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VTAF 01 – Sound in Buildings and Environment

12. Room Acoustics 2 (Properties)

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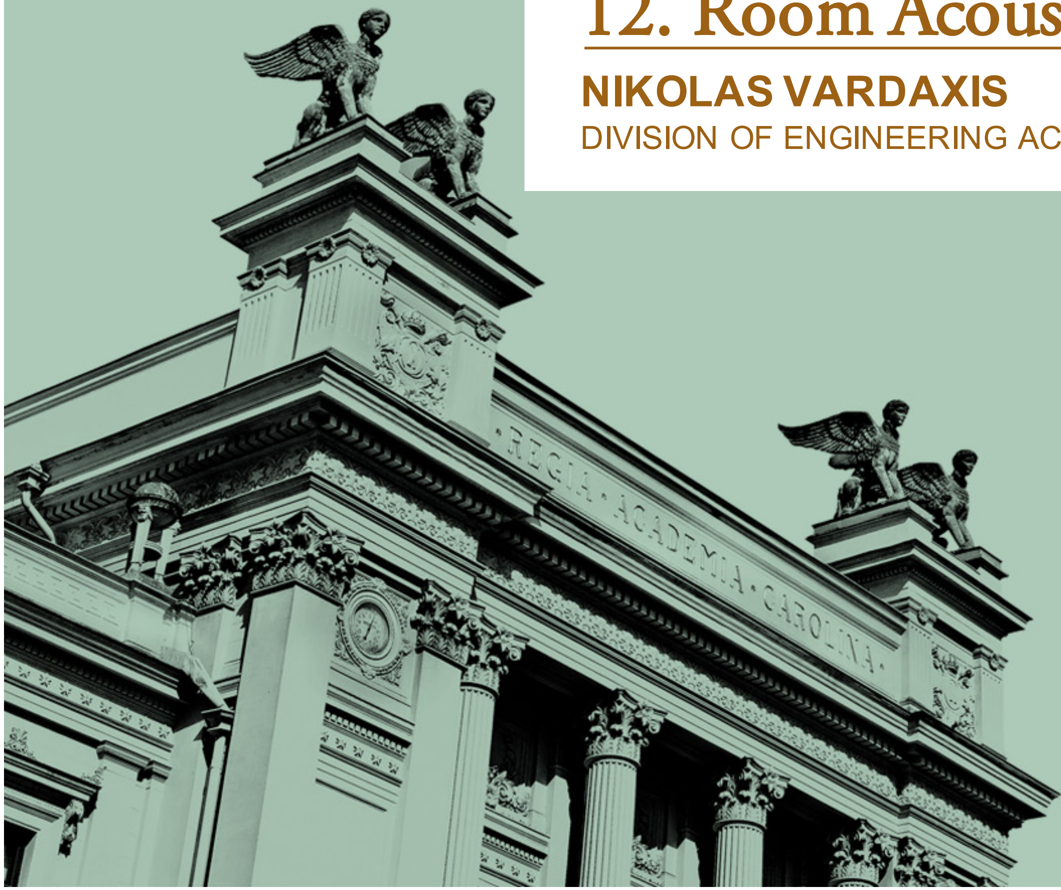
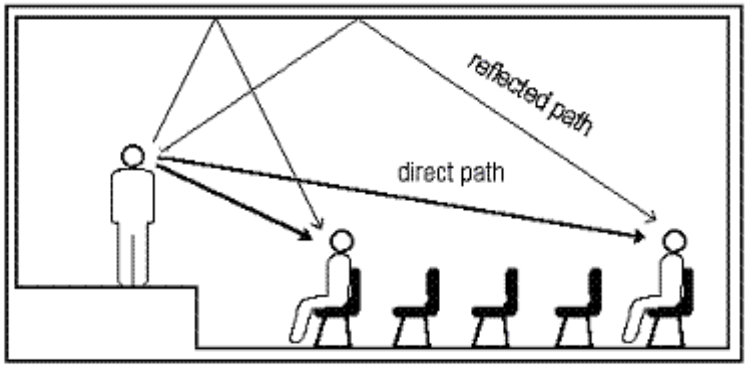
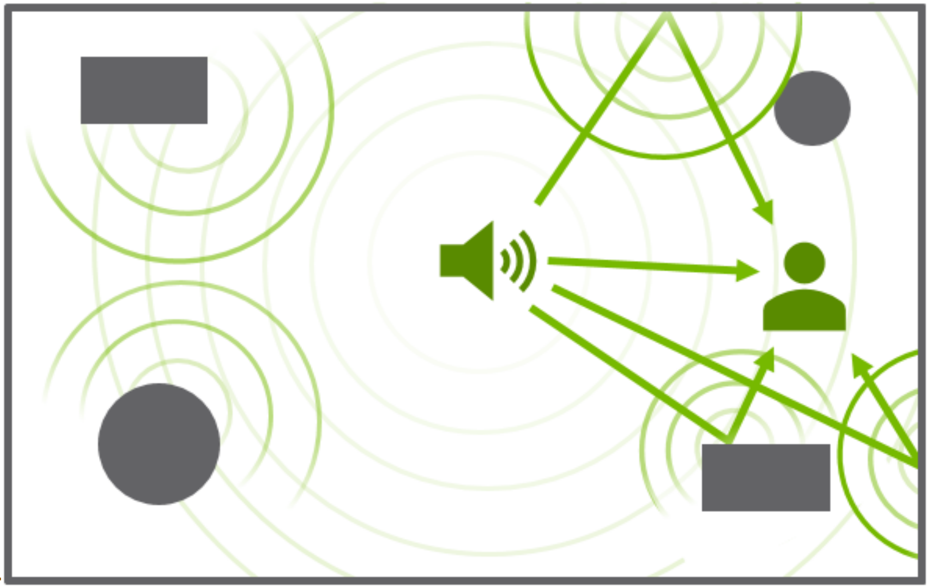


