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CERTIFICATION COURSES

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Architectural Acoustics

Lecture 21: Introduction to Auditorium Design

Dr. Sumana Gupta
Department of Architecture & Regional Planning

Learning Objective

Outline of acoustical requirements

Matrices of measuring sound quality

Outline of acoustical requirement

Adequate loudness - reaching remote seats

Diffused sound level - Uniformly distributed energy

Optimum reverberation - liveliness

Free from defects - shape size and form

Isolation from noise and vibration - outside and inside

Auditorium characteristics

Large volume – medium to large auditoriums

Hall volume influences both the reverberation time and room gain.

Energy losses – Travelling sound wave, Audience absorption

Shape and size should be optimum
Appropriate seating plan – closer to the source: stage

Auditorium characteristics

Type of performance	Volume / audience (min)	Volume / audience (max)	Desired RT
Speech	2.3	3.1	0.7 – 1.0
Musical entertainment	6.2	7.8	>2.00 to 2.25
Play with music	4.5	5.7	1.50 to 2.00
Multipurpose auditorium	5.1	7.1	0.8 – 1.8
Motion picture	2.8	3.5	0.7 – 1.0
Churches	5.1	8.5	1.50 to 2.00

Measuring sound quality

Loudness

Spatial Impression

Intimacy

Early Decay Time

Clarity

Warmth and Brilliance

Measuring sound quality

Loudness

Strength factor, G, measured in decibels.

Loudness can affect perception of other acoustic qualities
Like intimacy and spatial impression

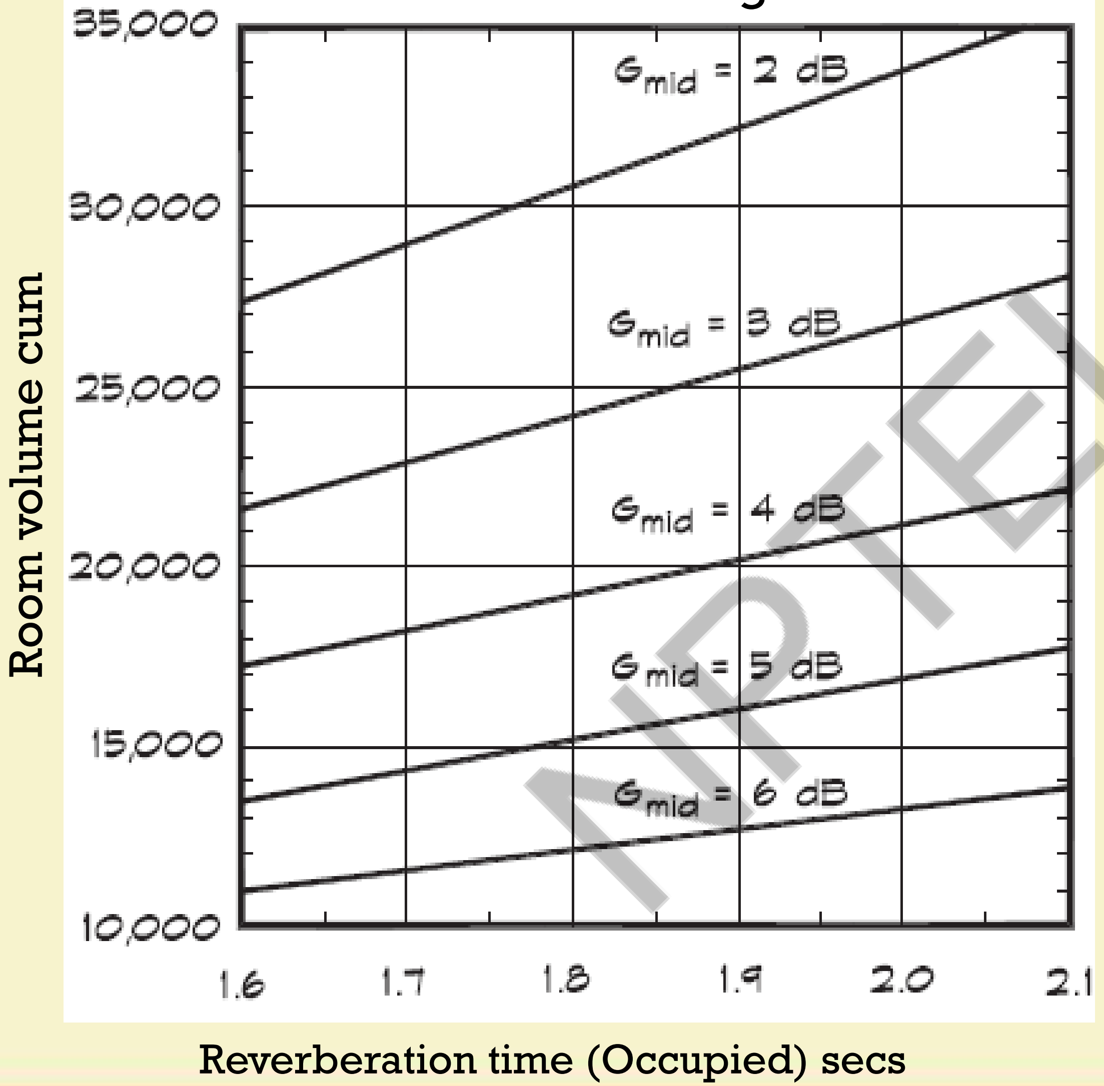
At low capacities a high volume per seat is necessary to control excessive loudness.
At high capacities a low volume per seat helps preserve acoustical energy.

Room gain is computed from the ratio of the reverberation time to the room volume, both easily measured quantities. To start if room gain and RT is known Volume can be obtained from Baranek Computational Chart

Room Gain = the measured Sound Pressure Level (SPL) of the source at a position in the empty hall – SPL of the same source in a free field measured 10 m away.

Desired Value = 4 Db to 5.5 dB

Computational Chart for determining Volume of Concert Hall (Beranek, 1996)



Measuring sound quality

Spatial impression

When total reflected energy from the lateral reflections is > the total energy from the overhead reflections the hall is said to achieve a desirable **spatial impression**

Intimacy

It refers to the feeling of being close to the source of the sound / music.
Feeling of being one with the source, no detachment. Can be achieved better in small halls.
Can be measured by the Initial time delay gap (ITDG) between source sound and first reflection, earlier the better, so small spaces are more intimate .
Receiver positions also can have different ITDG. Middle of hall value of ITDG is ideally **12 – 25 msec.**
Adding ceiling reflectors or protrusions from the walls.

Early decay Time (Reverberation time)

Decay of the source sound initially by 10dB of sound is the early decay time (EDT)
Six times EDT is the Reverberation time estimate.

Measuring sound quality

Clarity

Refers to hearing every separate note, greater clarity leads to better speech intelligibility.

Clarity is produced when a room has a high ratio of early sound energy (upto 80ms) to later reverberant energy (beyond 80ms).

Clarity Index or C_{80} = 10 log (Early sound energy / late sound energy) dB

C_{80} (3) = Average of clarity at three frequencies 500 Hz, 1000Hz and 2000Hz

C_{80} (3) Optimum Value = 1dB to (-4)dB

For better clarity late reflections are to be reduced, suggested absorbers at back side of hall

Measuring sound quality

Warmth - cozy smooth music

Brilliance - bright, clear, ringing sound

The Bass Ratio measures warmth

Treble Ratio measures brilliance

Too much of warmth makes the hall dark in contrast to bright brilliant sound

.

Bass ratio = RT 125 +RT 250 / RT 500+RT1000

Treble ratio = RT 2000 +RT 4000 / RT 500+RT1000

It can also be computed from Absorption coefficient at the given frequencies

Bass ratio between 1.1 to 1.45 implies warmth when RT of the hall is 1.8 secs

Increasing treble improves clarity in movies
Makes sounds harsh like shriek, falling plates and gunshots.
Snare drums, high hats, cymbals can be amplified by increasing treble ratio.

Refer: (Lecture 15, Slide-8)

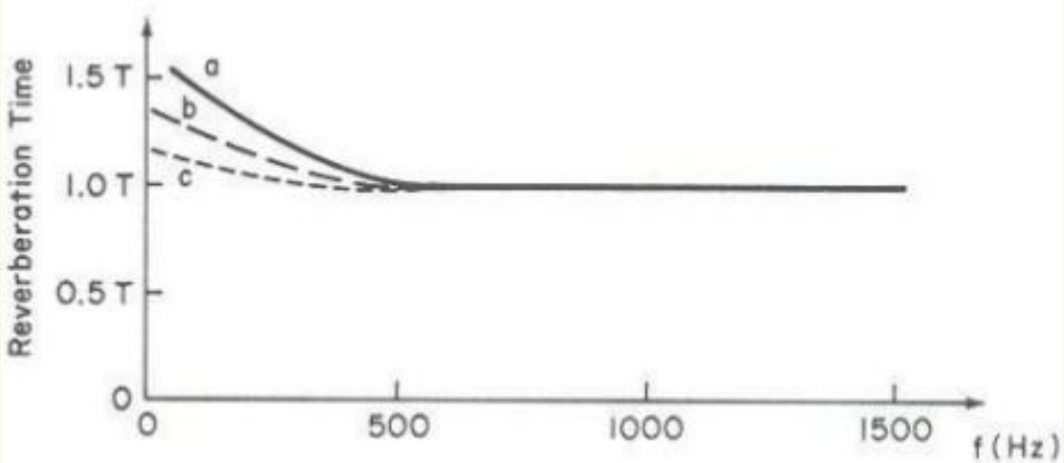
RT = 0.161Volume / Area. α

Assuming uniform application of same material in area A AND IN Volume V

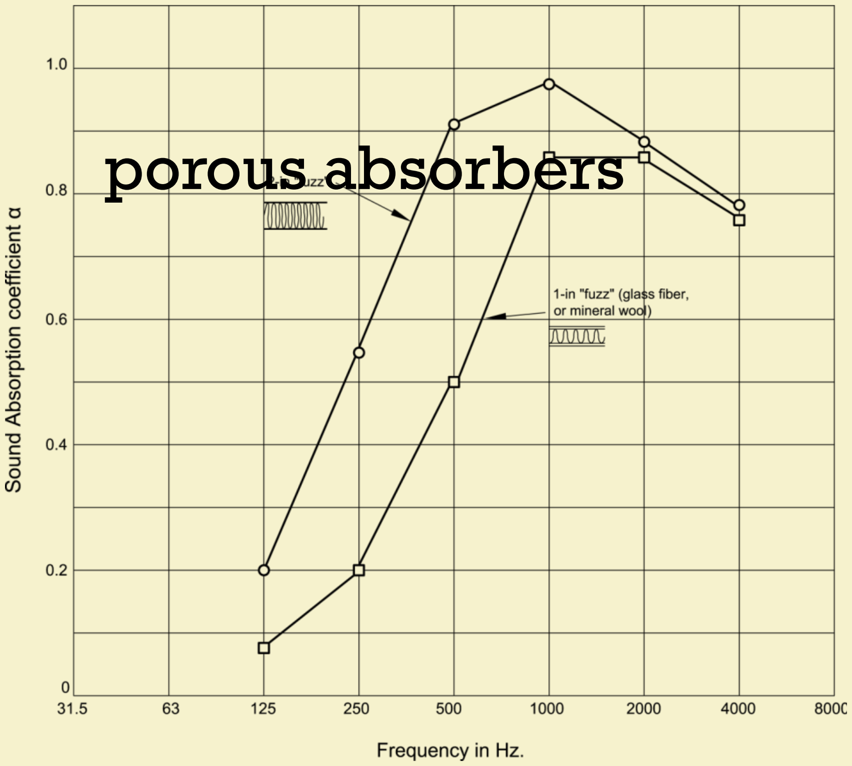
Bass ratio = RT(α125) +RT(α250) / RT(α500) +RT(α1000)

$$= \frac{V/A\,(1/\,\alpha125 + 1/\,\alpha250)}{V/A\,(1/\,\alpha500 + 1/\,\alpha1000)}$$

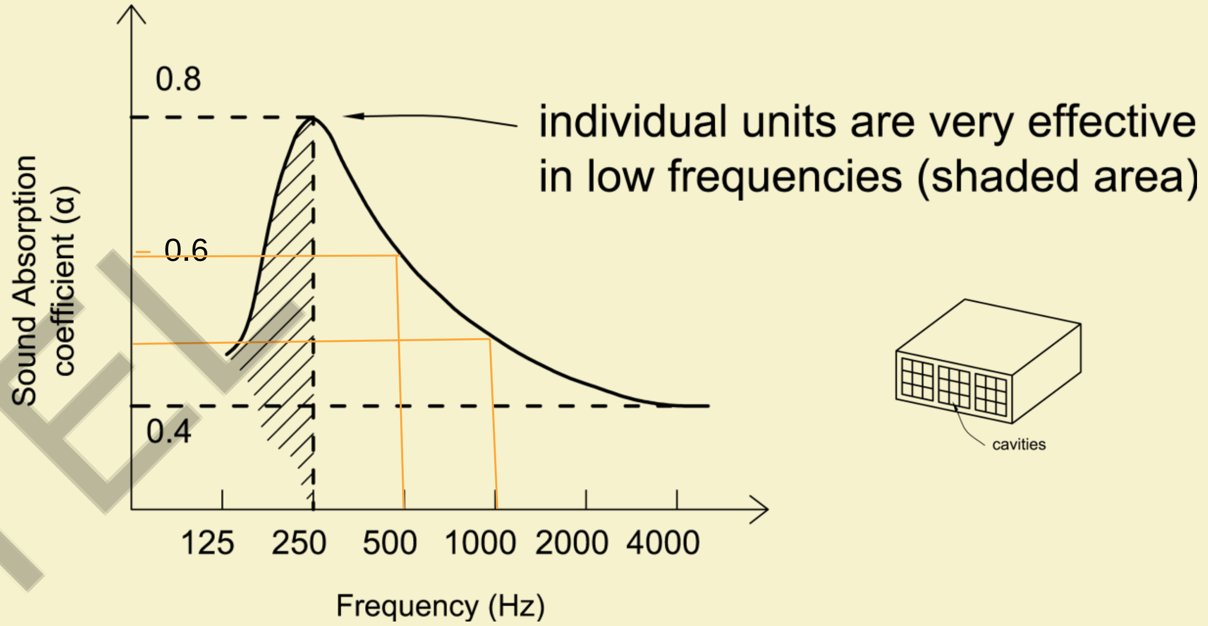
$$= \frac{(\alpha500 \times \alpha1000)}{(\alpha125 \times \alpha250)} \times \frac{(\alpha125 + \alpha250)}{(\alpha500 + \alpha1000)}$$



Slide 11 of lecture 11



Slide 16 of Lecture 12



Estimated Bass Ratio for Cavity absorber = ?

Estimated Bass Ratio for 2" fuzz = 3.2

Tasks

Estimate the bass ratio and treble ratio for different types of absorbers

Like Wood panel of ¾" at a spacing 3"-4"from wall has $\alpha 125 = 0.3$, $\alpha 250 = 0.25$, $\alpha 500 = 0.2$, $\alpha 1000 = 0.17$ (Ans: 0.67)

Concrete block unpainted $\alpha 125 = 0.36$, $\alpha 250 = 0.44$, $\alpha 500 = 0.51$, $\alpha 1000 = 0.29$ (Ans: 0.933)

Revisit Lecture 15, 16

References:

Concepts in Architectural Acoustics, M. David Egan

Architectural Acoustics by M. Long

Room Acoustics by Heinrich Kuttruff

http://www.concerthalls.org

Beranek (1996) Leo Beranek, How They Sound, Concert and Opera Halls. © 1996, Woodbury, NY: Acoustical Society of America.

