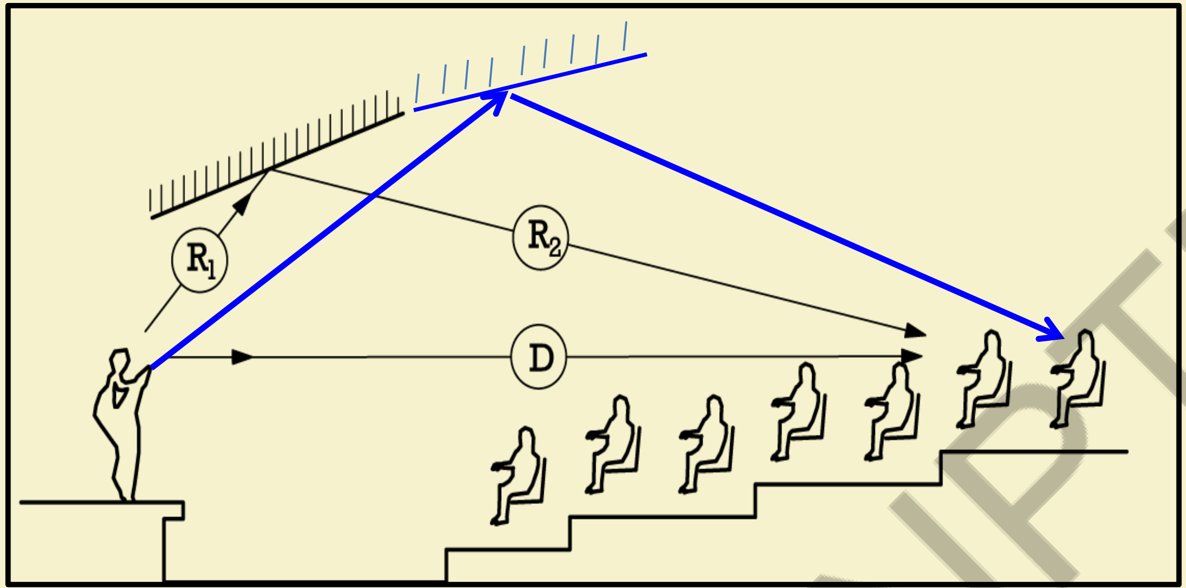


Greater ceiling height
Loss of sound energy
Large volume

Flat structural ceiling

Utilising the ceiling

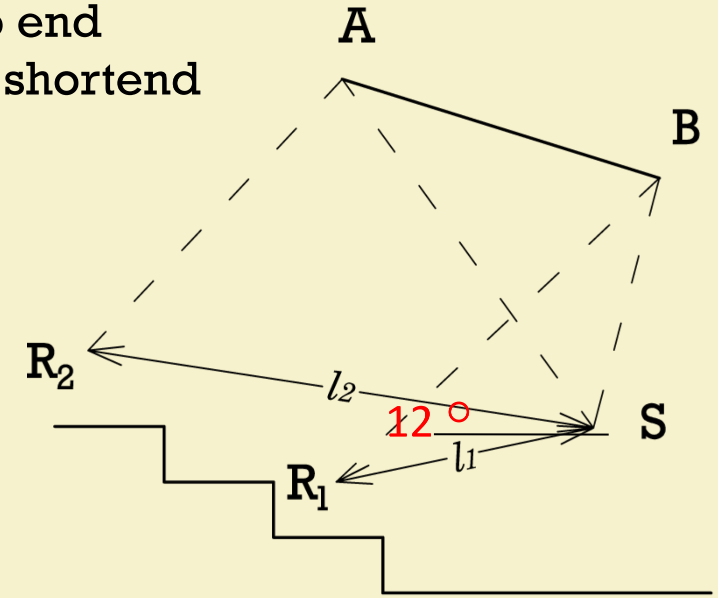
Curved /stepped ceiling



Front half of stepped or curved ceiling should be reflective

Similar ray diagram can be drawn for stepped ceiling

False ceiling at an angle
Reduces the volume
80 and 150 cu ft/seat (2.3 to 4.3 cu m/seat)
Directs the sound to end
Reflected path gets shortend



Direct sound path = D

Sound path for reflection = (R_1+R_2)

Time delay in milliseconds = $\dfrac{(R_1+R_2) - D}{0.34}$

Side and back Walls

Beyond critical distance direct sound becomes weaker and reflected sound reinforces it.

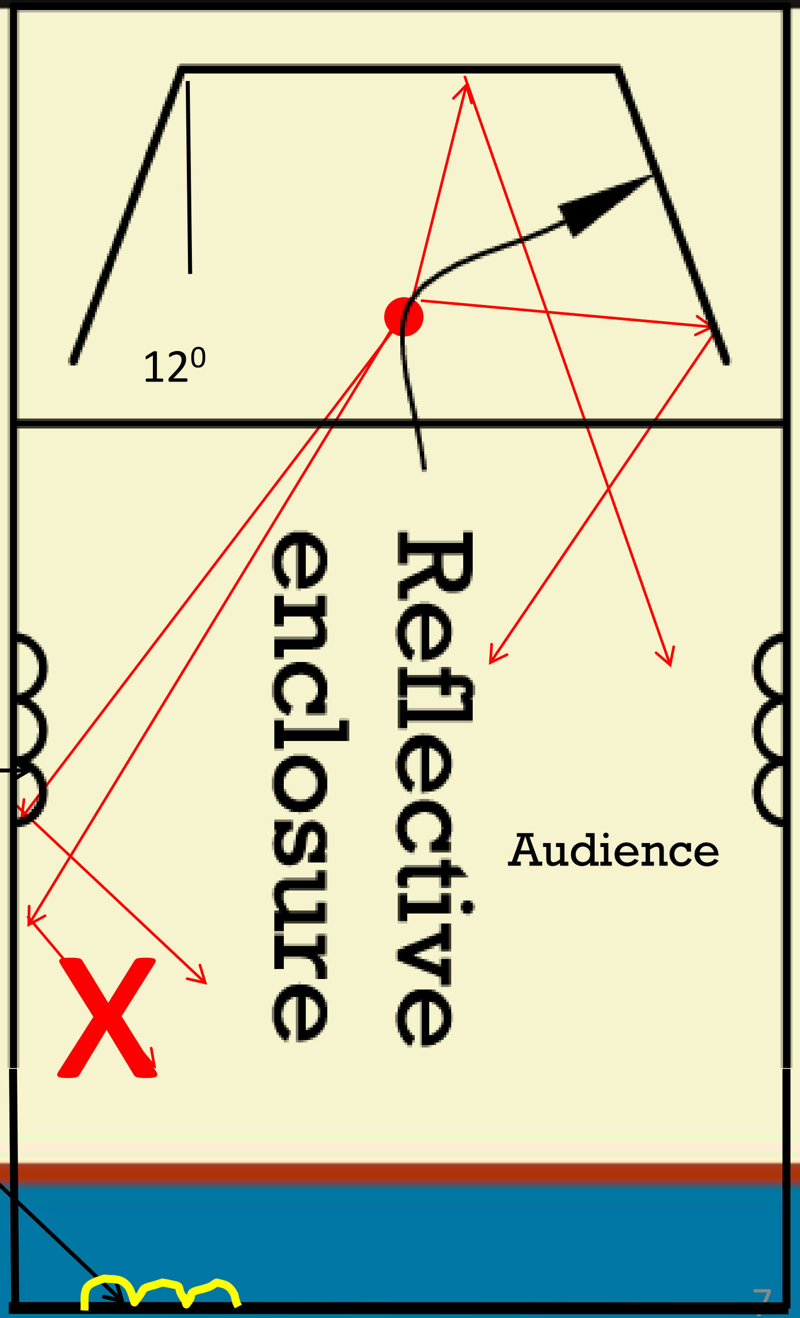
Stage enclosure area must have reflective surface

