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NPTEL ONLINE CERTIFICATION COURSES

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Architectural Acoustics

Lecture 6: Room Acoustics I

Dr. Sumana Gupta

Department of Architecture & Regional Planning

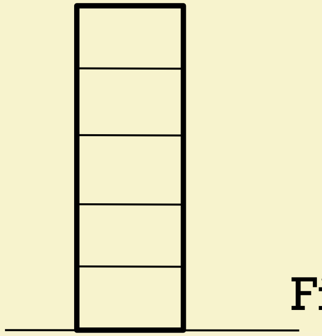
Learning Objective

- Room acoustics
- Phenomena of reflection
- Echo, flutter echo
- Creep of sound

- Diffusion and Diffraction
- Standing wave

Frequency of Audible sound and its wavelength in Air

20 Hz	63 Hz	125 Hz	250 Hz	500Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	160000 Hz	20000 Hz
17m 51ft	5.32m 16ft	2.66m 8ft	1.33m 4ft	0.662m 2ft	330mm 1ft	160mm 6inches	80mm 3inches	40mm 1.5inches	20mm 0.75inch	17mm $11/16^{th}$ inch



Five storey structure

Challenge : Dealing with sound within closed spaces

- Small rooms
- Large spaces

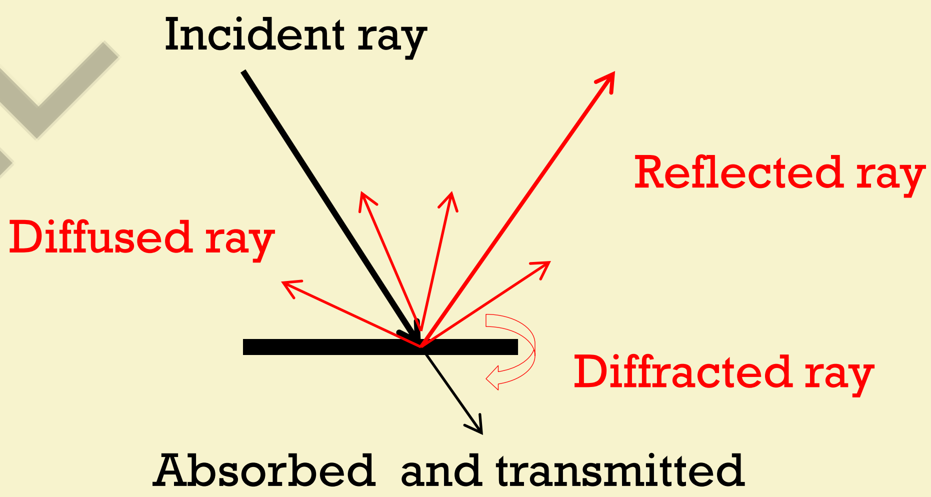
A small leaf

The interaction of sound with solid surfaces could well be taken as the beginning of room acoustics.

Definition

Sound wave upon encountering an object:

- Reflection, diffusion, diffraction
- Absorption
- Transmission



Each of these occurs to some degree when an impact takes place.

We are concerned with only one phenomena at a time

Importance of these phenomena

Unamplified speech can be augmented by physically placing hard surfaces in positions where they can distribute sound to the audience.

Walls and ceilings are our places of interest.

The purpose of the space has to be known i.e. the frequencies of interest has to be known.

Ray diagram or Geometrical acoustics

Limitations:

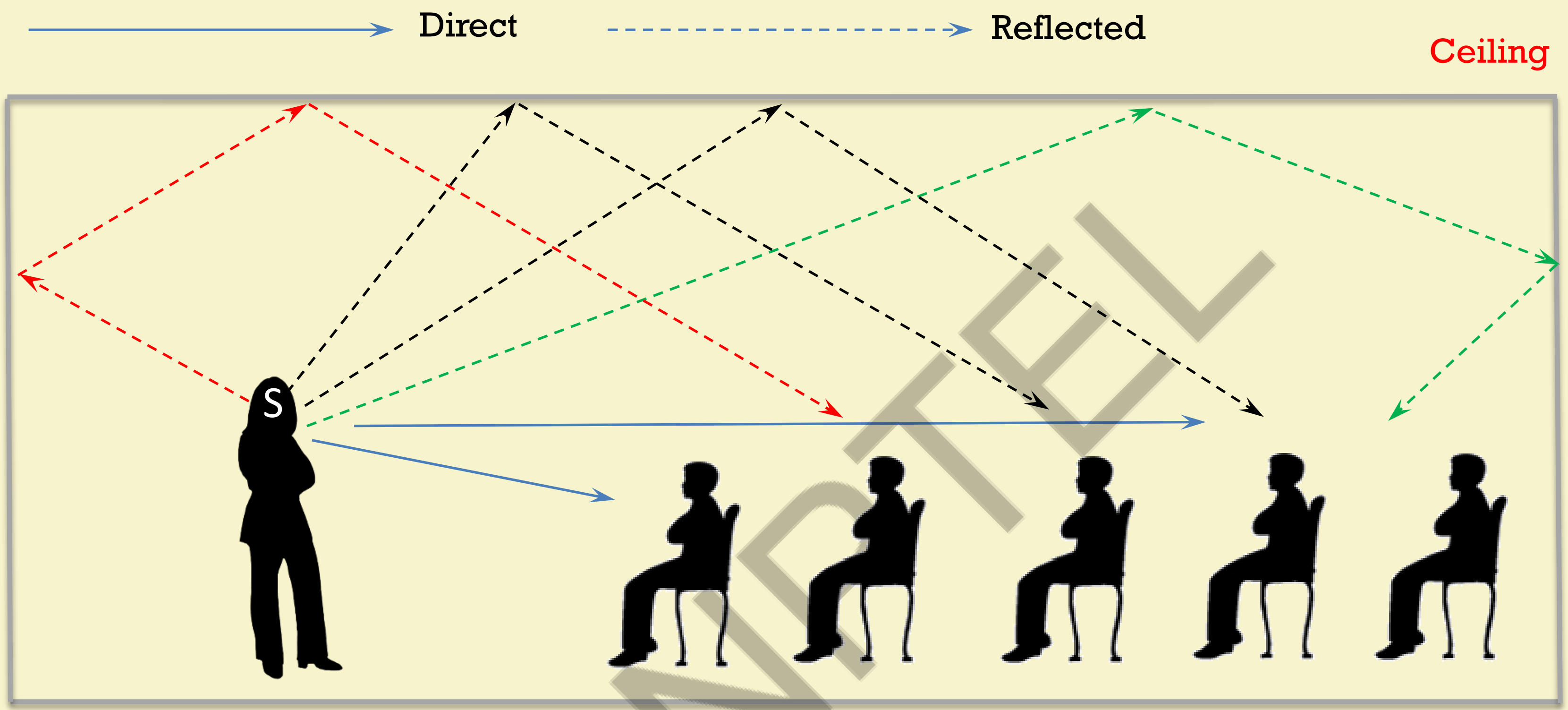
Sound reflects as represented by ray diagram only when the surfaces which it hits is very large compared to the wavelength.

Source is considered as static which may not be actually true.

Detailed study may not be possible with respect to diffusion or scattering of sound

Phenomena of Reflection

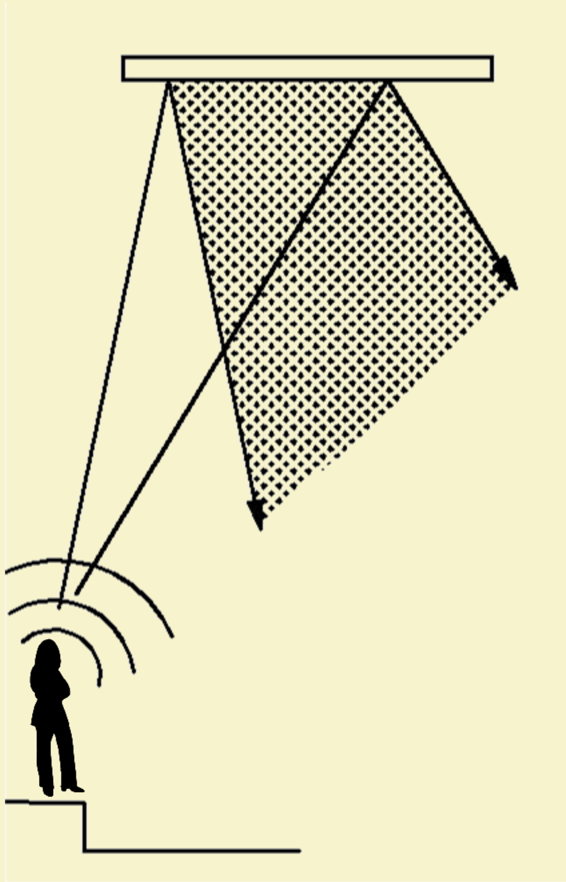
Ray diagram from Source to Receivers



Section of a room

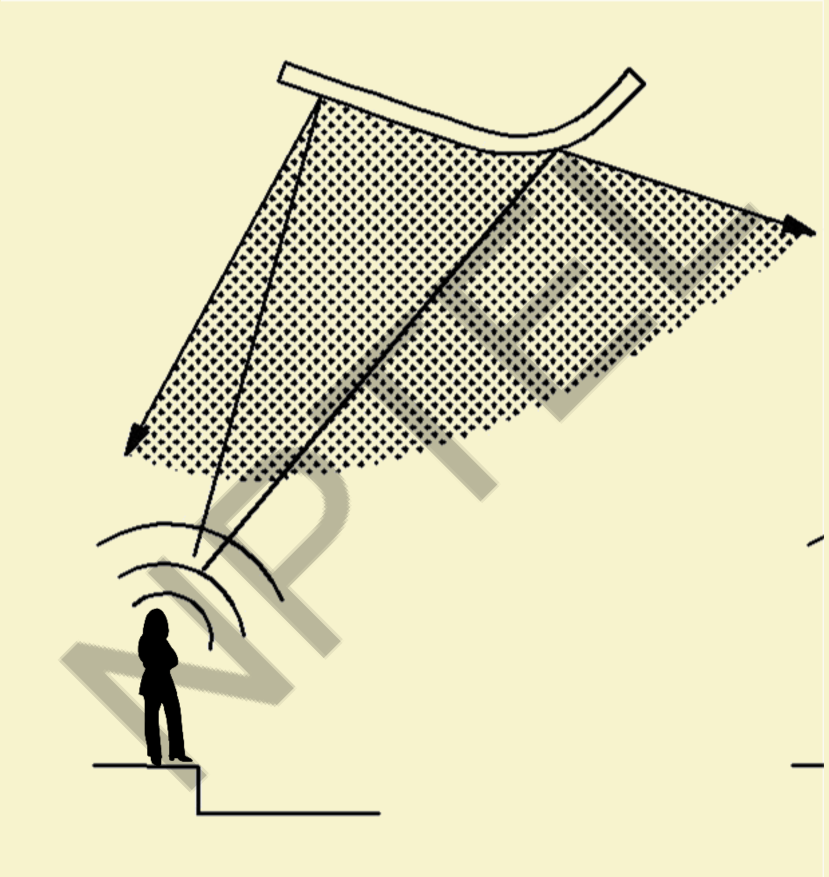
Shape of reflector determines the sound path

On a flat surface



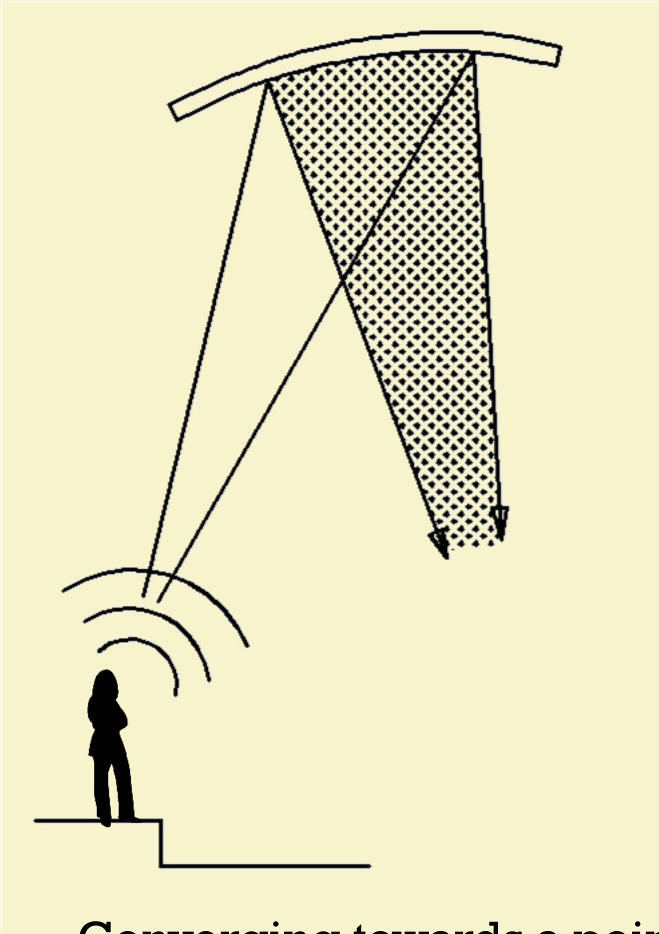
Uniform over a space

On a convex surface



Scattered - covering a larger space

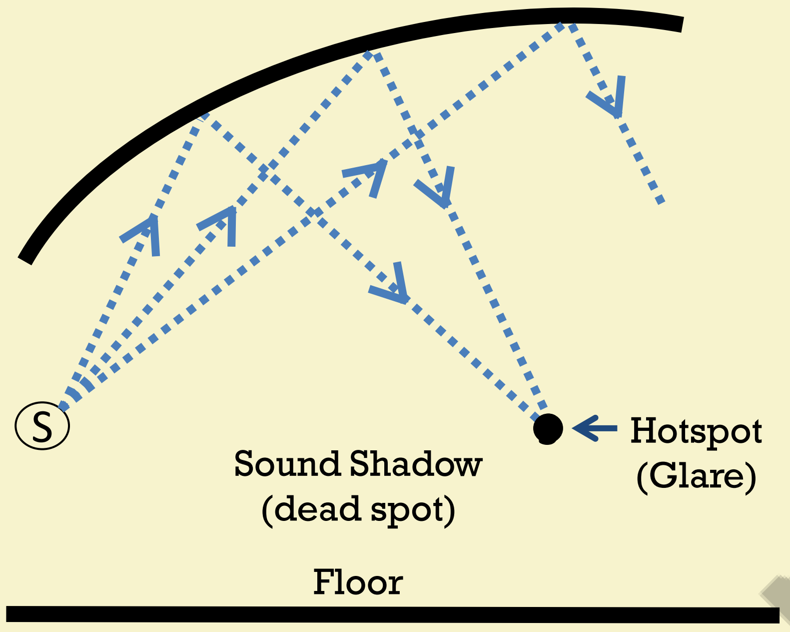
On a concave surface



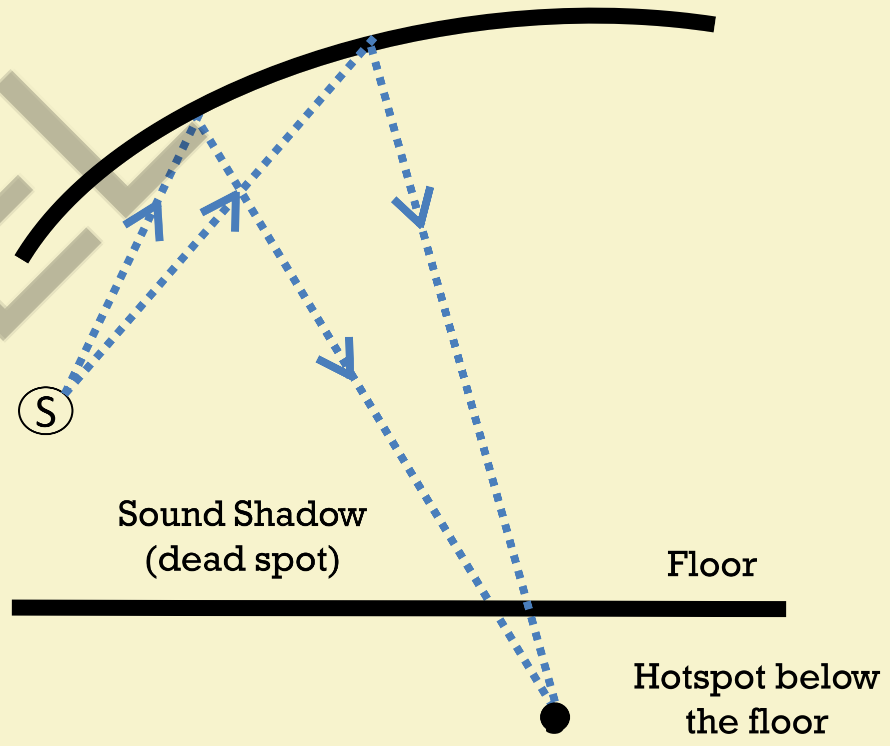
Converging towards a point

Sound concentration – hot spot and dead spot

Non uniform distribution of sound



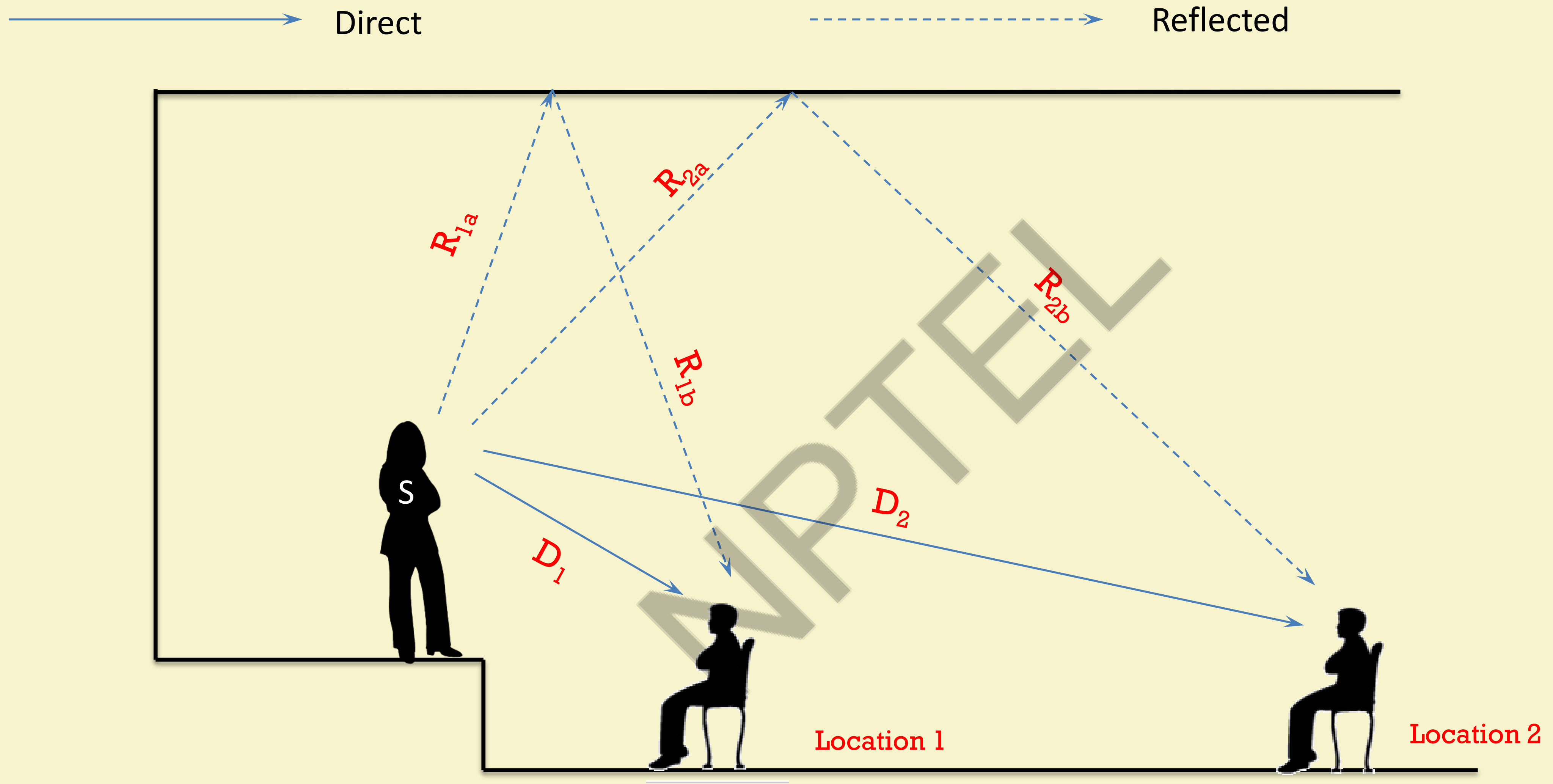
Sound focused on a hotspot



Sound rays concentrating further below

Direct

Reflected



Path difference = Reflected path – direct path

Echo

Normal speech - Around ten syllables/second (average = 1/10 seconds / syllable)

The human ear also cannot distinguish reflected sound from direct sound if delay is less than 1/10 of a second.

With speed of sound 340m/sec distance covered in 1/10 sec = 34m

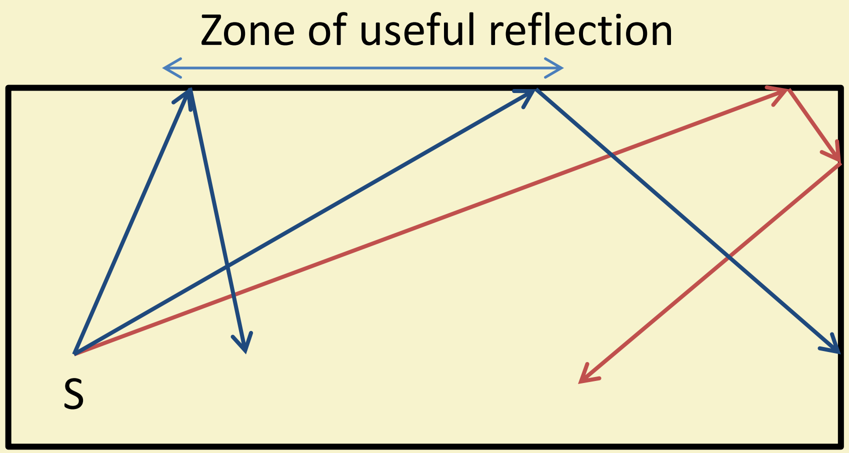
Sound energy reaching ones ear within that time does not overlap with sound of the next syllable expected after 1/10 seconds

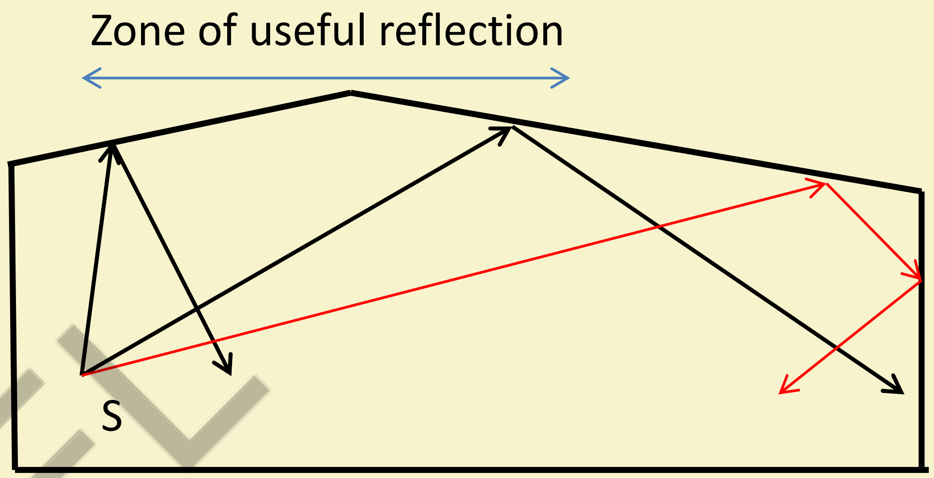
So after reception of direct sound by a receiver if reflected sound of the same syllable reaches receiver beyond 0.1 seconds with enough energy echoes will happen.