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Architectural Acoustics

Lecture 22: Introduction to Auditorium Design

Dr. Sumana Gupta

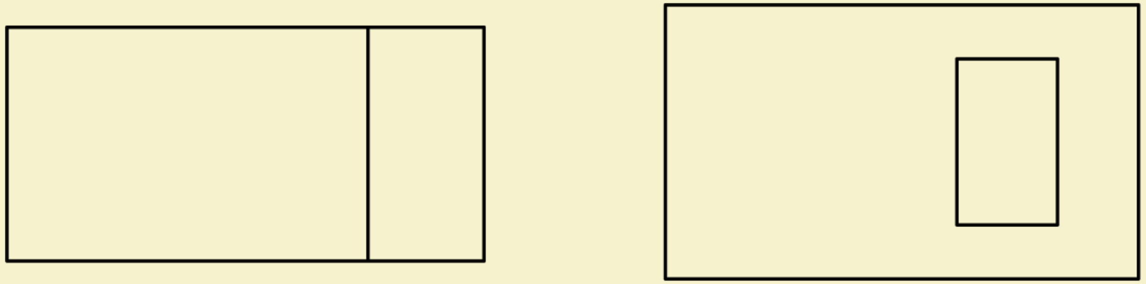
Department of Architecture & Regional Planning

Learning Objective

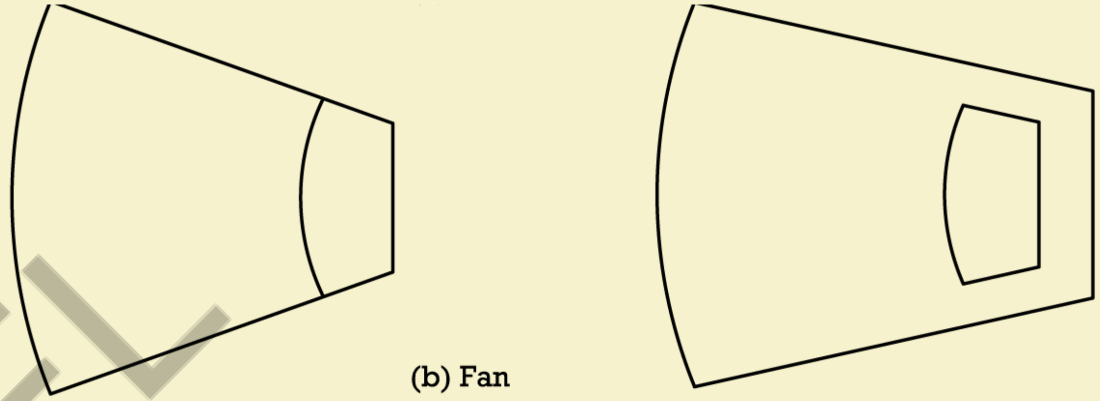
Shapes of Auditorium

Seating plan

Shapes



(a) Shoebox



(b) Fan

Strong side reflections are generated by wall surfaces of narrow rectangular rooms.

Narrow halls also yield low delay times for early reflected sound.
Initial Time Delay Gap is low - Intimacy

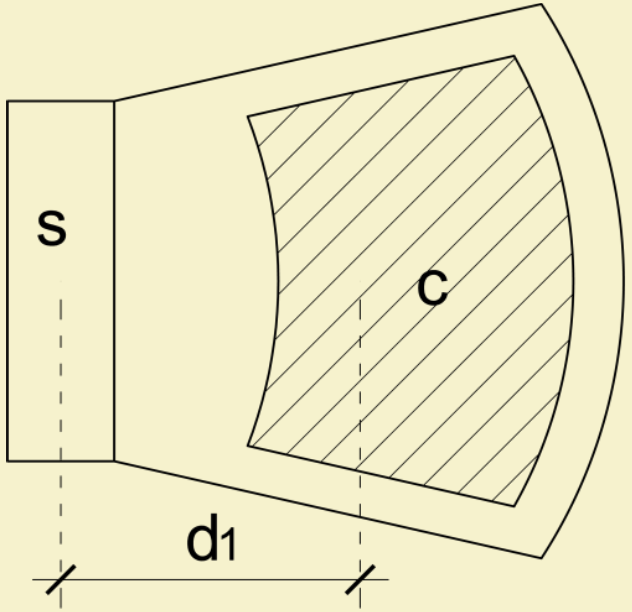
Intimacy has the prime weightage of 40% (Beranek, 1962)

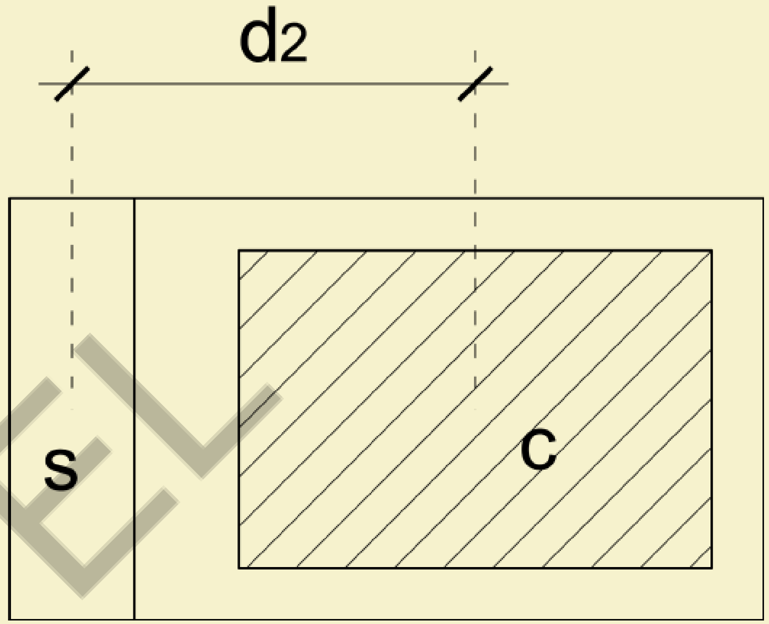
Ex - Symphony Hall, Boston Capacity – 2625, 39 m × 23.6 m × 18.6 m
Concertgebouw, Amsterdam

Fan shaped surfaces bring audience closer,
Accommodates more people in lesser distance

Curved back wall may lead to sound focusing

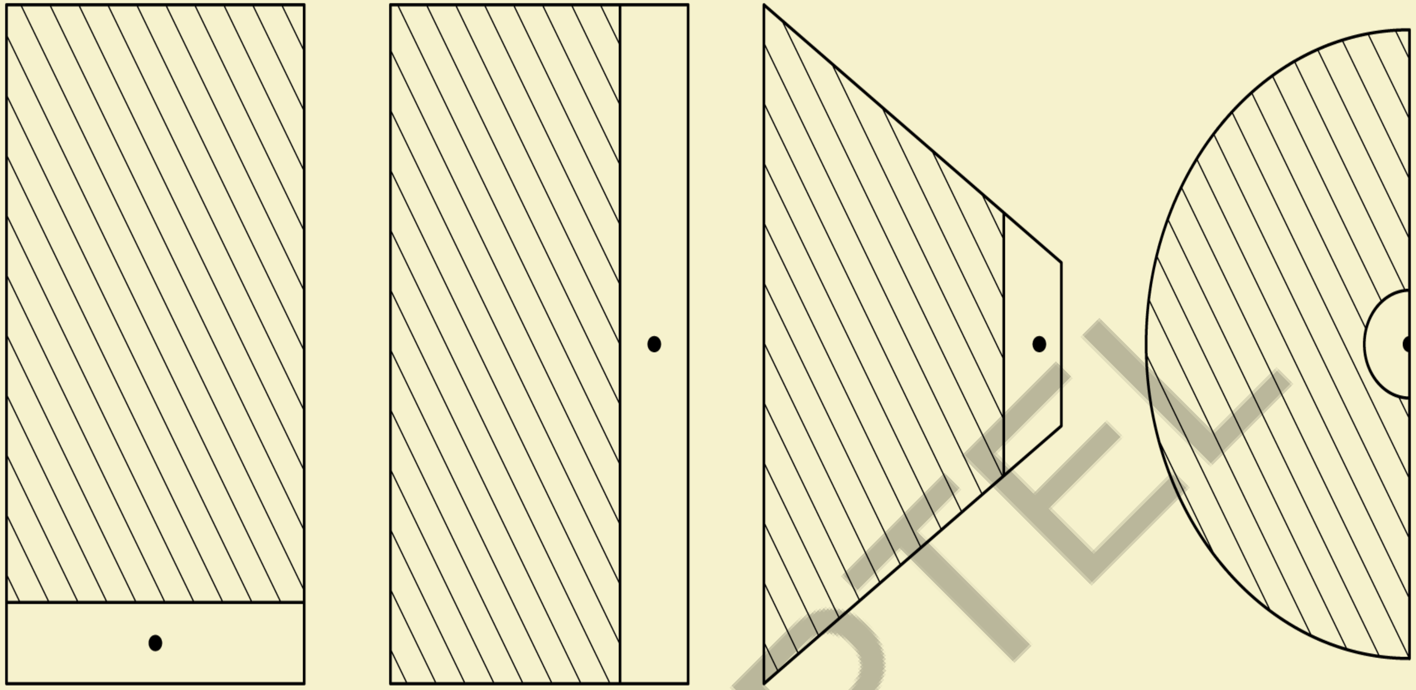
Shapes





For the same capacity of audience, a fan shaped auditorium will allow lesser distance between the source and the listener than a rectangular shape ($d_1 < d_2$). So, it is preferred for achieving adequate loudness.

Shapes



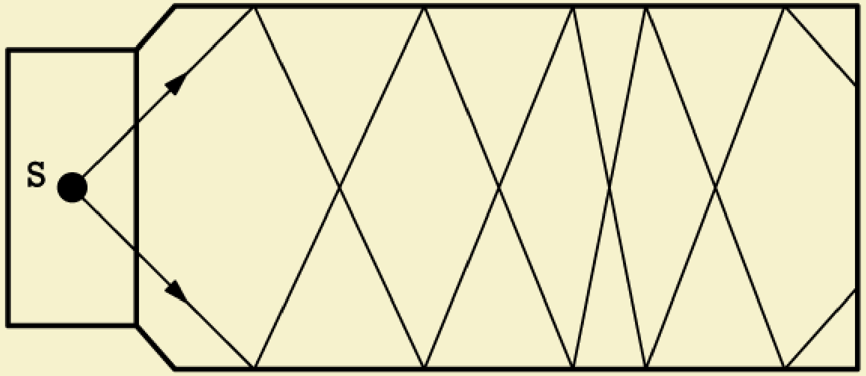
0.784 0.594 0.647 0.550

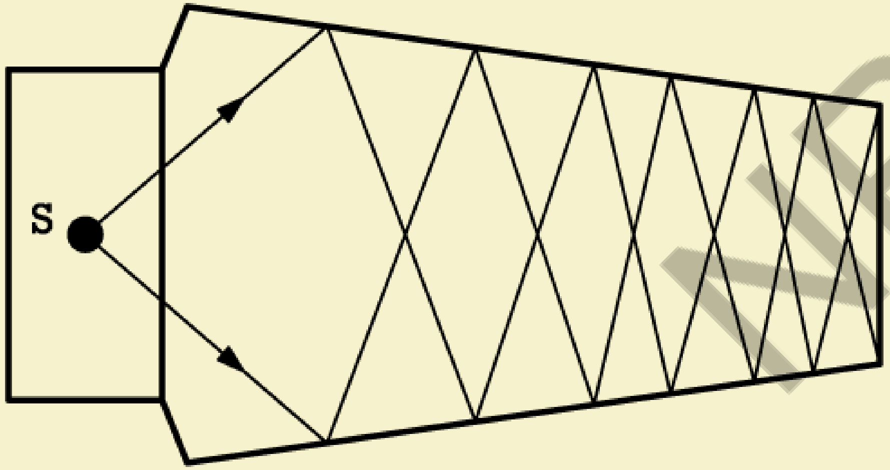
Normalized average distance from listeners to source for various room shapes

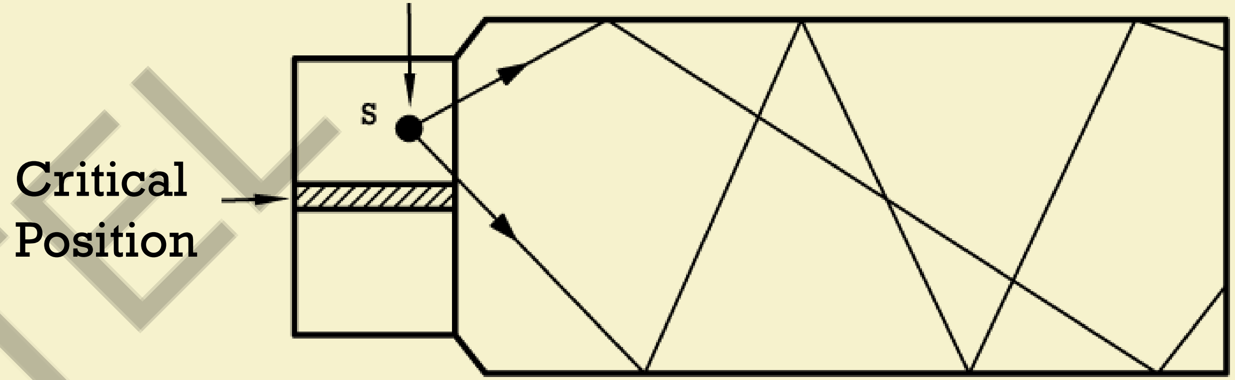
The closer the audience the higher the direct sound intensity received

Average distance of all listeners from sound source to the square root of the area occupied by the audience

Shapes

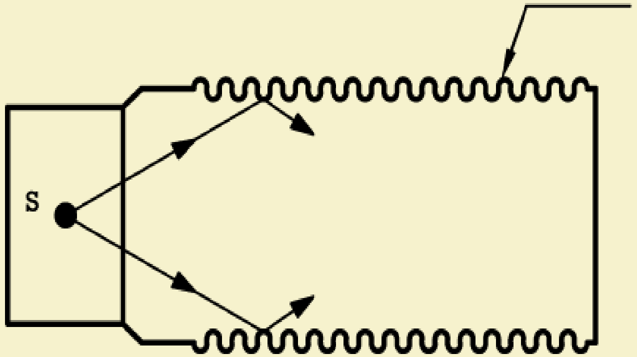






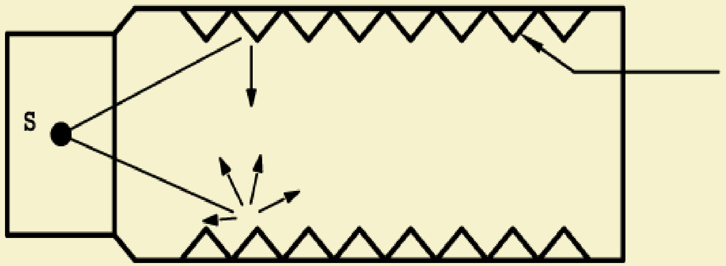
Eccentric position of sound source stops flutter echo

Shapes



Sound absorptive treatment in parallel walls absorb maximum sound energy, flutter echo can be stopped

Lateral reflections are lost

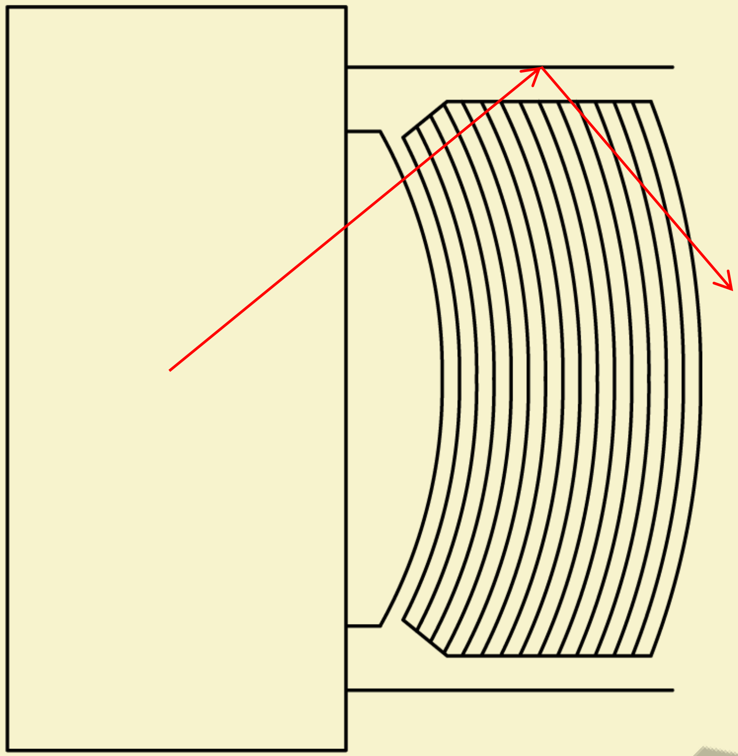


Rendered surface projection distribute sound at random angles, stop the regular reflection