Lateral reflections smear the perceived source direction hence absorbers to be added.

Thus side walls should have absorbers to stop lateral reflection

Absorbers on back wall prevent delayed reflection

Absorbers also control reverberation time



Small Lecture Hall

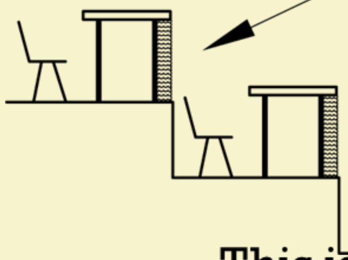
For small lecture halls raising the floor by steps is recommended

Splayed Reflective surface behind raised stage

Stage is raised

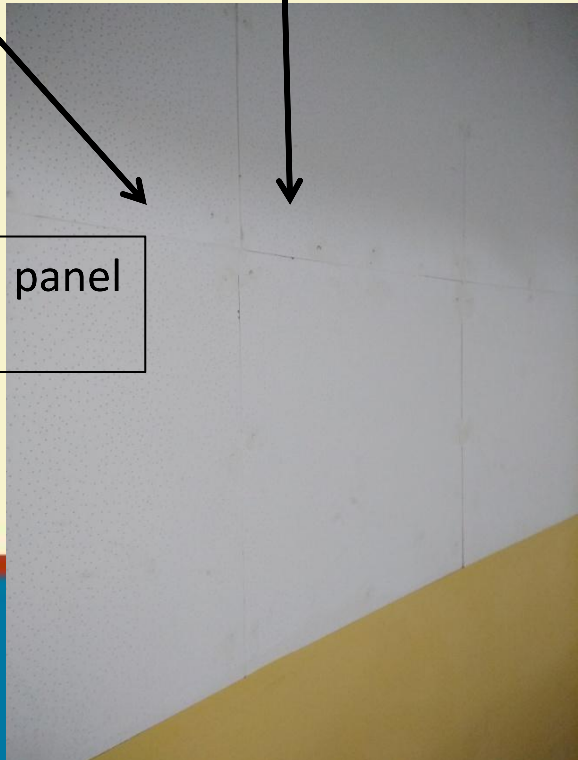
A relatively low hard ceiling is preferable for useful reflection

Back of the room and side walls should have absorbers



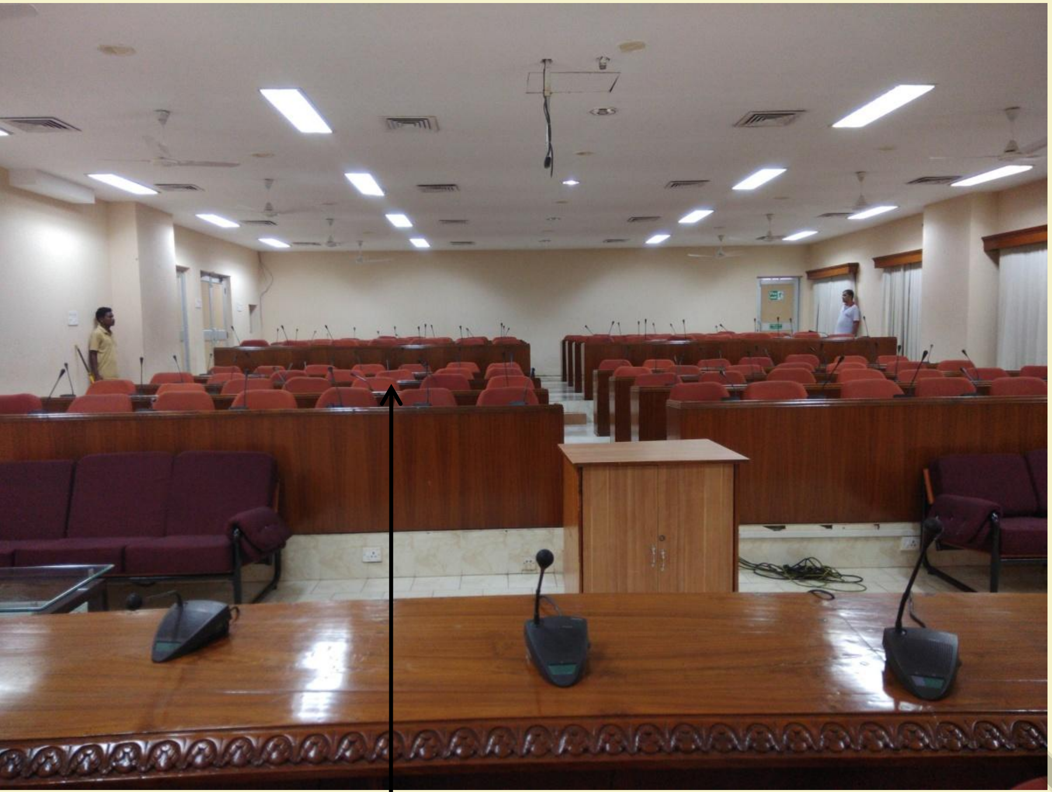
Front portion of listeners table should be treated with sound absporptive materials