RECAP: Room acoustics definition

- **Definition**
  - Dealing with behavior of sound in enclosed spaces

- Life in closed spaces or living environments
- We hear not only the source signal but also its reflections
- Multiple propagation paths in closed spaces





RECAP: important parameters

- T30, EDT: Reverberation
  - T60 = 2*T30
- C50: Clarity of speech (D50 - definition)
- C80: Clarity of music
- LF, LFC: Spatial impression
- Desired parameters depend on the purpose
  - Optimal T60 for speech: 0,4 -0,6 s
  - Optimal T60 for music: > 1 s

Introduction

- Limiting surfaces (walls, floor and ceiling) are the relevant elements of a room.
- The sound field is influenced by
  - geometry, thus surfaces
  - their absorption properties and
  - their diffusivity.
- To assess the sound field three methods are in use…

What is reverberation time? (efterklangstid)

Reverberation time: 0 s 0,5 s 1,2 s 2,0 s

Female song

Anechoic recording

With reverb

Values for RT

Noise recommendations:

	Small – Big rooms
Working space	T = 0.5 - 1.5 s
Canteen	T = 0.5 - 1.0 s
Office	T = 0.4 - 0.8 s

Speech inteligibility	(taluppfattbarhet):
	Small – Big rooms
Cinema (Bio)	T = 0.6 - 1.2 s
Bio, THX	T = 0.3 - 1,0 s
Classroom	T = 0.6 - 0.8 s
Meeting room	T = 0.6 - 0.8 s

Introduction

- ***Statistical room acoustics***
  - a diffuse sound field as a central simplification. The analysis focuses on the ratio of direct and diffuse sound and deals with the reverberation. Walls, floor and ceiling are described by the statistical absorption coefficient α_s.
- ***Geometrical room acoustics***
  - models the sound propagation as energy that propagates along straight sound rays.
  - high frequency approximation that holds for wave lengths that are much smaller than the dimensions of the elements of the room.
  - The reflection properties are defined by an absorption coefficient and a diffusivity to describe the scattering behavior.

Introduction

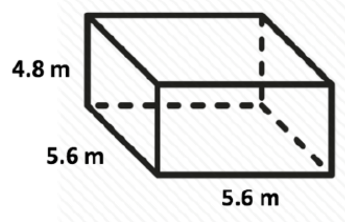
- *Statistical room acoustics*

Usually in Octave bands!

Example 1 (found in older exams 2016)

In an empty reverberant room with the dimensions 5.6 × 5.6 × 4.8 m3, the following reverberation times have been measured for different frequencies:

f (Hz)	125	250	500	1000	2000	4000
T_{60} (s)	8.0	7.8	7.3	6.7	6.4	5.8



a) Calculate the average absorption coefficient of the walls / floor / ceiling for each frequency.

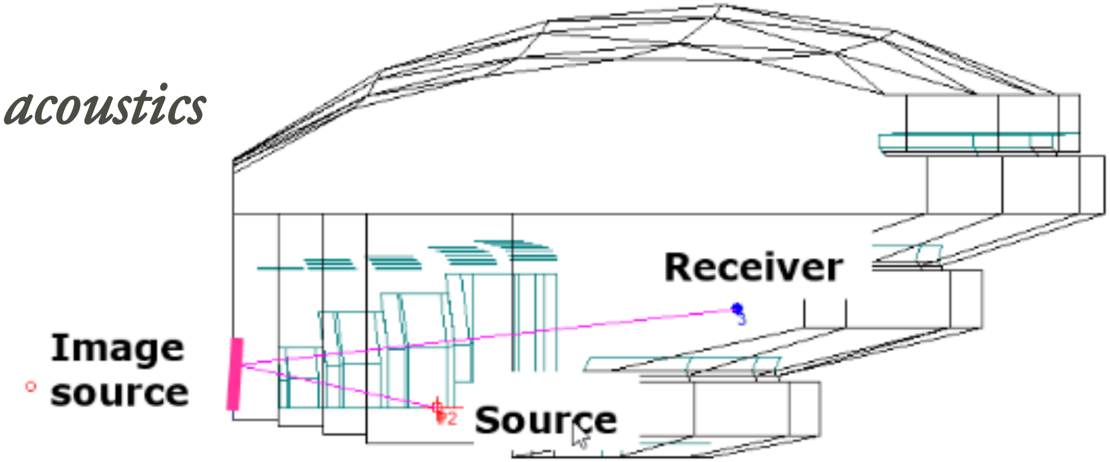
$$RT = 0.16\,\frac{V}{\sum aS} = \frac{0.16\,V}{a(2*5{,}6*5{,}6)+a(4*4{,}8*5{,}6)} = \frac{0.16\,V}{a*S_{tot}} \leftrightarrow a = \frac{0.16\,V}{RT*S_{room}} = \frac{0.16*150.5}{RT*170.24}$$