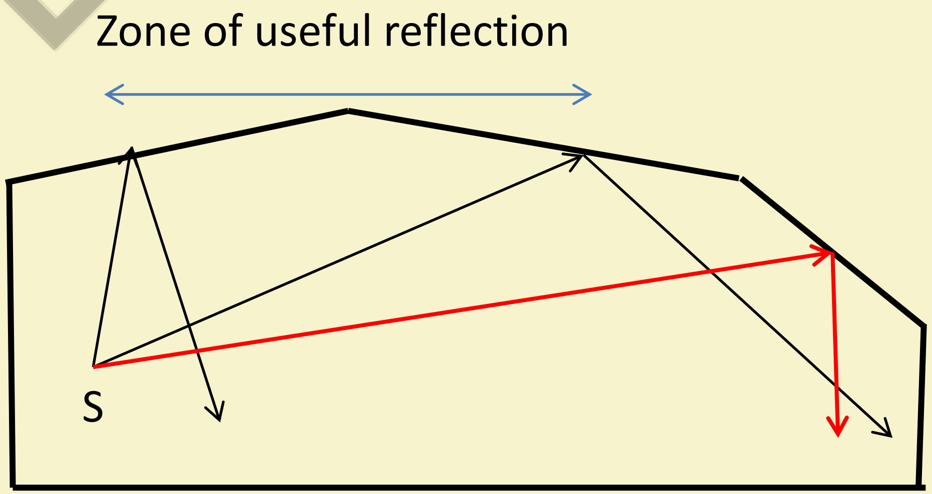
Path difference: Determines the condition of echo

Path difference up to 13m is good for speech and music

Flat Ceiling at different angles







Splayed surfaces direct sound downwards

Can reduce the delays

Flutter echo: Buzzing sound

Inter-reflective surfaces causing multiple reflection

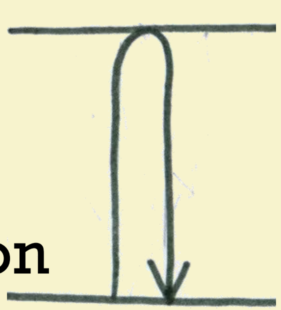
Different geometric combinations

Sufficient sound energy leads to flutters

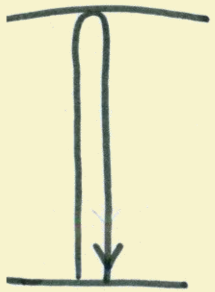
Example: Short burst of sound like clapping

Splaying of walls (1:10) can control flutter.

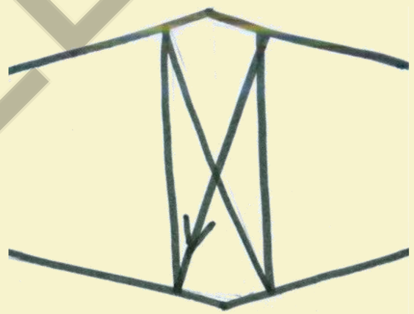
Axial modes actually keep on rebounding



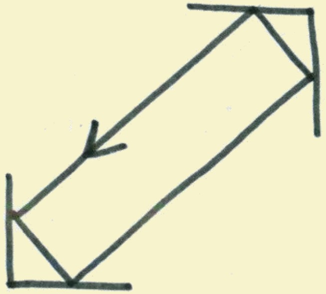
Parallel surfaces



Convex and flat surface



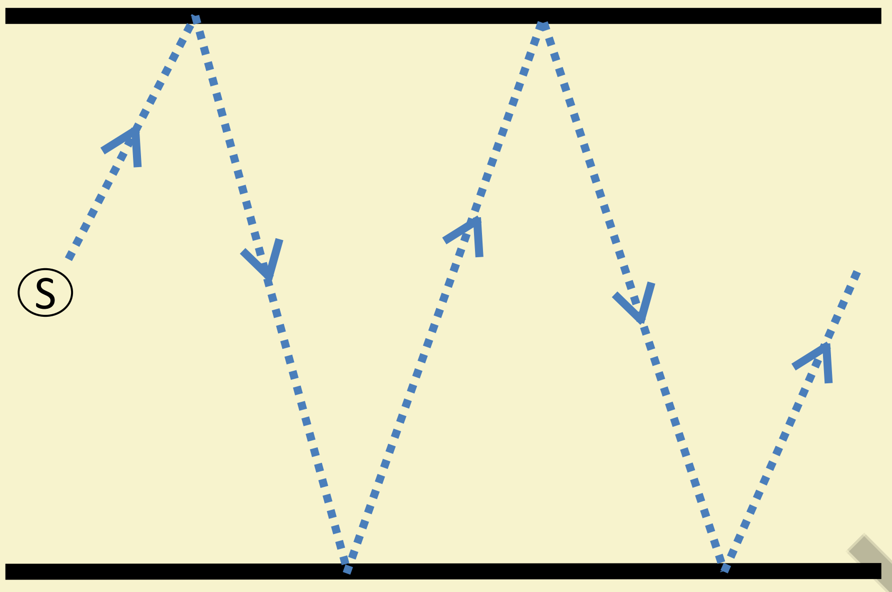
Double angled surfaces



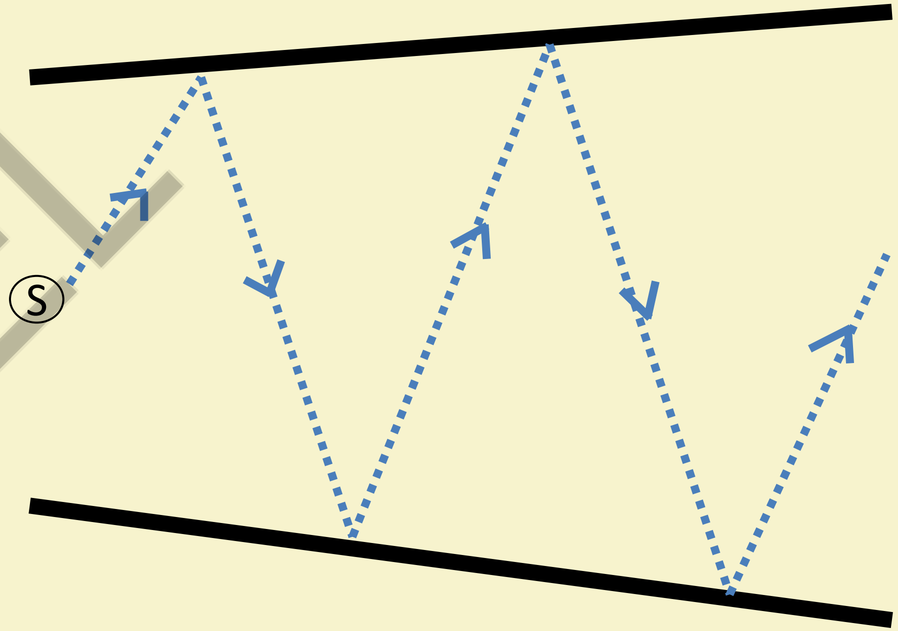
Opposing surfaces

Nested circles

Control of flutter echo

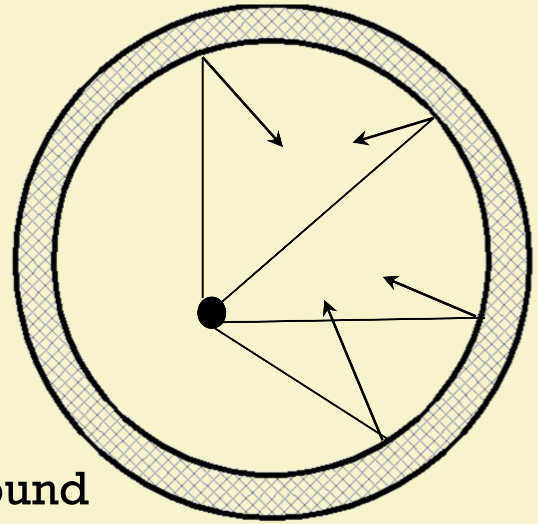


Sound reflection in a parallel surface

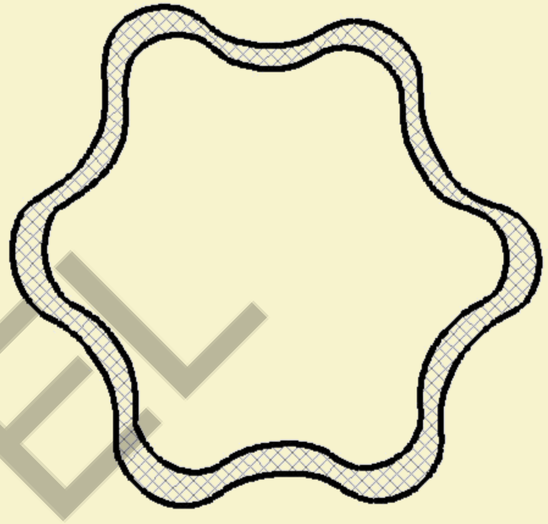


Sound reflection in a splayed surface

Position of source and variation in sound reflection

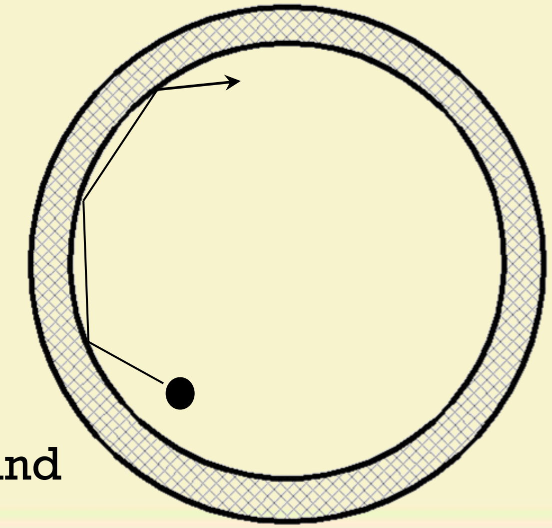


Focusing of Sound



A. Surface Undulations

Large scale, random sized surface undulations provide diffusion to minimize the focusing of reflected sound

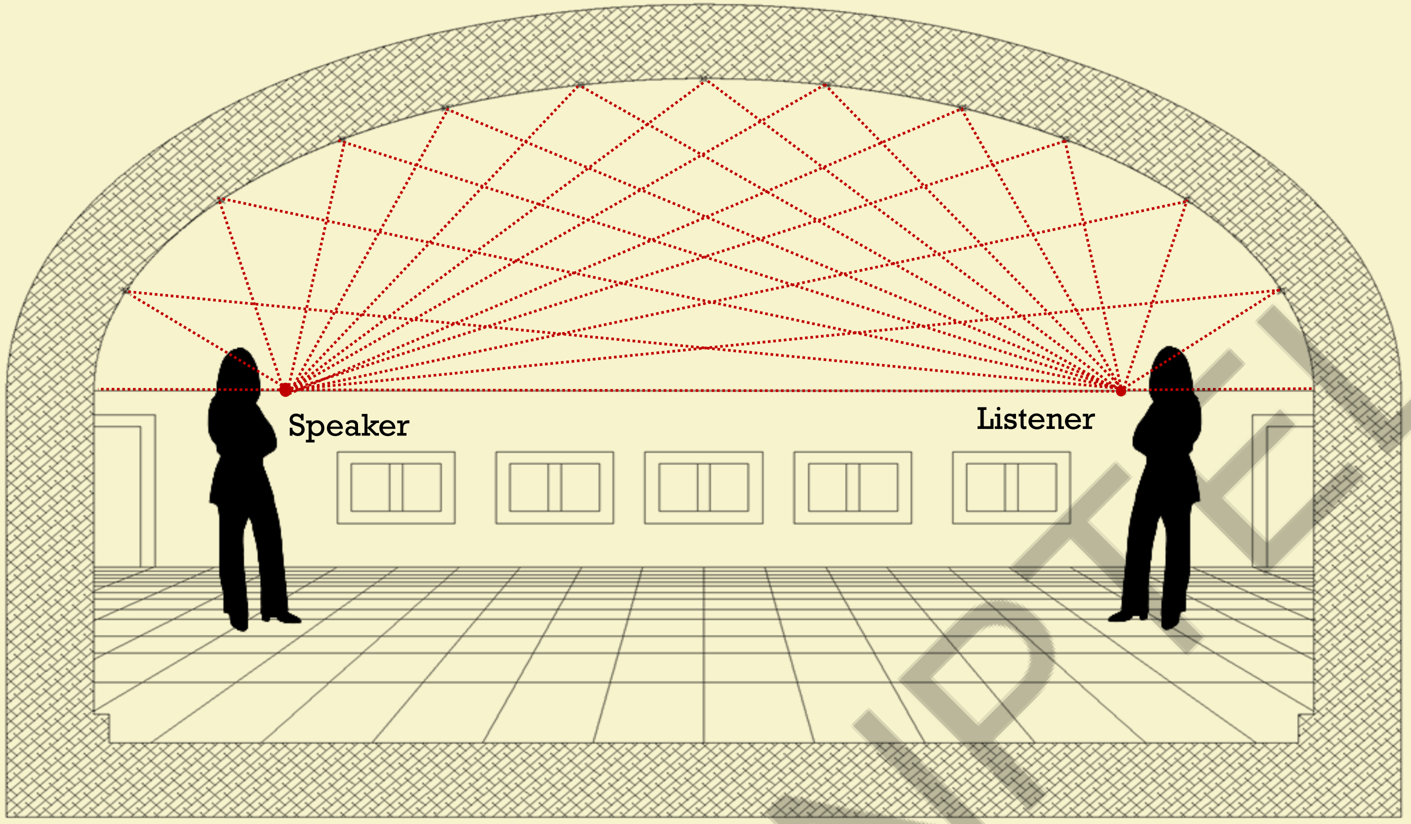


Creep of sound

Some of the sound rays strike the surface at a shallow angle and are reflected again and again, and so propagate within a narrow band completely around the room.

Faint sound may be heard round its entire circumference.

Whispering effect



Examples of whispering galleries:

Gol gumbaz, Bijapur

Victoria Memorial Hall, Kolkata

St. Pauls Cathedral, London

Source: Wikimedia Commons

What did we learn today?

Dimensional connect between room dimensions and wavelength of sound

Direct sound and Reflected sound in rooms and the relationship with distance and time

Different problems that may be encountered within room due to sound reflection

Tasks

1. You may try out ray diagrams in different sized rooms and find the path difference as an exercise.

2. You may look for appropriate radius of curvatures for different room heights to avoid sound concentration in the room.

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Architectural Acoustics

Lecture 7: Room Acoustics II

Dr. Sumana Gupta

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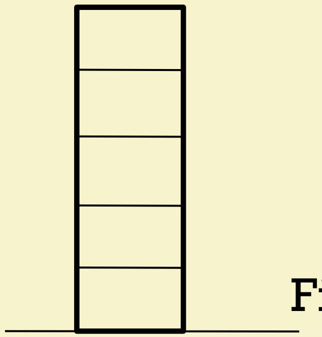
Learning objective

Room acoustics 2

- Diffusion
- Diffraction
- Standing wave
- Room modes and Colouration

Frequency of Audible sound and its wavelength in Air

20 Hz	63 Hz	125 Hz	250 Hz	500Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	160000 Hz	20000 Hz
17m 51ft	5.62m 17ft	2.66m 8ft	1.33m 4ft	0.662m 2ft	330mm 1ft	160mm 6inches	80mm 3inches	40mm 1.5inches	20mm 0.75inch	17mm 11/16th inch



Five storey structure

Challenge : Dealing with sound within closed spaces

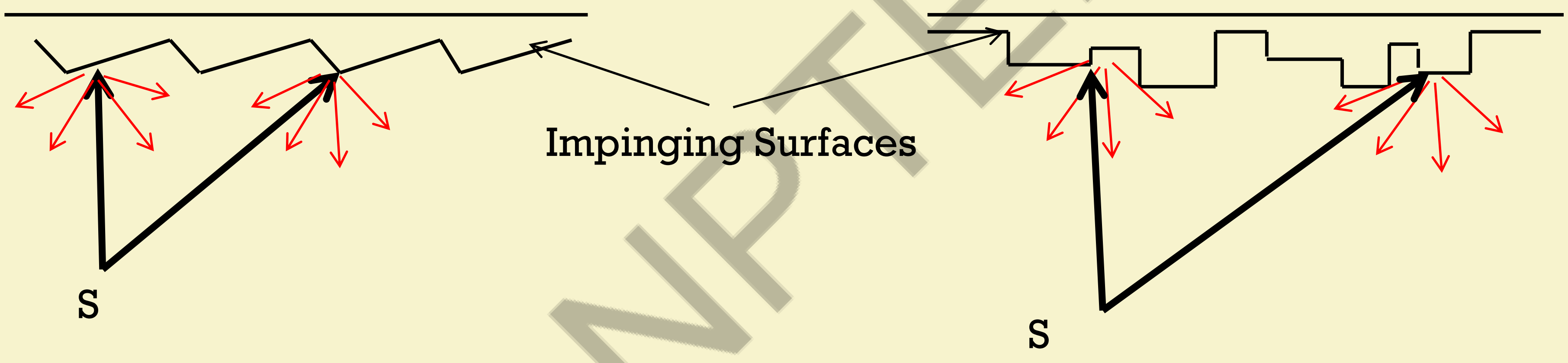
- Small rooms
- Large spaces

A small leaf

Diffusion of sound

It implies scattering or random distribution or spreading of sound from a surface on which it falls.

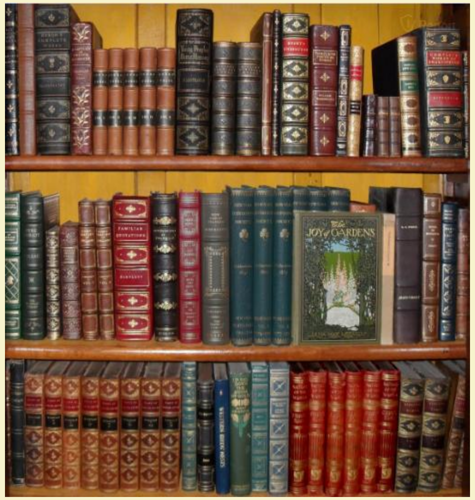
Surface irregularities, breaks, projections, wedges, instead of continuous reflective surfaces cause diffusion.



Size of undulation must follow wavelength

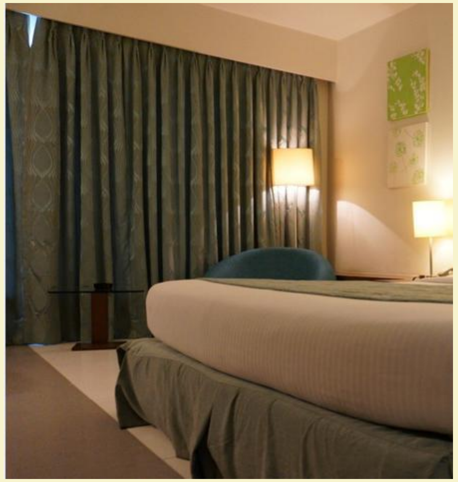
Diffusion is omnidirectional unlike reflection which is specular.

Practical Examples



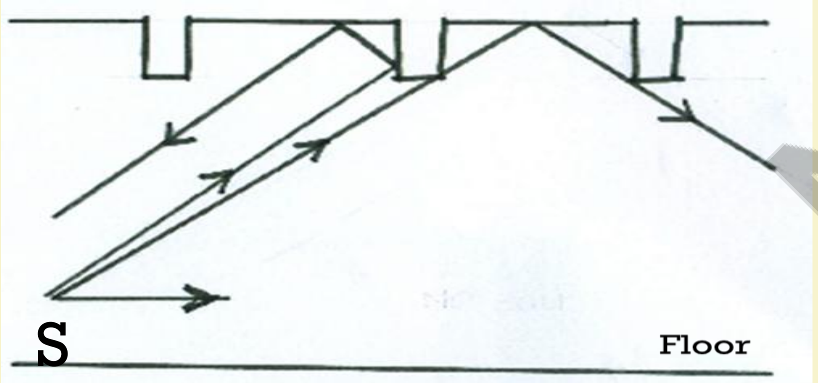
Stack of books
source: pixabay.com

Wedged surface
source: freefoodphotos.com

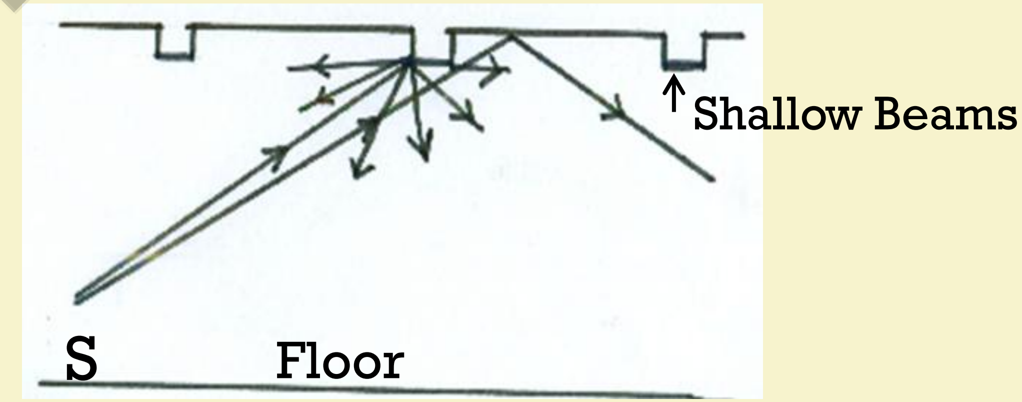


Folds of curtain
source: pixabay.com

Deep Beams



Deep beams may reflect back sound



Shallow beams may diffuse sound

Need for Diffusion

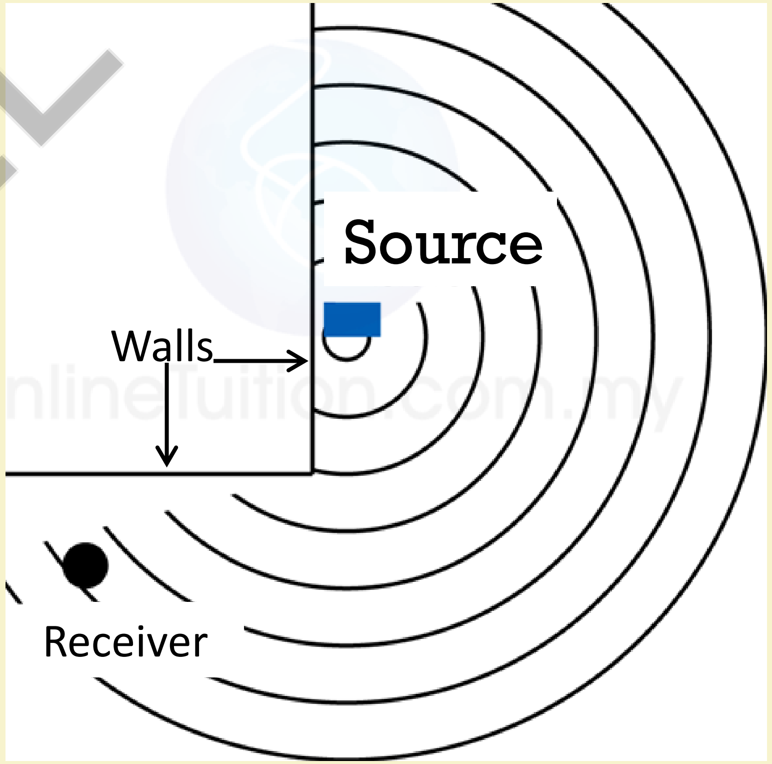
Diffusing surfaces help in uniform distribution of sound in the space
It also implies uniform decay of sound in the room.

Adequate diffusion is critical for obtaining an even distribution of reverberant sound in a listening space.