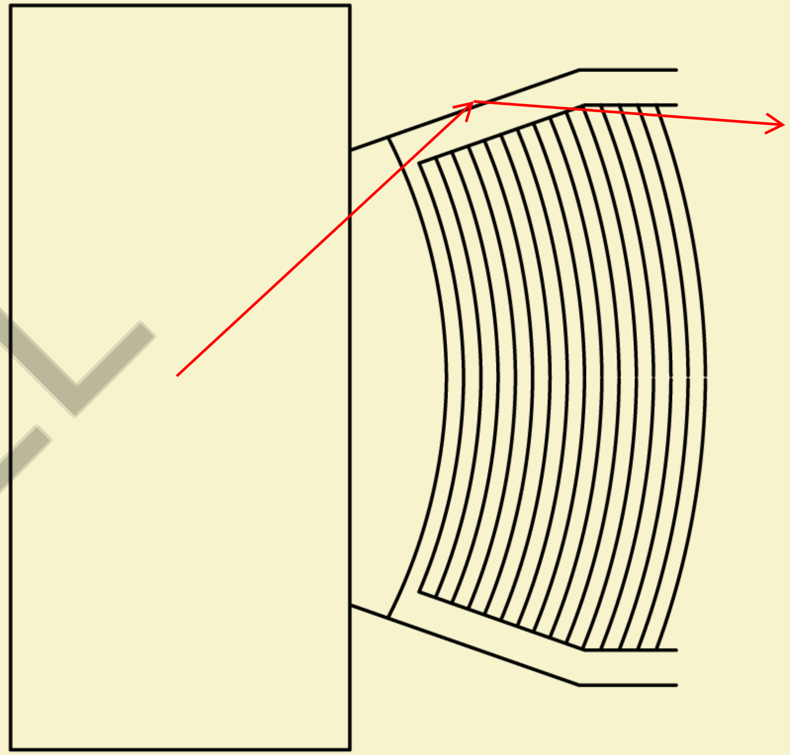
Lateral reflections can be diffused
Specular reflection can be checked

¼ of a wavelength to have appreciable effect at a given frequency

Shapes



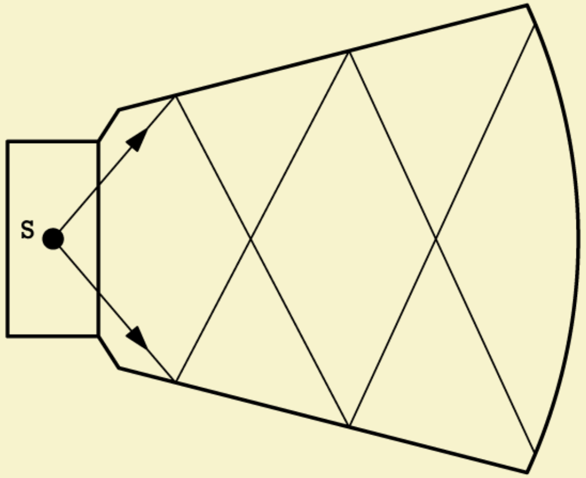
Floor side walls rectangular near stage causes flutter



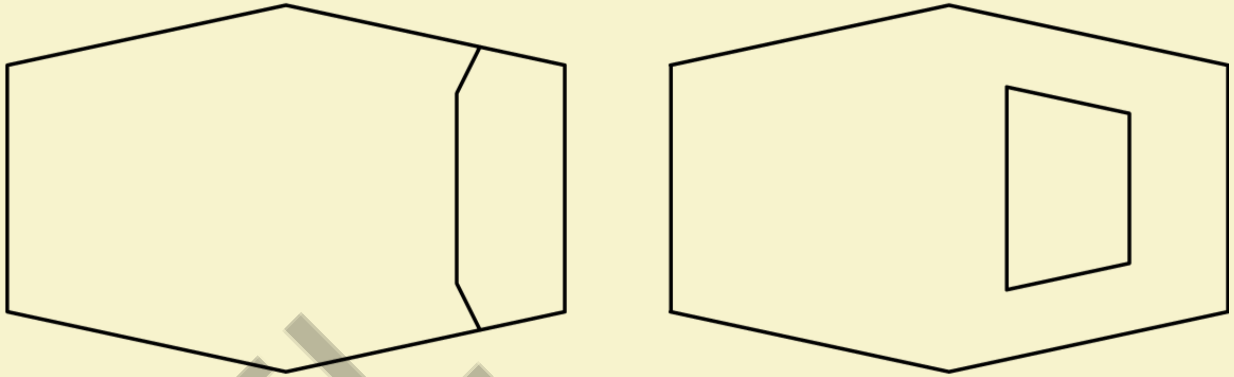
Angled side wall allows better side wall reflection

Side wall design near the stage

Shapes

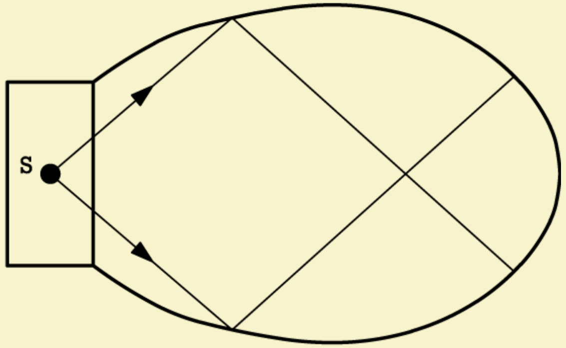


Fan shaped

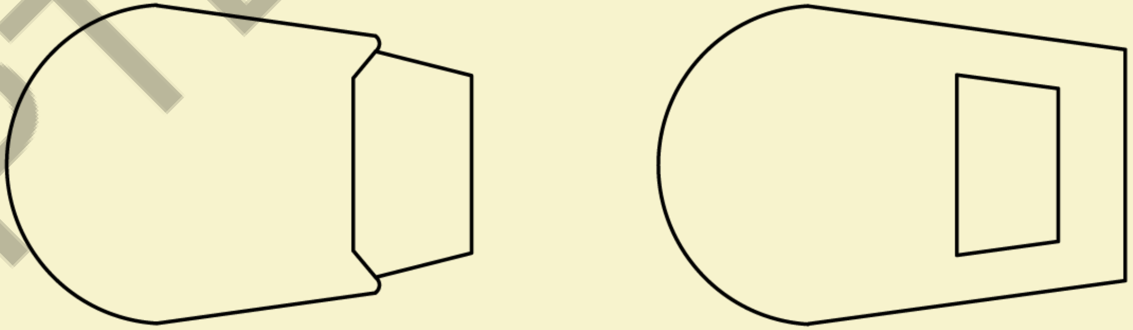


Diamond

Opposing surfaces : causes flutter



Oval shape



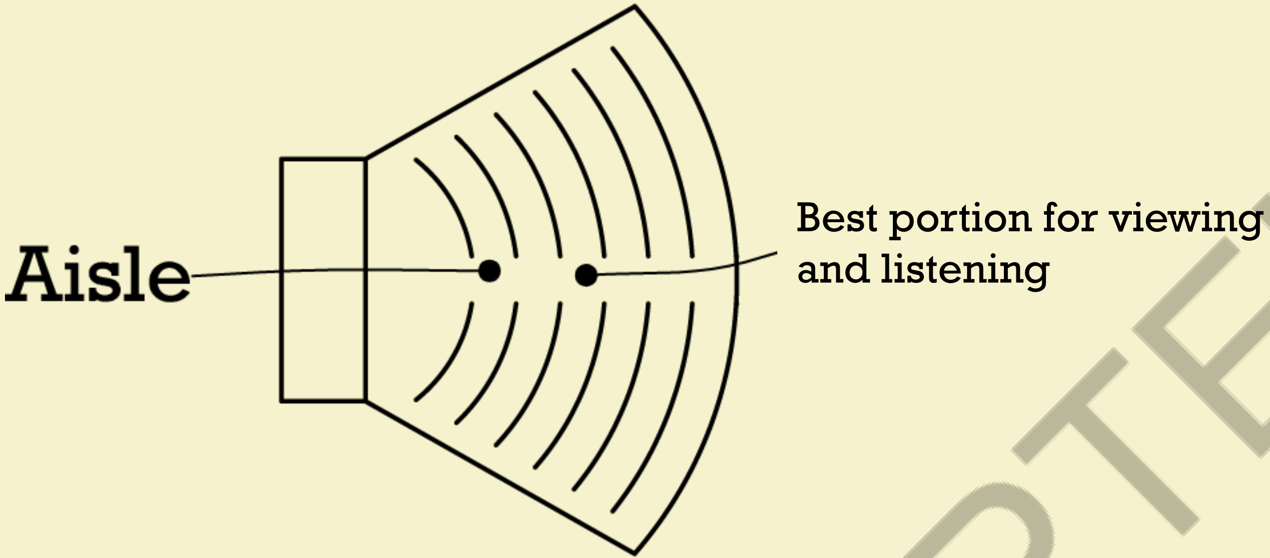
Horse shoe shape

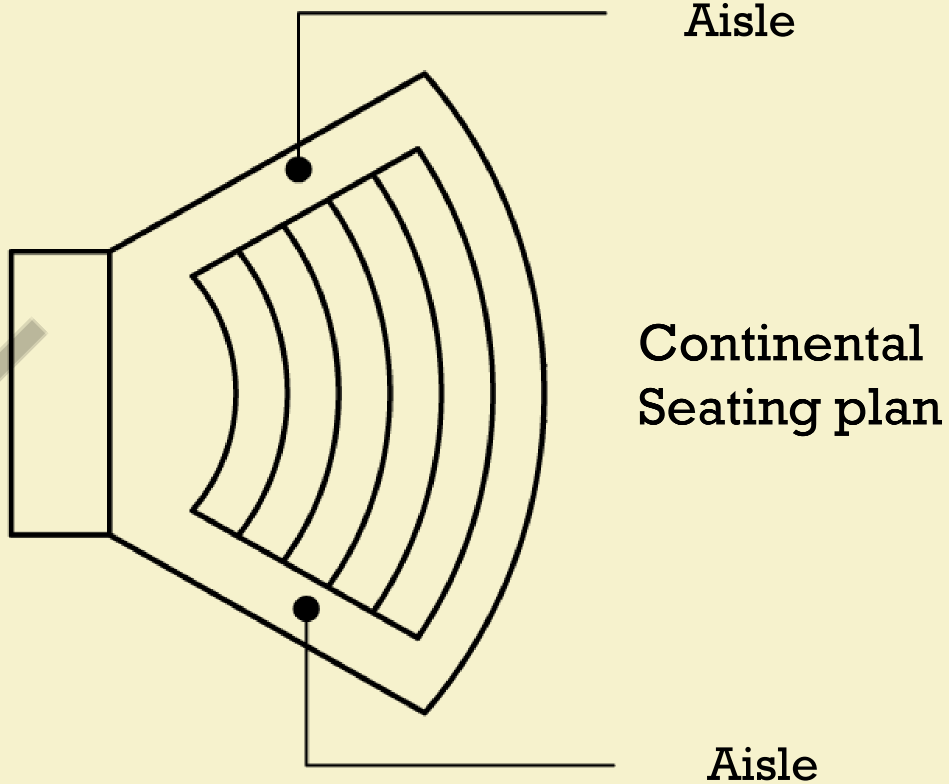
Refer Lecture 6

Circular or multifaceted like hexagon, octagon to be avoided.
Focus sound and create localized regions of high level

Seating layout

Seating area more circular minimizes the source-receiver distance





Normal row-to-row spacing is 36 to 38”

Best portion for both hearing and viewing is the central part

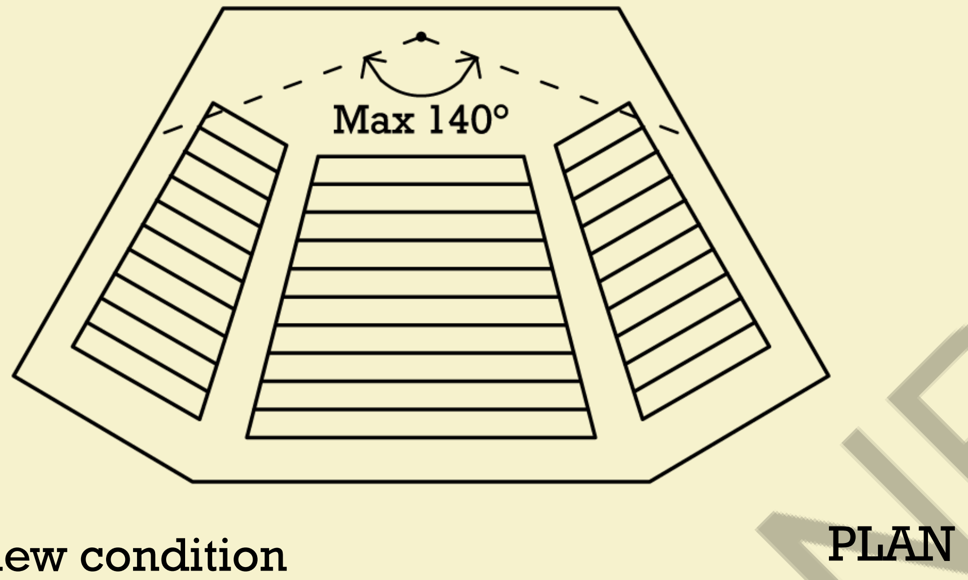
Aisles should not be encouraged in the middle of the auditorium

Seating plan with side aisles is called continental seating

Seating layout

Human voice cannot extend without reinforcement

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



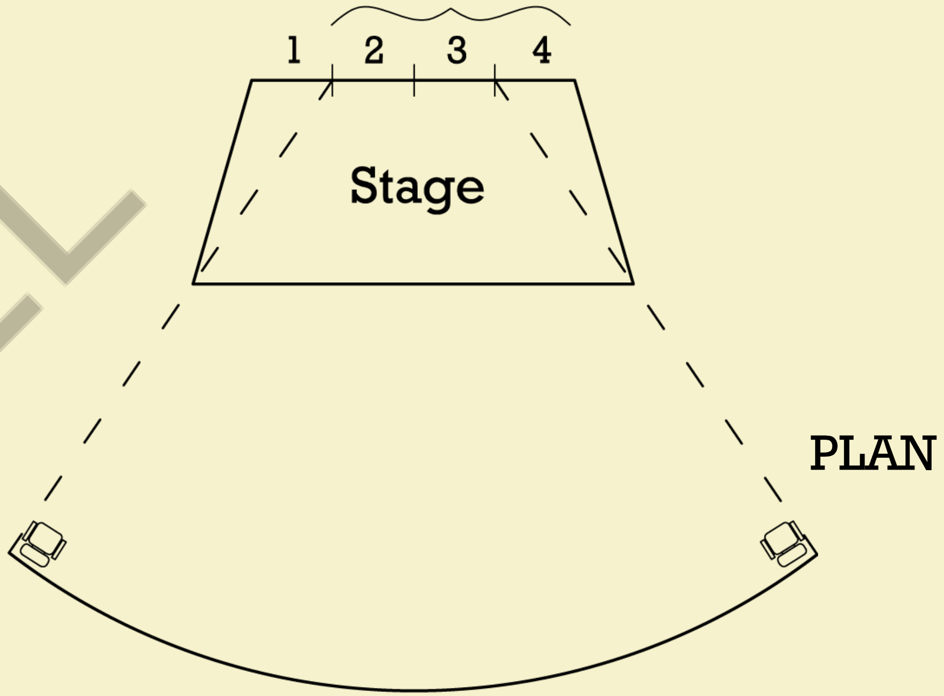
View condition

Included angle between the outermost seats

Less than 140^0 for speech

Up to 80^0 for music, lower the better

From extreme corner seat ¾ of the back of stage should be visible



With a hard ceiling, the depth can be increased and the length-to-width ratio can exceed one.

Picture taken from center of stage at Kalidas Hall, IIT Kharagpur

Tasks

Revisit Lecture 6,7,16

References:

Concepts in Architectural Acoustics, M. David Egan
Architectural Acoustics by M. Long
Room Acoustics by Heinrich Kuttruff
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Beranek (1996). Leo Beranek, How They Sound, Concert and Opera Halls. © 1996, Woodbury, NY: Acoustical Society of America.

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Architectural Acoustics

Lecture 23: Introduction to Auditorium Design

Dr. Sumana Gupta

Department of Architecture & Regional Planning

Learning Objective

Stage

Sections

Stage design

Stage floor height

Set low enough that a person sitting in the front row can see the actors' feet,
Lowest point of interest on stage is called the arrival point of sight (APS)

Eye height of a seated person - 44" to 48"
Stage height - 40" to 42"

It should be high enough that the Arrival Point of Sight does not force excessive floor rake.

A 1:9 rake for the first ten rows, and thereafter a 1:8 slope, yields a good result for a theater stage having a normal 42" (1.07 m) height.