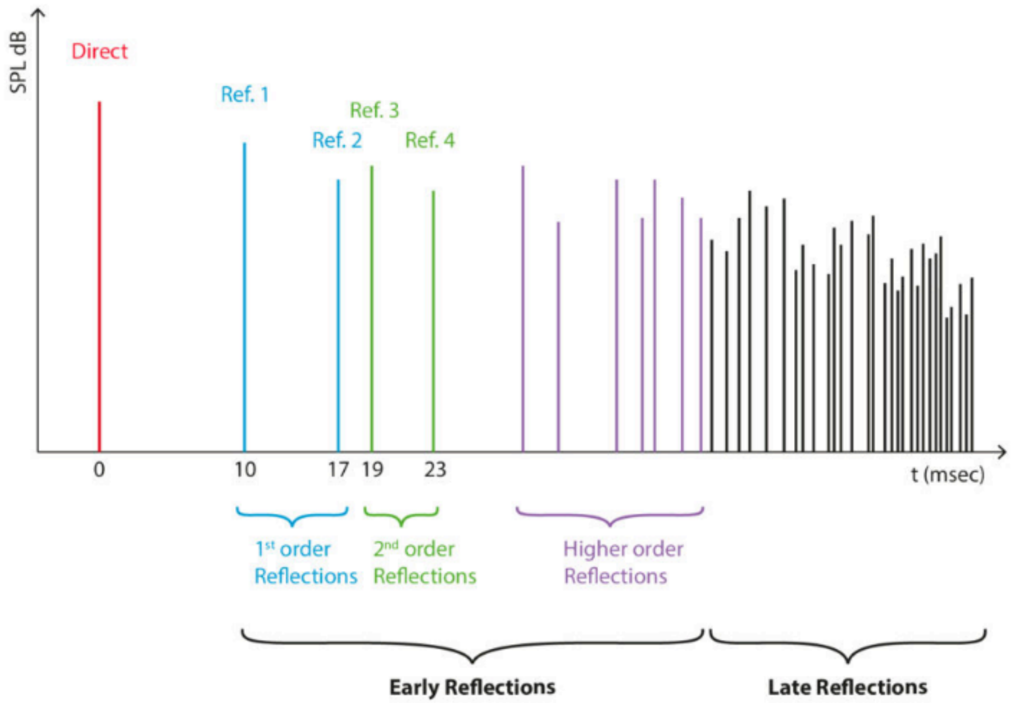
Finally, using the given values for RT (T_{60}) we complete the table as:

f (Hz)	125	250	500	1000	2000	4000
T_{60} (s)	8.0	7.8	7.3	6.7	6.4	5.8
a *(Hz)*	*0.0177*	*0.0181*	*0.0194*	*0.0211*	*0.0221*	*0.0244*

Introduction

- *Geometrical room acoustics*





[ODEON Room acoustics software]

Introduction

Wave based room acoustics

- Solving the wave equation.
  - **The sound propagation is modeled physically correct and considers wave phenomena such as resonance, interference and diffraction.**
- However analytical solutions are available only for simple geometries.
- Solutions with numerical approximations such as the:
  - **Boundary Element method (BEM) or**
  - **Finite Element method (FEM)**
  - **Big computational efforts**
  - **Limited to small geometries or low frequencies.**
- The boundary surfaces have to be described with their proper impedances. A difficulty arises as in practice this information is usually not available.

Large rooms

- Sound fields in large rooms are characterized by a high density of room resonances already at relative low frequencies.
  - Statistical room acoustics

Statistical room acoustics

- Based on the concept of a diffuse sound field, which means that
  - » the sound energy density in the whole room is constant.
  - » there is no predominant sound incident direction –
  - » Equal statistical distribution of reflections

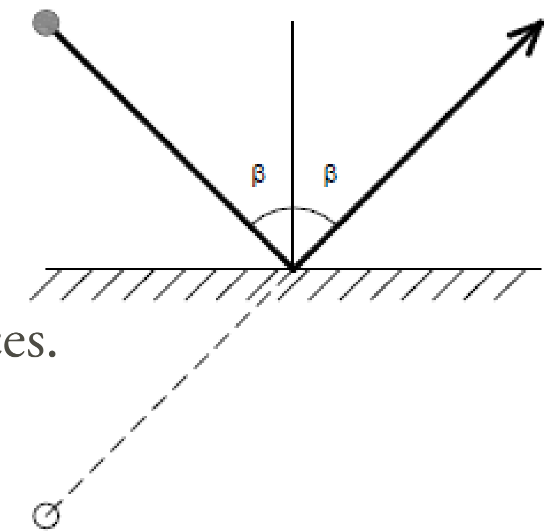
Statistical room acoustics

- Absorption of audience
  - audience contributes significantly or even dominates the absorption
  - exact absorption coefficient depends on different factors such as density and arrangement of the seating, the upholstering of the seats or the type of clothes people are wearing

Hz	125	250	500	1000	2000	4000
upholstered seat, row spacing 1.15 m	0,30	0,35	0,50	0,60	0,70	0,70