This is to take care of over reflection



Perforated panel absorber

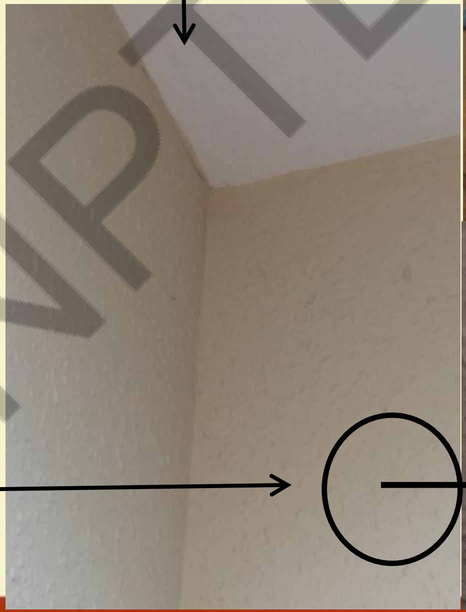
Small Hall : example

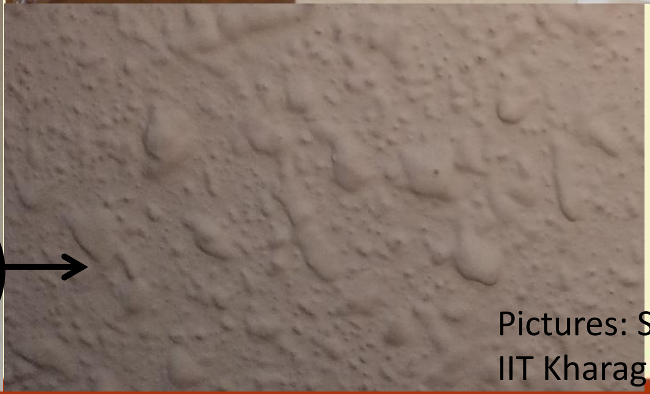


Flat reflective ceiling

Raised stage

Gently raised floor





Absorbing wall

Pictures: Self, Vikramsila Complex, IIT Kharagpur

Raised Platform / stage

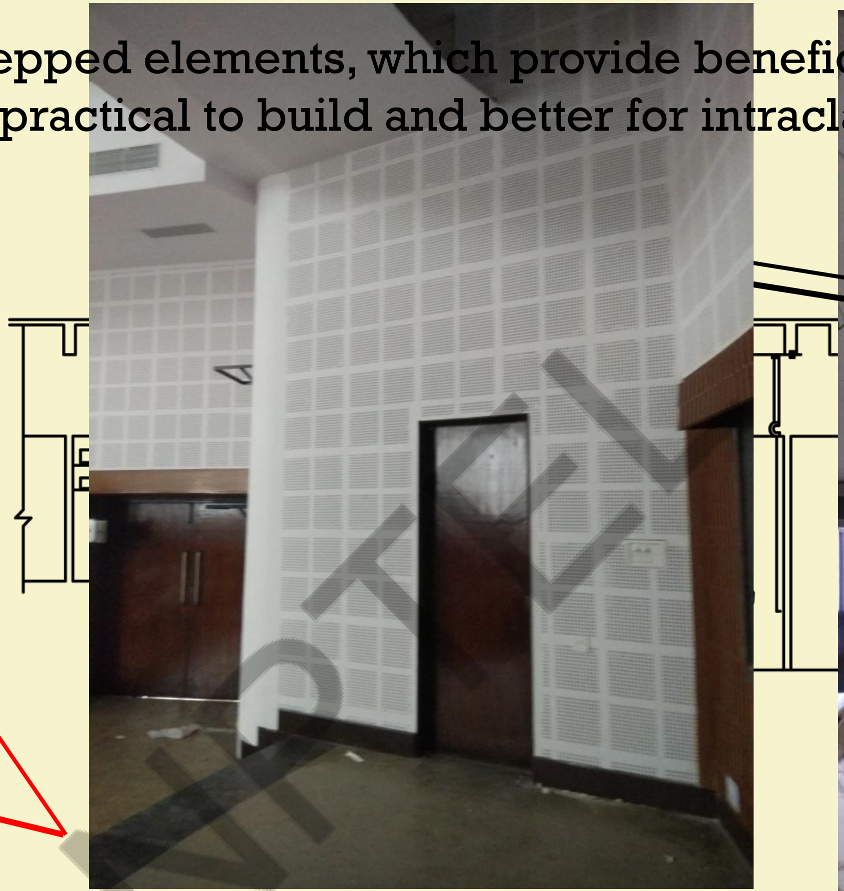
Raised sitting

Double entry to lock outside sound

Pictures: Self, Vikramsila Complex, IIT Kharagpur