In general the higher the APS the lower the seating rake

Lower the APS steeper the rake

Stage floor to be made of Hard wood – Absorbs sound

Stage design

Ensemble - Musicians' ability to hear each other
and the perception that musicians are playing in unison

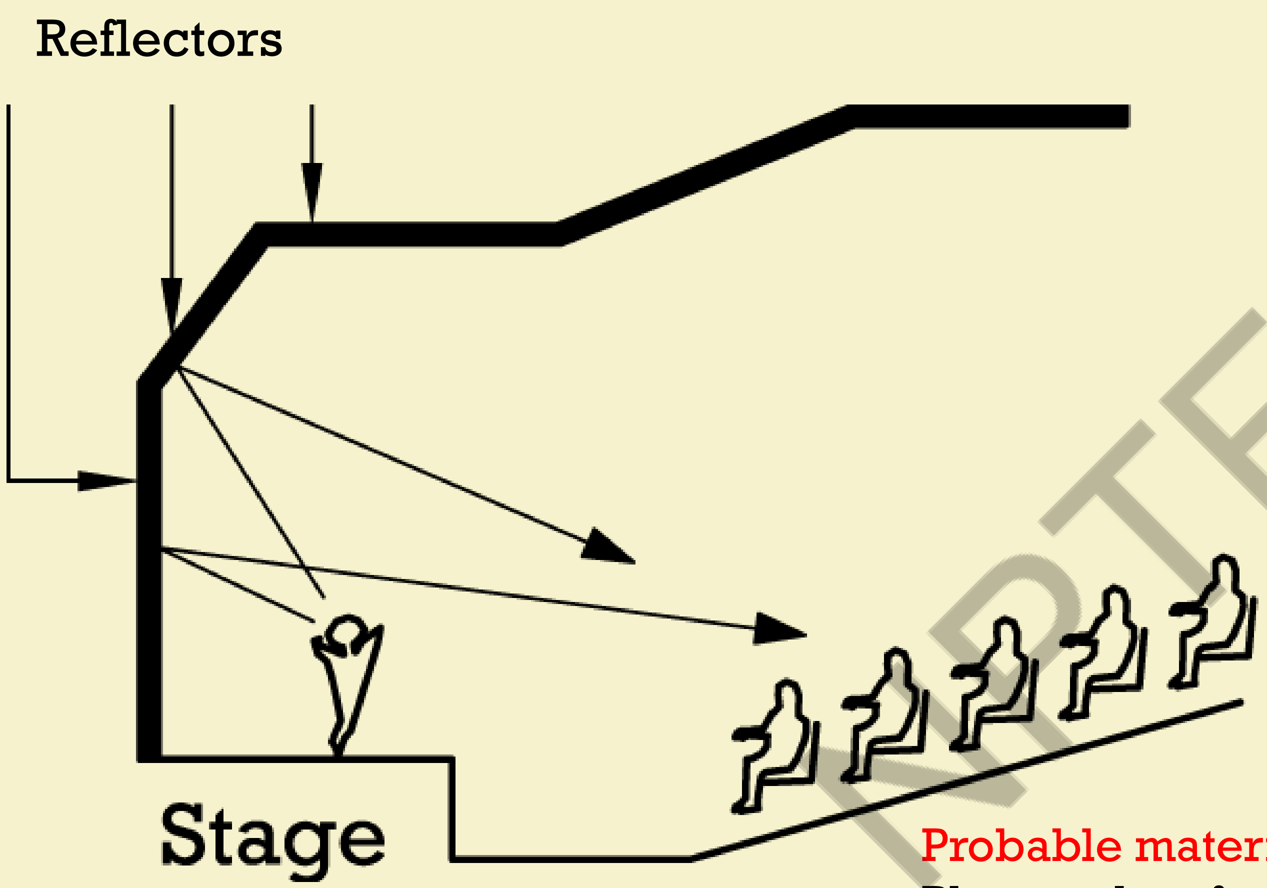
Support factor measures the musician's ability to hear himself and others near him.

Support factor is the ratio of the energy returned between 20 and 100 msec, compared to the initial level between 0 and 10 msec.

Stage platform volume can control the Support factor and hence Reflector heights above stage can be determined.
Preferred volume is 1000 to 2000 cum

Above stage – Kalidas Hall, IIT Kharagpur

Sound source – closely surrounded by large reflective surfaces to reinforce source sound

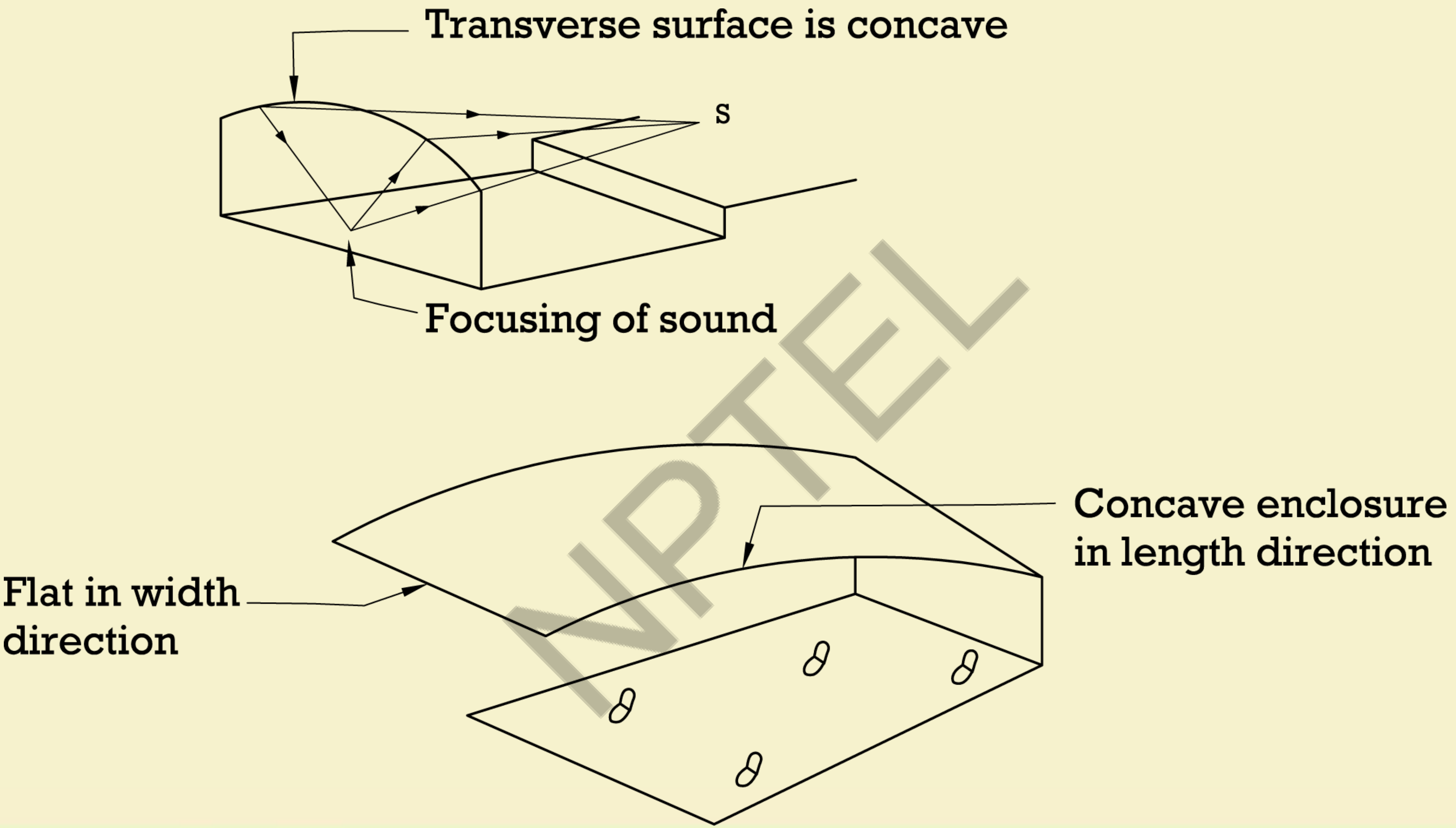


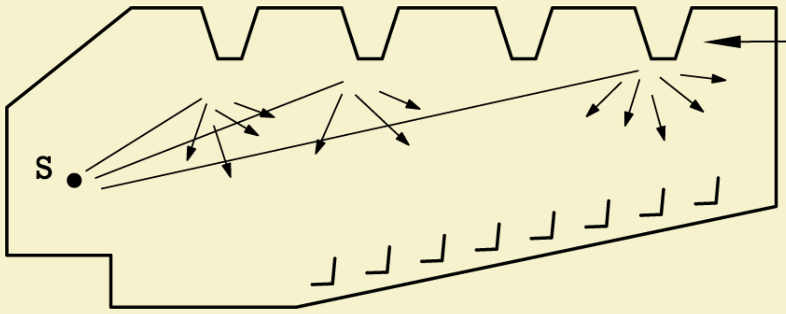
Back reflecting sound gives directivity to the sound source and is called precedence effect or space effect or Hass effect.

Probable materials:
Plastered surface,
POP, Gypsum board
Plywood, Plexiglas

Refer lecture 16

Shape of structural ceiling

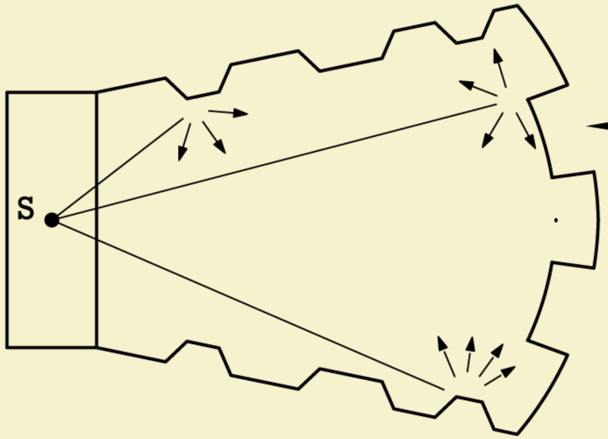




SECTION

Exposed beam in ceiling/ coffered ceiling - Diffusers

Diffusion depends on the frequency
Angle of incidence

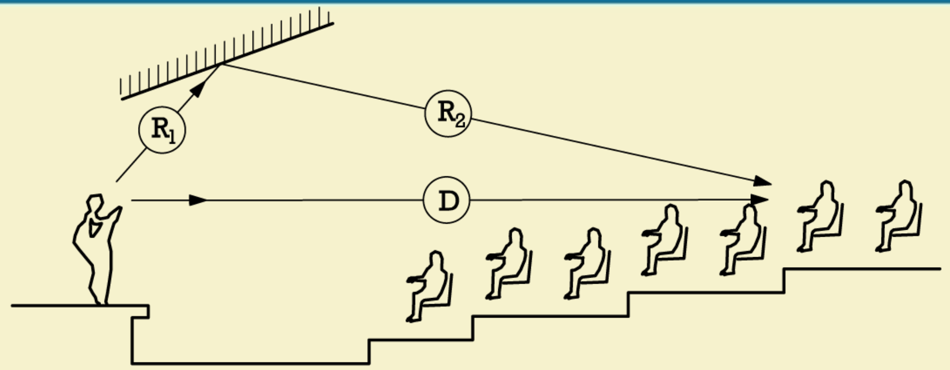


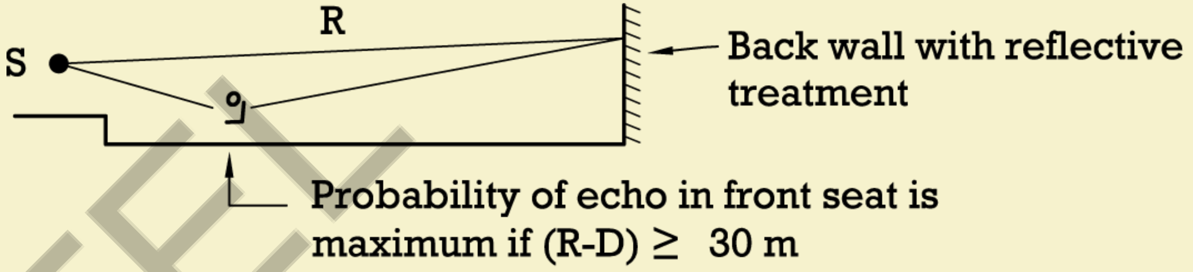
PLAN

Projected structural element, columns, enclosures

Surface Diffusivity Index (Haan and Fricke, 1997)

High Diffusivity (SDI = 1)
Coffered ceiling with deep (> *100 mm or 4 in) recesses*
Random diffusing elements over the whole surface (> *50 mm or 2 in deep)*
Medium Diffusivity (SDI = 0.5)
Broken surfaces with shallow recesses (< *50 mm or 2 in deep)*
Flat surface behind a semitransparent hard screen
Low Diffusivity (SDI = 0)
Smooth flat or curved surfaces
Absorptive surface



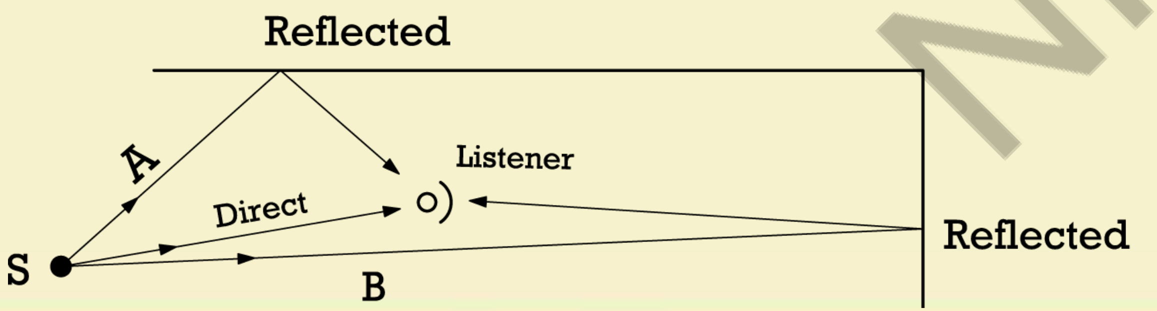


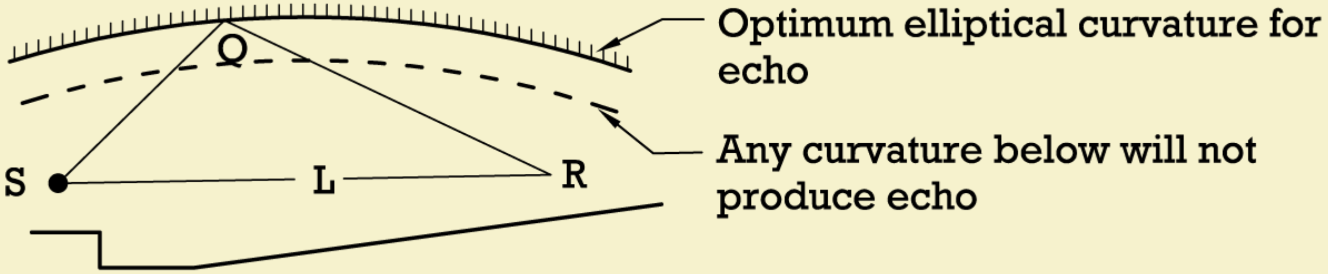
Direct sound path = D

Sound path for reflection = (R_1+R_2)