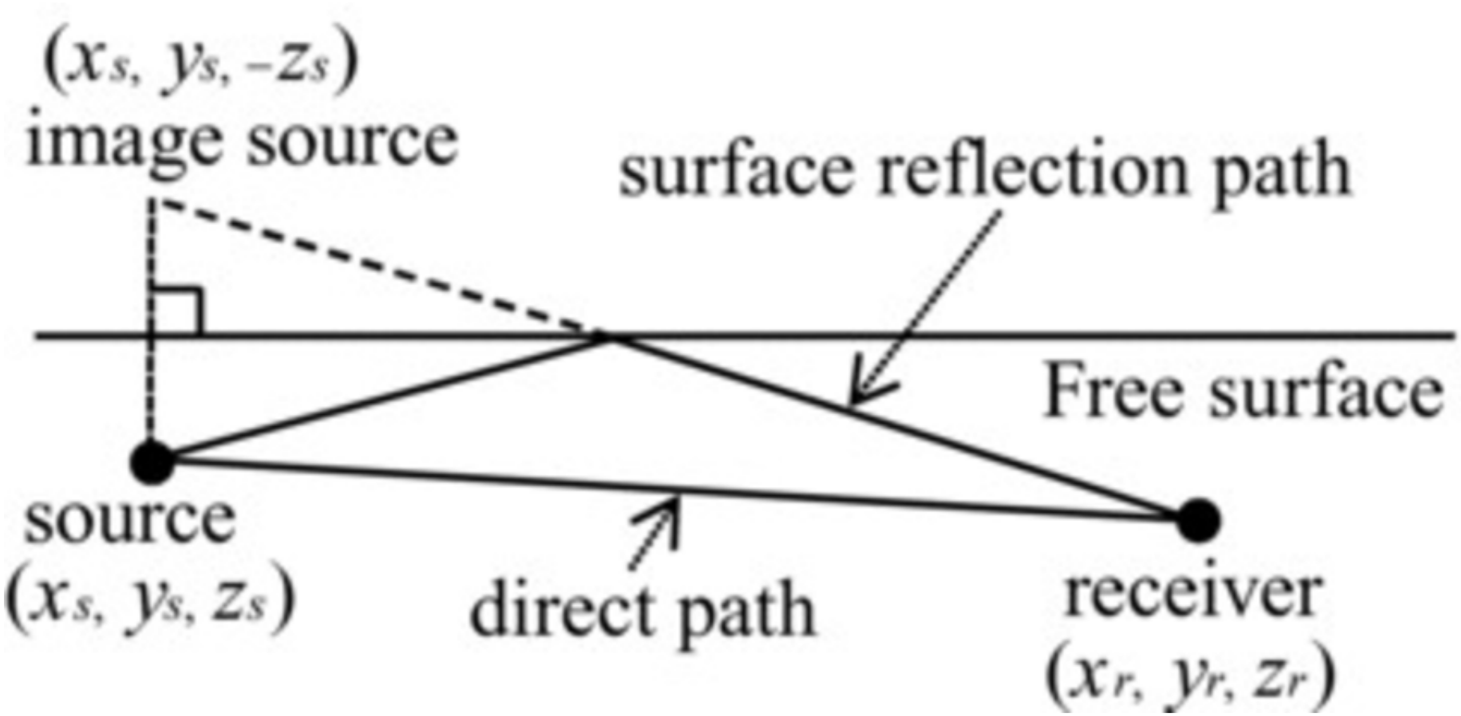
Geometrical acoustics

- Reflection at plane surfaces, specular sources
- If a sound ray hits a surface, it looses a certain amount of its energy depending on the absorption coefficient of the corresponding surface.
- The remaining energy is reflected according to the law of reflection
  - angle of incidence = angle of reflection.

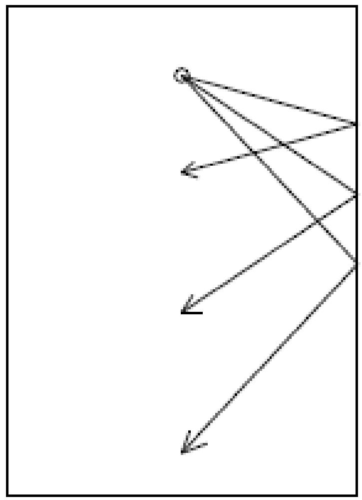


- The sound path is determined with mirror sources.

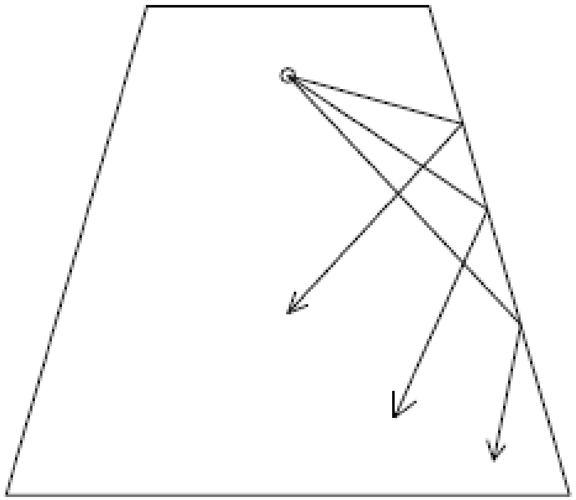
Reflection at plane surfaces, specular sources