Large Lecture Hall

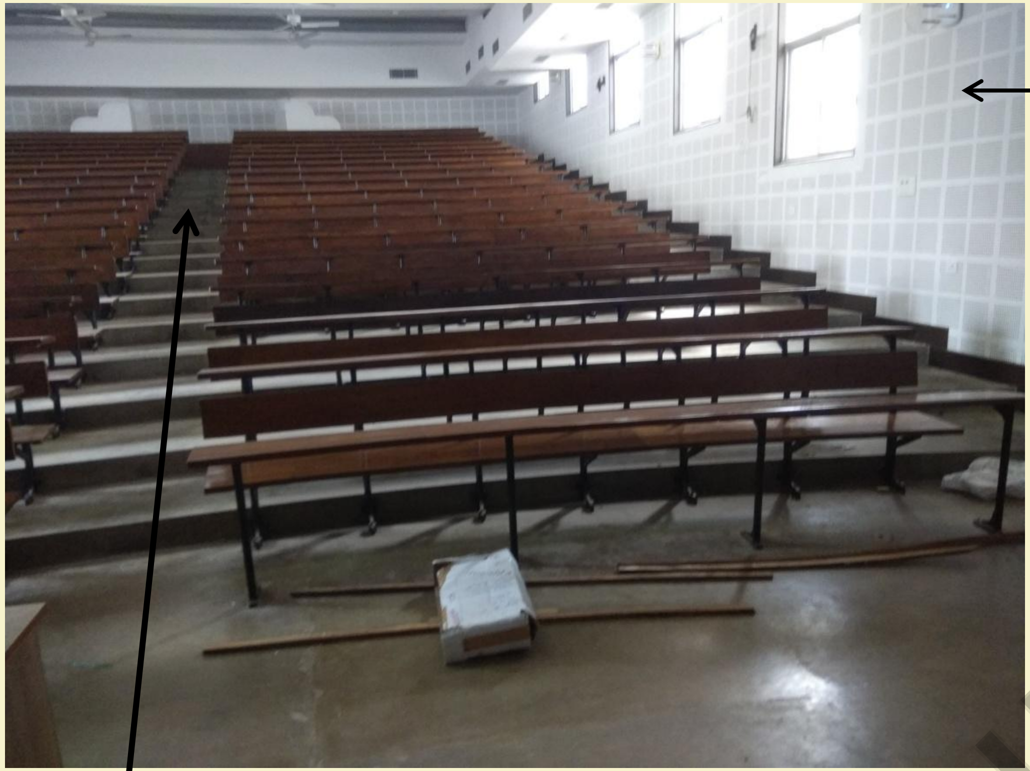
The ceiling can be a series of flat-stepped elements, which provide beneficial early reflections.
Flat ceiling elements are both more practical to build and better for intraclass discussions



A slant of 1:12 for walls and ceiling around speaker to avoid flutter

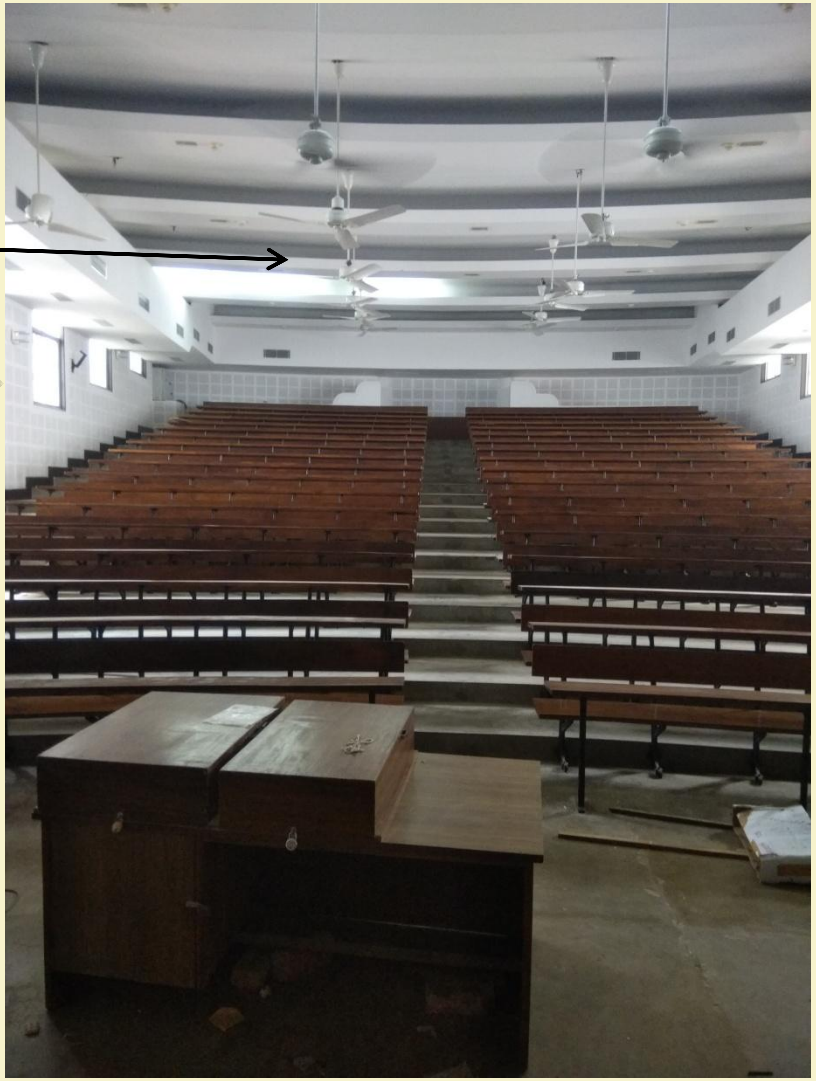
Pictures: Self, Nalanda Complex, IIT Kharagpur

Large lecture Hall (250)