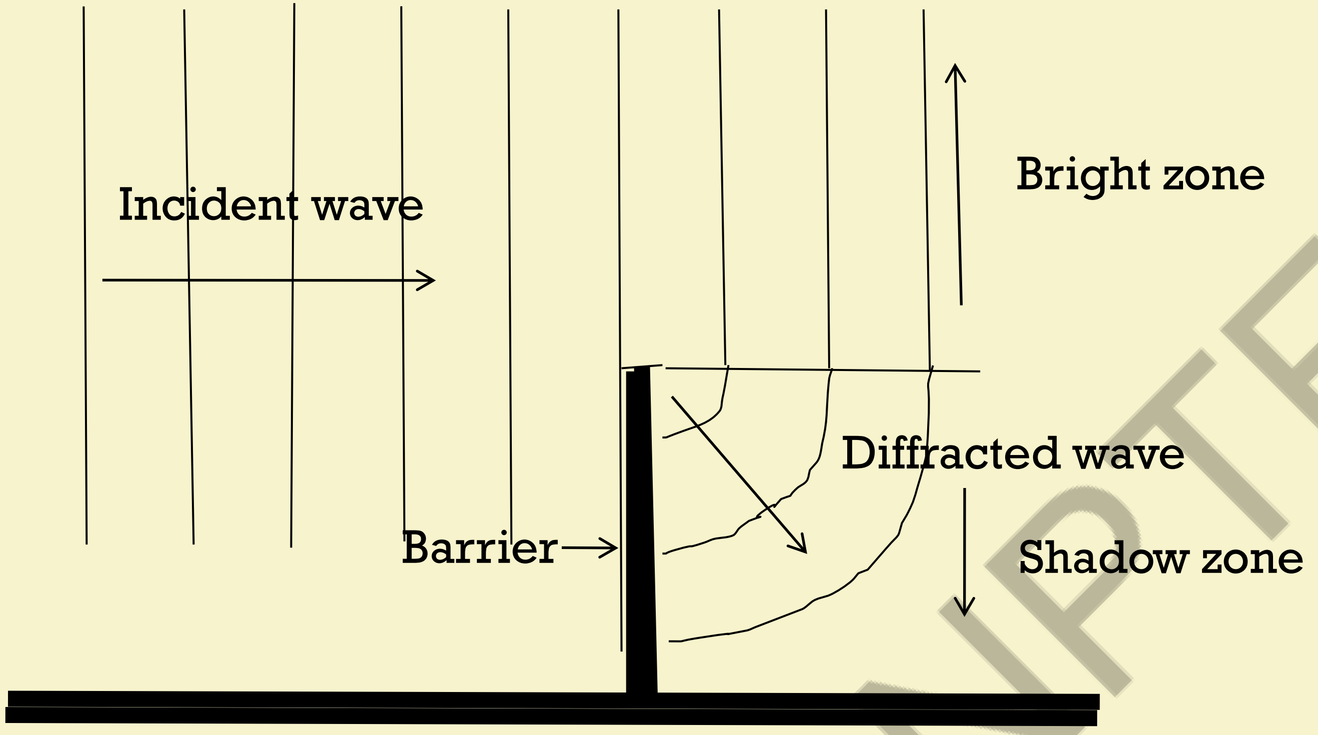
Sound reflection from flat surface causes glare while diffused surface helps avoid direct sound to receiver.

Why can we hear sound even behind a wall?

Bending of sound



Diffraction



Diffraction with a simple barrier

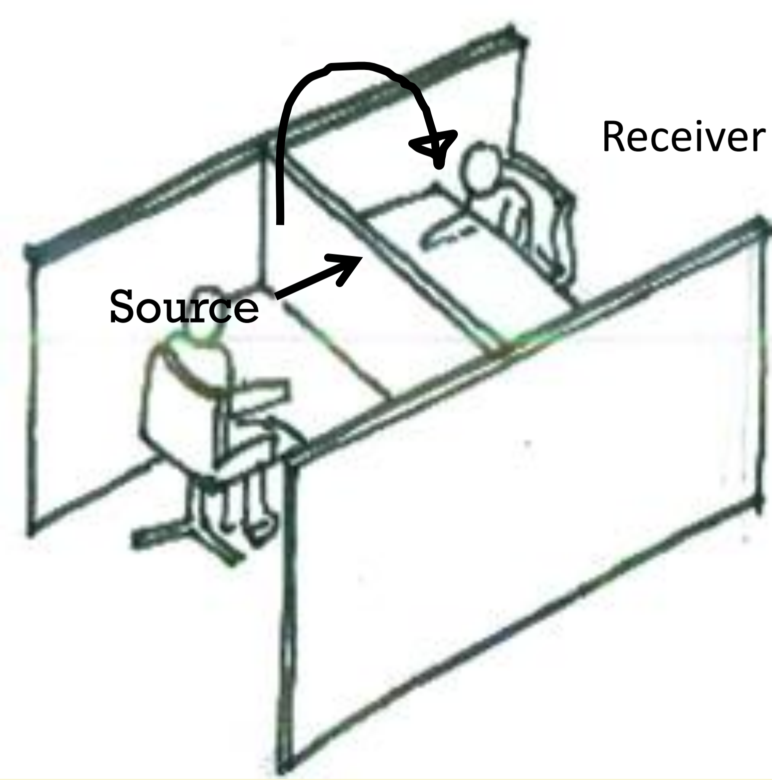
Diffraction

•When a plane wave encounters a barrier, the lower portion of it is cut off leaving the rest to propagate over it.

•The high and low-pressure regions of the wave impinge on the inactive air in the shadow zone and propagate into it.

•This way the wave diffracts or is bent into the space behind the barrier. The greater the diffraction angle the greater the reduction or attenuation.

•Further is the receiver in diffracted region from the source higher is the reduction of sound.



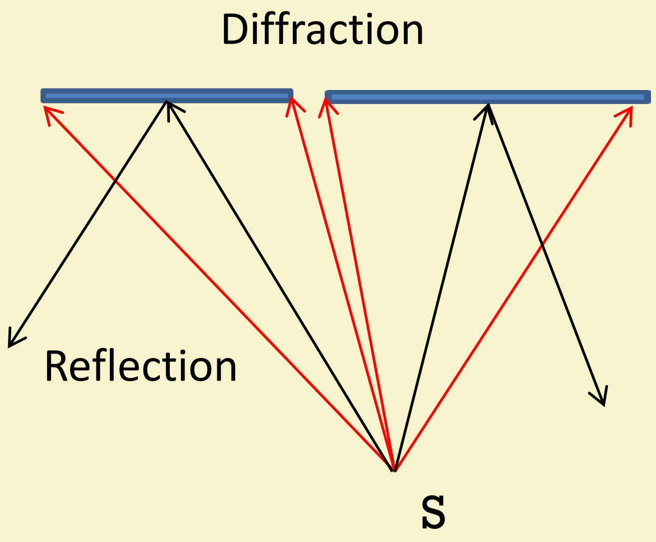
Partition in an office

Areas of diffraction in rooms

Near ends of reflective panels in acoustically treated room

particularly for low frequencies – large wavelengths

A loss in reflected energy of those particular frequencies happen



To take care of the combined effects

- distance from source
- size of surface
- nature of surface
- curvature of surface

Points to note

The purpose of the room and the range of frequency expected to be produced by source and undergoing these phenomena has to be known.

This decides the dimension of the reflecting surface, diffusing surface or diffracting surface

Longer wavelength than desired gets diffracted at the corner and lost instead of getting reflected

Shorter wavelengths than desired will get reflected instead of diffused from diffusing surface

Suggested sizes:

Reflectors > 4λ **Diffusers = λ** **Diffractors < λ**

The sound pressure level is the most commonly used indicator of the acoustic wave strength.

It correlates well with human perception of loudness.

When a sound is generated within a solid enclosure such as a pipe, tube, or room, it expands naturally to fill the space.

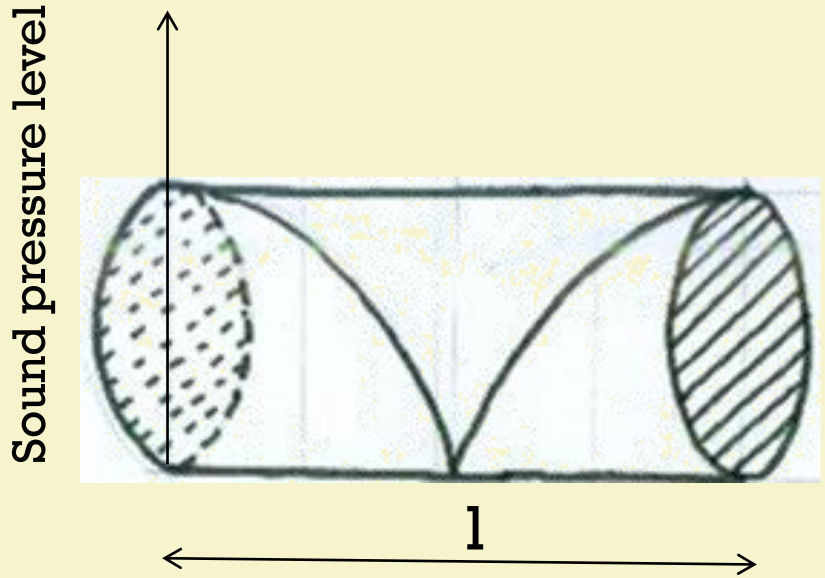
If the lateral dimensions of the space are small compared with a wavelength then the sound propagates along the space as a plane wave until it encounters an impedance boundary.

In closed tube the impedance at the end is very high at the boundary.

It doubles like a sea wave hitting the sea wall.

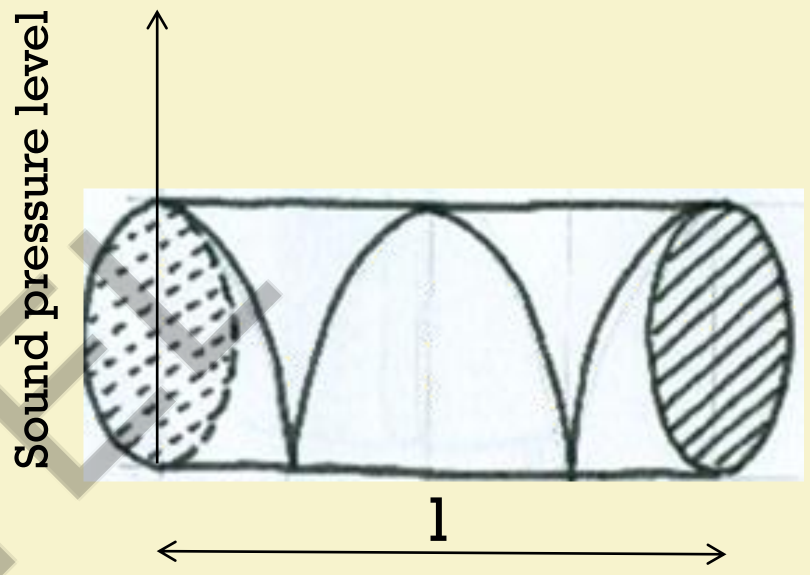
When the room dimension is equal to wavelength then room modes are formed.

Standing wave in closed tube



Relative pressure diagram in closed tube (first mode)

$$f_1 = C/2l$$



Relative pressure diagram in closed tube (second mode)

$$f_2 = C/l$$

Room modes and standing waves

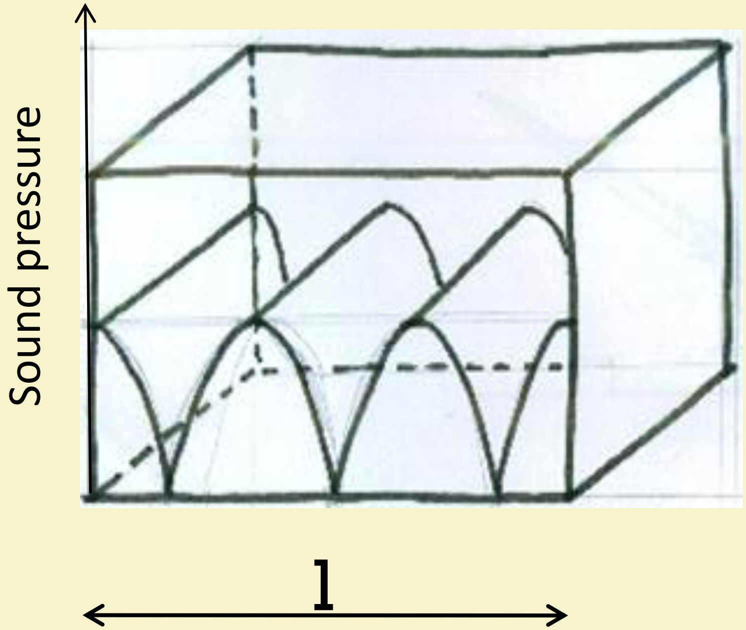
Low frequency means large wavelength

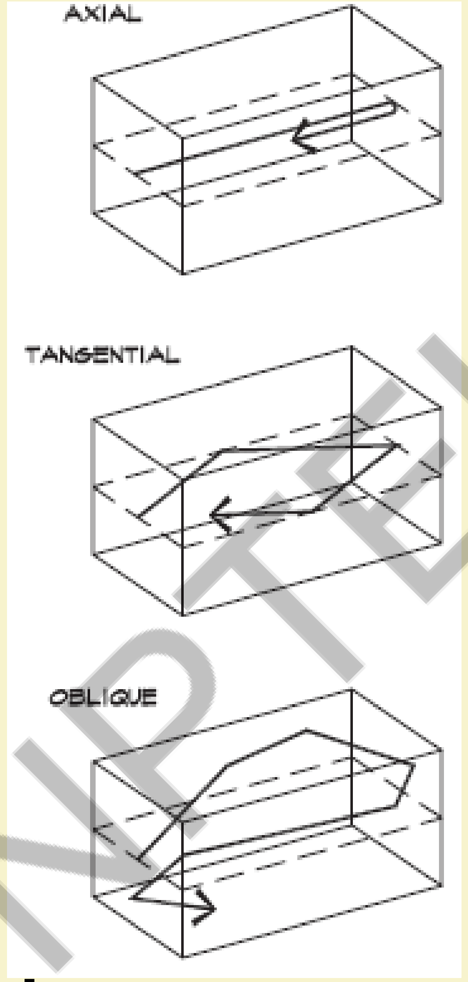
Smaller the room more importance is of standing waves.

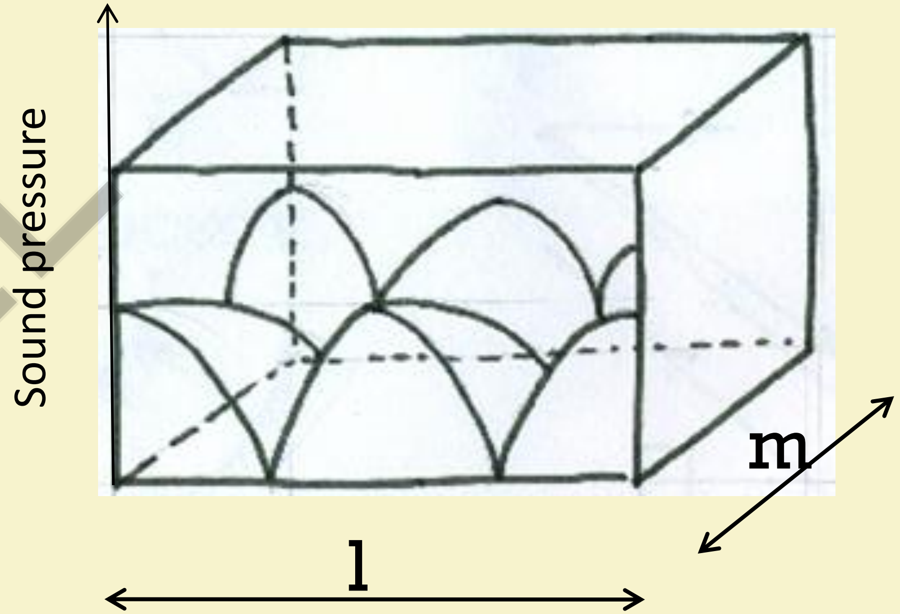
Small rooms behave as a closed tube. Certain frequencies persist, much like those in the case of a closed tube.

If both ends are closed, the wave can reflect back and forth many times with little attenuation.

Sound pressure is forced to a maximum at the ends, resulting in a pressure minimum in the center







Sound intensity pattern for an axial mode

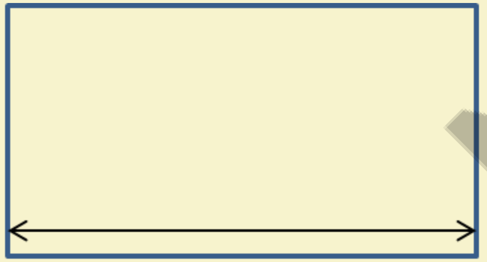
Sound intensity pattern for a tangential mode

If the room dimensions are a low integer multiple of one another, then modal frequencies will coincide.

Under these conditions the energy in the room will tend to combine into a few modes, which will strongly disturb the sound quality.

This phenomena is called colouration

Room dimensions which are multiple of each other is thus not recommended



l

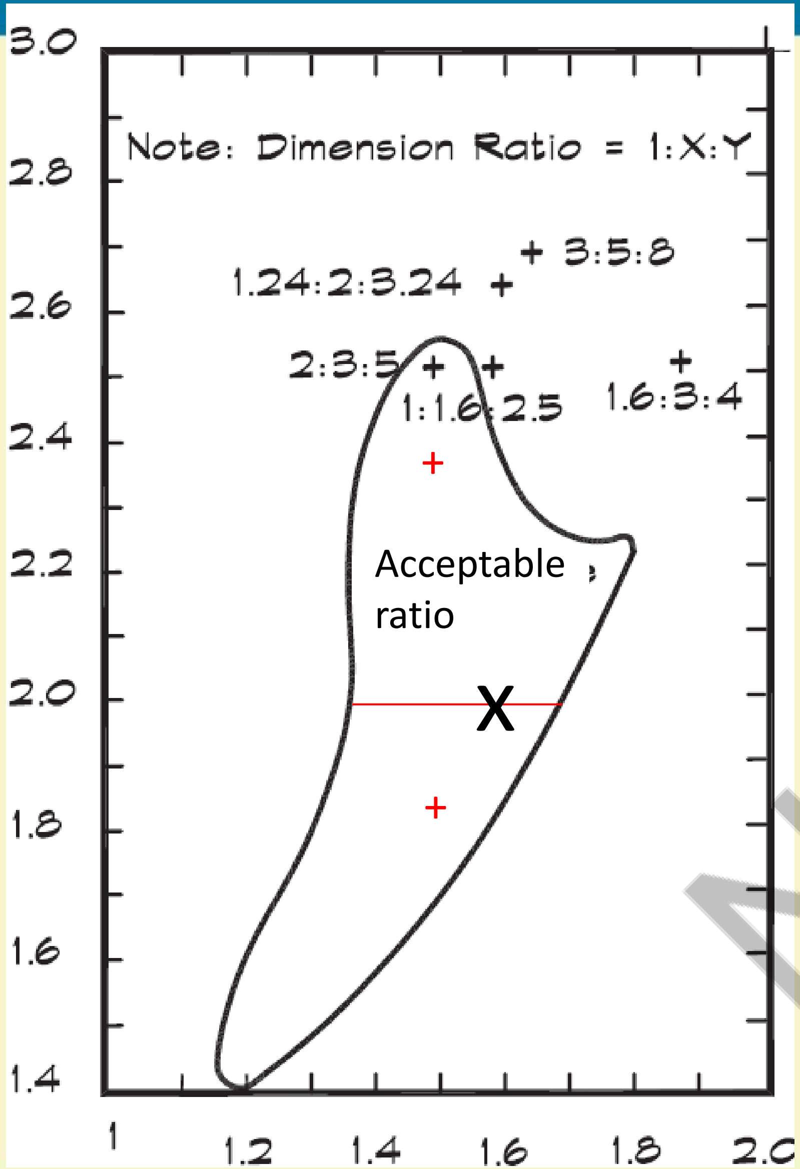
$$f_n = \frac{nC}{2l}$$

n = 1, 2, 3,….
f = frequency
C = velocity of sound
l = length of room

Say length = 17ft

First room mode frequency = 33 Hz
Second room mode will be = 66 Hz

Y/Z



X/Z

Z:X:Y = 1:2:3

The curve encloses dimension ratio of width to length of a rectangular room having height as one unit.

Derived by Scientist Bolt in 1946

Y= length
X= width
Z= height

Graph is helpful for smooth response at low frequency

What did we learn?

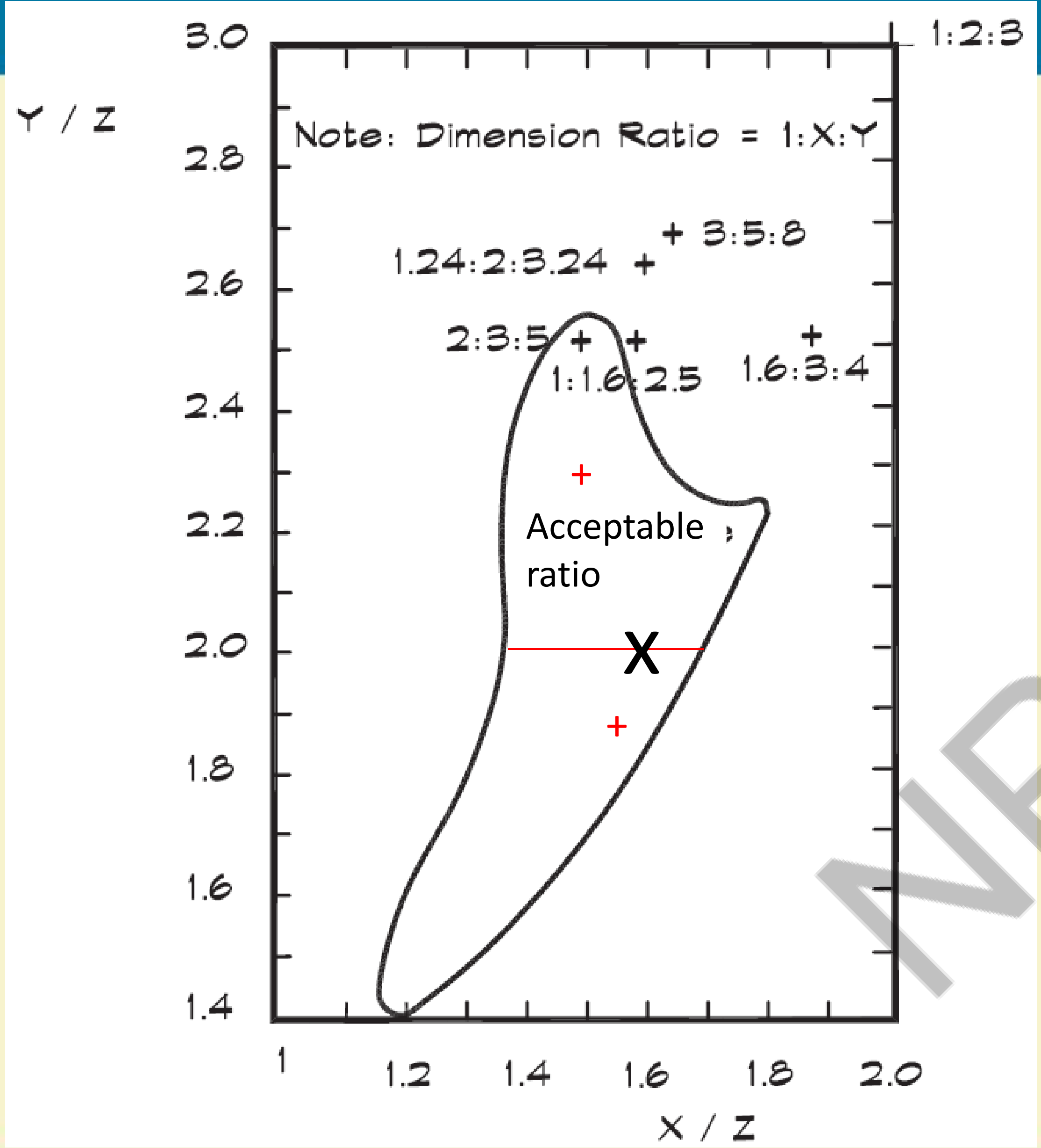
Phenomena of diffusion and diffraction with reference to our domain area
Some applications in practical

Role of wavelength , formation of standing wave, room modes

Length breadth and Height should not be numerical multiple of each other

Tasks

Try some dimensions which will allow diffusion for specific wavelength range
Try a list of dimensions appropriate to avoid room modes but architectural space generated is utilizable. example - classroom



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Diffusion of sound

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Diffusing surfaces help in uniform distribution of sound in the space

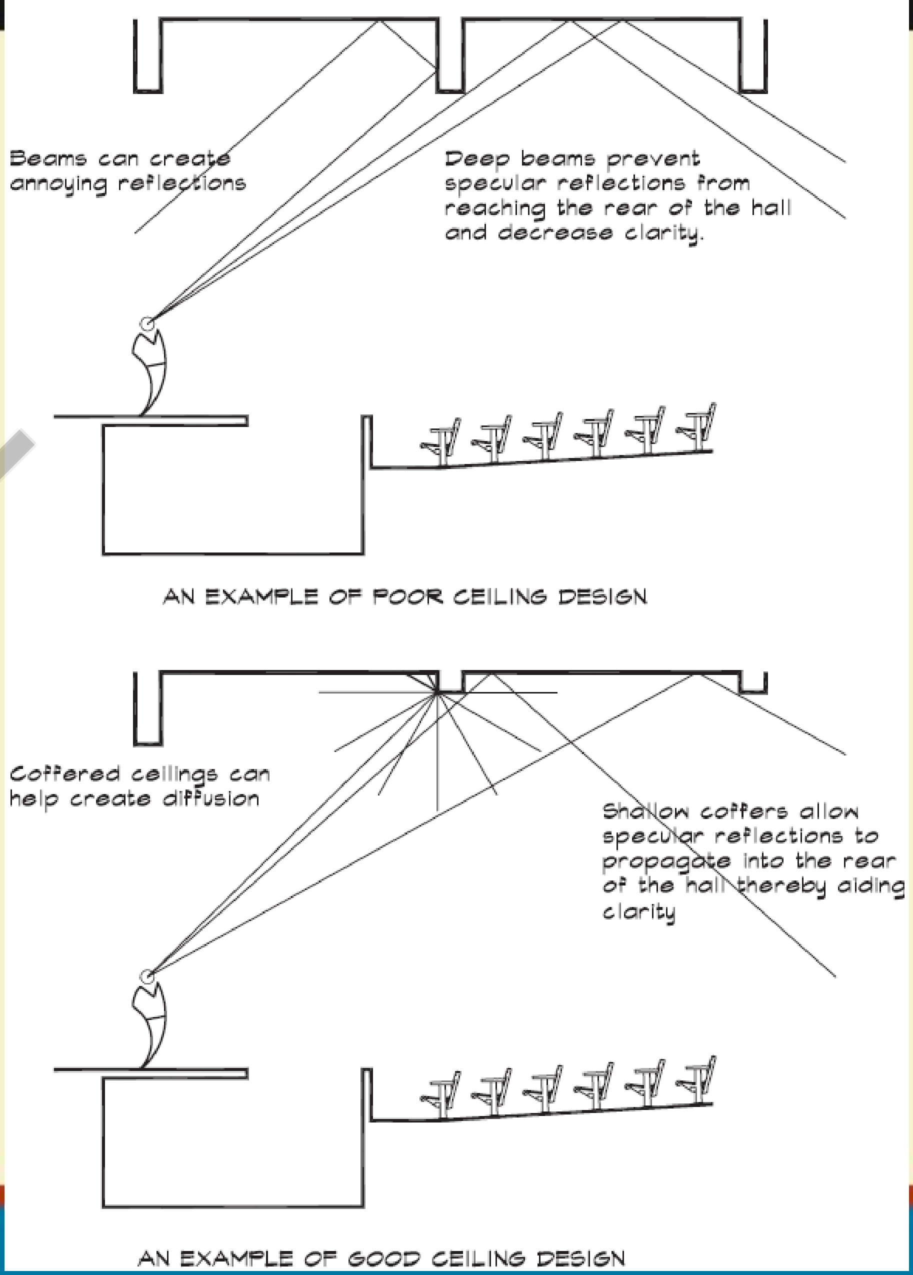
It also implies uniform decay of sound in the room

Adequate diffusion is critical for obtaining an even distribution of reverberant sound in a listening space.