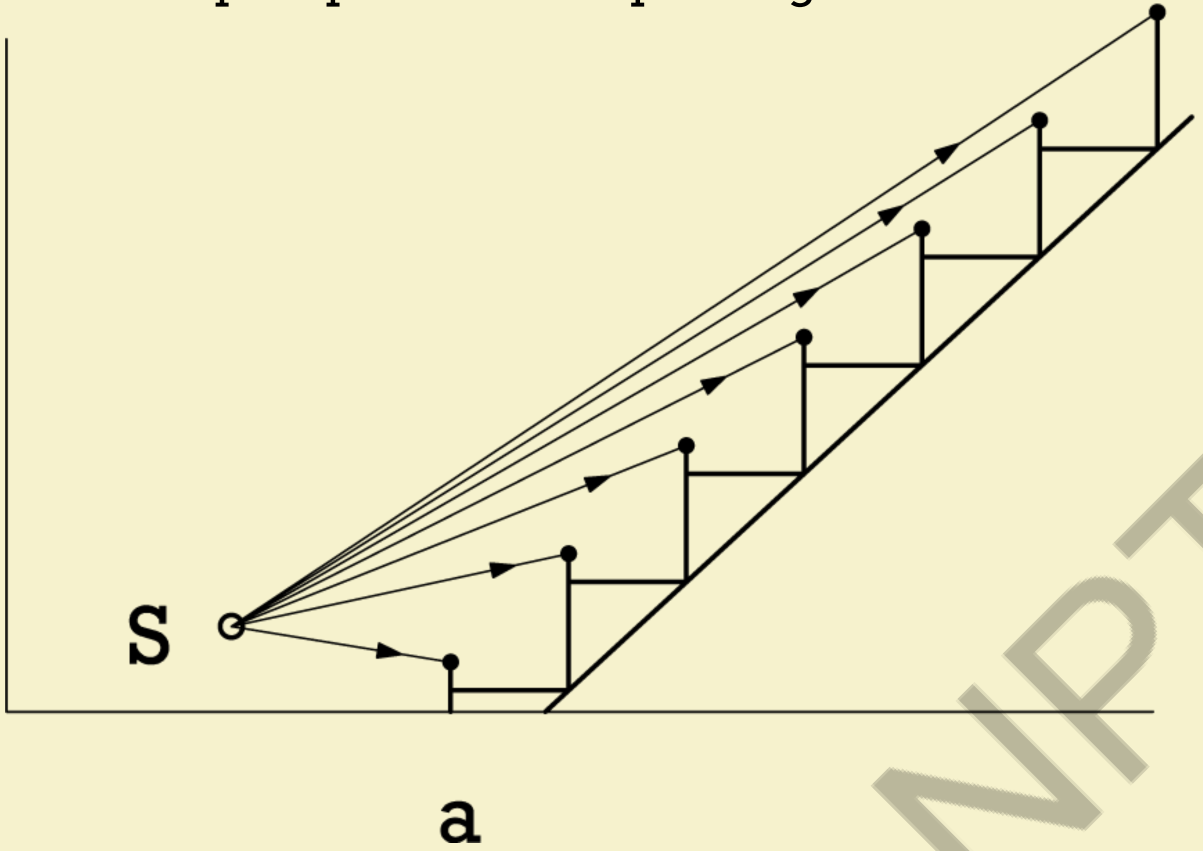
Time delay in milliseconds = $\dfrac{(R_1+R_2) - D}{0.3}$

So, $(R_1+R_2) - D < 9.0$ m for sound velocity = 300 m/sec

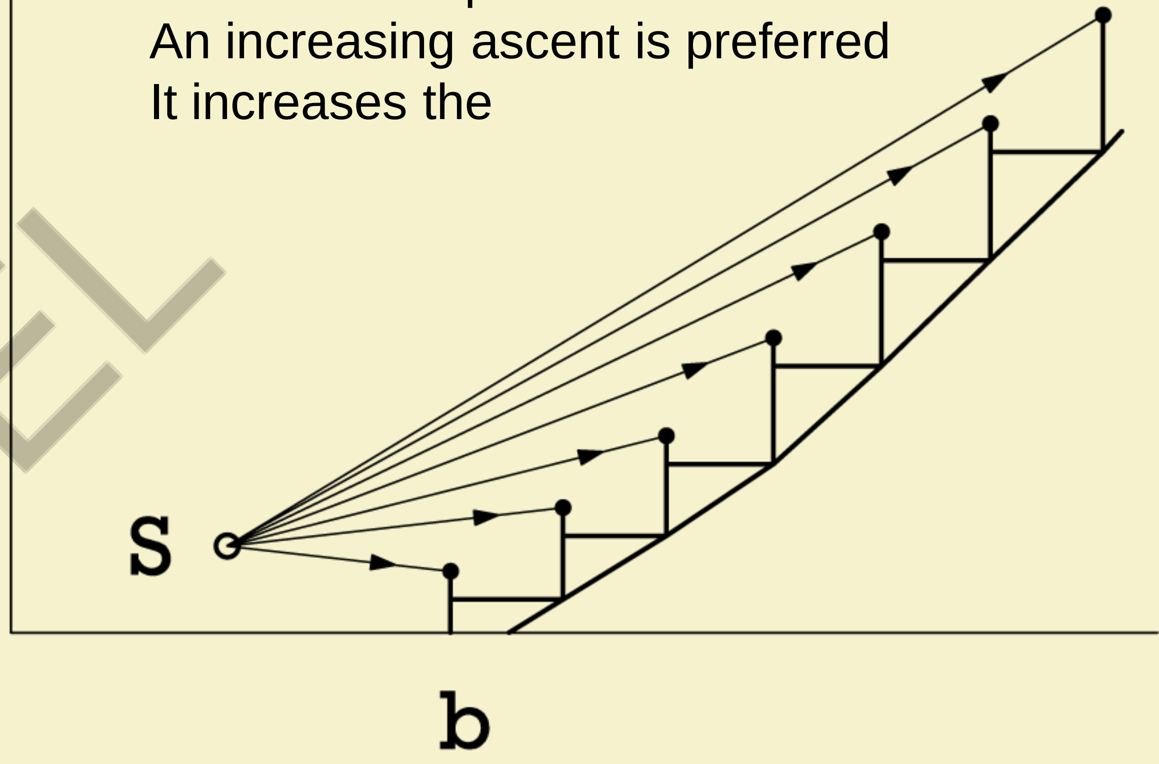




Floor slope - provides adequate sight line



A constant slope is less favourable
An increasing ascent is preferred
It increases the



Audience can see the lowest point of interest on stage, called the arrival point of sight (APS)

Reduction of direct attenuation by sloping the seating area
(a) Constant slope; (b) Increasing slope

Reasons for this changing slope of floor

- Audience can see the lowest point of interest on stage, called the Arrival Point of Sight (APS)
- Low frequency sound decays – detrimental for speech intelligibility and music

A changing slope can break

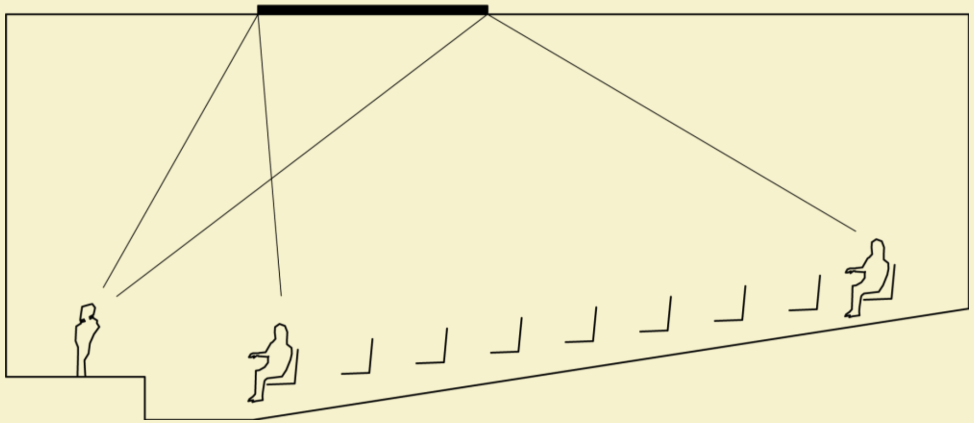
Attenuation of sound waves parallel to audience, sound of particular frequency diffracts and gets absorbed by audience or seats – vertical resonance.

Grazing attenuation is only present at very shallow angles, less than 5°

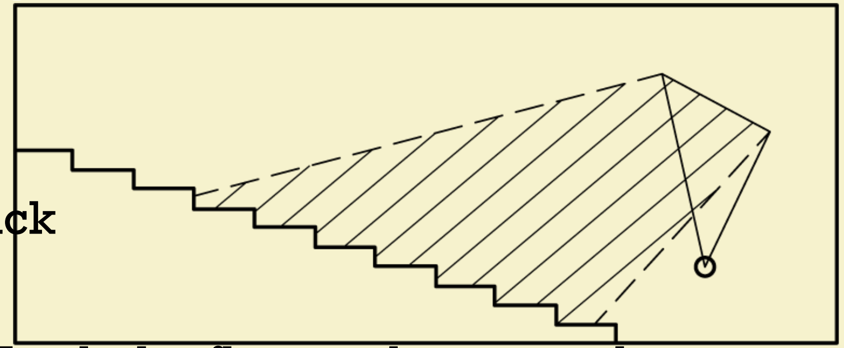
Grazing attenuation should be controlled by raising the talker height and by sloping the floor.

Overhead reflections can be beneficial for reinforcement

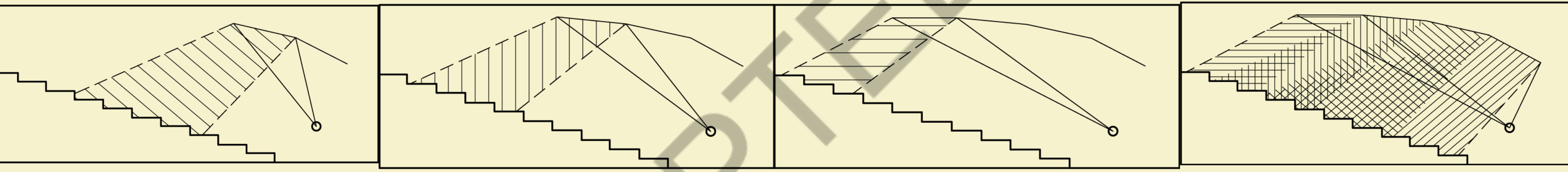
Positioning of reflective surfaces on ceiling

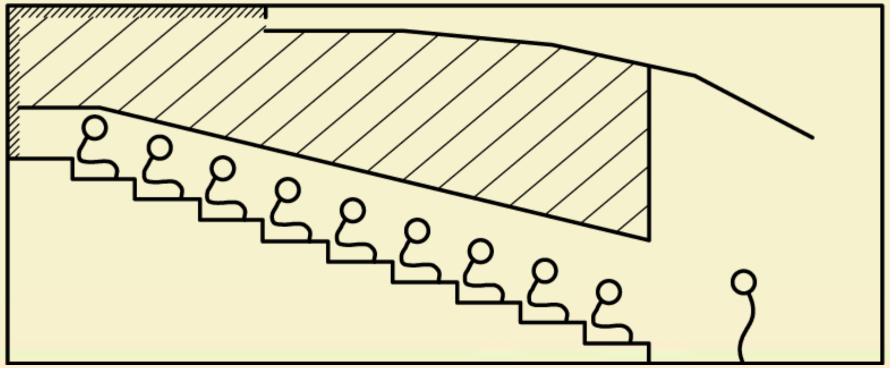


Flat ceiling, small hall
Useful length of ceiling
reflector to reach sound to back



Angled reflector above speaker
spreads sound to audience



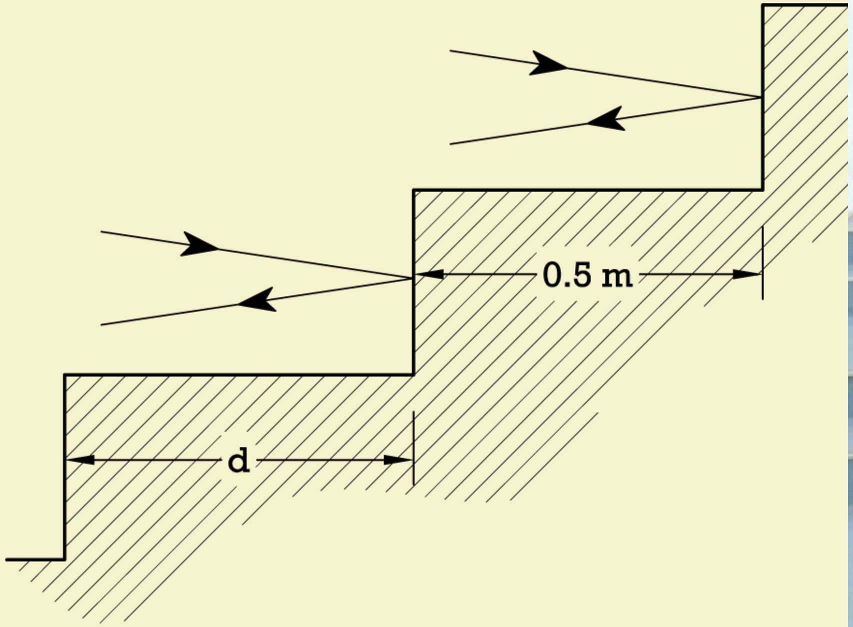


Surfaces in different angles reflect sound till back

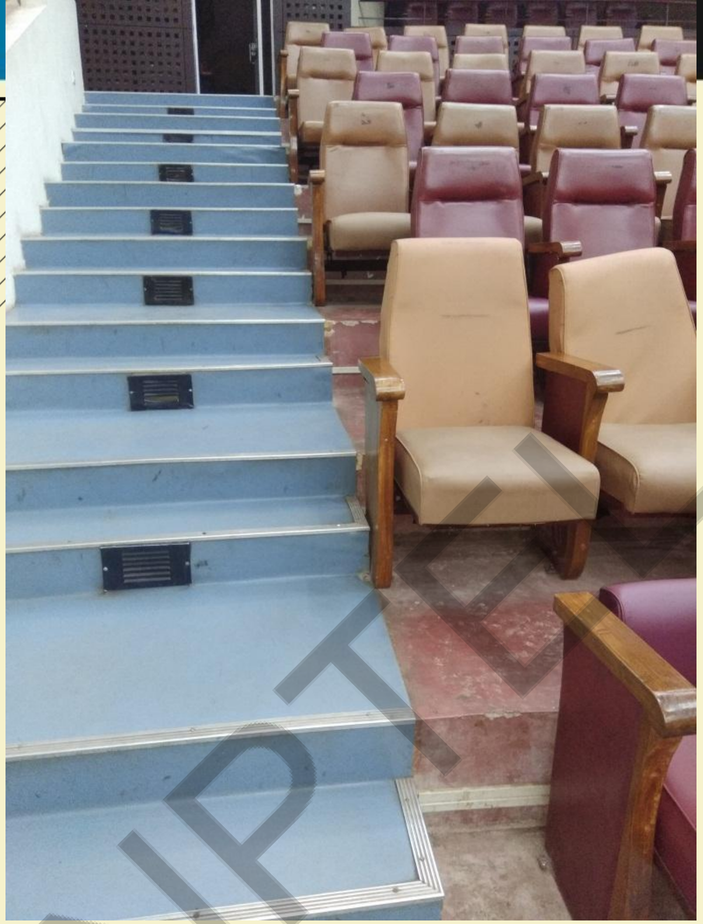
Lower part of hall side walls - useful lateral reflections -Envelopment

Back of ceiling and hall, upper part of side walls – Absorbing or scattering surface, stops delayed reflection

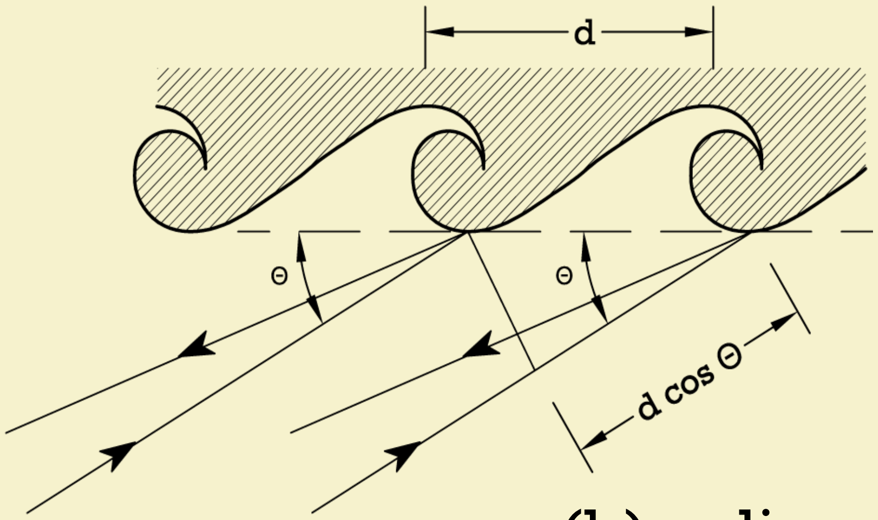
Echelon Effect



Echo from (a) Stairs



Stairs – Kalidas Hall, IIT Kharagpur



(b) palings

These echoes combine to produce a musical note which will be heard along with the direct **sound**. This is called **echelon effect**.