Absorbing wall

Stepped reflective ceiling

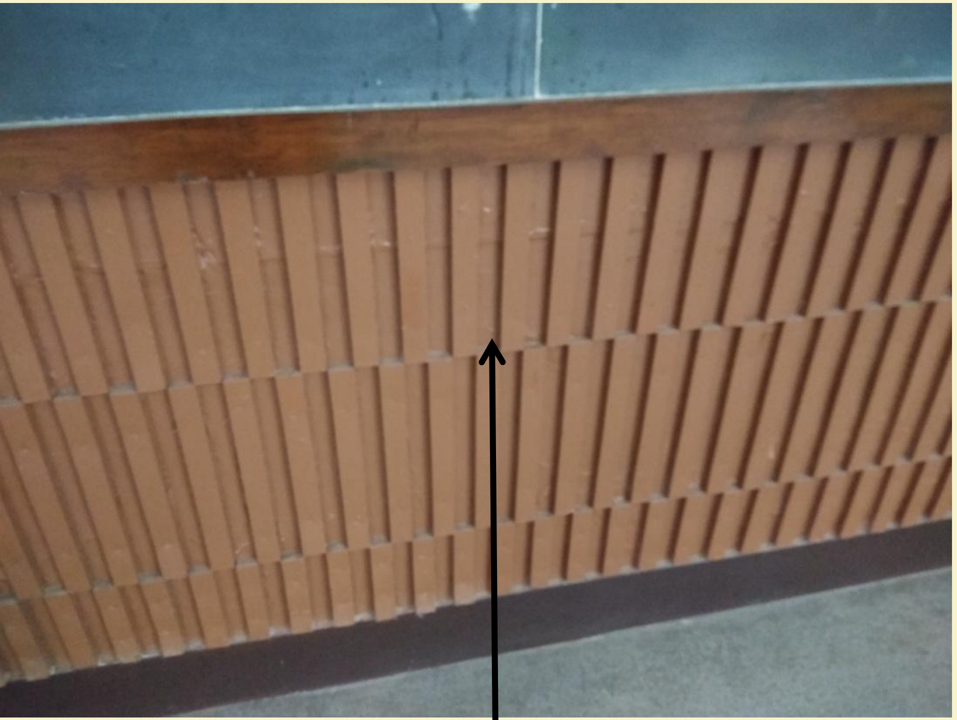


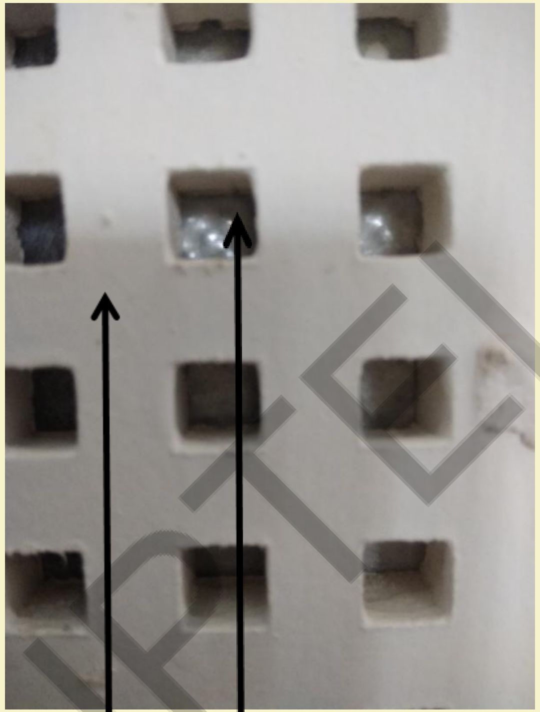
Gradual rise

Splayed wall for early reflection

Pictures: Self, Main Building, IIT Kharagpur

Large lecture Hall





Perforated tiles with 50mm glasswool insulation

Slat resonators for
low frequency absorption

Other spaces

Library

- Minimum outside noise
- Privacy needed
- Reading section should be in quite zone
- Children section away from reading section – enclosed with wall preferred
- E book section should be secluded

Gymnasiums

- May be considered as huge echo chamber
- Huge volume hard, bare surfaces; as is common with gymnasiums hence high RT
- Ceiling absorption is more effective in large volumes (lecture:
- Baffles suspended from ceiling
- Absorbers in walls

Gymnasium using PVC banners
and Polyester panels for soundproofing.

Source: https://acousticalsolutions.com/application/kcpc-gymnasium/

Tasks

Referred Books:
Concepts in Architectural Acoustics, M. David Egan
Architectural Acoustics by M. Long
Room Acoustics by Heinrich Kuttruff
Source: https://acousticalsolutions.com/application/kcpc-gymnasium/

IIT KHARAGPUR

NPTEL ONLINE CERTIFICATION COURSES

NPTEL

Architectural Acoustics

Lecture 20: Acoustical Criteria and Space Design

Recording studio

Dr. Sumana Gupta

Department of Architecture & Regional Planning

Continuation of absorbers……

Learning Objective

Acoustical details

- recording studio
- control room

Purpose

Recording studio is a space which houses instruments and performers in an organised manner
Individual or multiple persons can perform (size of room and microphones for pick up to be planned)

Range of frequencies that could be considered for acoustical design is 63 Hz to 8000 Hz.

The technical hub associated with a recording studio is the control room

Control rooms house the recording and electronic processing equipment necessary for mixing sound.

It is also the client presentation area

Three basic functions: recording listening mixing

Why to be specially dealt with?

In studios the tolerant ears of a live audience are replaced by a most sensitive electronic instrument, microphone.

A highly sensitive microphone can catch all types of acoustical defects and fluctuations.

Sound has to be recorded in its purest form

High degree of diffused sound / uniform sound

Ideal reverberation time to be established and maintained
(Bass Reverberation to be controlled)

Visual communication with control room needed.

Studio – Acoustical and functional requirement

A good studio must incorporate some acoustical factors:

It should be Quiet (NC 10 to 15) - sound isolation

Free from acoustical defects such as flutter

Adequate absorption (often variable absorption is required)

Reasonable diffusion

Isolated areas for recording individual instruments like drums

Visual communication between the control room and the studios

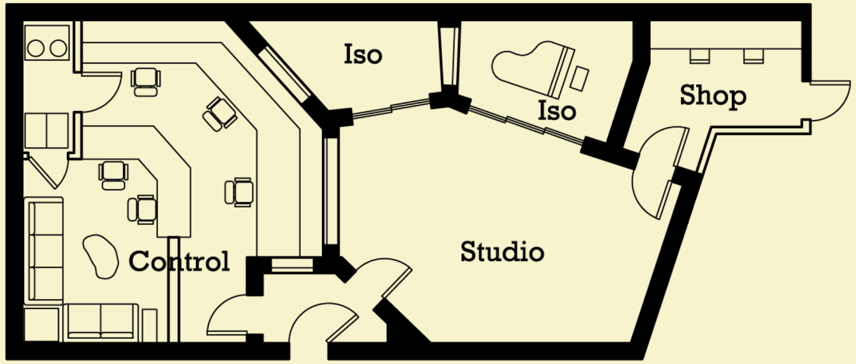
Control of bass reverberation (using low-frequency panel absorbers / cavity absorbers)

Size and shape of studio

- Smallest dimension $\geq$ 2.4m (8 ft) (Caution for standing waves)

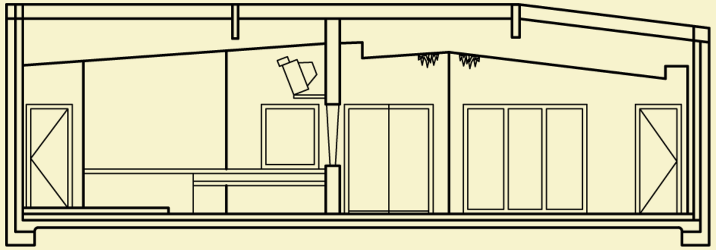
- Space needed for circulation per musician
  (for movement and placement of microphone etc)
  0.37 sqm - 0.55 sqm (4-6 sqft)

- Space requirement for each musical instruments
  Small: 1.4 -1.85 sqm (15 to 20 sqft)
  Large: 1.8 - 3.7 sqm (20 to 40 sqft)



FLOOR PLAN

No walls at 90^0



LONGITUDINAL SECTION

Irregular shapes are encouraged - avoiding 90^0 bends and sharp corner in studios

Hum Studio A, Santa Monica, CA, USA
Drawing adapted from:
Long, M., 2005, "Architectural acoustics". Elsevier.