Sound reflection from flat surface causes glare while from diffused surface direct sound to receiver can be avoided

Surface irregularities, breaks, projections, wedges, instead of continuous reflective surfaces cause diffusion

.17 Design of Coffered Ceilings



Ray diagram

Some sketches, books in book shelve beams and columns in a room, cu

Excessive diffusion reduces clarity

Diffraction of sound

Points to note:

The purpose of the room and the range of frequency expected to be produced by source and undergoing these phenomena is to be known

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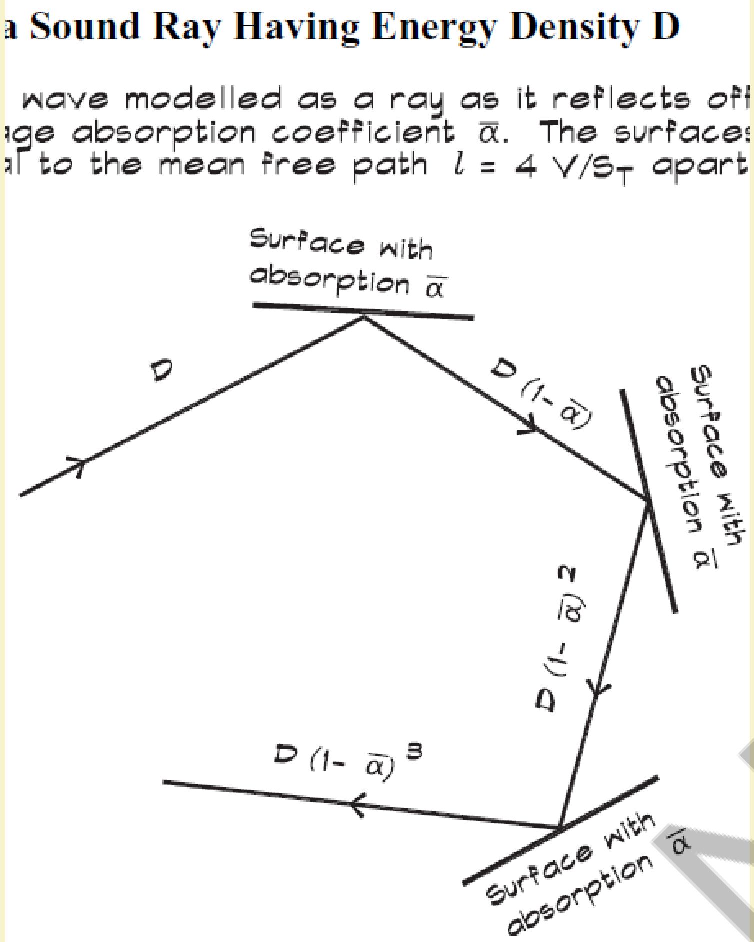
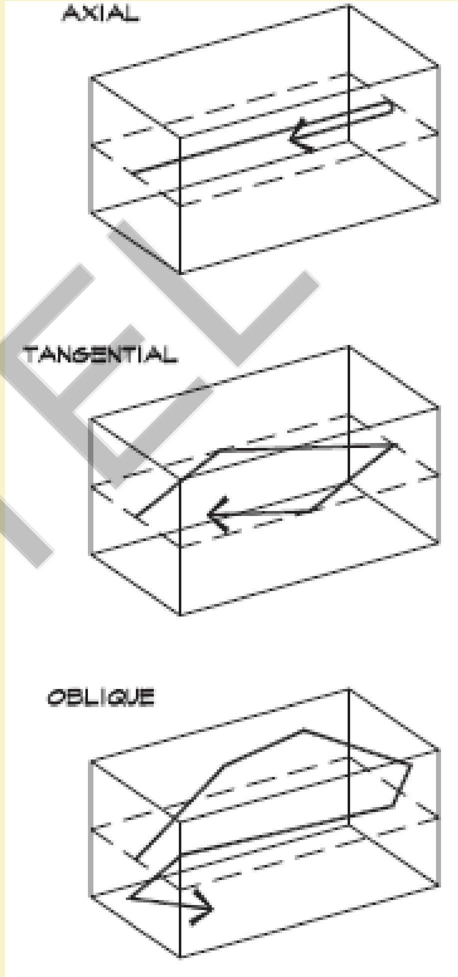
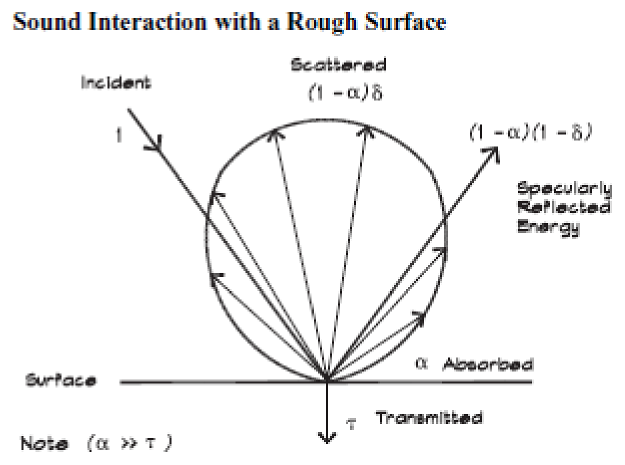

a Sound Ray Having Energy Density D
wave modelled as a ray as it reflects off
ge absorption coefficient $\bar{\alpha}$. The surfaces
al to the mean free path $l = 4\ V/S_T$ apart
Surface with absorption $\bar{\alpha}$
D
D (1- $\bar{\alpha}$)
Surface with absorption $\bar{\alpha}$
D (1- $\bar{\alpha}$) 2
D (1- $\bar{\alpha}$) 3
Surface with absorption $\bar{\alpha}$


AXIAL
TANGENTIAL
OBLIQUE


Sound Interaction with a Rough Surface
Incident
1
Scattered
$(1-\alpha)\delta$
$(1-\alpha)(1-\delta)$
Specularly Reflected Energy
α Absorbed
Surface
τ Transmitted
Note $(\alpha \gg \tau)$

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Architectural Acoustics

Lecture 08: Indoor Acoustics, Reflection and Absorption

Dr. Shankha Pratim Bhattacharya

Department of Architecture & Regional Planning

Learning Objective

Classify and compare the behaviour of sound in enclosed space

Relate the reflection - absorption of sound

Derive the concept of Sound Absorption coefficient

General Behaviour of Sound in Indoor

Propagation of sound

Striking the Boundary Surface

REFLECTION

DIFFUSION

ABSORPTION

TRANSMISSION

Reflection

Most of the sound energy revert back to the space after striking the boundary surface

The sound energy revert back in a specific direction and follow a systematic rule

Almost no decay or loss of sound energy

Sound energy density in the room remains almost unchanged

Energy density may fluctuate over a wide range of maxima - minima

Most of the sound energy revert back to the space after striking the boundary surface

The sound energy revert back in a divergent paths in irregular manner

Sound energy density in the room remains almost unchanged

An uniform energy density will observed in the space: Smaller range of maxima – minima

Absorption

Most of the sound energy decay during striking the boundary surface

Very small amount of energy revert back to the space

Sound energy density in the room remains decreased rapidly

There are TWO types of Sound Transmission

Air-borne Sound Transmission

Sound energy penetrate the boundary element and reaches to the other part.

The propagation of sound encounter a loss of sound energy due to the resistivity of the boundary element

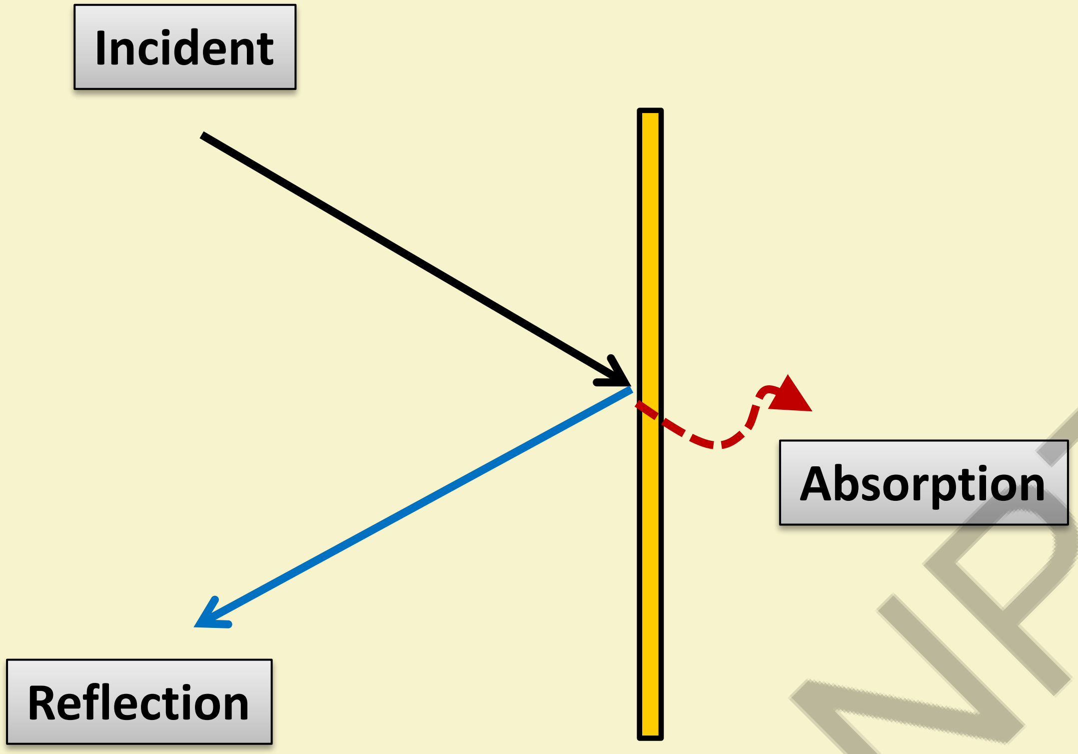
Sound energy density in the receiving end will decrease

Structure-borne Sound Transmission

Sound energy travel or conducted through the boundary element and reaches to the other part.

A gradual loss of sound energy will noticed due to the resistivity of the boundary element

Reflection - Absorption



Incident = Reflection + Absorption

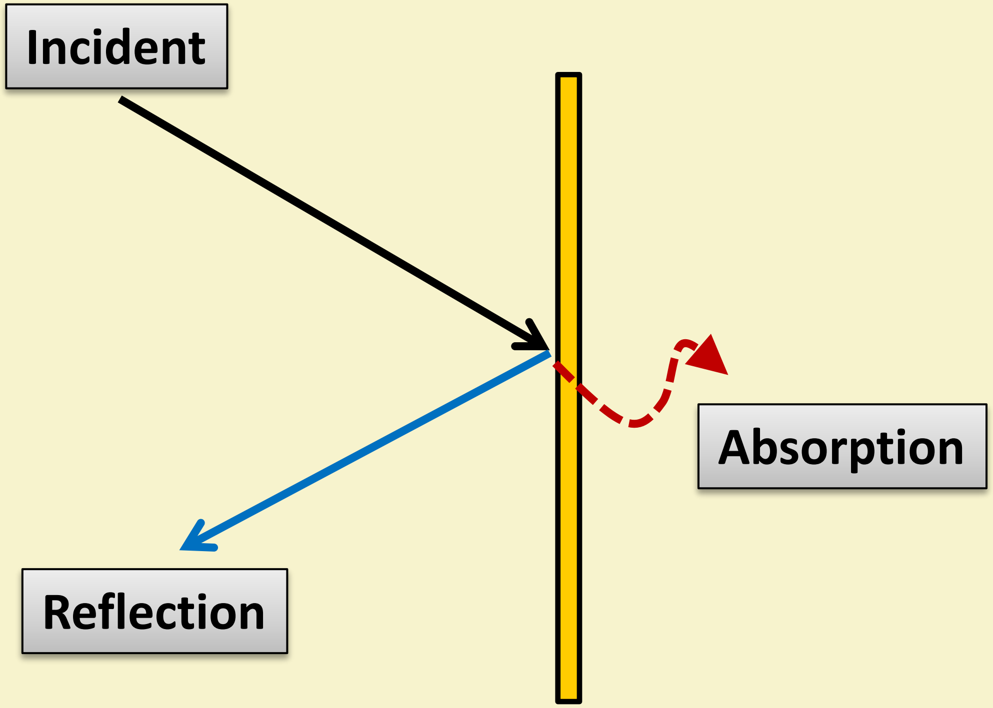
Reflection > Absorption

Reflective Surface / Reflective Material

Reflection < Absorption

Absorptive Surface / Absorptive Material

Reflection - Absorption



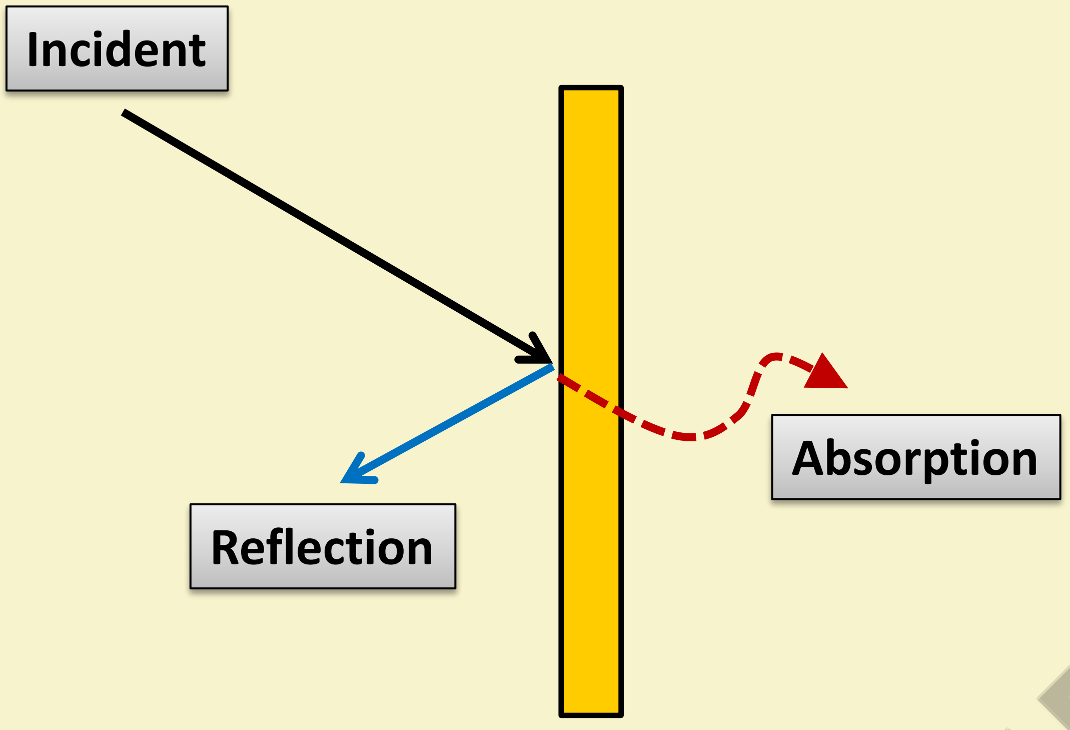
Incident = Reflection + Absorption

Reflection > Absorption

Reflective Surface / Reflective Material

Examples:

- **Hard Plastered Surface,**
- **Exposed Concrete,**
- **Surface with Metal or Stone cladding**



Reflection - Absorption

Incident = Reflection + Absorption

Reflection < Absorption

Absorptive Surface / Absorptive Material

Examples:

- Soft Fabric Surface,
- Soft Panels
- Surface with regular Recess

Reflection - Absorption

Incident Sound Energy

Absorptive Surface / Absorptive Material

Reflected Sound Energy

Sound Energy Absorbed

Mechanical or Heat Energy

- Friction
- Vibration
- Resonance

Sound Absorption Coefficient

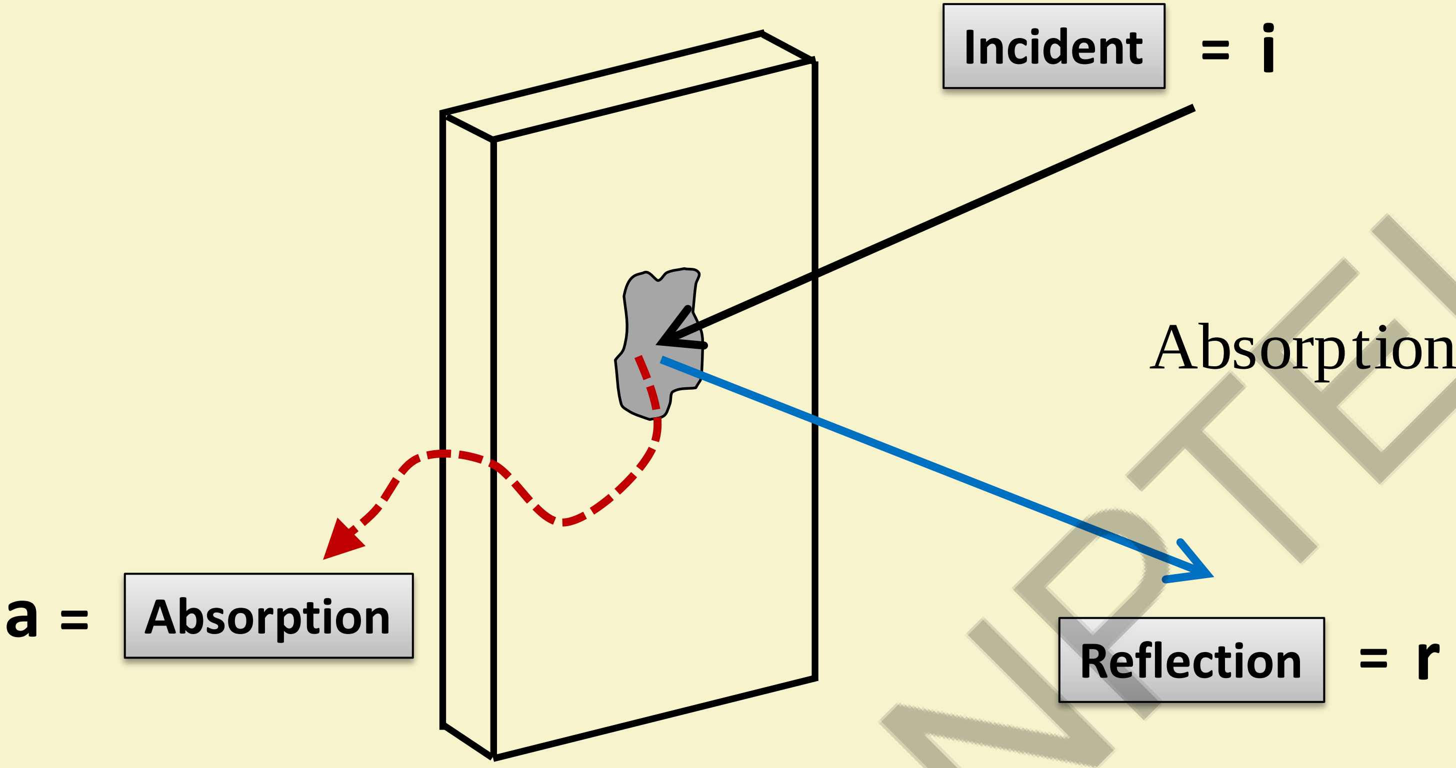
The **measurement of absorption** of any material is like any other **physical quantity**.

It is expressed in a non - dimensional ratio terms called **Absorption Coefficient**

This will help measurement of absorption by different materials/surfaces and have a comparison among them.

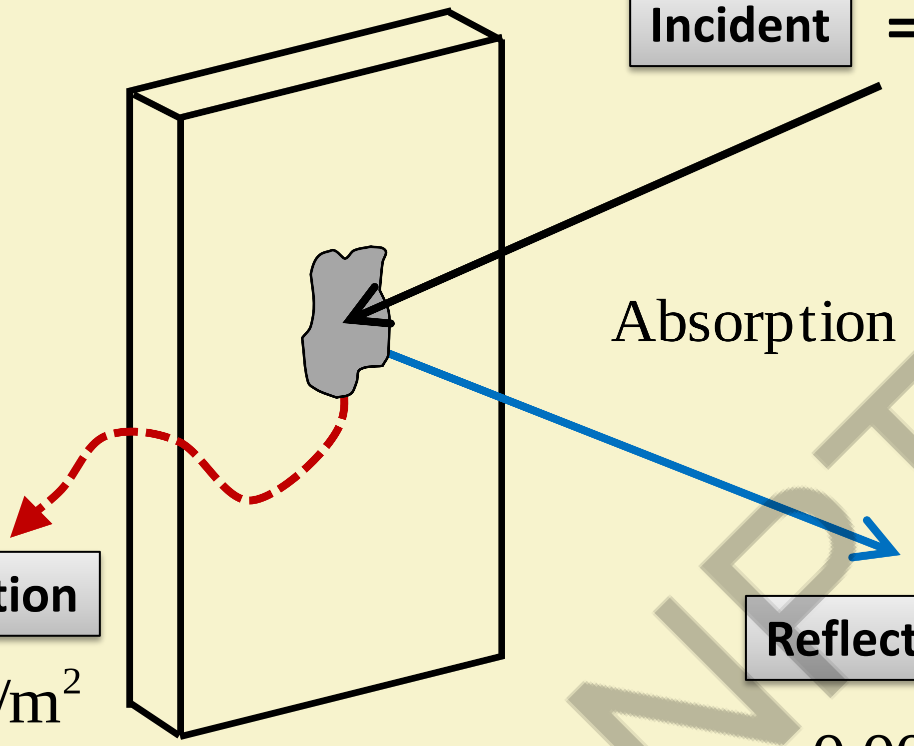
The **Absorption Coefficient** of a given surface/material is also defined as:
"The ratio of amount of **sound energy absorbed** by the area of given surface/material in a certain time to the **sound energy incident** on the area of given surface/material in an equal time".