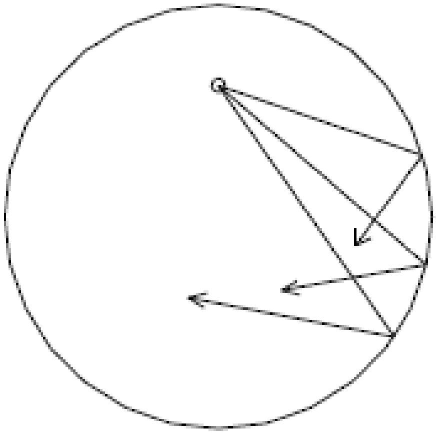
Effect of basic reflections



Rectangle:
Lateral reflections occur in the entire space

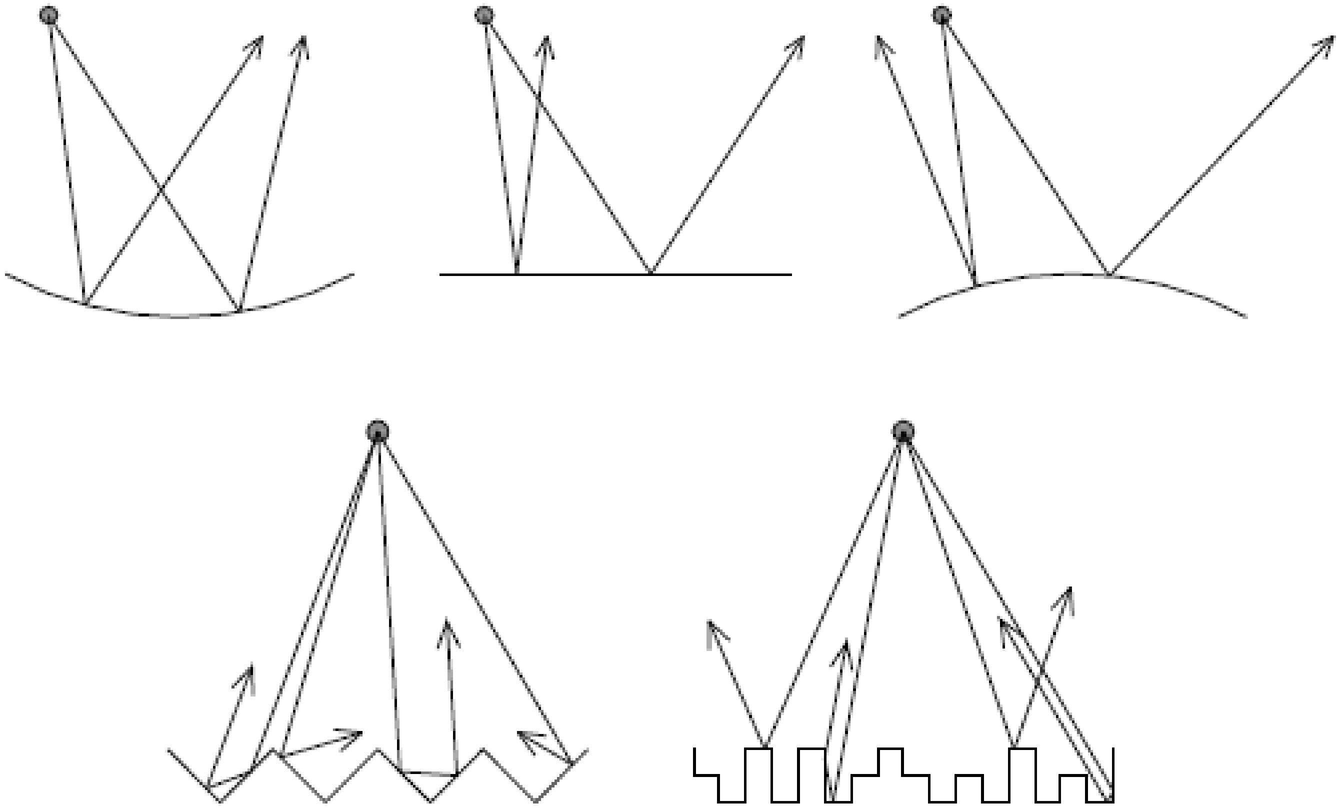


Fan-shape:
Reflections scatter and are directed mainly to the rear part of the space (not in the middle)



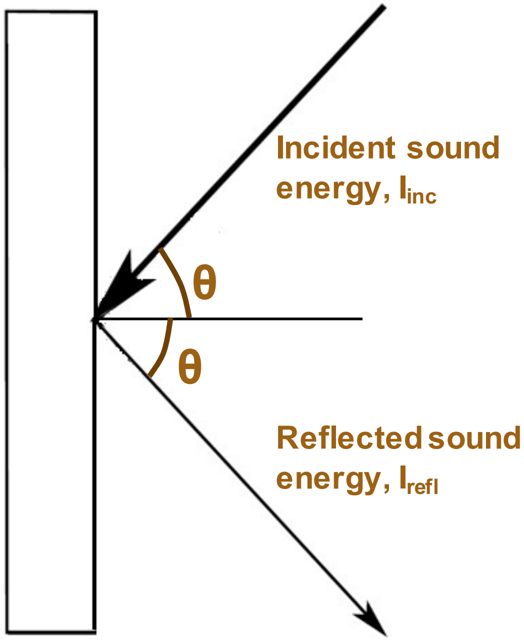
Round:
Reflections from concave surfaces cause sound to strongly focus on some parts of the space

Effects of shapes (geometry)



Reflection from a surface

- Specular reflection: Angle of reflection equals angle of incidence

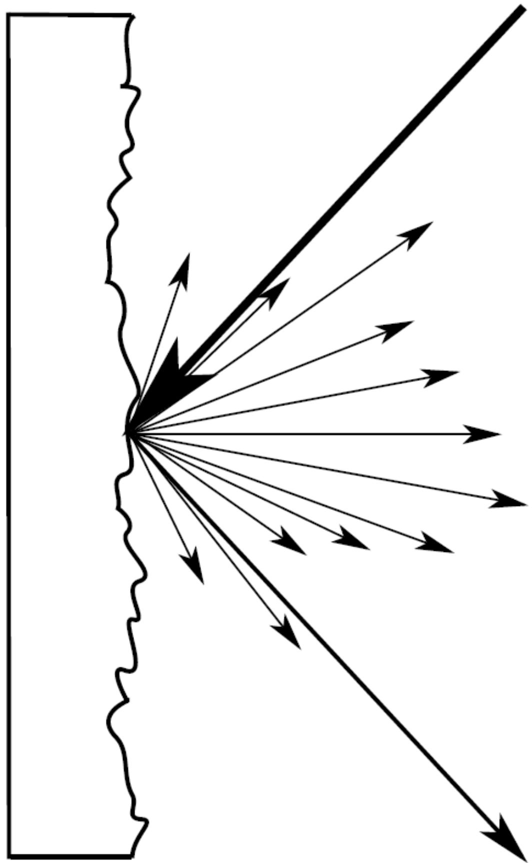


Absorption coefficient:

$$\alpha = \frac{I_{inc} - I_{refl}}{I_{inc}} = \frac{I_{abs}}{I_{inc}}$$

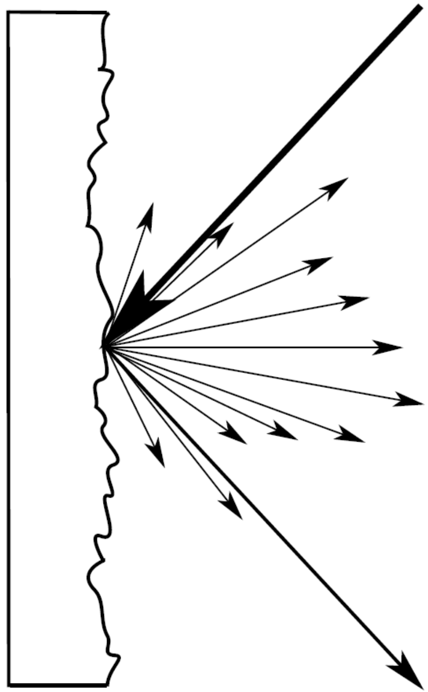
Reflection from a surface

- Diffuse reflection
  - Scattered in many directions

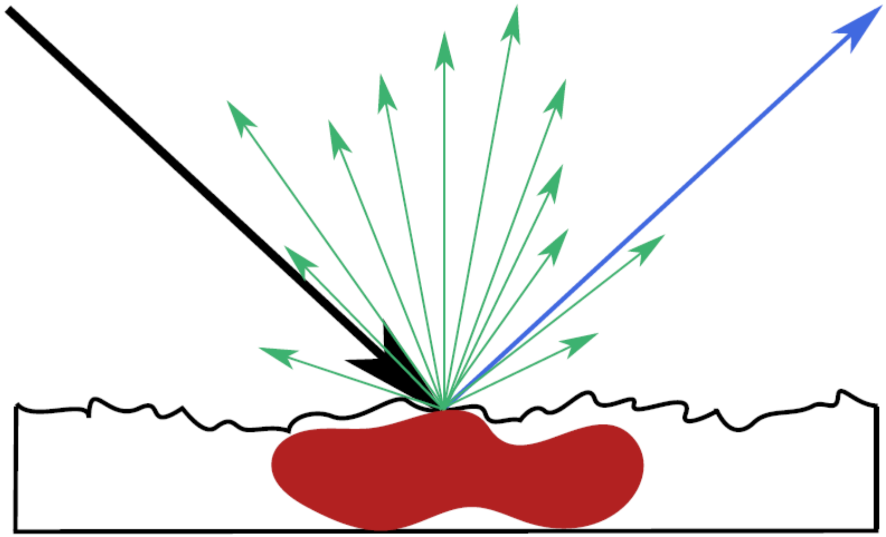


Reflection from a surface

- Scattering coefficient, *s*
- Fraction of energy which is scattered
- Always between 0 and 1



Absorption and scattering



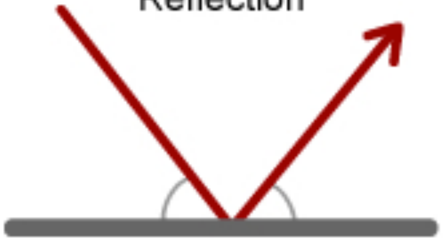
$$\alpha + (1-\alpha)\cdot(1-s) + (1-\alpha)\cdot s = 1$$