Solution: To have varying widths of treads

Tasks

Revisit Lecture 6, 7,16

References:
Concepts in Architectural Acoustics, M. David Egan
Architectural Acoustics by M. Long
Room Acoustics by Heinrich Kuttruff
ACOUSTICS OF THE SYDNEY OPERA HOUSE CONCERT HALL Part One: The Client's Perspective Lisa Taylor and David Claringbold

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Architectural Acoustics

Lecture 24: Introduction to Auditorium Design
Balcony and ceiling design

Dr. Sumana Gupta

Department of Architecture & Regional Planning

Learning Objective

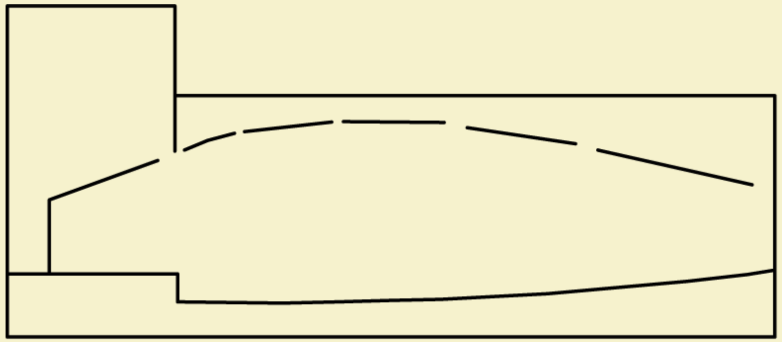
Balcony Design

Ceiling Design

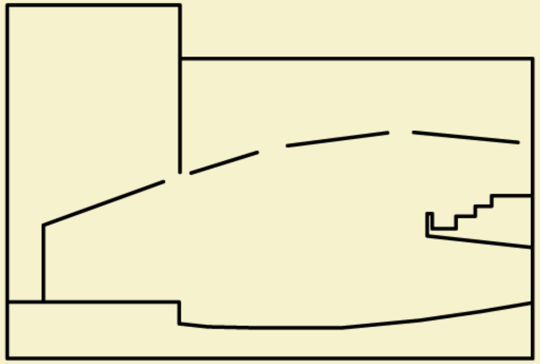
Balcony projection brings audience closer to stage

Energy losses minimized – Travelling sound wave, Audience size

Intimacy is increased

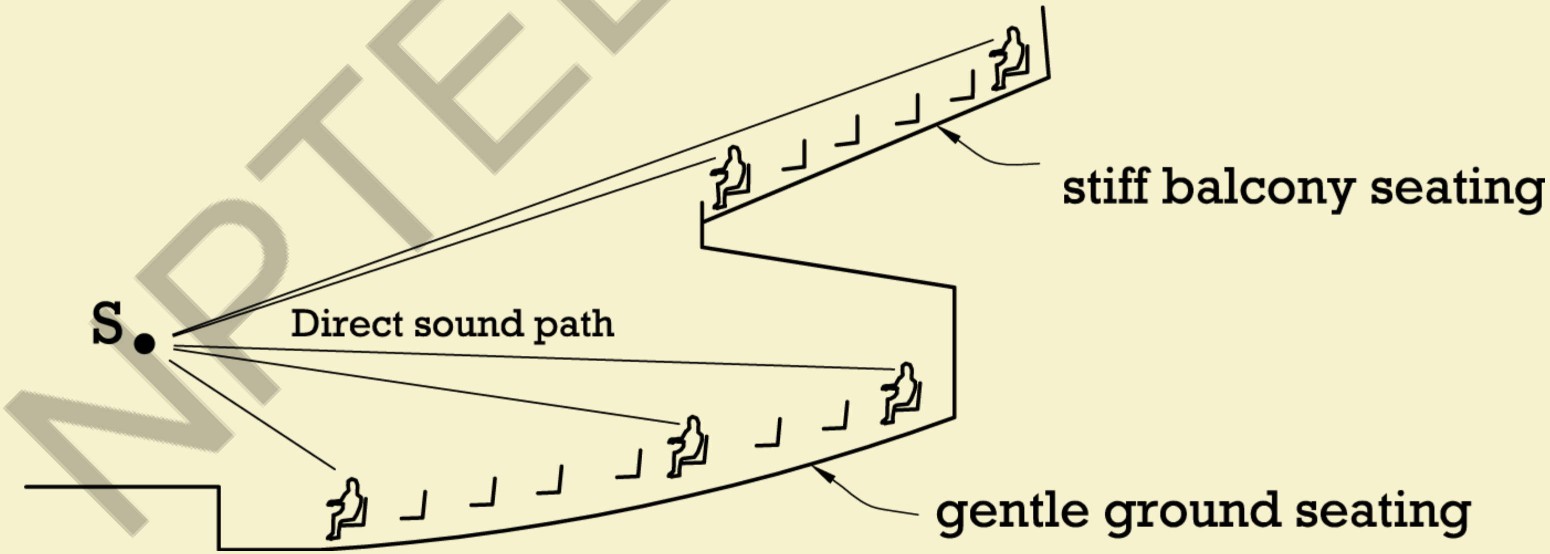


Section



Section

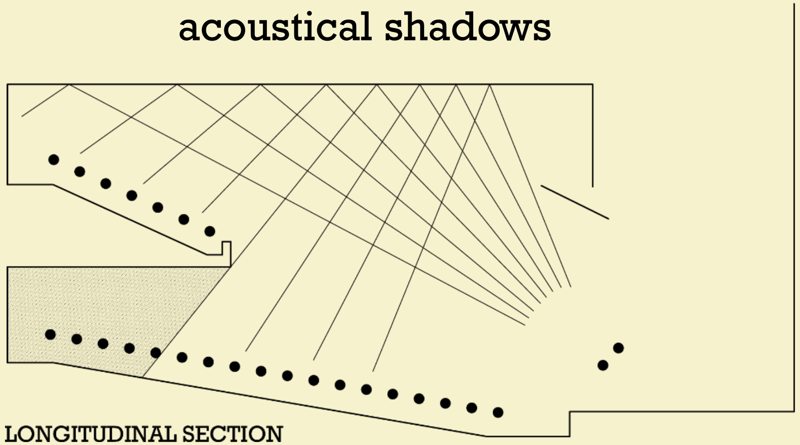
Adopted from General Shapes of Auditoria (Doelle, 1972)



In case of live performance direct sound reaches audience

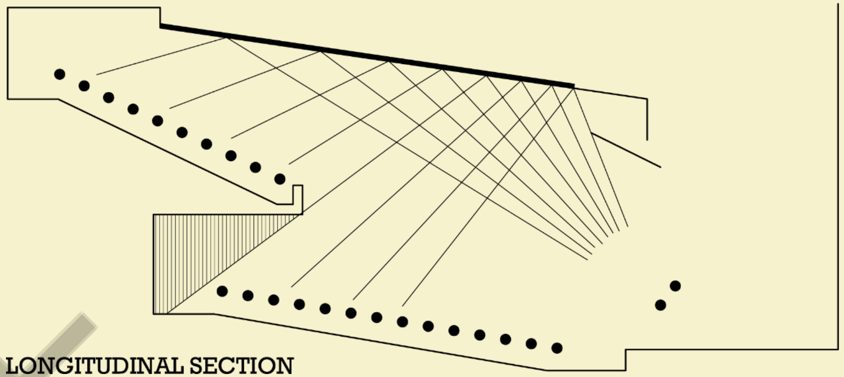
Ceiling and reflected sound

Deep balconies create acoustical shadows

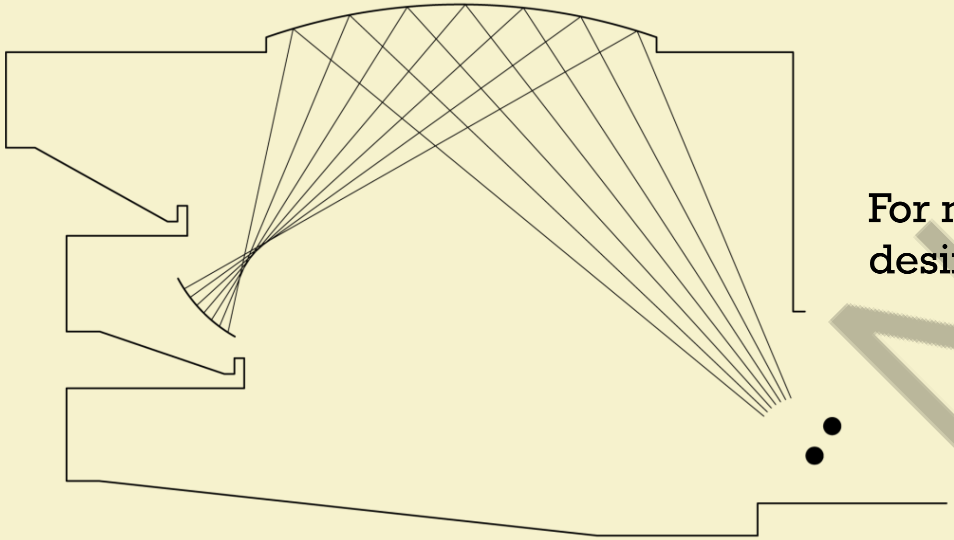


LONGITUDINAL SECTION

For speech – flat ceiling

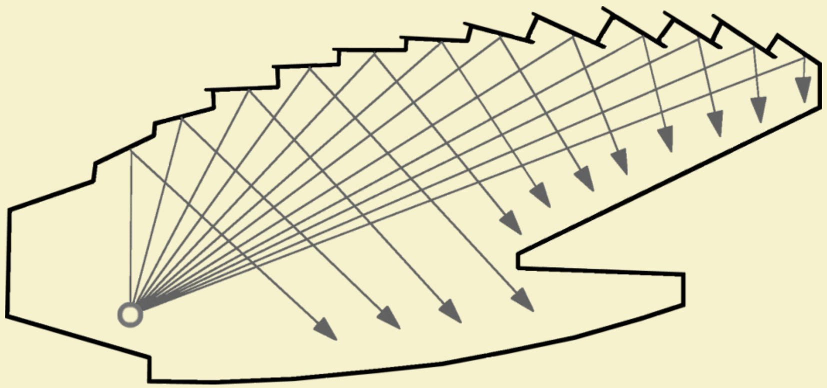


LONGITUDINAL SECTION



LONGITUDINAL SECTION

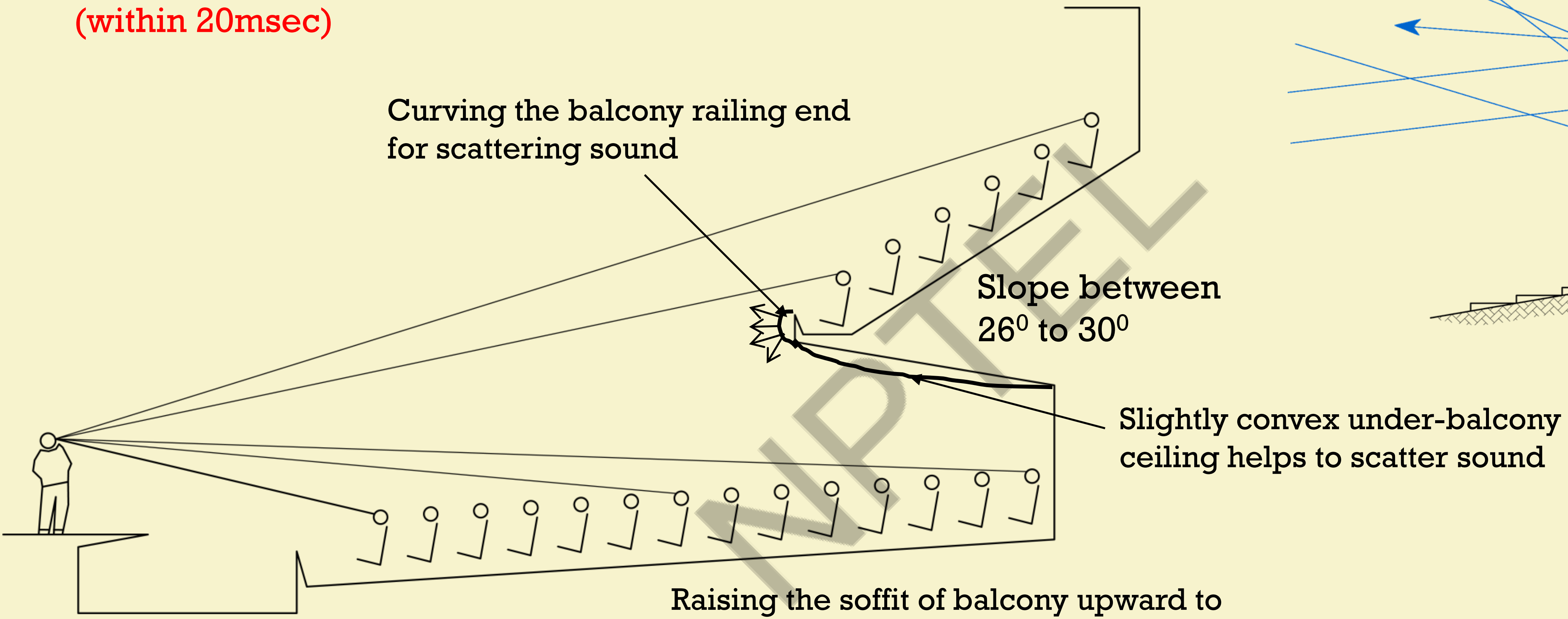
For music – shaped ceiling desired for envelopment



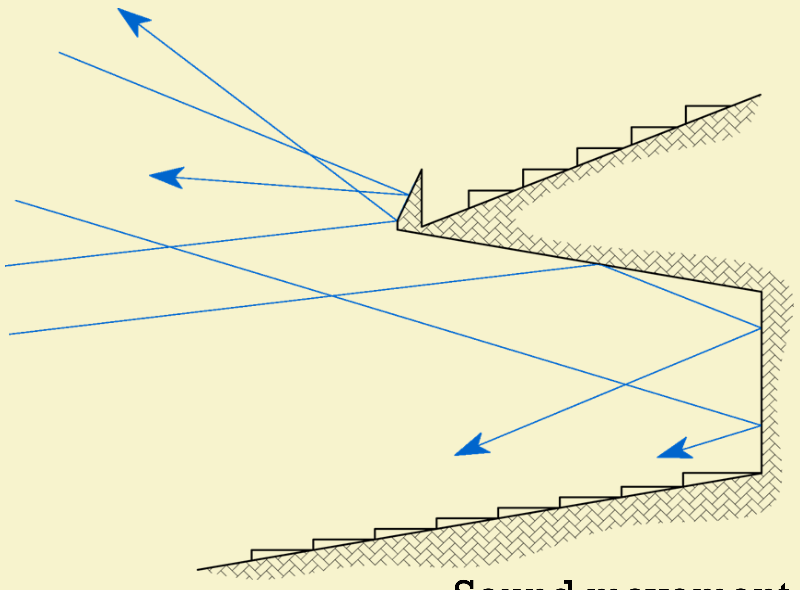
LONGITUDINAL SECTION

Balcony details

Top of the balcony should not be more than
65 feet above the stage to avoid longer path differences
(within 20msec)

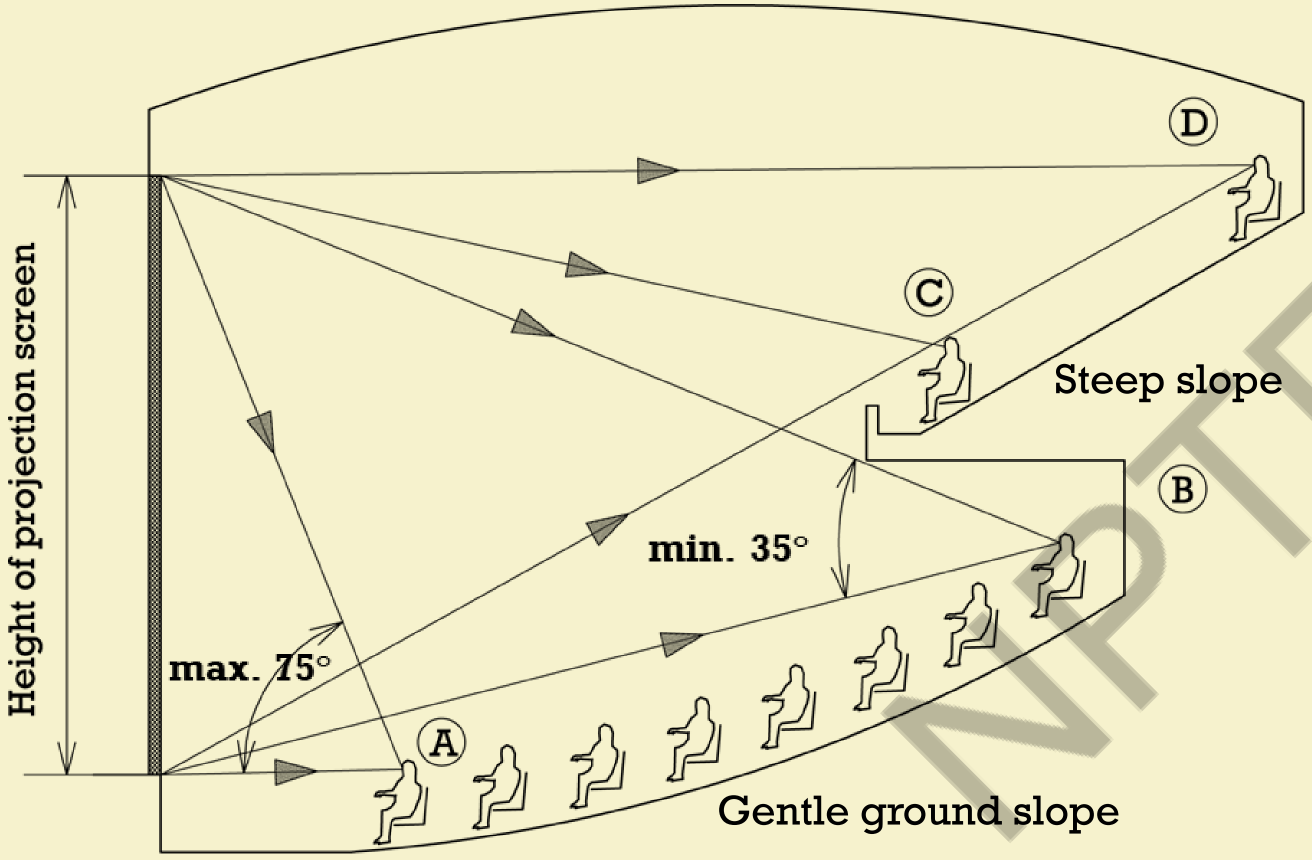


Raising the soffit of balcony upward to
increase under balcony volume
for better RT