Sound Absorption Coefficient



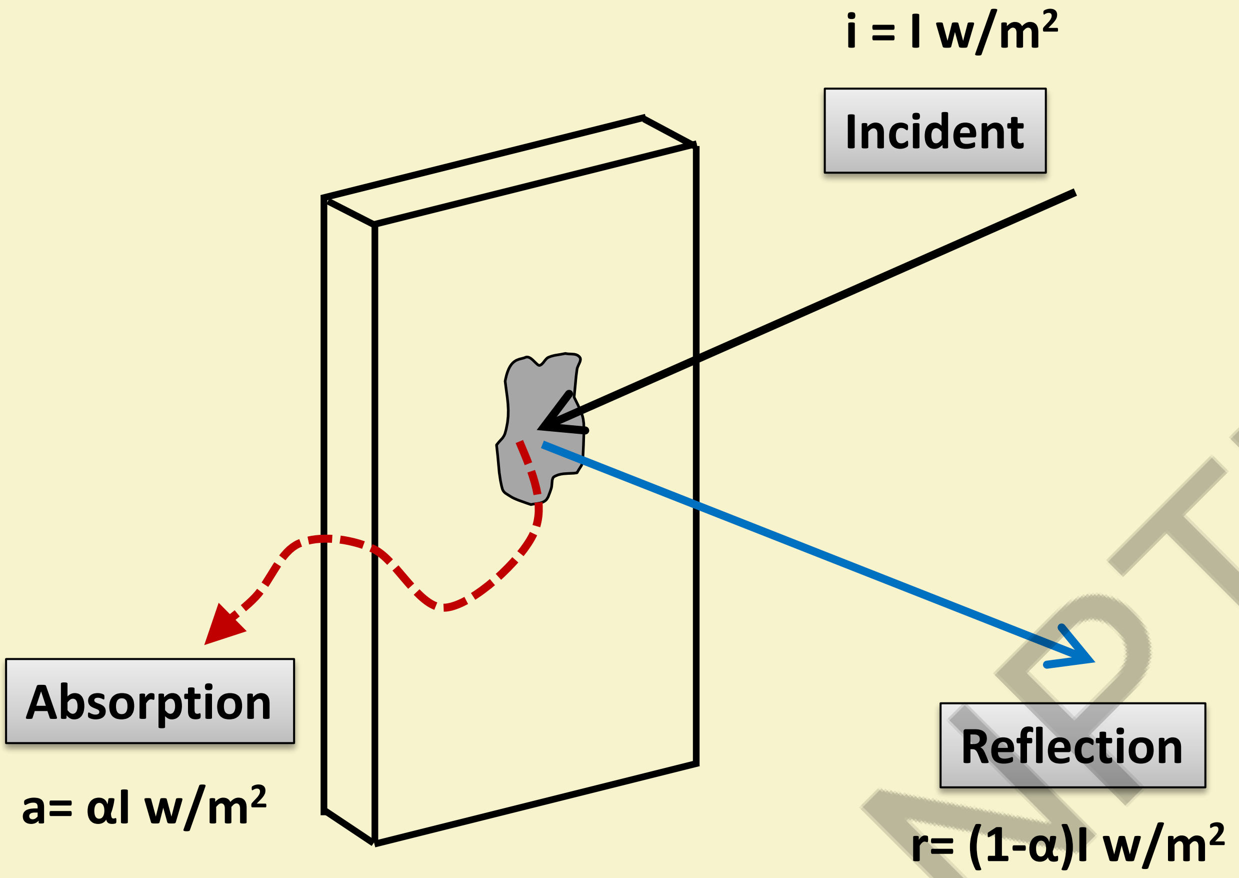
$$\text{Absorption Coefficient} = \frac{\text{Sound Absorbed}}{\text{Sound Incedent}} = \frac{a}{i}$$

Sound Absorption Coefficient



$$\text{Absorption Coefficient} = \frac{\text{Sound Absorbed}}{\text{Sound Incedent}} = \frac{a}{i} = \frac{0.004}{0.01} = 0.4$$

Sound Absorption Coefficient



If, i = I w/m²

$$\text{Absorption Coefficient} = \alpha = \frac{a}{i}$$

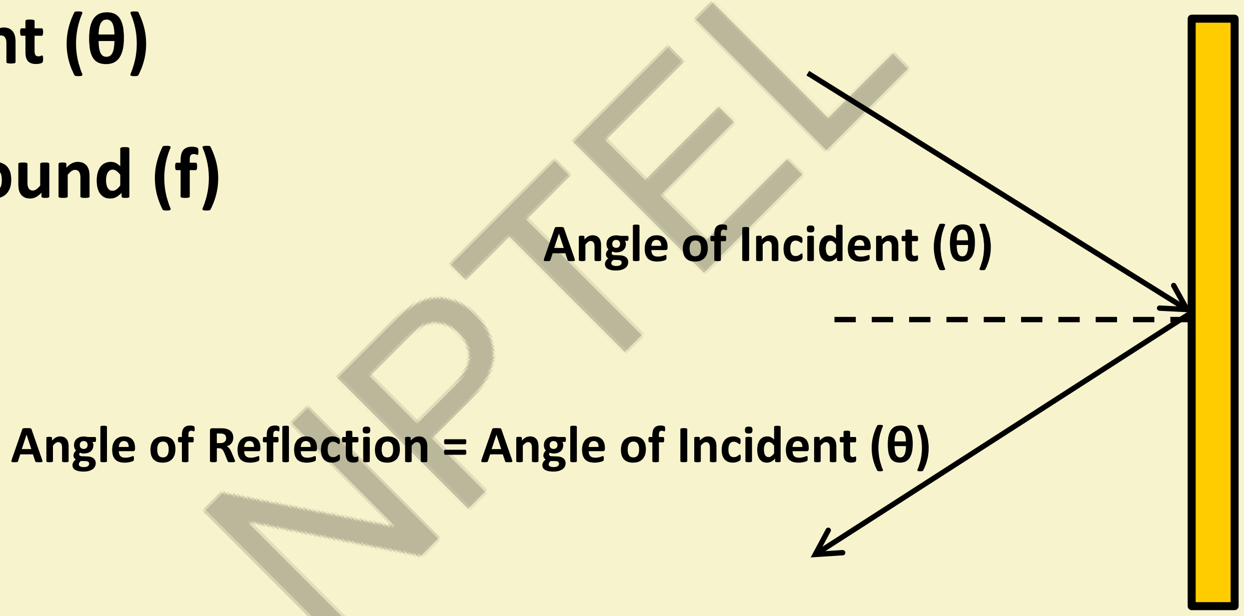
$$\alpha = \frac{a}{i} \Rightarrow a = \alpha \times I$$

$$r = (i - a) = I - \alpha \times I = (1 - \alpha)I$$

NRC

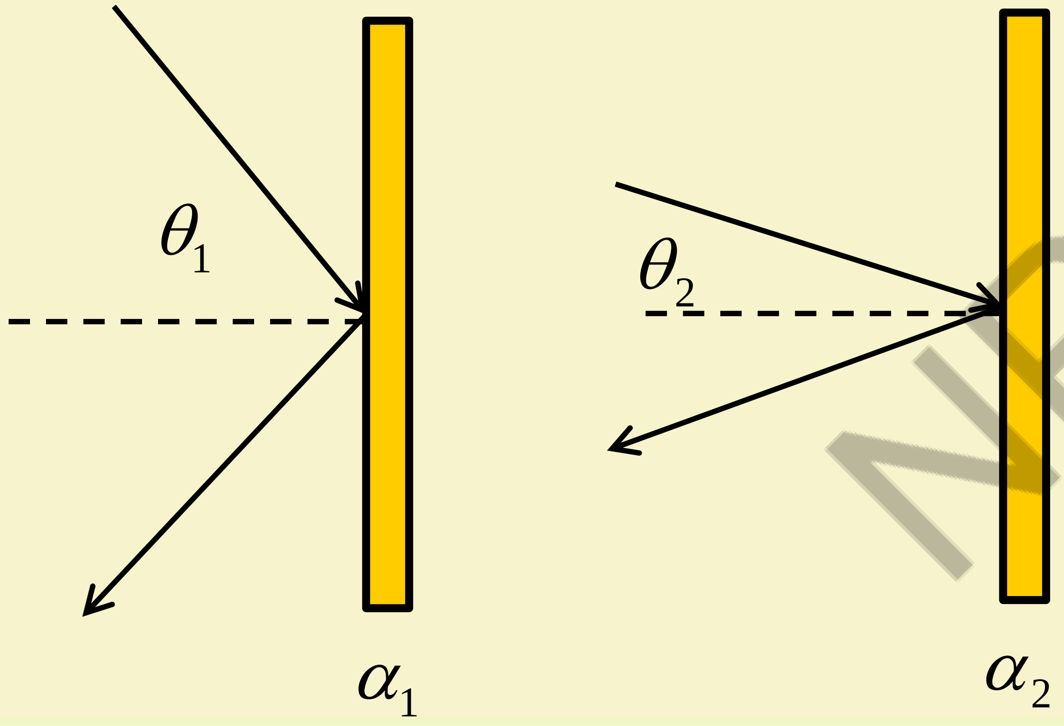
Sound Absorption Coefficient (α) depends upon

1. **Angle of Incident (θ)**
2. **Frequency of Sound (f)**



Random Incident Sound Absorption Coefficient

Average value of Sound Absorption Coefficient for **different angle of Incident** for a **specific sou**



$$\bar{\alpha} = \frac{\sum_{i=1}^{n} \alpha_{\theta}^{i}}{n}$$

Noise Reduction Coefficient (NRC)

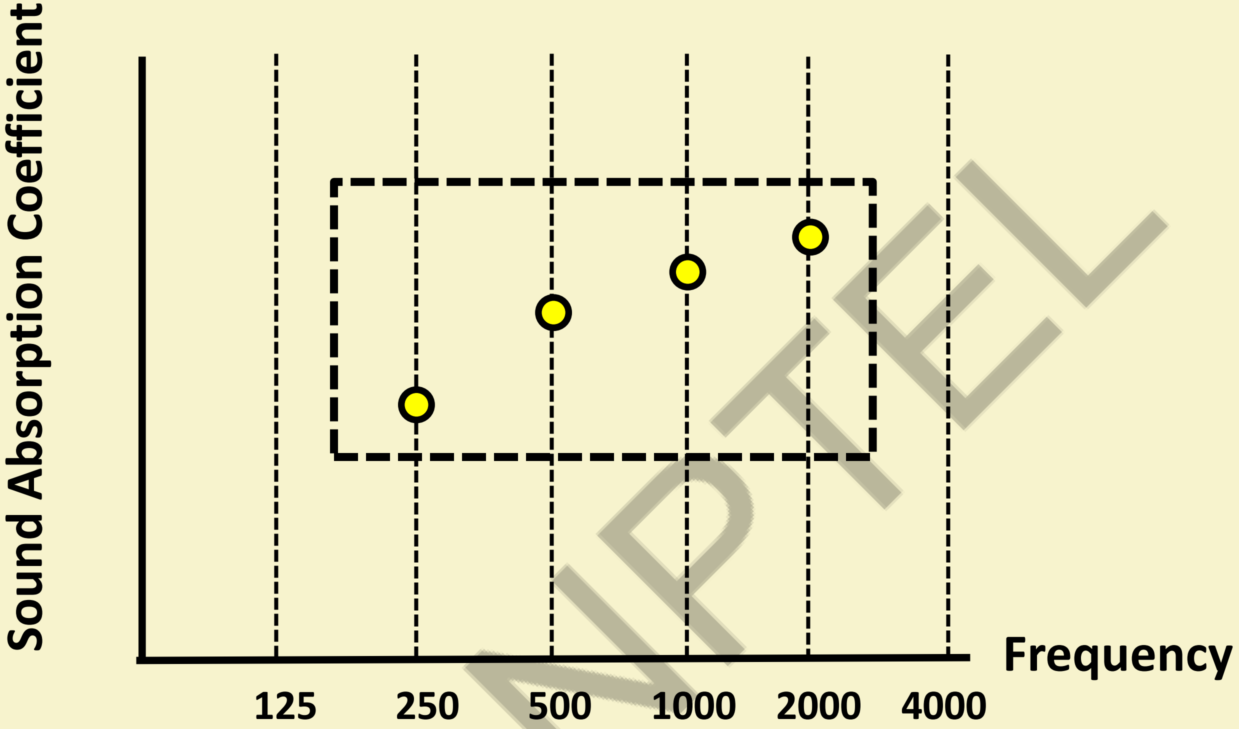
The **average** of **Random Incident** Sound Absorption Coefficient of **four selected Octave band frequencies [250, 500, 1000 & 2000]** expressed in **nearest multiple of 0.05** is called ‘Noise Reduction Coefficient’ of the material

$$NRC = \frac{1}{4}\left[\bar{\alpha}_{250} + \bar{\alpha}_{500} + \bar{\alpha}_{1000} + \bar{\alpha}_{2000}\right]$$

This NRC value is **published in the material information brochure** of the various acoustical absorber manufacturers .

This NRC value can be used for **any acoustical calculations.**

NRC



Sound Absorption Coefficient
Frequency
125
250
500
1000
2000
4000

Noise Reduction Coefficient (NRC)

Frequency	Random Incident Sound Absorption Coefficient
250	0.75
500	0.78
1000	0.83
2000	0.85

Average of Four : (3.21)/4 = 0.8025

NRC= 0.80

$$NRC = \frac{1}{4}\left[\bar{\alpha}_{250} + \bar{\alpha}_{500} + \bar{\alpha}_{1000} + \bar{\alpha}_{2000}\right]$$

Concept of Open Window Unit

$i = 0.01\ w/m^2$ $a = 0.004\ w/m^2$ $r = 0.006\ w/m^2$

$\boxed{\text{Total Absorption} = 0.004 \times 10 = 0.04\ w}$

Total Reflection = 0.006 X 10 = 0.06 w

$i = 0.01\ w/m^2$ $a = r = 0.005\ w/m^2$

$\boxed{\text{Total Absorption} = 0.005 \times 8 = 0.04\ w}$

Total Reflection = 0.005 X 8 = 0.04 w

Area, $S = 10\ m^2$

$\alpha = 0.4$

$\boxed{S \times \alpha = 10 \times 0.4 = 4}$

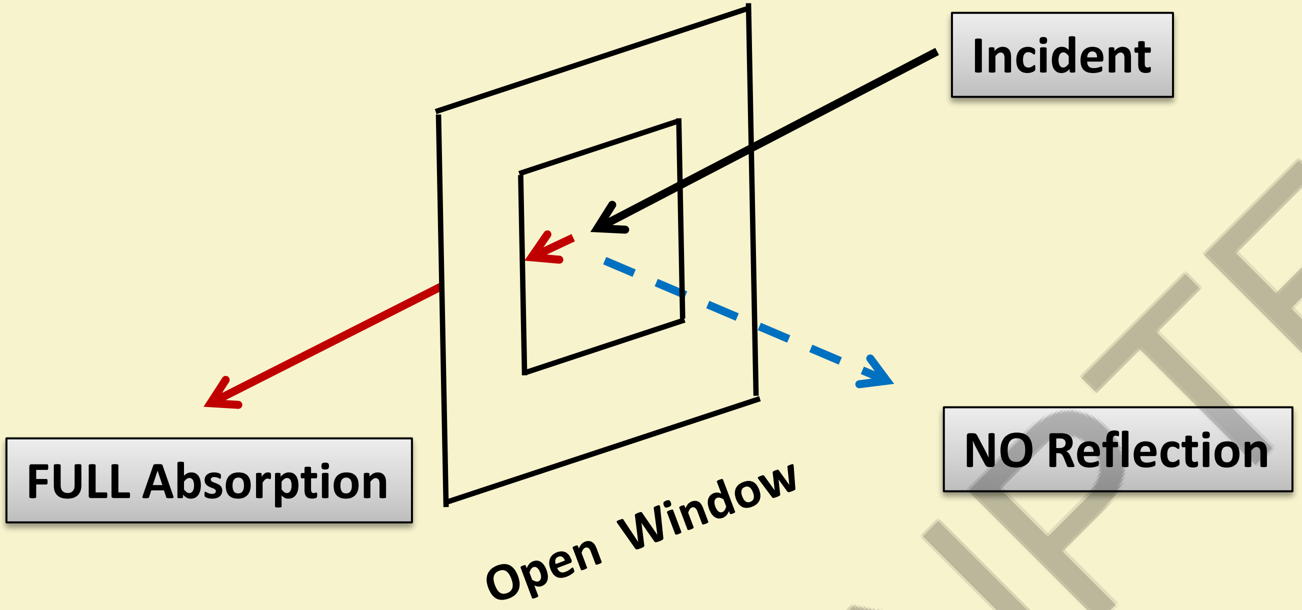
Area, $S = 8\ m^2$

$\alpha = 0.5$

$\boxed{S \times \alpha = 8 \times 0.5 = 4}$

Concept of Open Window Unit

Which Surface is having α =1.0 ?

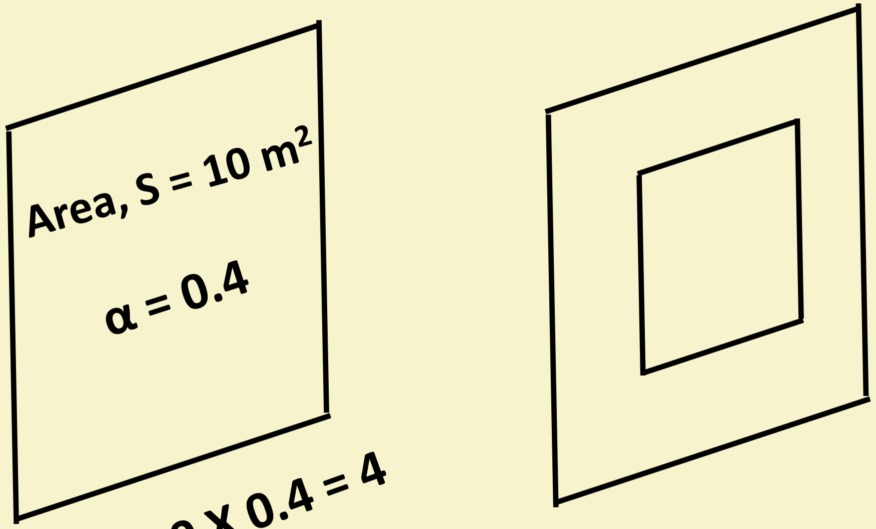


$$\text{Absorption Coefficient} = \alpha = \frac{a}{i}$$

[a = i]

$$\alpha = 1.0$$

Concept of Open Window Unit

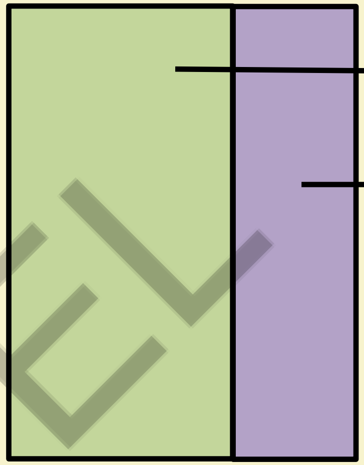


$S \times \alpha = 10 \times 0.4 = 4$

Open window of $4m^2$

Rest $6m^2$ R Area having Full reflection

$S \times \alpha = 4 \times 1 = 4$

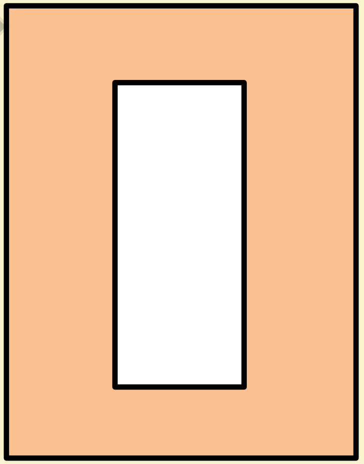


$S_1 = 12m^2 \quad \alpha_1 = 0.4$

$S_2 = 4m^2 \quad \alpha_2 = 0.3$

$S_1 \times \alpha_1 + S_2 \times \alpha_2 =$
$= (12 \times 0.4) + (4 \times 0.3) = 6$

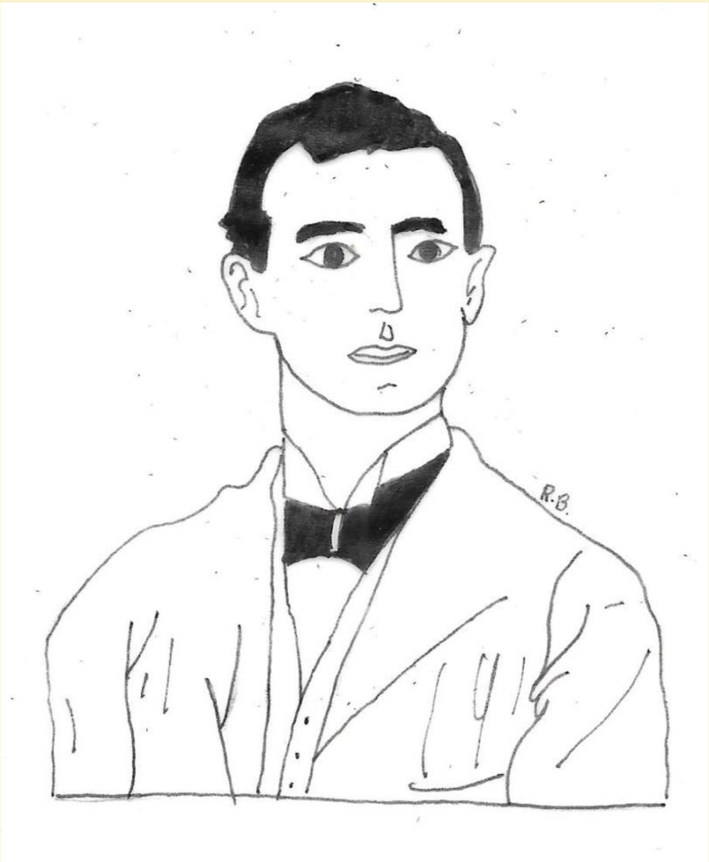
Equivalent to



6 m^2 of Open Window area
\+
Rest 10 m^2 of Fully Reflective area

Concept of Open Window Unit

So the **product** of the exposed **surface area** to the sound and the corresponding **Sound Absorption Coefficient** is given an unit of ‘Open Window Unit (OWU)’ or m^2 Sabine or Sabine



Wallace Clement Sabine (1868 – 1919)

Sound Absorption Coefficients Of Materials

Material	Sound Absorption Coefficients
Glass, ordinary windows	0.1 - 0.2
Gypsum board, 12 mm	0.04 - 0.07
Plaster walls	0.01 - 0.03
Plywood panel, 3 mm	0.01 - 0.02
Concrete	0.02 -0.05
Timber Board	0.1 – 0.15
Curtain	0.25 -0.35
Mineral wool, 100 mm	0.65
Heavy Carpet	0.65
Polyurethane foam, flexible	0.95

Total Room Sound Absorption

$A = S_1 \alpha_1 + S_2 \alpha_2 + .. + S_n \alpha_n = \sum S_i \alpha_i$

where

A = the absorption of the room (m^2 Sabine)

S_n = area of the actual surface (m^2)

α_n = absorption coefficient of the actual surface

Mean Room Sound Absorption

The mean absorption coefficient for the room can be expressed as:

$\alpha_m = A / S$

Where

A = *the absorption of the room* (m^2 *Sabine*)

α_m = *mean absorption coefficient*

S = *total surface in the room* (m^2)

Home Work

Can you differentiate the different behaviour of sound in enclosed space by illustration?