Proportion of studios

Studio Type	Height	Width	Length
Small	1	1.25	1.60
Medium	1	1.50	2.50 (Best)
Low Ceiling	1	2.50	3.20
Unusual Length	1	1.25	3.20

(Derived from Bolt Area graph,
Refer Lecture 7, Module 2)

Small studio: Height = 2.4m, Width = 3m and Length = 3.8m
Low ceiling studio: Height = 2.4m, Width = 6m and Length = 7.7m

No dimension is a pure multiple to avoid Standing waves
pressure null points in the middle of room

Pressure null points and pressure maximum points if any are not the right positions of microphones

Optimum Reverberation Time

Reverberation time is generally very short

for speech broadcasting - 0.15 to 0.25 sec
for music recording <0.5 sec

Variable reverberation time may be desired

- By constructing separate studios for separate type of programme

- By providing the movable panel, partition wall which gives flexibility in room size, hence volume of room can change and that will give different RT.

- The best way to control RT is to provide a variable absorber (through hinged panel, rotatable panel and drums, dropping blocks etc)

(Refer to previous module on Absorbers)

Movable absorbers

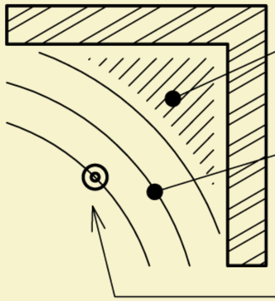
Absorbers could be added as per requirement

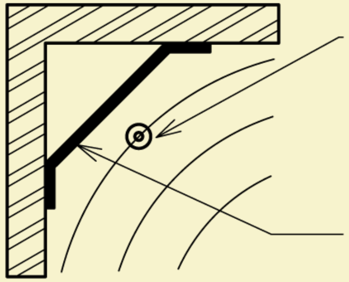
The distance could also be controlled

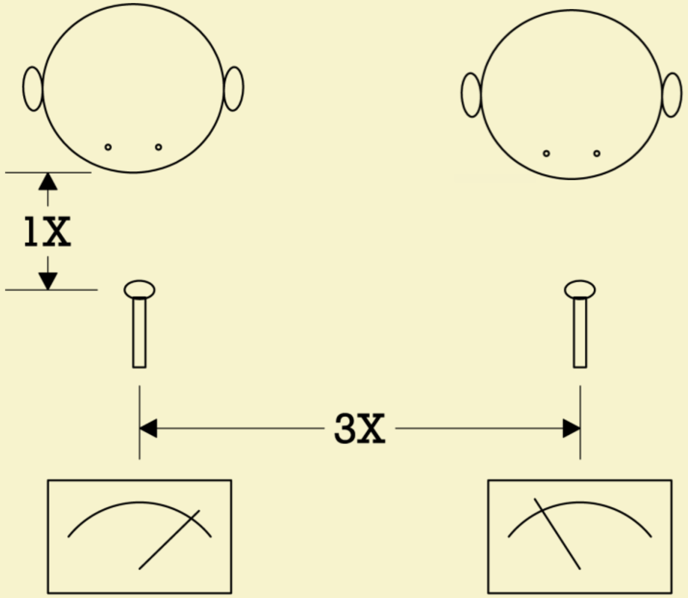
Stand-mounted portable absorbers used in an audio recording studio

Positioning of microphone

- In sound uniform zone
- Away from the corner







Meters showing pick ups from the singer

Rule of three

"Two microphones, intended to pick up two sound sources must be placed apart at least three times the distance that either microphone is from it's intended sound source."

The leakage signal into the other microphone is greatly reduced because of the distance

Apparent Reverberation time

The reproduced music from what is recorded in studios will be played in

a hall having different reverberation time

controlled by the electronic system

This is known as apparent reverberation time. It depends upon the following:

- Microphone position
- Microphone pick-up
- Control on graphic equaliser - mixing

Noise and vibration

'Sound lock' passage

'Buffer space'

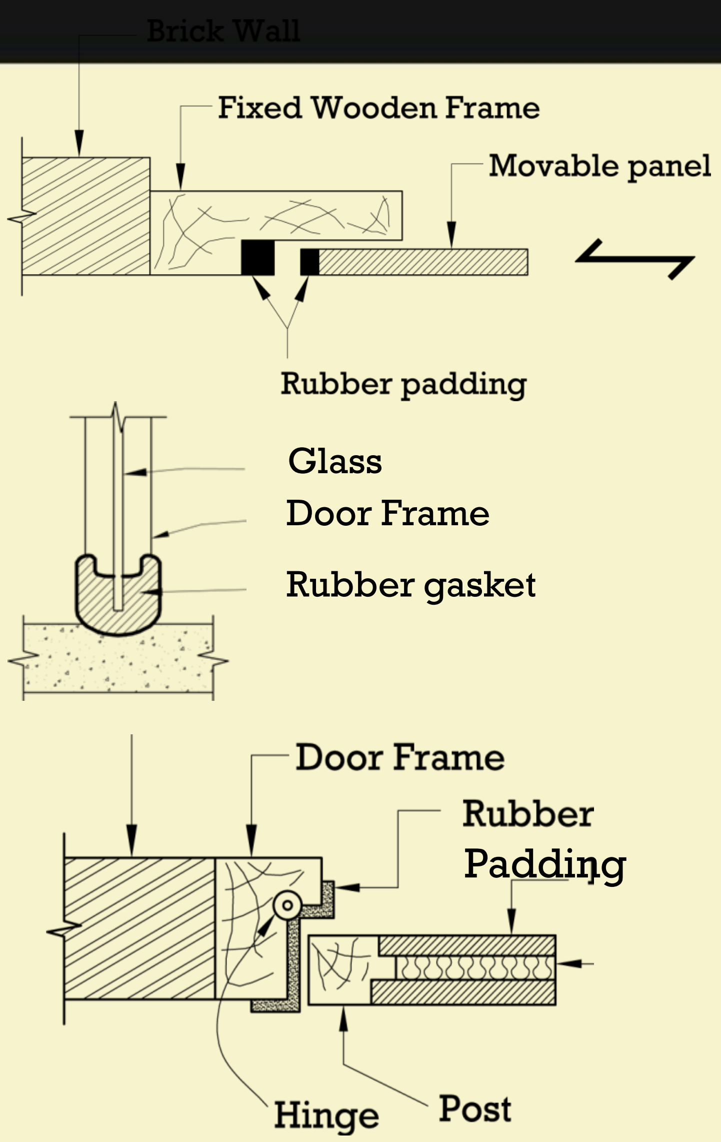
Windows to be avoided – prevents outside noise