Sound movement

Balcony and projection system



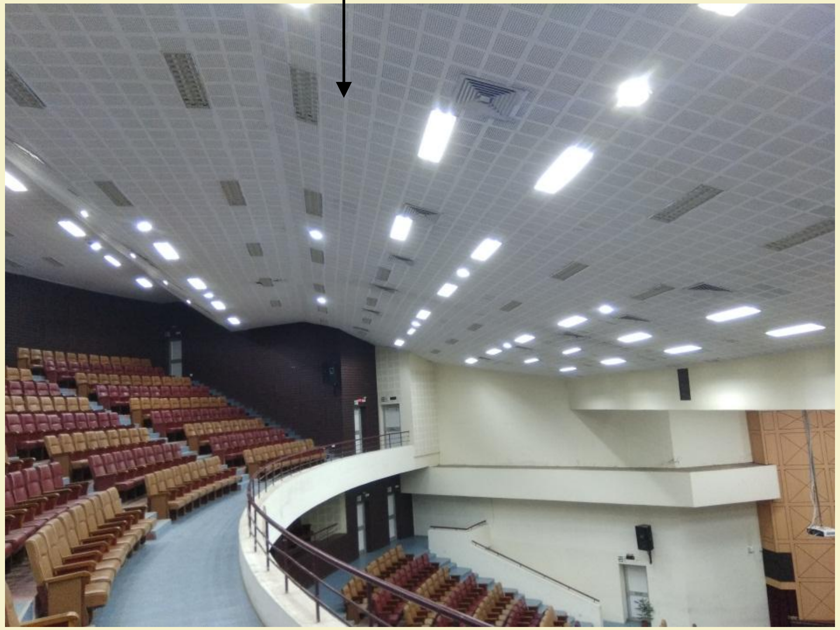
A – Full screen is exposed to eye but viewing the top portion is steep.
May give distorted view if the angle of viewing is more than 75^0 , preferred 50^0

B – The top part of the screen will cut off from the angle of viewing due to extra and flat projection of the balcony.

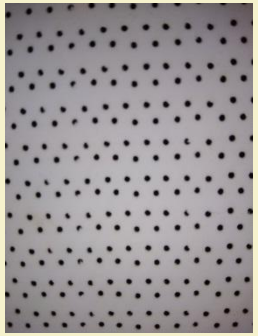
C – the bottom part of the screen will cut off from the angle of viewing due to height of front railing

D – The bottom part of the screen may get cutoff from the angle of viewing due to height of the front railing /head of first row viewer and improper ramp slope.

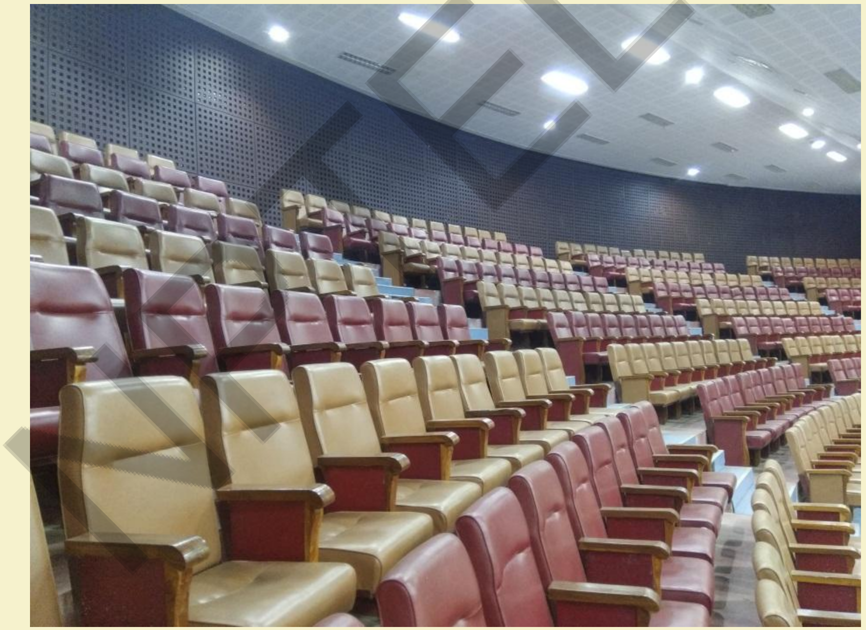
Stepped ceiling



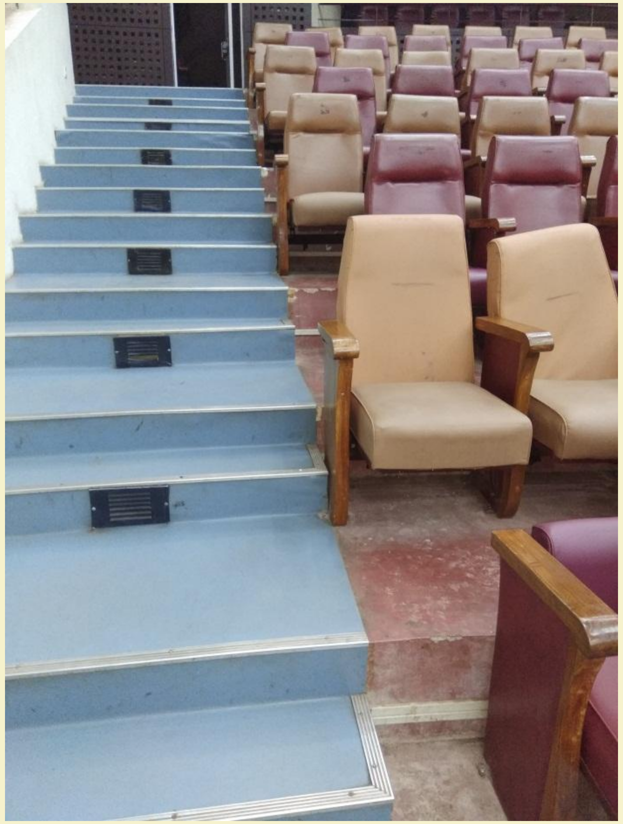
Transparent balcony railing



Absorptive
concave back wall
(checking potential echoes)



Steep balcony seating



Gentle slope in floor

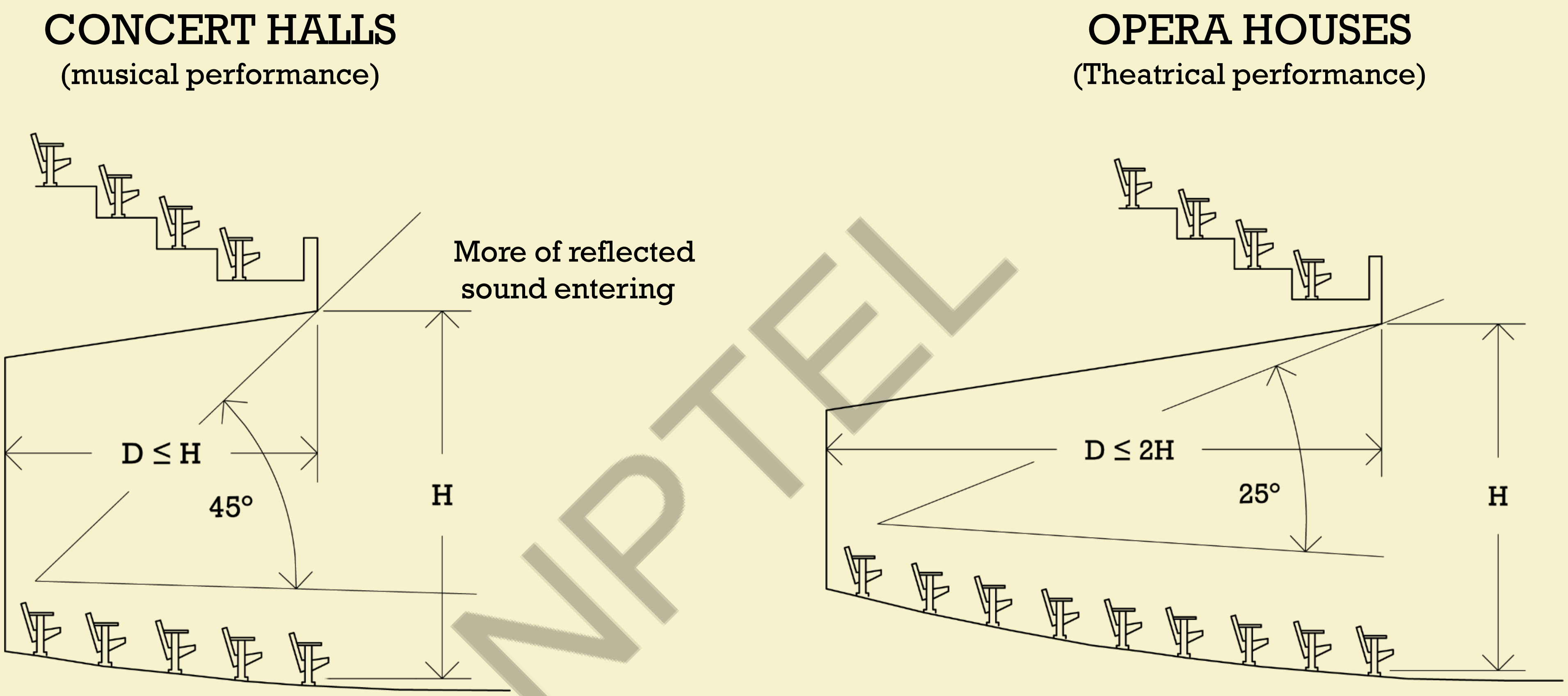
Pictures from Kalidas Auditorium, IIT Kharagpur

Projection window

Views: Projection room, Netaji Auditorium, IIT Kharagpur

Old system for projecting

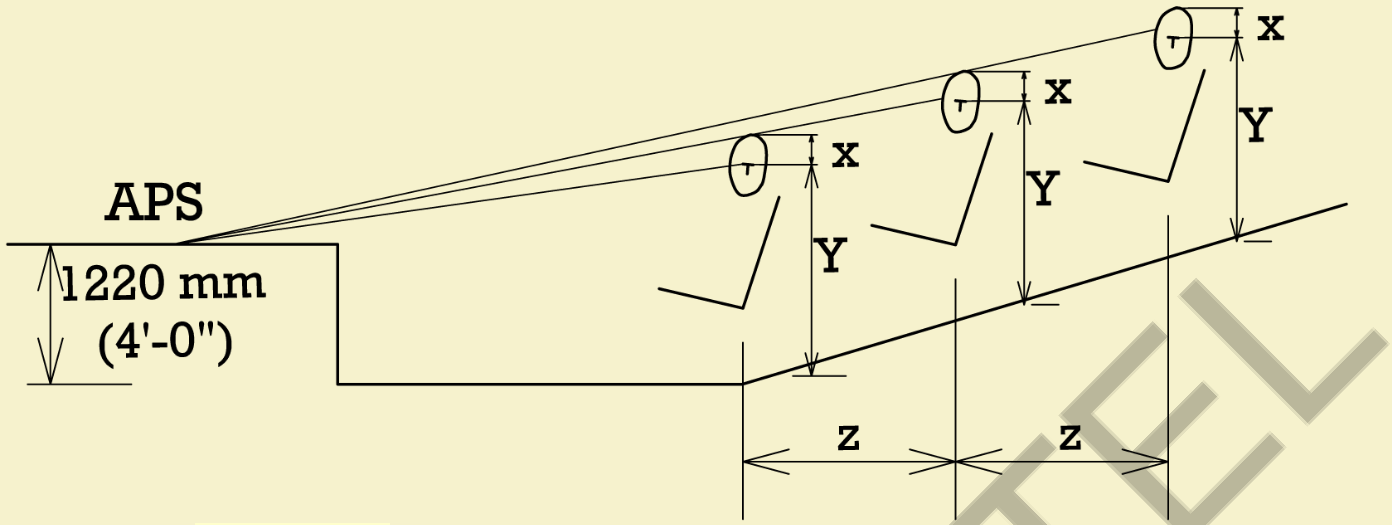
Balcony overhangs



Localised Volume reduction may leads to low RT and deteriorated sound quality

Excessive diffusion to be avoided to get reflected sound below balcony

Slope calculation



APS = Aerial point of sight

X = Distance from eye to top of head (5" or 125 mm)

Y = Height of eye level from floor (3'-8" or 1120 mm)

Z = Row Spacing (500 to 750 mm)

Calculation of slope is done considering alternate rows to reduce raking

Rear wall should not have large or unbroken concave geometry – potential echo producers

Preferred profiles are

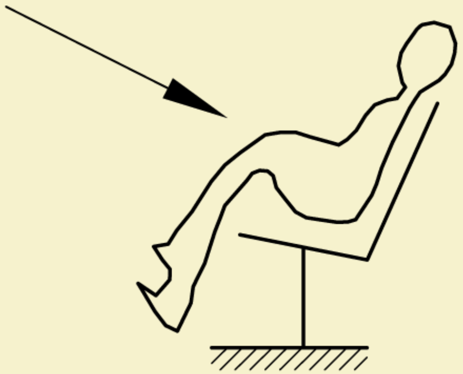
Serrated rear wall Wavy rear wall Segmented rear wall

Seated rows are often curved or angled toward the stage - direct-view orientation allows the audience to be "in conversation" with the performance

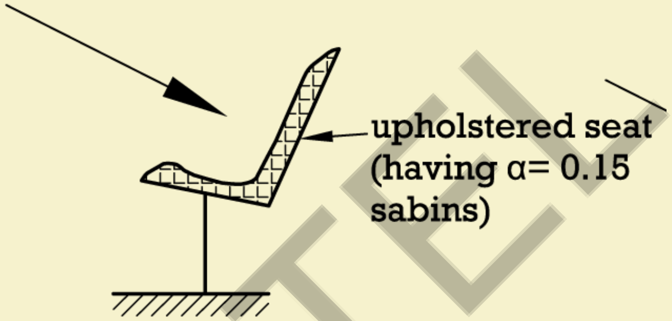
The view distance for understanding facial expression is 65 -70 ft (Jo Mielziner, *The Shapes of Our Theatre*)

Desired seat absorption

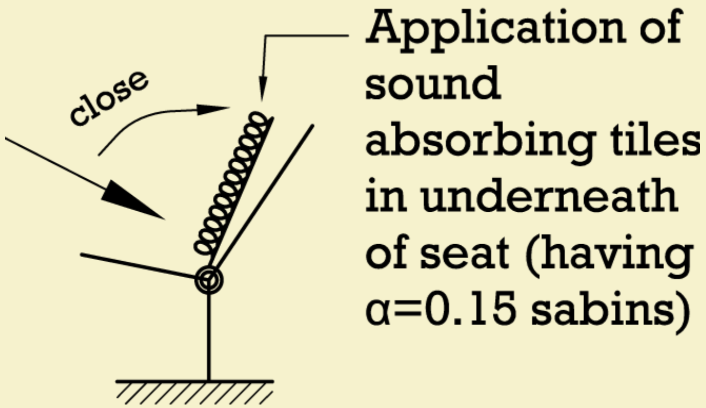
Fluctuating audience size



One audience member will absorb 0.15 sabin



One empty seat will absorb 0.15 sabin due to upholstered seat



One empty seat will absorb 0.15 sabin due to underneath treatment of acoustical materials

Target RT should be achieved, seats should be such so that empty hall and full hall should not affect RT

Shell structure

For speech intelligibility a flat or a slightly curved convex shape is ideal whereas for music high diffusion and low-radius curve is preferred (envelopment with lateral reflections)

Prefabricated diffusing materials are becoming available in wood, FRP, and masonry units

Dedicated hall for music - shell structure is preferred - merges with the proscenium arch and provides early reflections to ensemble Example: Carnegie Hall

But shell should neither be too deep, too high, nor too to avoid sound concentration. Depth is particularly critical (30 to 40 feet deep from the front edge of the stage)

Low frequency (bass) sound gets reflected from shell structures and hence gains warmth

The orientation of the shell ceiling helps in achieving envelopment.