Find the NRC value of a sound absorptive panel from the following data:
Frequency level sound absorption coefficient are 0.26, 0.28,0.32 & 0.37 for 250, 500, 1000 & 2000 Hz respectively

Bibliography

1. **Auditorium Acoustics and Architectural Design,** Michael Barron, Spon Press, 1st Edition
2. **Architectural Acoustics**, K.B.Genn, Burel & Kjaer, 2nd Edition
3. **Architectural Acoustics,** Marshall Long, El Sevier, Academic Press,
4. **Mechanical and Electrical Equipment for Buildings**, Walter T. Grondzik, Alison G. Kwok, Benjamin Stein and John S. Reynolds, John Wiley & Sons, Inc. (11th Edition) [Part-IV]

End of Lecture 08: Indoor Acoustics, Reflection and Absorption

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Architectural Acoustics

Lecture 09: Concept of Reverberation

Dr. Shankha Pratim Bhattacharya
Department of Architecture & Regional Planning

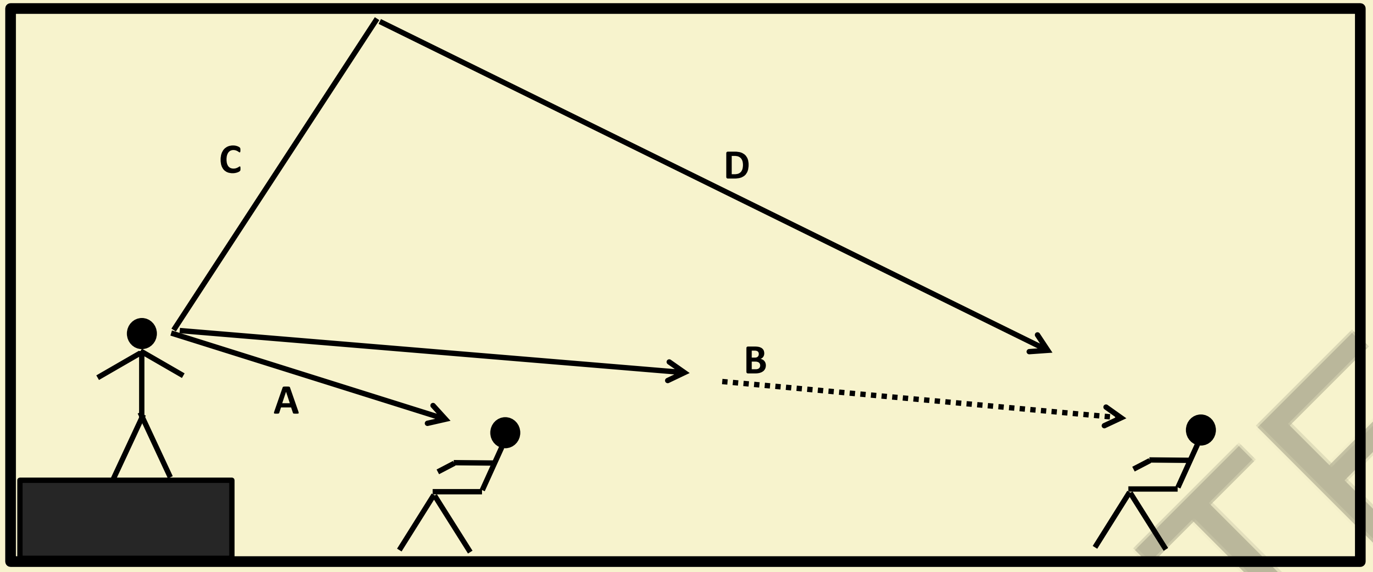
Learning Objective

Conceptualize the Reverberation and Reverberation Time

Associate the Reverberation Time with room reflection and absorption

Develop the fundamental equation to find Reverberation Time

Sound in Enclosed Space

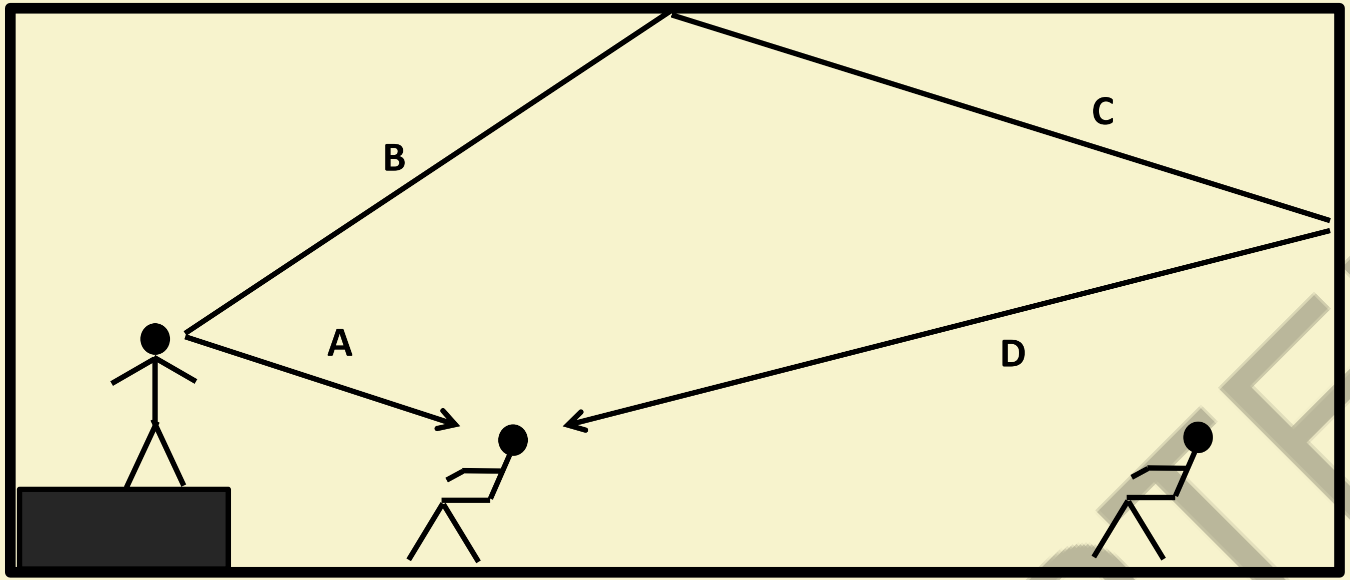


Front Seat Audience receives the **strong direct sound** from the source **(Path-A)**

Back Seat Audience gets the **week direct sound** from the source **(Path-B)**

Reflected sound from the source **reinforce the week direct sound (Path C-D)**

Sound in Enclosed Space

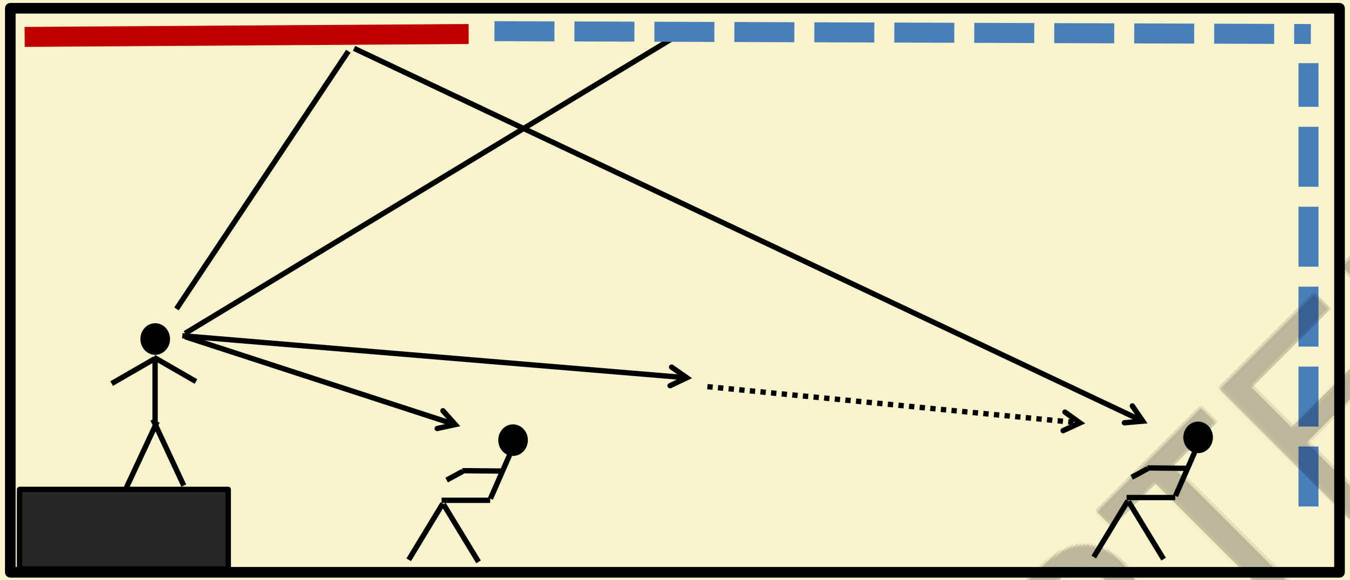


Front Seat Audience receives the **direct sound** from **Path-A**

Front Seat Audience also received the **reflected sound** from **Path-B-C-D**

If the path difference between direct and reflected **path is too high**, a **long delay** will occur for the front audience. That creates the **confutation of hearing**

Sound in Enclosed Space



Reflective Surface in the front

Absorptive Surface in the rear

Strengthen the week direct sound to the audience at back by sound reinforcement

Cutoff the rear side multiple reflection and omit the chance of long delay

Definition of Reverberation Time

The sound is spreads out in all directions inside a enclosed space.

The sound waves get reflected so many times in the boundary surfaces of the enclosed area.

Due to multiple reflection and absorption the sound is gradually die down.

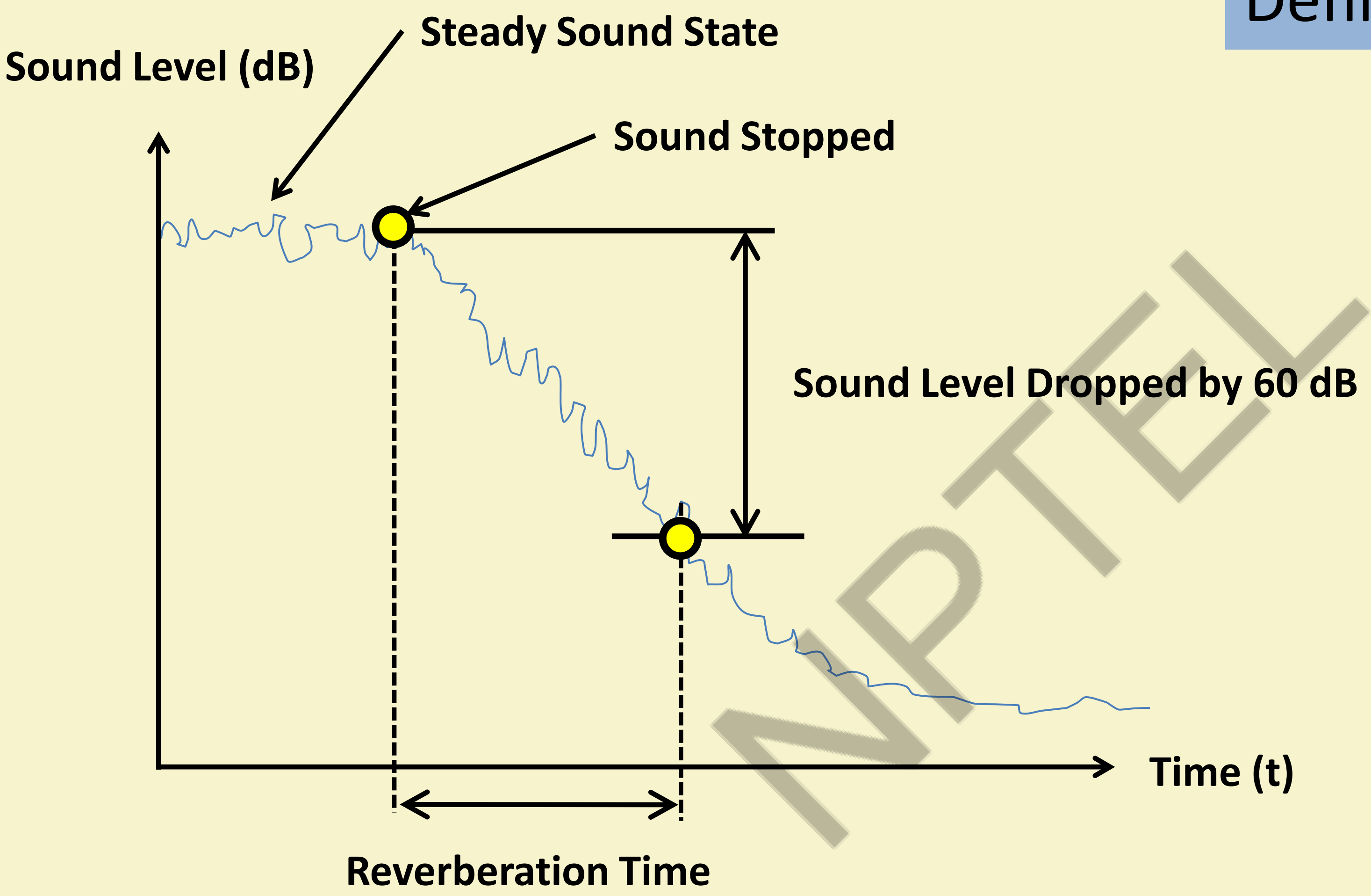
As a result, even though the source of sound produced a particular sound and stopped, the sound is continuously heard for a short interval of time, until the intensity falls below the limit of audibility.

This phenomenon of persistence of sound inside a hall for some time even after the source of sound is stopped is called reverberation.

Reverberation Time (RT)

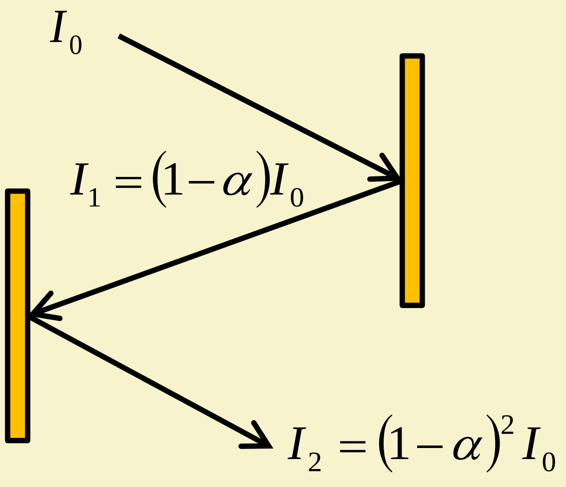
Reverberation time is the oldest and best known performance criteria in the field of acoustics. It is measured in **seconds** and is defined as the **time taken** for a generated **sound to decay by 60 dB** once the sound source has been stopped.

Definition of Reverberation Time



Derivation of Reverberation Time

Sound Intensity before first reflection = I_0

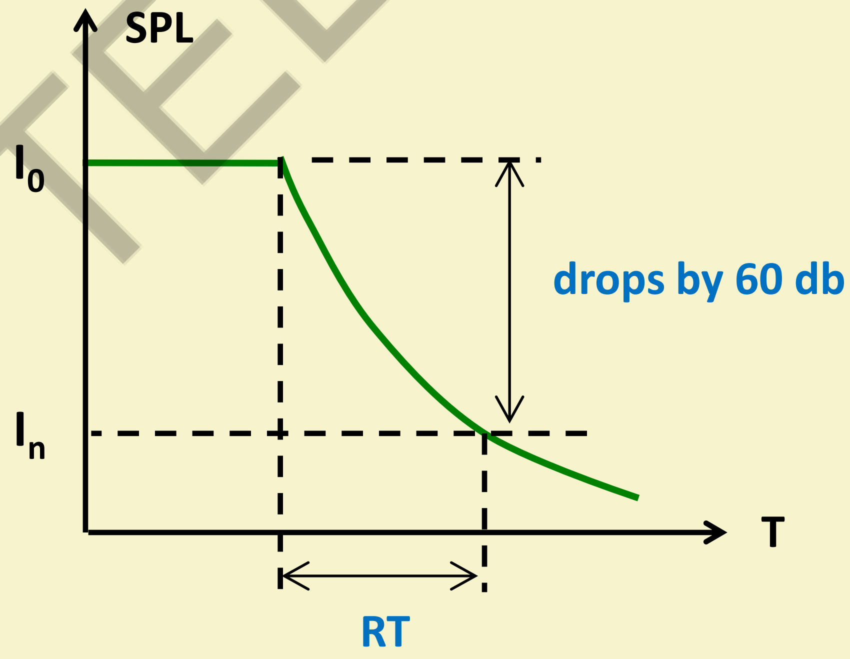


Sound Intensity after n^{th} reflection = I_n

$$I_n = (1-\alpha)^n I_0$$

Let after n^{th} reflection the **SIL drops by 60 db**

So, by definition **time duration** of **n** successive reflection is **Reverberation Time**

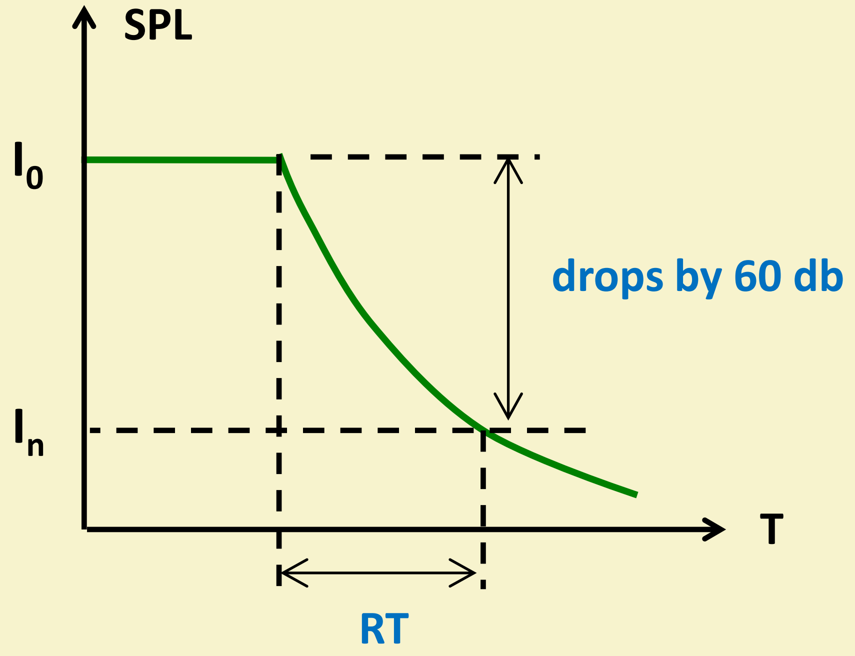


Derivation of Reverberation Time

As after n^th reflection the **SIL drops by 60 db**

$$\left(10\log\frac{I_0}{I_{ref}}\right)-\left(10\log\frac{I_n}{I_{ref}}\right)=60 \Rightarrow 10\log\left(\frac{I_0}{I_{ref}}\times\frac{I_{ref}}{I_n}\right)=60$$

$$\frac{I_0}{I_n}=10^6 \Rightarrow \frac{I_0}{I_0(1-\alpha)^n}=10^6 \Rightarrow (1-\alpha)^n=10^{-6}$$



Derivation of Reverberation Time

$$(1-\alpha)^n = 10^{-6}$$

Taking natural logarithm in both side

$$\log_e(1-\alpha)^n = \log_e 10^{-6} \Rightarrow n \times \log_e(1-\alpha) = -6\log_e 10 \Rightarrow n = \frac{-6\log_e 10}{\log_e(1-\alpha)}$$

$$\text{Mean Free Path} = \frac{4\text{V}}{\text{S}}$$

Volume of the Room is ‘V’
Total Surface Area of the Room is ‘S’

$$\text{Average Time Taken for Single Reflection} = \frac{4\text{V}}{\text{Sc}}$$

Velocity of Sound in Air is ‘c’

$$\text{Average Time Taken for 'n' Reflection} = \frac{4\text{V}}{\text{Sc}} \times n$$

Derivation of Reverberation Time

$$\text{Average Time Taken for 'n' Reflection} = \frac{4\text{V}}{\text{Sc}} \times n$$

This by definition is the 'Reverberation Time'

$$RT = \frac{-6\log_e 10}{\log_e(1-\alpha)} \times \frac{4V}{Sc} = \left(\frac{24\log_e 10}{330}\right) \times \left(\frac{V}{-S \times \log_e(1-\alpha)}\right)$$

$$RT = \frac{0.16V}{-S \times \log_e(1-\alpha)}$$

Carl Eyring Reverberation Time (1930)

Derivation of Reverberation Time

$$RT = \frac{0.16V}{-S \times \log_e(1-\alpha)}$$

Expanding $\log_e(1-\alpha)$

$$\log_e(1-\alpha) = -\alpha - \frac{\alpha^2}{2} - \frac{\alpha^3}{3} \ldots.$$

Neglecting the higher order of 'α'

$$\log_e(1-\alpha) \approx -\alpha$$

$$RT = \frac{0.16V}{S\alpha}$$

Sabine's Formula

$$RT_{60} = \frac{0.16 \times V}{S\alpha}$$

In metric units… Meter

RT_{60} is Reverberation Time (in sec.), or the time it takes for sound to decrease by 60 dB in a room

V is the volume of the Room

Sα is the Total surface absorption of the Room

$$RT_{60} = \frac{0.049 \times V}{S\alpha}$$

In Feet units

The factors that control reverberation time:

I. Absorption

Reverberation time depends on the absorption coefficient of various interior surfaces in a hall such as sound absorptive tiles, cushions, carpets, curtain etc.

Higher the total absorption of the hall shorter will be the reverberation time, and vice versa.

The factors that control reverberation time:

II. Frequency of sound

Most of the cases the sound absorption coefficient materials the increases with increase in frequency of sound. Hence, the reverberation time is shorter for high frequency

The factors that control reverberation time:

III. Volume of hall

The reverberation time also depends on the volume of the hall.