absorbed specularly reflected diffusely reflected

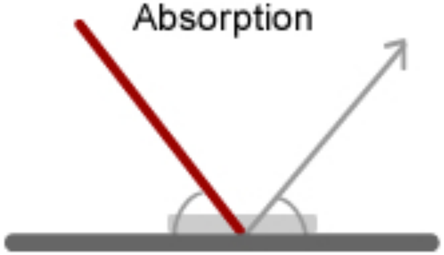
Geometrical room acoustics

- Sound properties in enclosed spaces

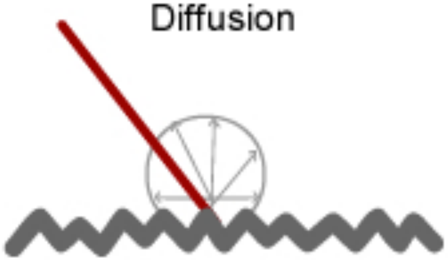
Reflection

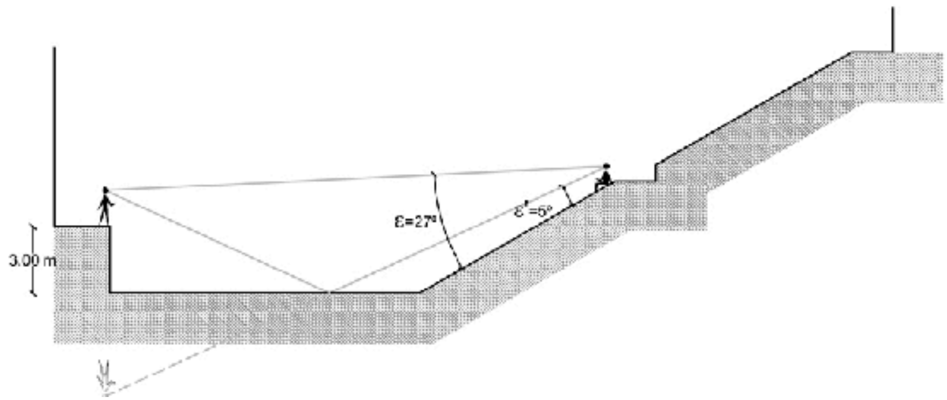


Absorption



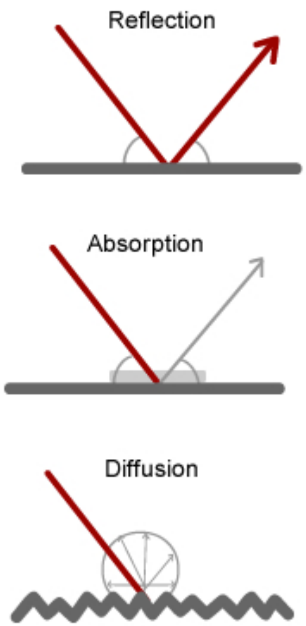