Studios can be planned in a particular floor

Area should be free from mechanical noise like:
air conditioning plant, generator room, pump room

Use of silencers for air through

Sealing of outside noise through gaps in door frames



Details to isolate sound

Control rooms

Axial symmetry about the longitudinal centerline of the mixer

Deflection of first reflected sound away from the mixer position

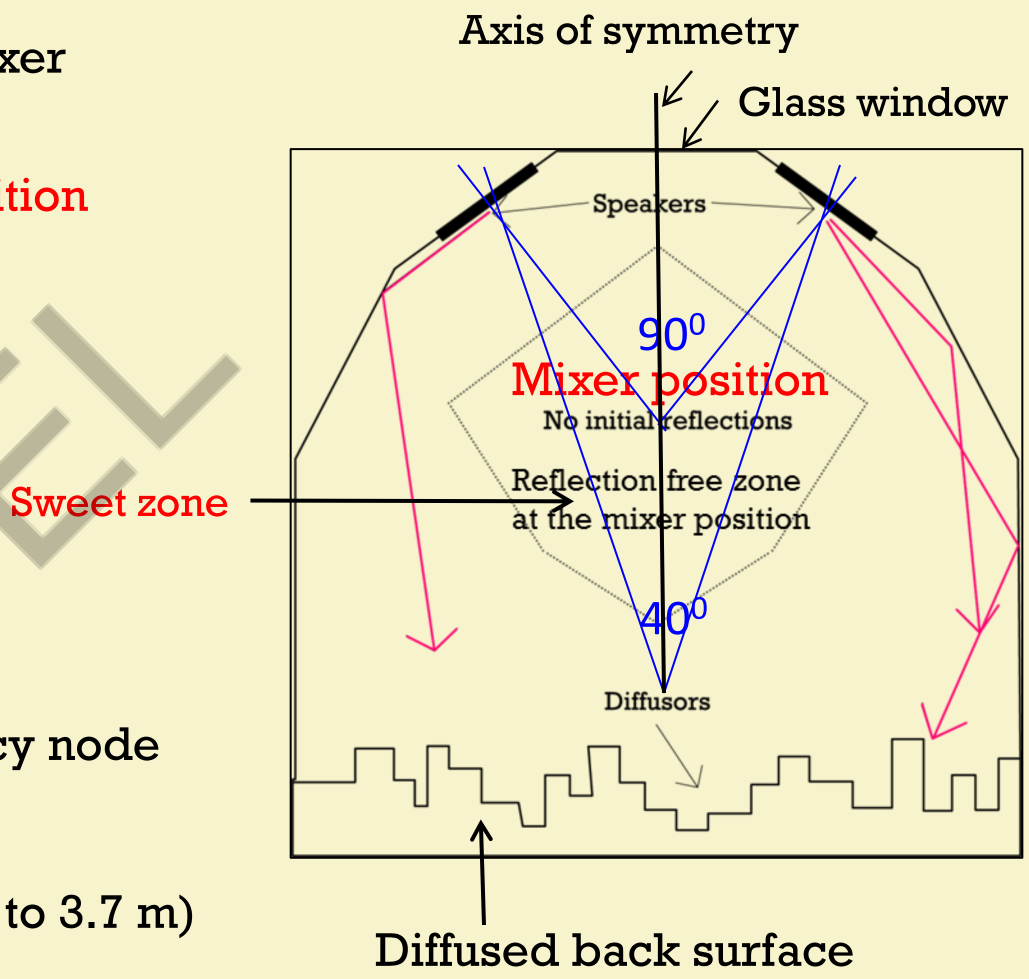
Low-frequency panel absorbers/ Helmholtz resonators

Visual communication with the studio spaces

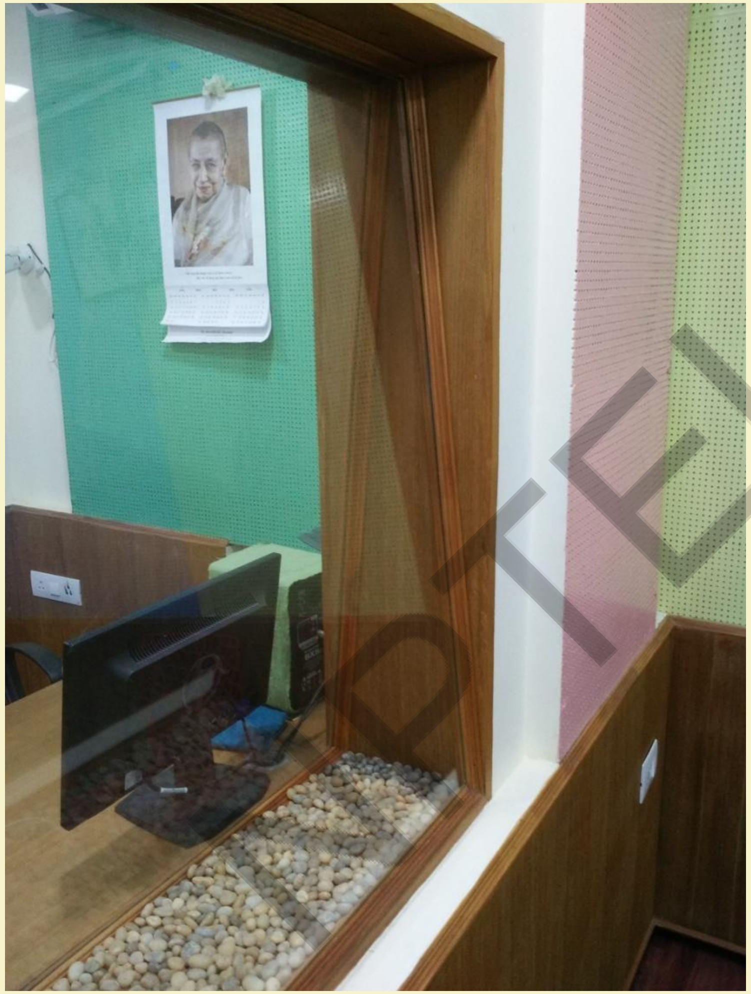
Speech isolation from the main studio

Listener position should not coincide with any low-frequency node

Included angle of around 60^0 at a distance of 11 to 12 ft. (3.4 to 3.7 m) from the mixer – 'sweet spot'