Higher the volume of the room, Reverberation Time will be higher

Live & Dead Room

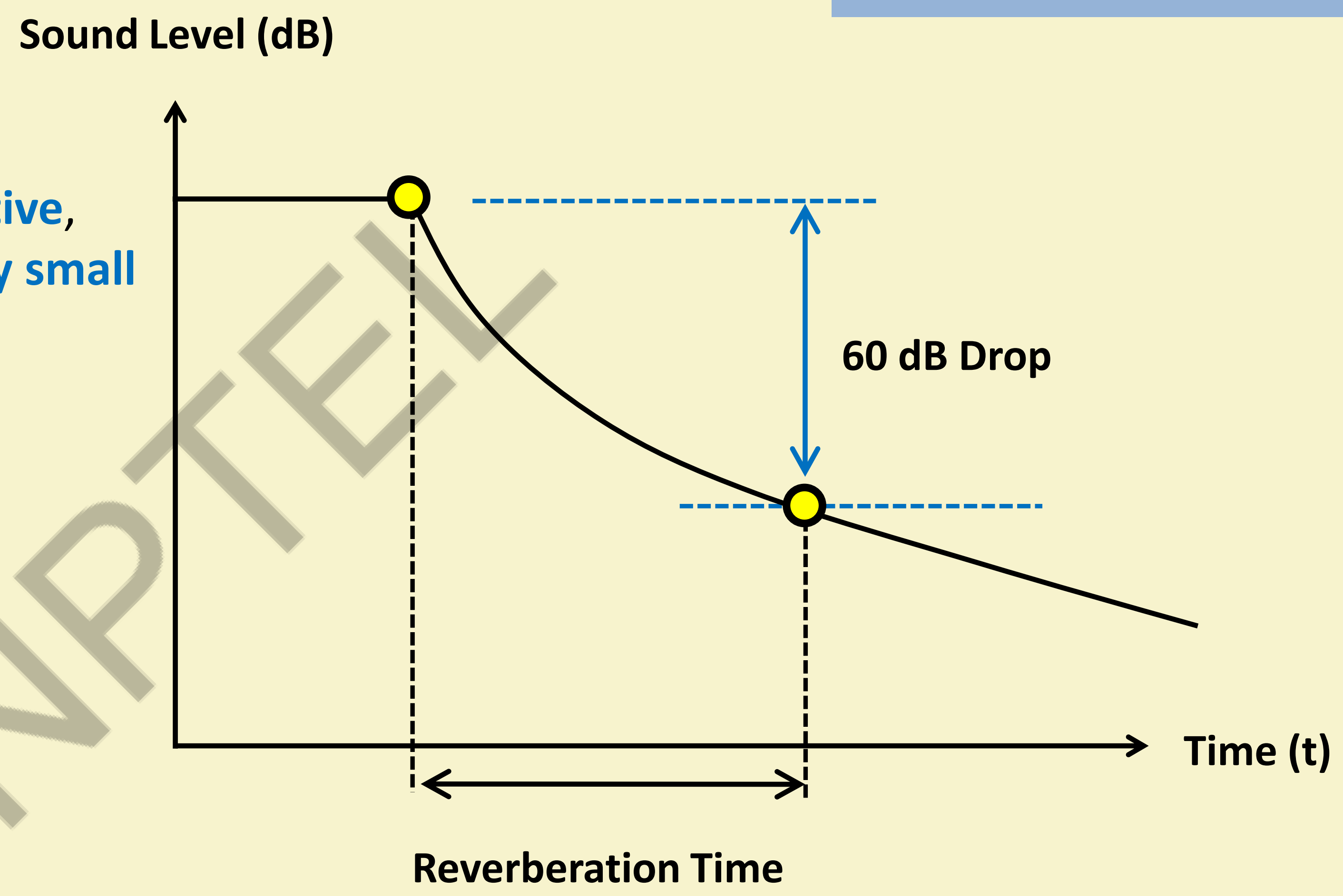
$$RT_{60} = \frac{0.16 \times V}{S\alpha}$$

If the Room interior surfaces are **mostly reflective**,
The Sound Absorption coefficient **α** will be **very small**

The decay of sound will occur in **slower rate**

Smaller value of Sα will provide very **high RT**

Live Room



Live & Dead Room

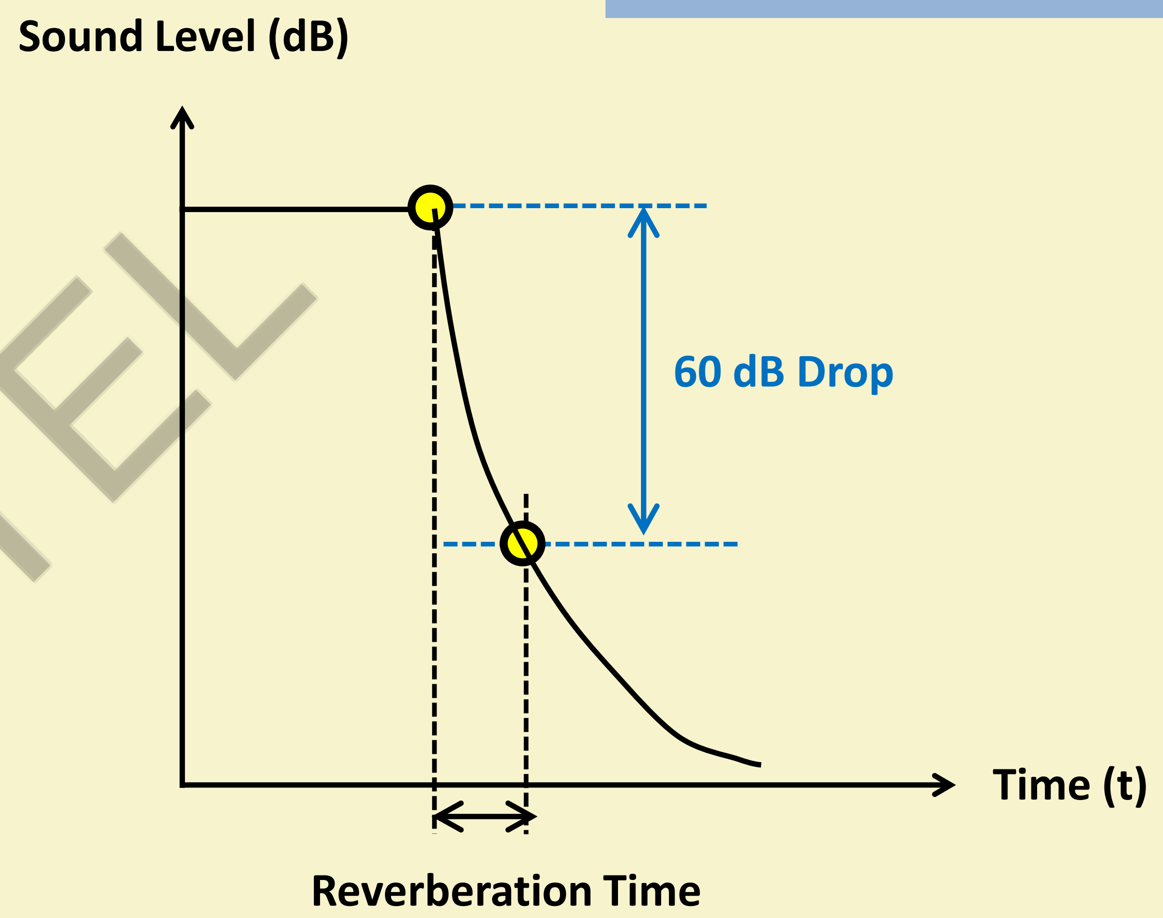
$$RT_{60} = \frac{0.16 \times V}{S\alpha}$$

If the Room interior surfaces are **mostly Absorptive**, The Sound Absorption coefficient **α** will be **very high**

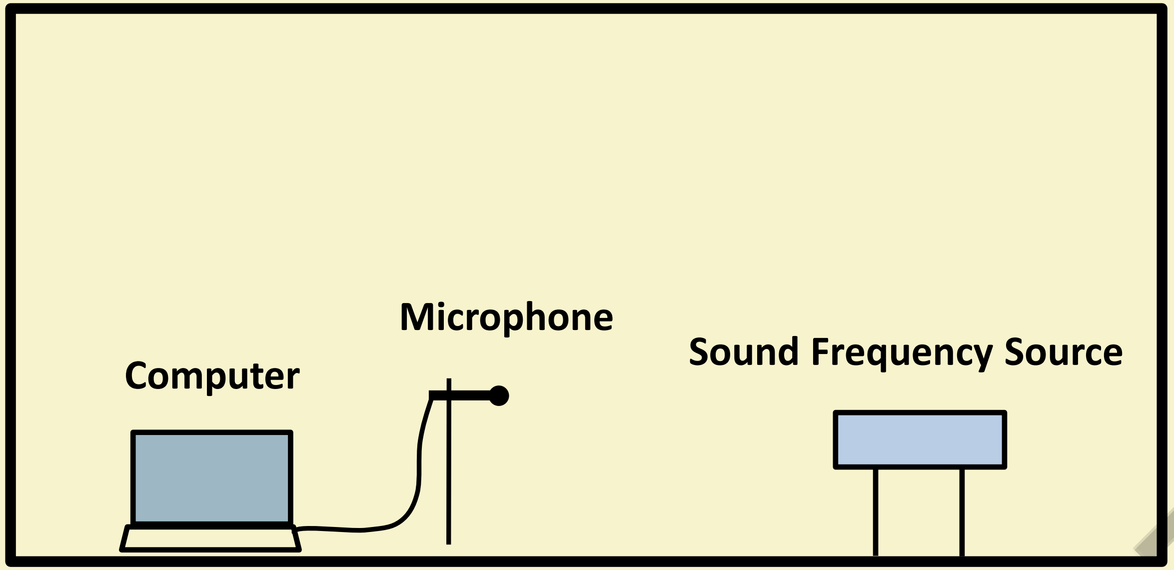
The decay of sound will occur in **faster rate**

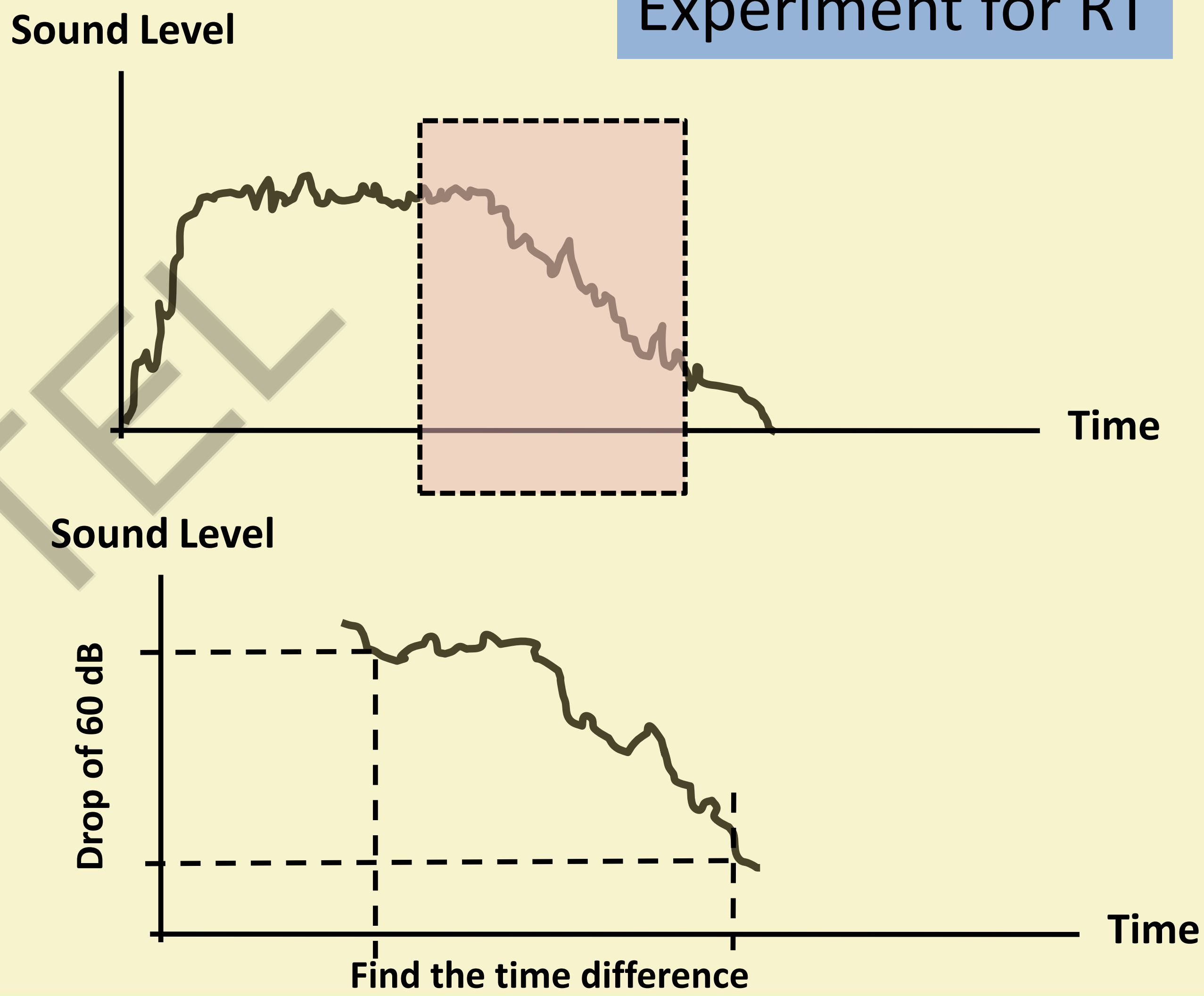
Smaller value of Sα will provide very **low RT**

Dead Room



Experiment for RT





Home Work

Discuss the change of Reverberation Time , in case of

(i) A change in Room Volume

(ii) Total Surface Absorption

(iii) Amount of Surface opening

(iv) More Occupancy and furniture density

If a sound having intensity 0.5 W/m^2 is successive reflected in a room by 50 times on the surfaces having sound absorption coefficient 0.2, then what will be the final intensity of sound?

Bibliography

1. **Auditorium Acoustics and Architectural Design,** Michael Barron, Spon Press, 1st Edition

2. **Architectural Acoustics**, K.B.Genn, Burel & Kjaer, 2nd Edition

3. **Architectural Acoustics,** Marshall Long, El Sevier, Academic Press,

4. **Mechanical and Electrical Equipment for Buildings**, Walter T. Grondzik, Alison G. Kwok, Benjamin Stein and John S. Reynolds, John Wiley & Sons, Inc. (11th Edition) [Part-IV]

End of Lecture 09: Concept of Reverberation

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Architectural Acoustics

Lecture 10: Application of Reverberation Time

Dr. Shankha Pratim Bhattacharya

Department of Architecture & Regional Planning

Learning Objective

Formulate the procedure to obtain Reverberation Time of a Enclosed Space

Interpret the necessary changes of parameters to achieve required Reverberation Time

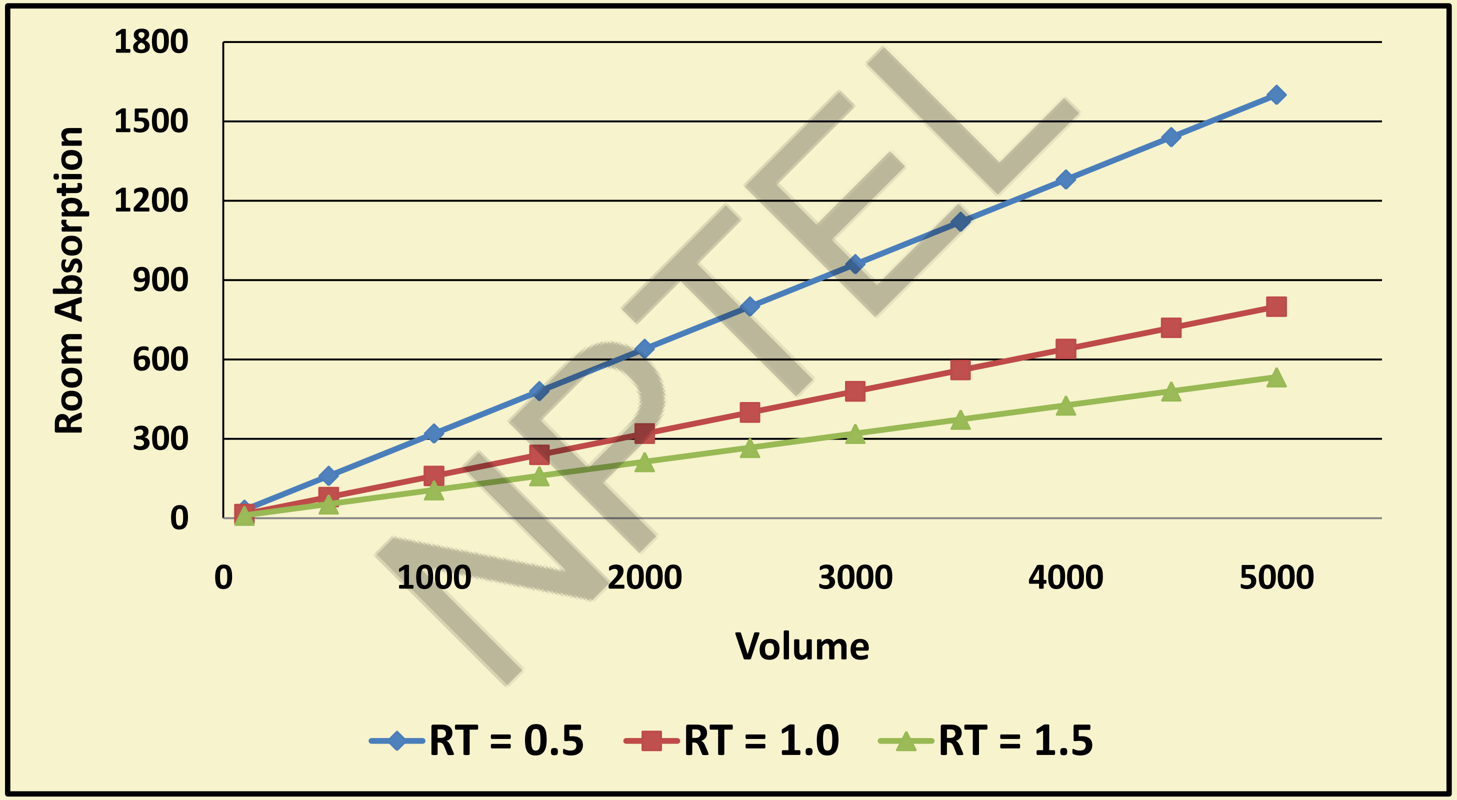
Sabin's Formula

$$RT_{60} = \frac{0.16 \times V}{\sum S\alpha}$$

RT is the Reverberation Time (Sec) of a enclosed Space

V is the Volume of the Space

Sα is the Total interior surface absorption of the Room

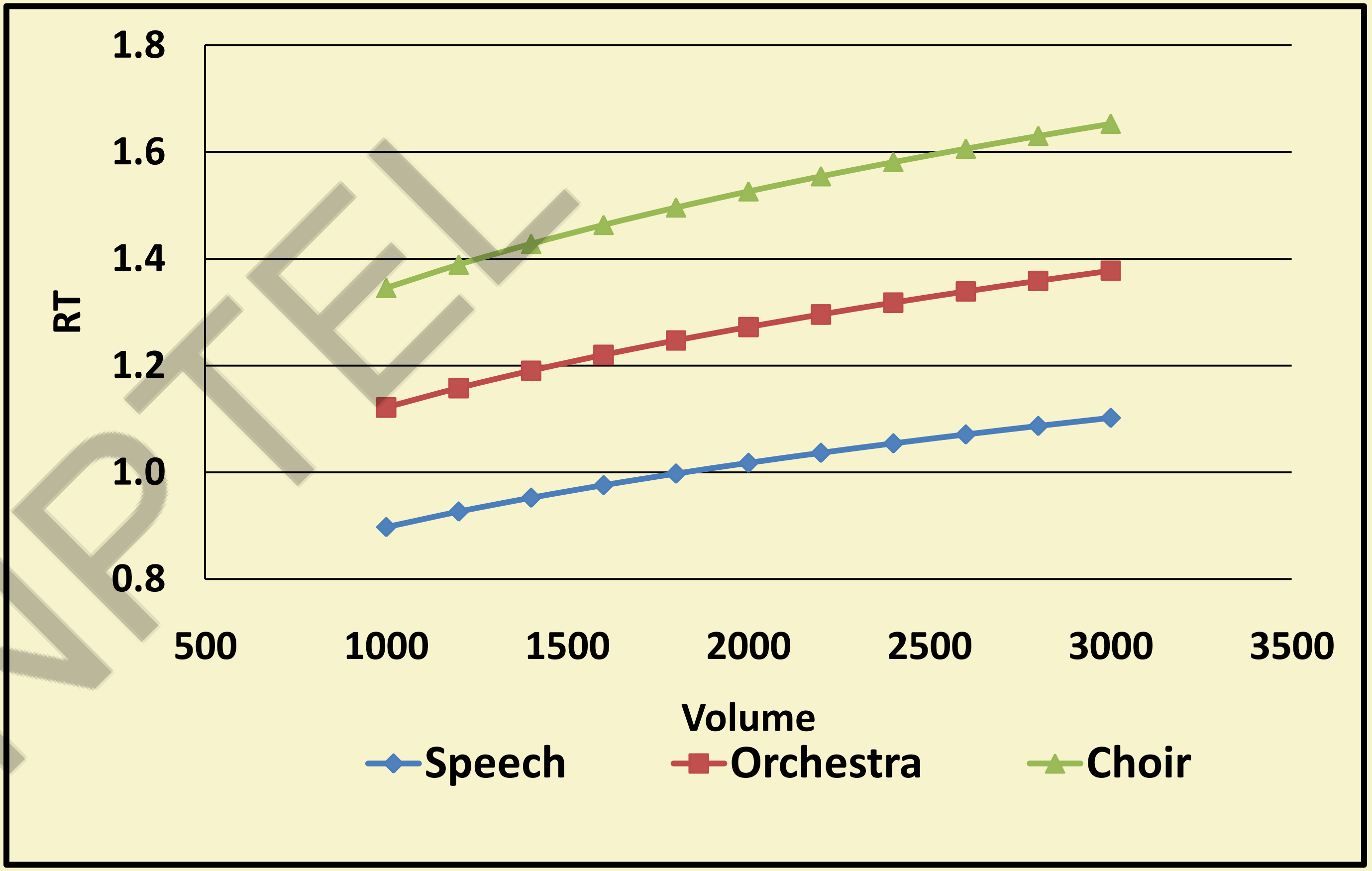


Empirical Formula

Ideal Reverberation Time can be determine by some empirical formula

$$RT = K\left(0.012\sqrt[3]{V} + 0.107\right)$$

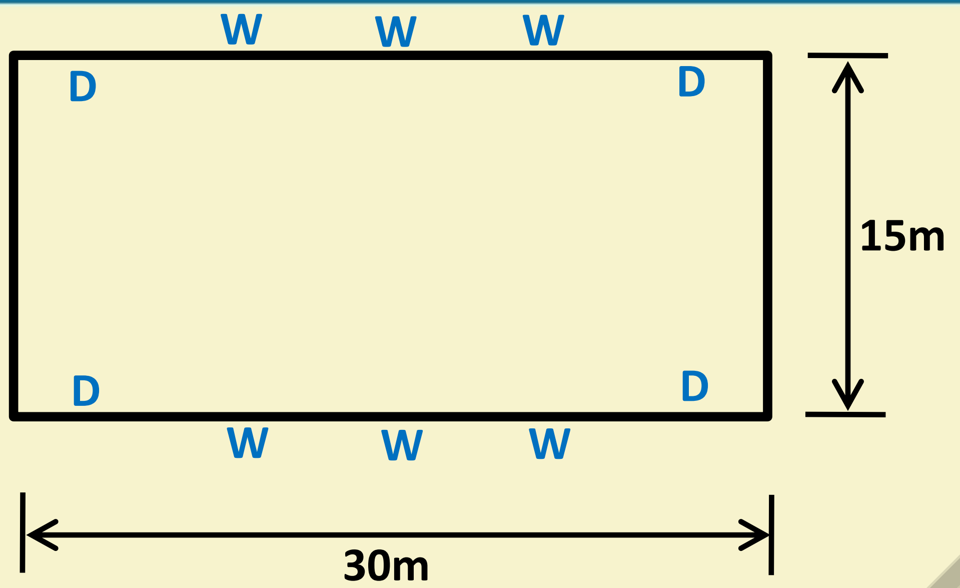
RT is the Reverberation Time in Sec
V is the Volume of the Room in m^2
K is a constant
K = 4 for Speech
= 5 for Orchestra
= 6 for Choir



Standard Reverberation Time

Room Characteristics	Very Soft	Soft	Normal	Hard	Very Hard
Prescribed RT Range	**0.2 < *RT* < 0.25**	**0.4 < *RT* < 0.5**	**0.9 < *RT* < 1.1**	**1.8 < *RT* < 2.2**	**2.5 < *RT* < 4.5**
Space	Radio TV studio	Restaurant Theatre Lecture hall	Cinema Hall, Office Library, Multipurpose Auditorium Residence	Hospital Church	Large church Factory
Mean Absorption coefficient of room interior surfaces	**0.40**	**0.25**	**0.15**	**0.10**	**0.05**

Calculation of Reverberation Time



PLAN

SECTION

Door : 2m X 2.5m (4 nos)

Window : 3m X 1.5m (6 nos)

1. Calculation of interior surface area

Door :	(2X2.5) X 4	= **20m²**
Window:	(3X1.5) X 6	= **27m²**
Ceiling:	(15X30)	= **450m²**
Floor:	(15X30)	= **450m²**
Wall:	[2X(15+30)]X6 - (20+27)	= **493m²**

Volume of the Hall = 15 X 30 X 6 = **2700** m^3

Calculation of Reverberation Time

Sound Absorption Coefficient of interior surface area

Door and Window:	***Glass and Aluminum frame***	**0.01**
Ceiling and Wall :	***Plaster***	**0.02**
Floor:	***Wooden Floor***	**0.12**

2. Calculation of Total Absorption of interior surface area

Door : = **20 X 0.01 = 2.0** m^2 Sabine

Window: = **27 X 0.01 = 2.7** m^2 Sabine

Ceiling: = **450 X 0.02 = 9.00** m^2 Sabine

Floor: = **450 X 0.12 = 54.00** m^2 Sabine

Wall: = **493 X 0.02 = 9.86** m^2 Sabine

Total **73.33** m^2 Sabine

Calculation of Reverberation Time

Absorption from Chair and Audience:

Cane Chair : 0.01 per Seat
Cushioned Chair : 0.5 per Seat
Audience : 0.4 per person

Capacity of the Hall is 300

3. Calculation of Absorption from Chair / Audience

Only Cane Chair, No Audience	**: 300 X 0.01 = 3.00**
Only Cushioned Chair, No Audience	**: 300 X 0.5 = 150**
Hall full with Audience	**: 300 X 0.4 = 120**

Calculation of Reverberation Time

Empty Hall

- **Cane Chair**: **Sα = (73.33 + 3) = 76.33**

$$RT = \frac{0.16 \times V}{S\alpha} = \frac{0.16 \times 2700}{76.33} = 5.7$$

- **Cushioned Chair**: **Sα = (73.33 + 150) = 223.33**

$$RT = \frac{0.16 \times V}{S\alpha} = \frac{0.16 \times 2700}{223.33} = 1.9$$

Full House: **Sα = (73.33 + 120) = 193.33**

$$RT = \frac{0.16 \times V}{S\alpha} = \frac{0.16 \times 2700}{193.33} = 2.2$$

Calculation of Reverberation Time

Lets take a base design condition as:

The Hall is provided **Cane chairs** and **half of the hall is occupied** by audience