Ceiling height should be 1/3 (larger halls) or 2/3 (smaller halls) of the average width of the auditorium

Listening position and sound quality

Objective: Listening position should not affect sound quality.

The first ear receives sound a millisecond before the other ear if source is towards the first ear

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

When two sounds arrive at the listener the perceived direction is determined by first sound to arrive, even when the second sound is as much as 10 dB stronger.

For equal level sources, delay gaps as low as one millisecond can bias the perceived direction

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

In the vertical plane the ability of the brain to interpret time delays is much weaker

Hence a properly designed loudspeaker cluster located above a stage is used to augment the natural sound of the performers while maintaining the illusion that all the sound is coming from the stage.

Tasks

Revisit Lecture 6, 7, 13,16

References:
Concepts in Architectural Acoustics, M. David Egan
Architectural Acoustics by M. Long
Room Acoustics by Heinrich Kuttruff
Acoustics of the Sydney Opera House Concert Hall Part One: The Client's Perspective Lisa Taylor and David Claringbold

Architectural Acoustics

Lecture 25: Introduction to Auditorium Design some examples

Dr. Sumana Gupta

Department of Architecture & Regional Planning

Symphony Hall Boston, 1900

Shoebox hall, RT – 1.8 sec, Capacity - 2625

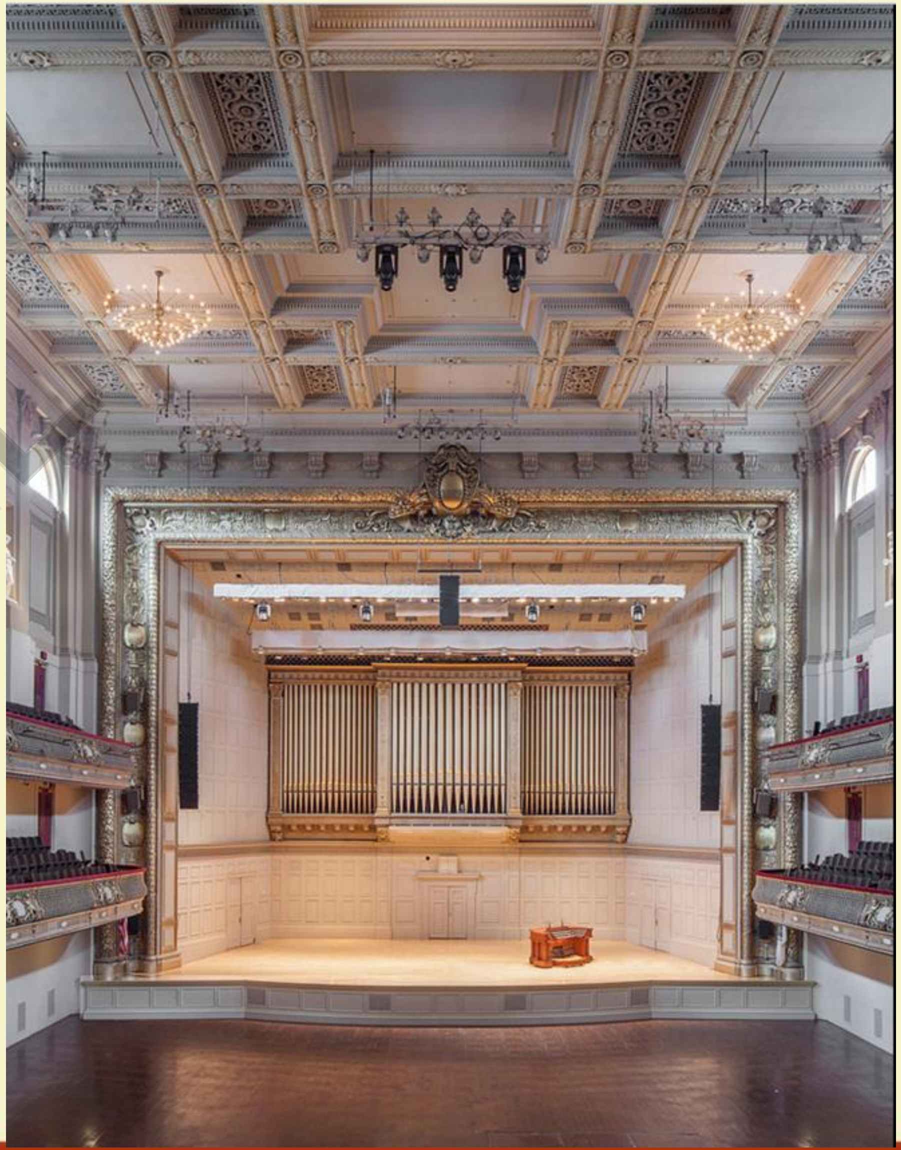
18.6m high, 22.9m wide, and 38.1m long

Wooden flooring

Side balconies are very shallow to avoid trapping or muffling sound

Coffered ceiling diffuses sound
flat portions allow specular reflections till back

Statue-filled niches along three sides
Leather seats



https://commons.wikimedia.org

Avery Fisher Hall, New York

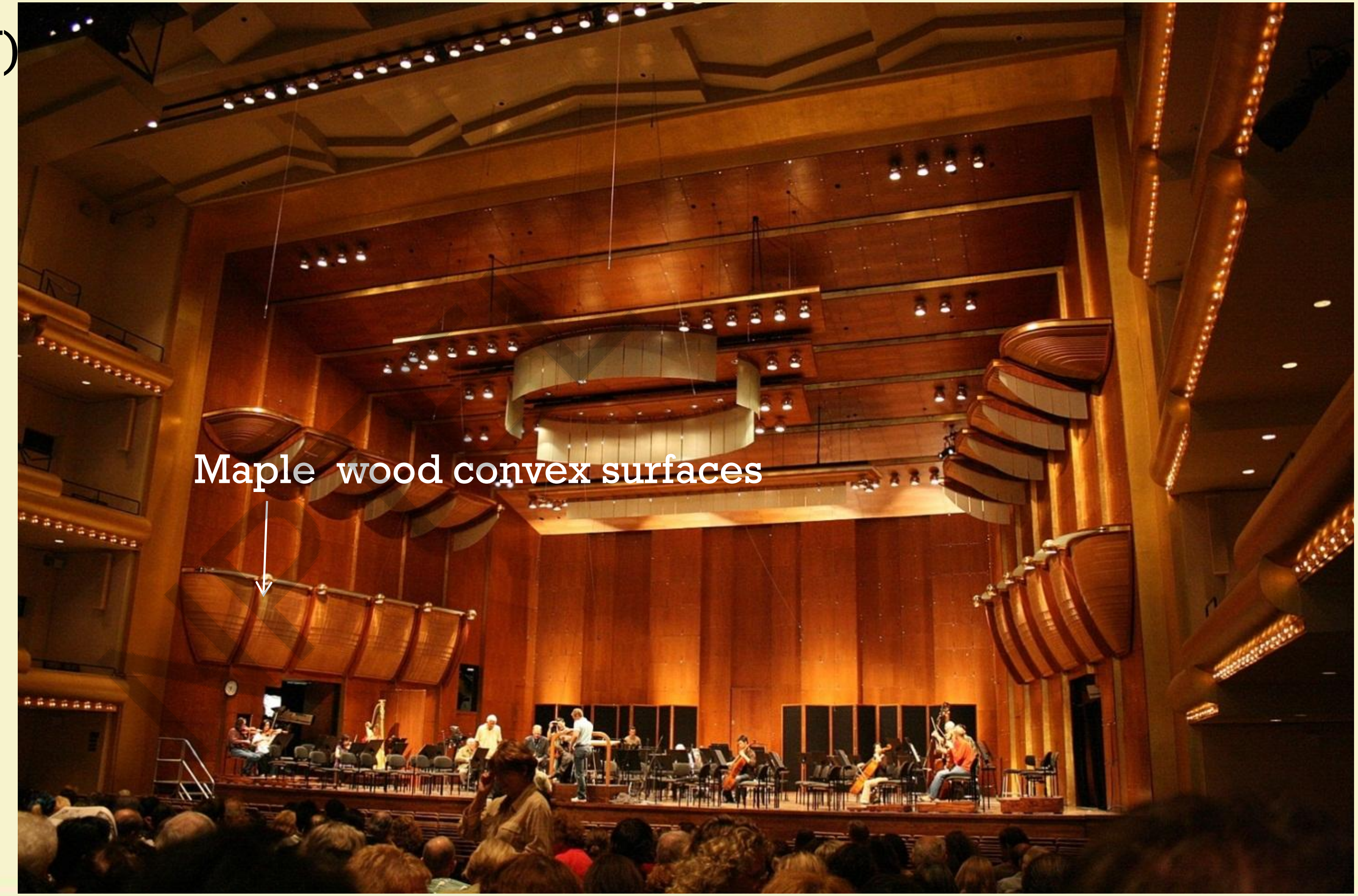
Capacity – 2738, 1962 (BBN)

Shoebox hall

The ceiling is high to increase reverberation time but the clouds are too high to reinforce early reflections adequately.

Sidewalls are too far apart to provide early reflections to the center seats.

The bass is weak because the very large stage does not adequately reinforce the low string instruments.



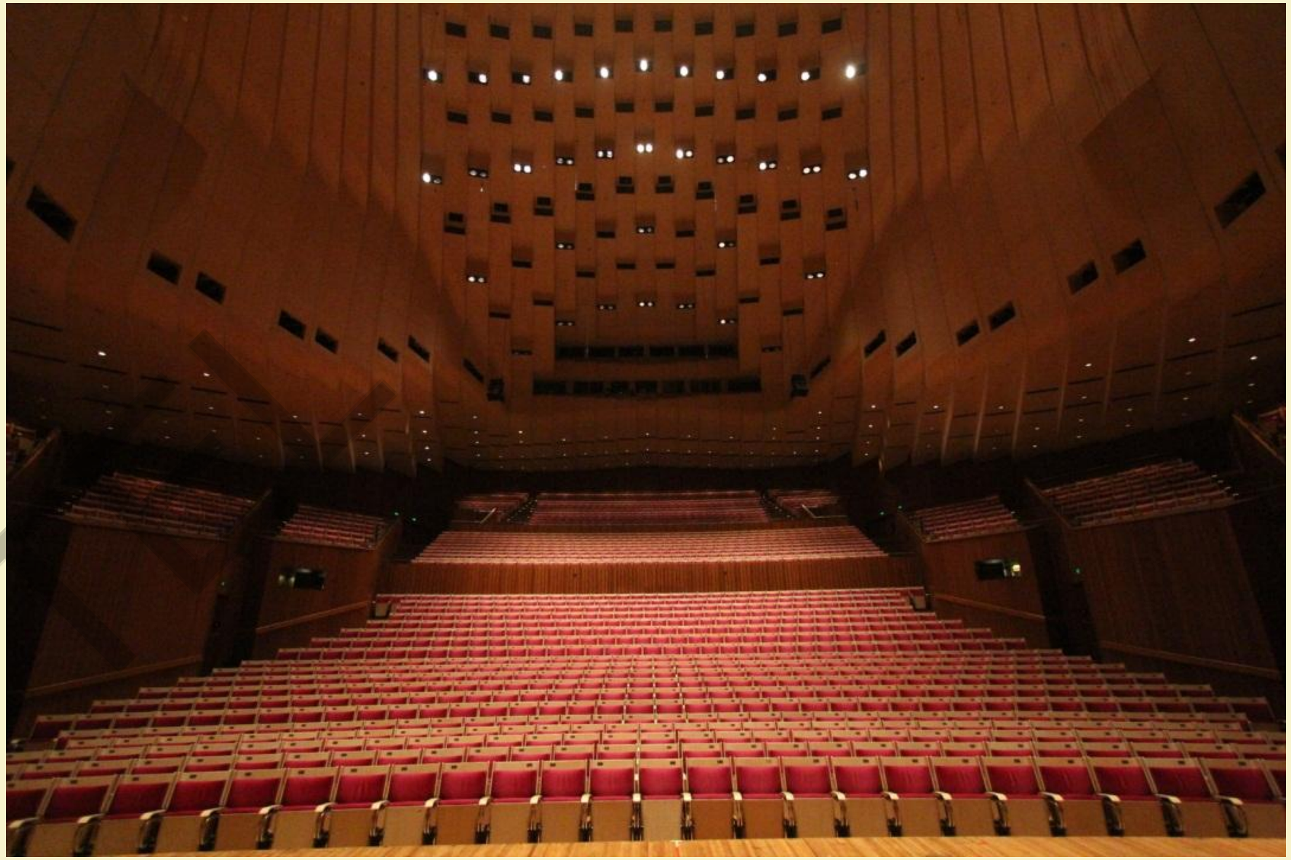
https://commons.wikimedia

Sidney Opera House (1973)

View towards stage

17m x 11m x 25m (h) unusually high

A set of 18 acrylic rings / clouds - adjustable



View from stage

Ceiling and seating frames - white birch veneer.

The seats are upholstered in wool

Sidney Opera House

Reflective ceiling in stage

Donut like acrylic clouds

Built – 1973
Capacity - 2,679

Reflective flat wall (MDF) panels covered the sawtooth walls near stage (renovation – 2003)

Meyerhoff Symphony Hall, Baltimore

1982, Capacity - 2443

Acoustical design was by Bolt, Beranek and Newman and uses a series of convex curves to avoid flat surfaces or ninety-degree angles inside the hall.

The auditorium is oval, its cylindrical wall extends the entire height of the building with the roof sloping down over the stage area (62 ft above to 44 ft stage).

The walls of the stage are covered in a light-colored wood and feature box seats.

Suspended "clouds" above the stage (originally were 52 precast concrete) which helped diffuse sound.

The stage is 65 ft (20 m) wide and 35 ft (11 m) deep.

The rear wall moves to provide an additional 12 ft (3.7 m) of space.

(Source: Wikipedia)

https://commons.wikimedia.org/w/index.php?curid=48412085

Verizon Hall, Kimmel Centre (2001)

Verizon Hall was over 225 rubber isolation pads which help absorb vibrations and eliminates extraneous noise

Shape of a violin or cello—with no straight lines or squared angles

Adjustable acoustic features to suit the purpose – retractable curtains

Series of operable doors along the sides of the hall that can be opened or closed to change the power of the sound and reverberatio

Large canopy above the stage with sound-reflecting panels that could be raised and lowered - ensemble.

(Capacity – 2500)

Walt Disney Auditorium

Capacity – 2265
RT – 2.2 sec
Year: 2003

Convex walls and ceiling of the hall are finished with reflecting Douglas-fir wood while the floor is finished with oak.

Row upon row of concave curves

All surfaces reflected sound forming a transparent mesh

Illusive

500 doors of which 200 are acoustical doors

https://commons.wikimedia.org/w/index.php?curid=61997445

Bing Concert Hall (2013)

Capacity - 842 seats

Bing Concert Hall, Stanford University, Convex walls for uniform spreading of sound

Source: flickr.com

Acoustical requirements

Adequate loudness – reaching remote seats

Diffused sound level - Uniformly distributed energy

Optimum reverberation - liveliness

Free from defects – shape size and form

Isolation from noise and vibration – outside and inside

Conclusion

Loudness – Strength Factor G $_{Mid}$

Spatial impression – Lateral reflection and envelopment

Intimacy - Initial Time Delay Gap (12 – 25 msec)

Early Decay Time (Reverberation time)

Clarity Index or C_{80}

Warmth and Brilliance – Bass ratio and treble ratio

Background noise - NC Curve 25

Volume, sight line, view, seating plan

References:

Concepts in Architectural Acoustics, M. David Egan

Architectural Acoustics by M. Long

Acoustics of the Sydney opera house concert hall Part One: The Client's Perspective
Lisa Taylor and David Claringbold , Proceedings of 20th International Congress on Acoustics, ICA 2010 23-27 August 2010, Sydney, Australia

Wikipedia