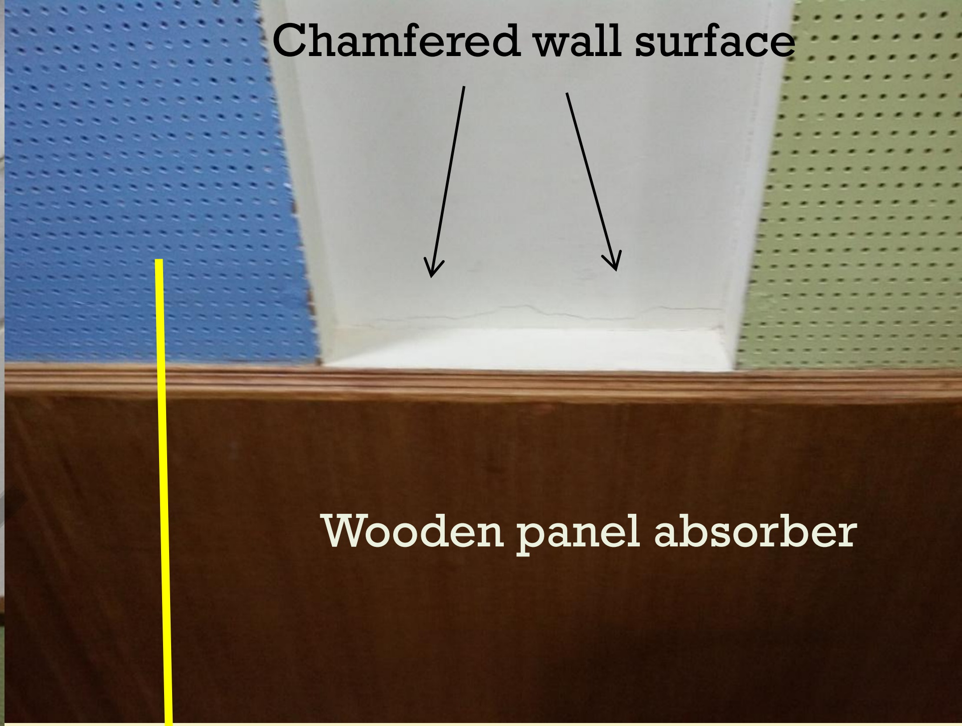


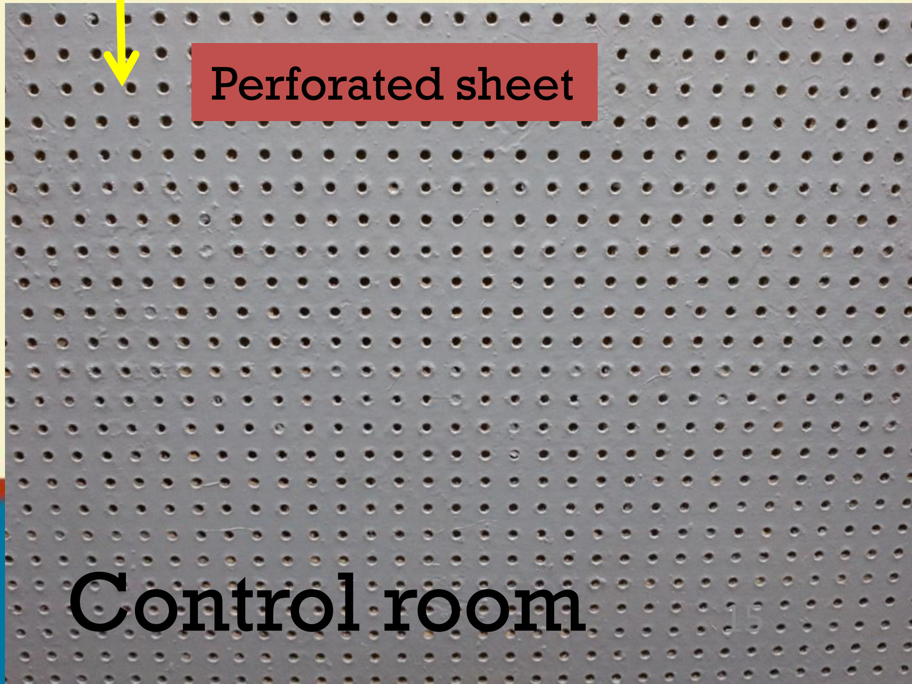
Studio and Control Room



Community radio station, Pudiya Udayam – Studio and Control room


Slanting
double glass
Absorbing surfaces


Chamfered wall surface
Wooden panel absorber


Perforated sheet
Control room

Sound Control room, IIT Kharagpur

Folded false ceiling

Irregular wall surface

Microphones at different locations

Carpets for high frequency absorption

Music recording room
(Source: Wikimedia Commons)

Conclusions

Original sound which is recorded has to be reproduced

Reflection is not much encouraged, low reverberation is desired

Microphone position is important to record sound in studio

Similarly in control room mixer location is also important

Tasks

Calculate the studio space required for 3 performers two of them using small instruments and one using a big instrument and find the dimension of the room which satisfies
the proportions
the ‘rule of three’.

Clue: Consider the maximum areas required for each of them and add to get the area.
Consider height of the minimum dimension and then use the proportions chart to fit the area closest.
Use the rule of three considering the microphones and the area per instrument and develop a plan.

Books referred:
Concepts in Architectural Acoustics, M. David Egan
Architectural Acoustics by Marshall Long
Room Acoustics by Heinrich Kuttruff
Soundspace Architecture for sound and vision, Peter Grueneisen