Half empty Cane Chair: 150 X 0.01 = 1.5
Half full Audience : 150 X 0.4 = 60

Total **61.5** m^2 Sabine

Sα = (73.33 + 61.5) = 134.83

$$RT = \frac{0.16 \times V}{S\alpha} = \frac{0.16 \times 2700}{134.83} = 3.2$$

Case: I

Calculation of Reverberation Time

Doors & Windows are covers with heavy curtail having α = 0.65
Wall is treated with Sound Absorption tiles having α = 0.45

Calculation of Total Absorption of interior surface area

Door : = ~~**20 X 0.01 = 2.0** m² Sabine~~ = **20 X 0.65 = 13** m^2 Sabine

Window: = ~~**27 X 0.01 = 2.7** m² Sabine~~ = **27 X 0.65 = 17.55** m^2 Sabine

Ceiling: = **450 X 0.02 = 9.00** m^2 Sabine

Floor: = **450 X 0.12 = 54.00** m^2 Sabine

Wall: = ~~**493 X 0.02 = 9.86** m² Sabine~~ = **493 X 0.45 = 221.85** m^2 Sabine

Total ~~**73.33** m² Sabine~~ **315.4** m^2 Sabine

Half the audience + Half empty
Cane Chairs =61.5 m^2 Sabine

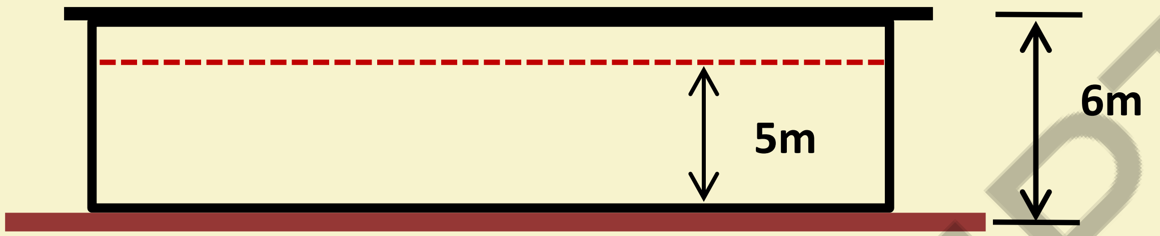
Sα = (315.4 + 61.5) = 376.9

$$RT = \frac{0.16 \times V}{S\alpha} = \frac{0.16 \times 2700}{376.9} = 1.15$$

Case: II

Calculation of Reverberation Time

Doors & Windows are covers with heavy curtail having α = 0.65
Wall is treated with Sound Absorption tiles having α = 0.45
A suspended Ceiling is provided with acoustical tiles having α = 0.3
The hanging depth of the suspended ceiling is 1m



SECTION

New Volume of the Room = 15 X30 X 5 = **2250m^3**

New surface area of the Wall (exposed to sound) = [2X(15+30)]X5 - (20+27) = **403m^2**

Case: II

Calculation of Reverberation Time

Calculation of Total Absorption of interior surface area

Door : = **20 X 0.65 = 13** m^2 Sabine

Window: = **27 X 0.65 = 17.55** m^2 Sabine

Ceiling: = ~~**450 X 0.02 = 9.00** m^2 Sabine~~ = **450 X 0.3 = 135** m^2 Sabine

Floor: = **450 X 0.12 = 54.00** m^2 Sabine

Wall: = ~~**493 X 0.45 = 221.85** m^2 Sabine~~ = **403 X 0.45 = 181.85** m^2 Sabine

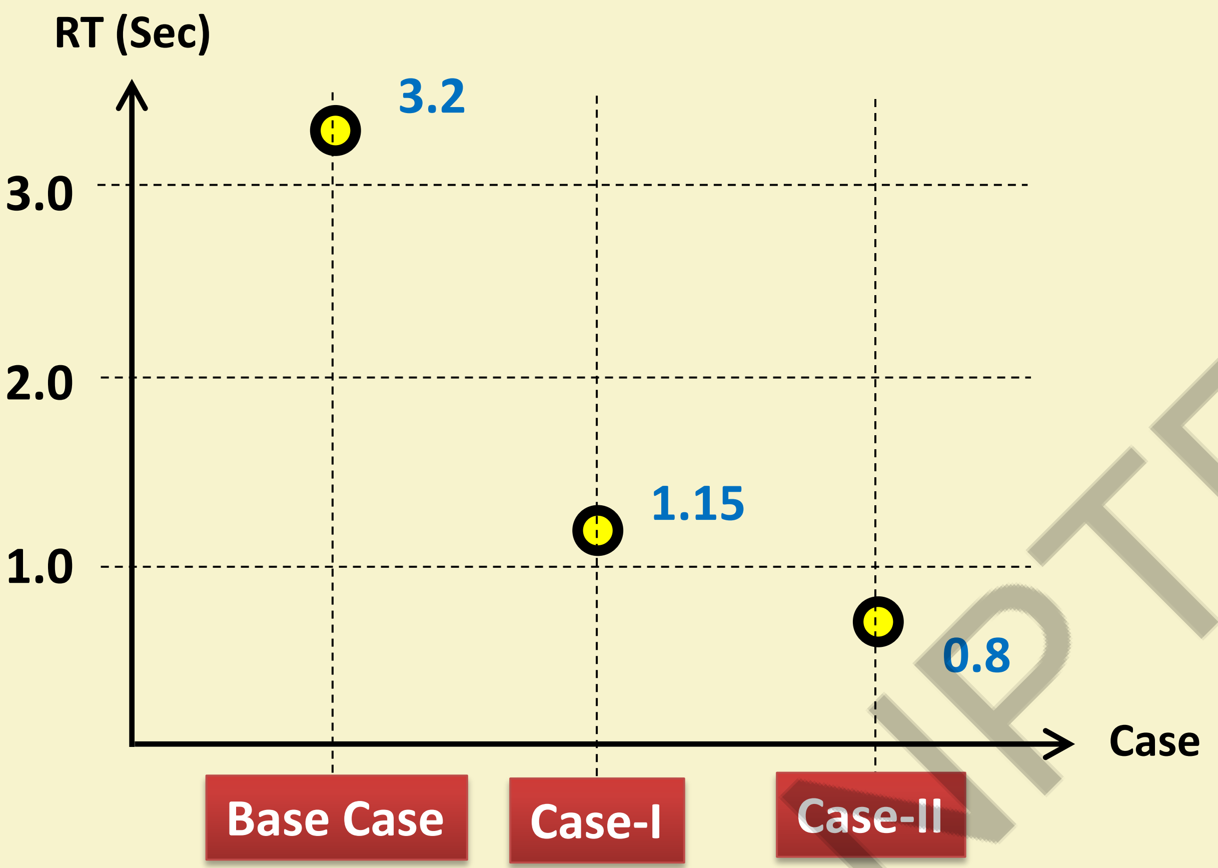
Total ~~**315.4** m^2 Sabine~~ **400.9** m^2 Sabine

Half the audience + Half empty Cane Chairs =61.5 m^2 Sabine

Sα = (400.9 + 61.5) = 462.4

$$RT = \frac{0.16 \times V}{S\alpha} = \frac{0.16 \times 2250}{462.4} = 0.8$$

Calculation of Reverberation Time



Base Case

All Surfaces Un-treated

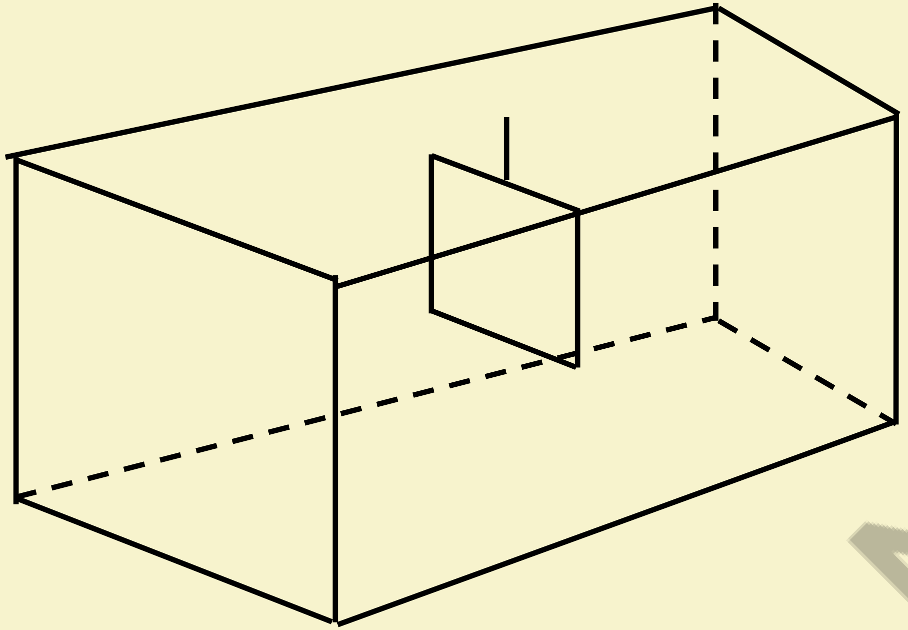
Case-I

Wall is treated and Curtains in Doors and Windows

Case-II

Treated Suspended at 1 m depth Door, Window & Wall as previous

Method-I: Determination of Sound Absorption Coefficient of a panel



Empty Room

$$RT_1 = \frac{0.16\times V}{S\alpha} \Rightarrow S\alpha = \frac{0.16\times V}{RT_1}$$

Empty Room + an additional hanging absorber panel (A, α_{new})

$$RT_2 = \frac{0.16\times V}{(S\alpha + A\alpha_{new})} \Rightarrow (S\alpha + A\alpha_{new}) = \frac{0.16\times V}{RT_2}$$

$$A\alpha_{new} = \frac{0.16\times V}{RT_2} - S\alpha = \frac{0.16\times V}{RT_2} - \frac{0.16\times V}{RT_1}$$

$$\boxed{\alpha_{new} = \frac{0.16\times V}{A}\left(\frac{1}{RT_2} - \frac{1}{RT_1}\right)}$$

Method-II: Determination of Sound Absorption Coefficient of a panel

Application of RT

A portion of area – A is treated with α_1

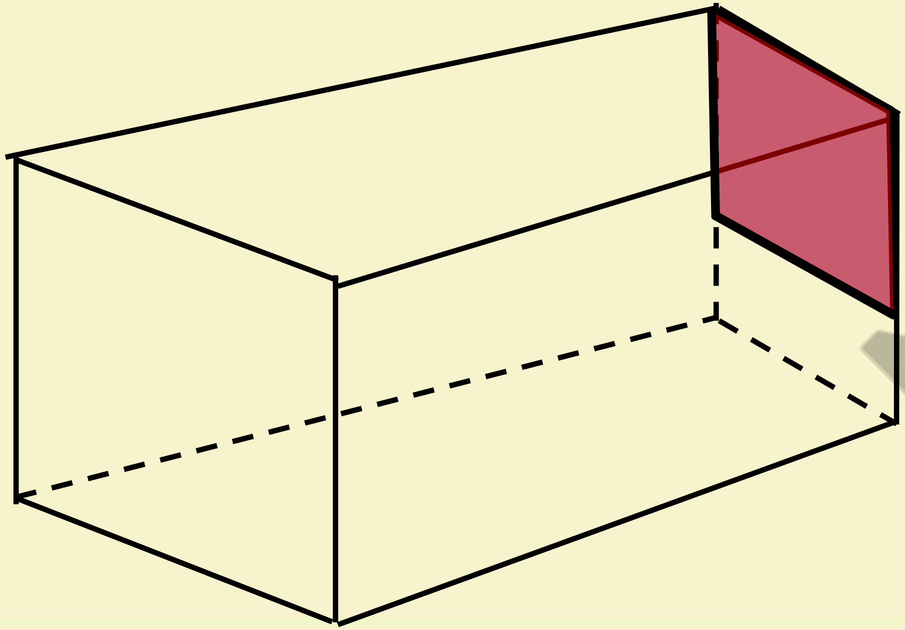
Known Value : α_1

$$RT_1 = \frac{0.16 \times V}{(S-A)\alpha + A\alpha_1}$$

The same portion of area – A is treated with α_2

Unknown Value : α_2

$$RT_2 = \frac{0.16 \times V}{(S-A)\alpha + A\alpha_2}$$



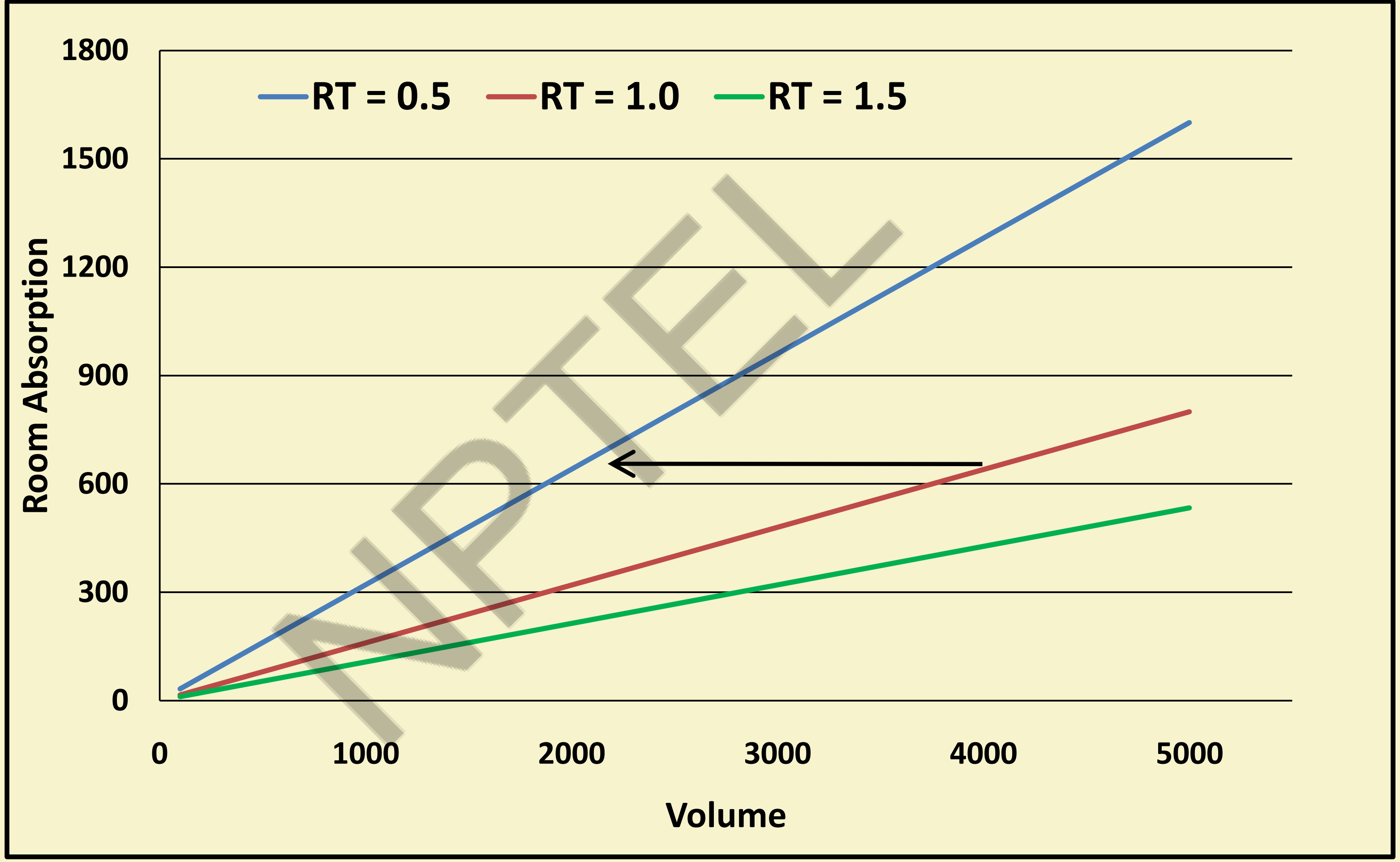
$$(S-A)\alpha = \left(\frac{0.16 \times V}{RT_1} - A\alpha_1\right) = \left(\frac{0.16 \times V}{RT_2} - A\alpha_2\right)$$

$$\Rightarrow \left(\frac{0.16 \times V}{RT_1} - A\alpha_1\right) = \left(\frac{0.16 \times V}{RT_2} - A\alpha_2\right)$$

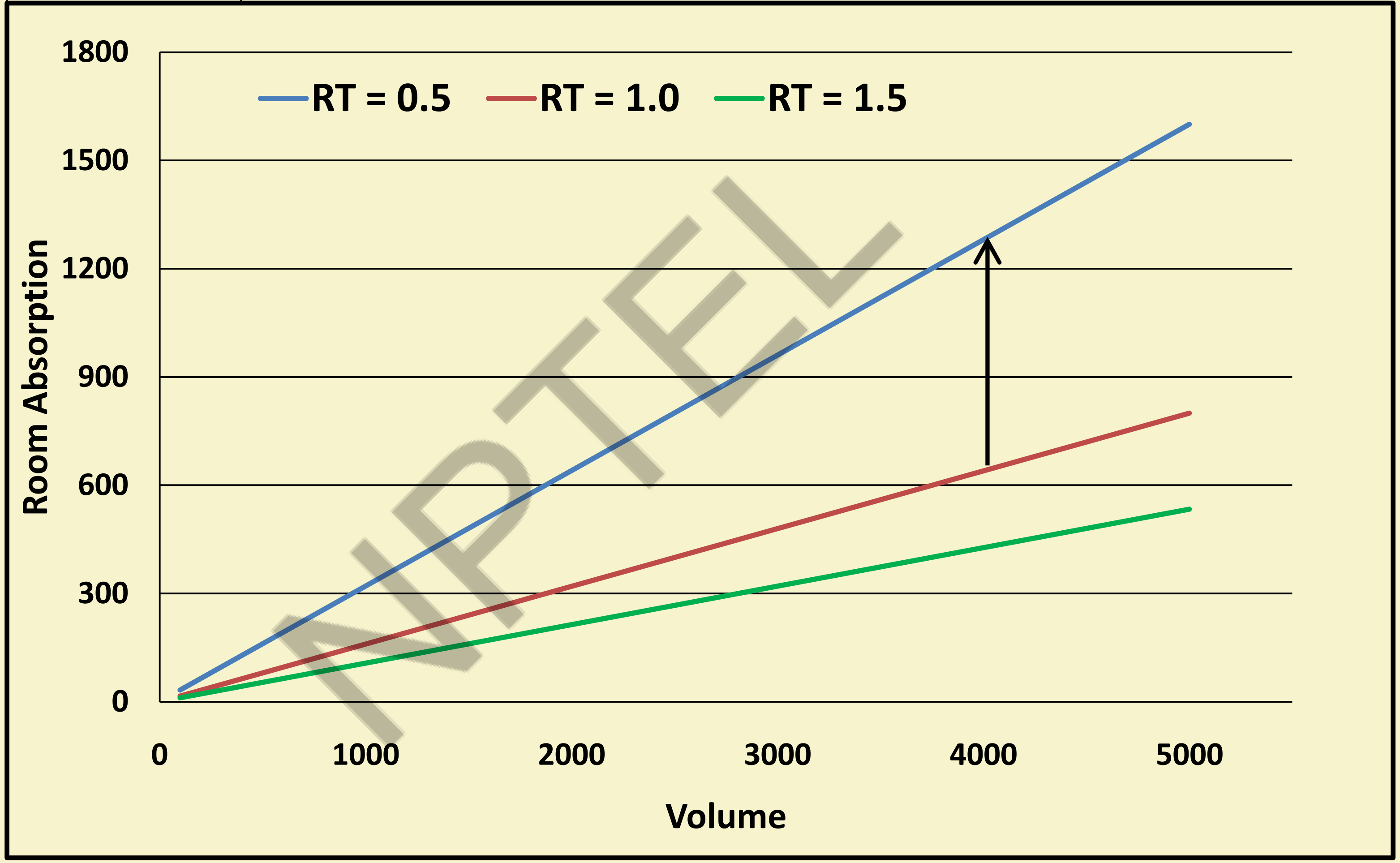
$$\Rightarrow A(\alpha_2 - \alpha_1) = 0.16 \times V\left(\frac{1}{RT_2} - \frac{1}{RT_1}\right)$$

$$RT_{60} = \frac{0.16 \times V}{\sum S\alpha}$$

Option - 1 Reduce the room volume



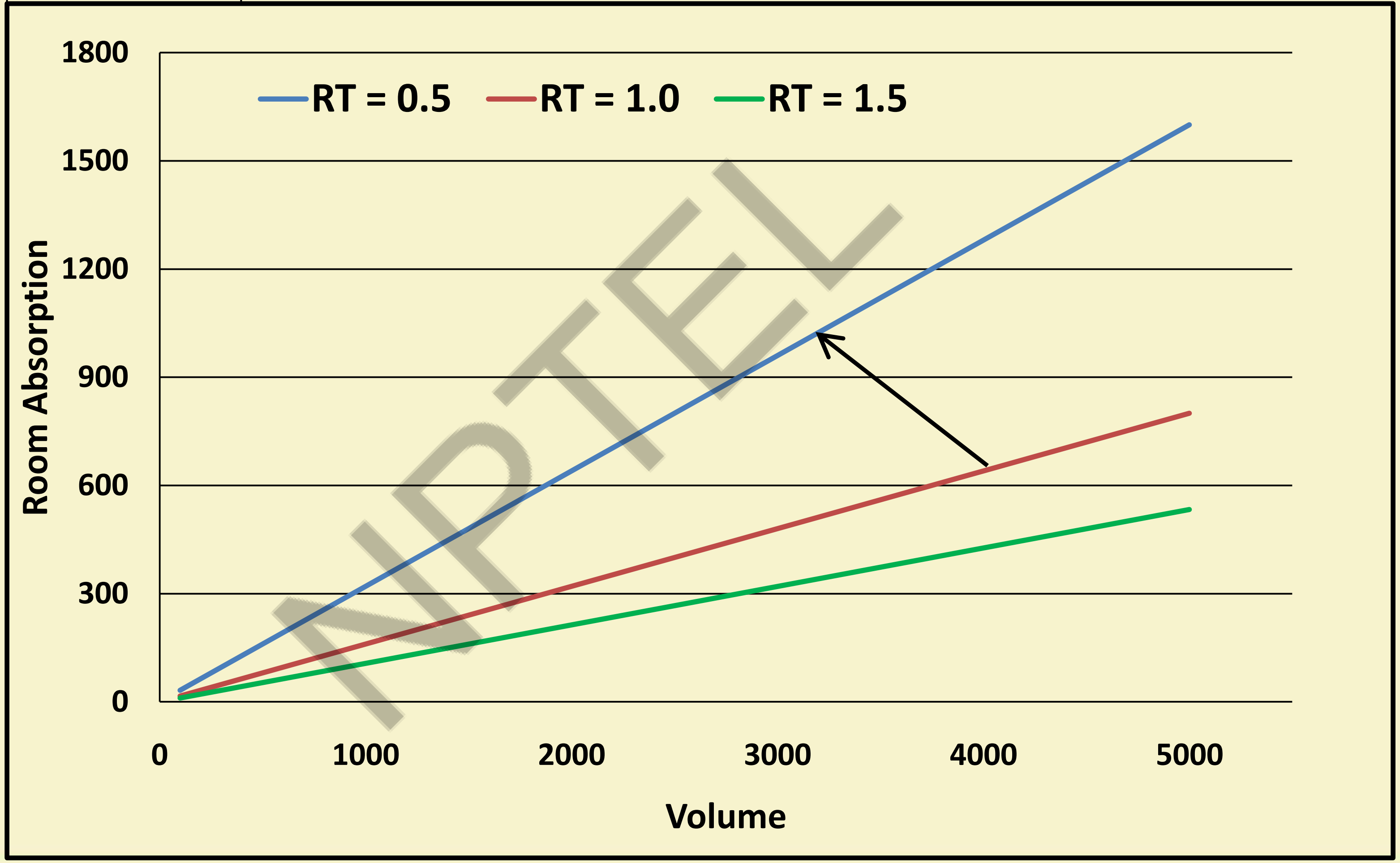
Option - 2 Increase the Room Absorption



Design Fundamentals

Option - 3

Reduce Room Volume & Increase the Room Absorption



Home Work

Calculate the RT of a room in empty condition and having following data:
Dimension: 10m X 20m X 5m (Height)
All surfaces are having a sound absorption coefficient 0.1

What should be the sound absorption coefficient of the acoustical tiles that need to render only in the ceiling to achieve the design Reverberation time of the Room as 1 sec.

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2. **Architectural Acoustics**, K.B.Genn, Burel & Kjaer, 2nd Edition
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End of Lecture 10: Application of Reverberation Time