Diffusion

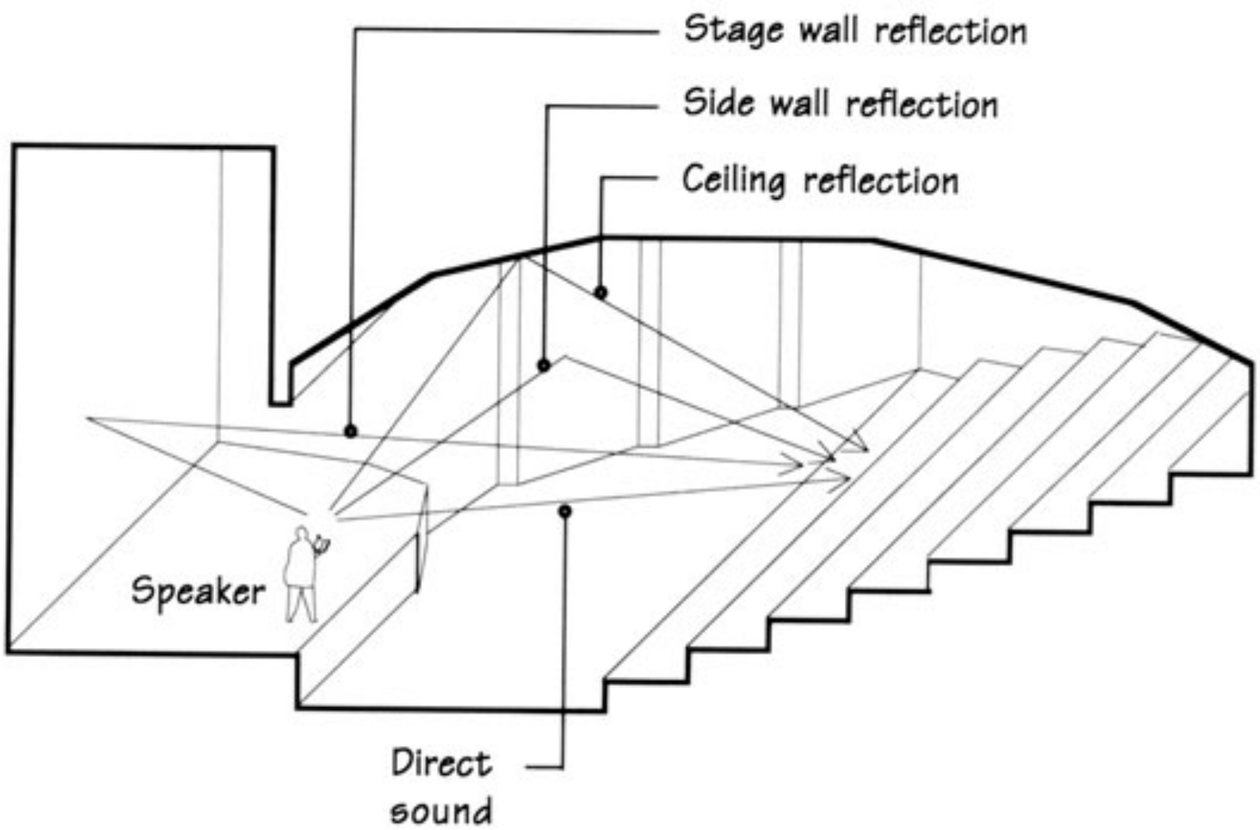




Geometrical room acoustics

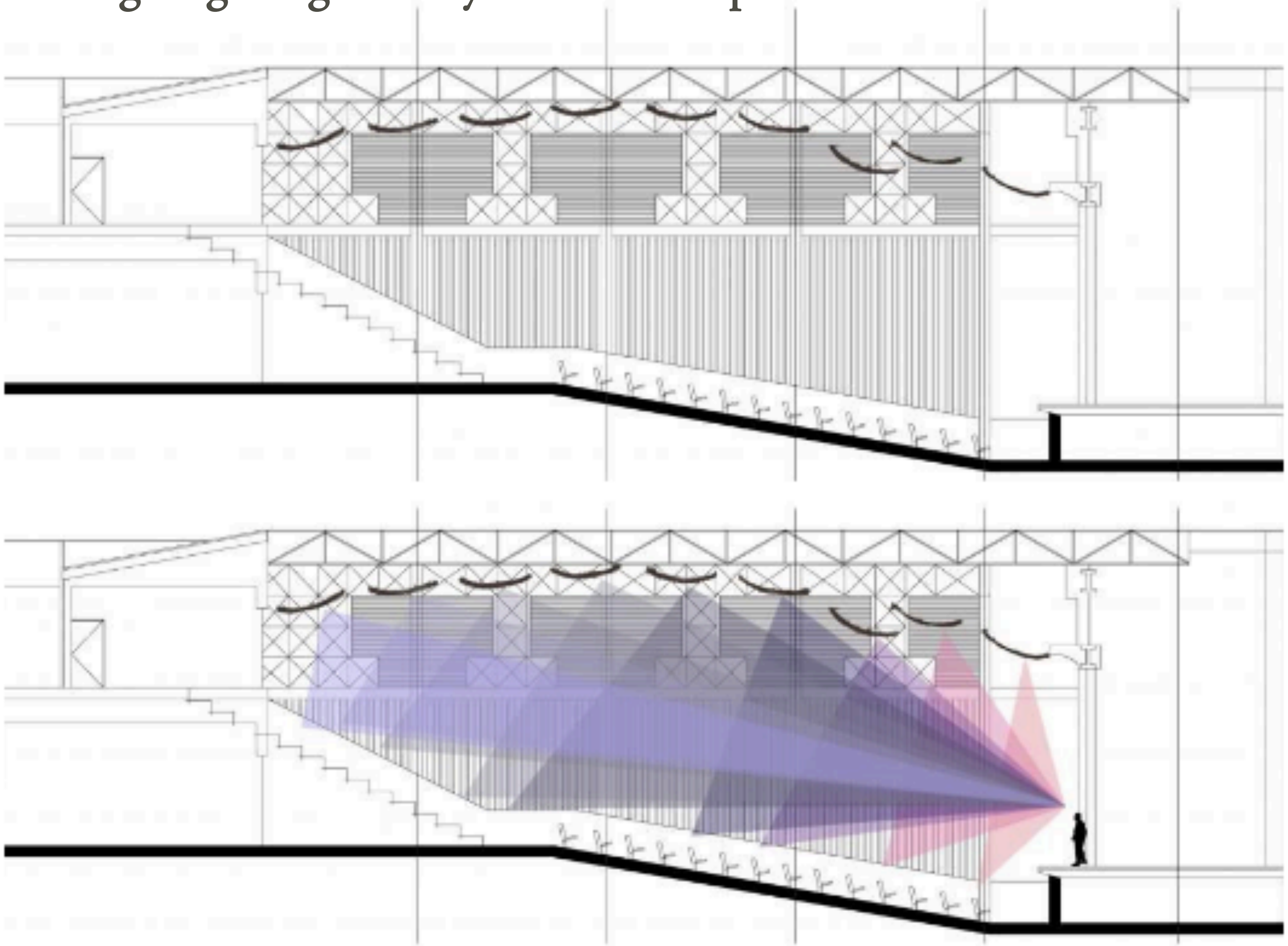
- Sound properties in enclosed spaces





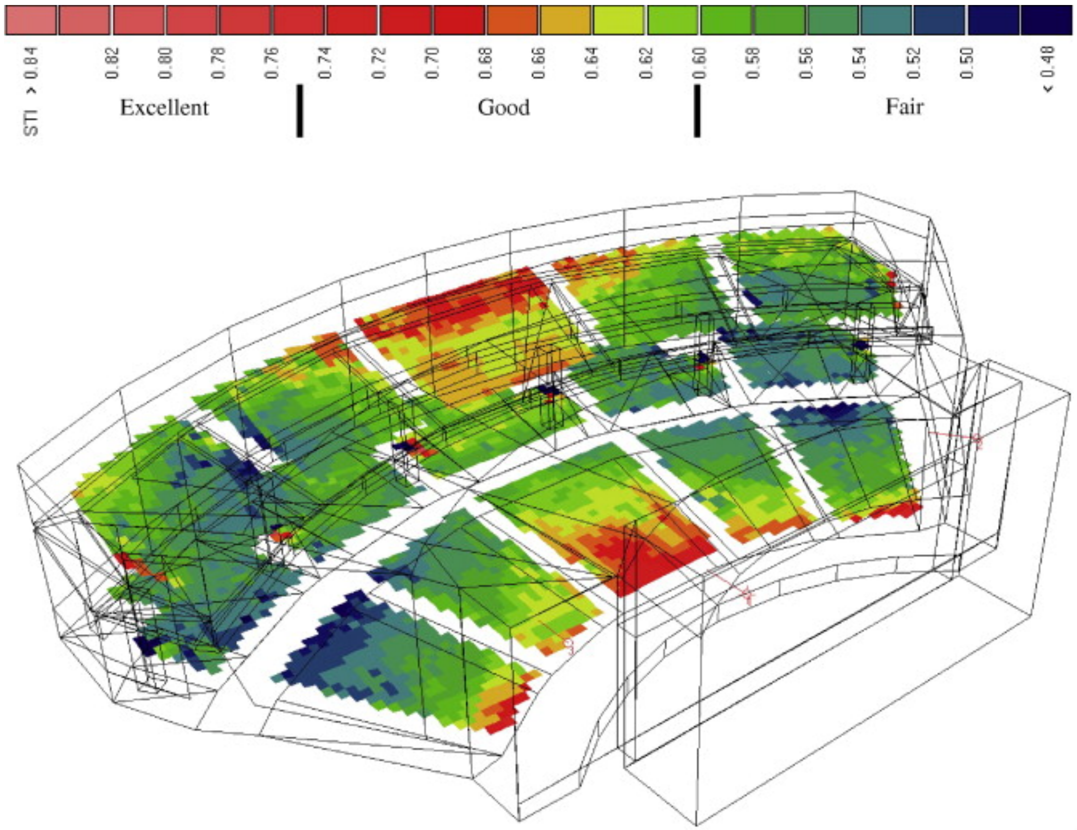
Geometrical room acoustics

- Designing the geometry in enclosed spaces

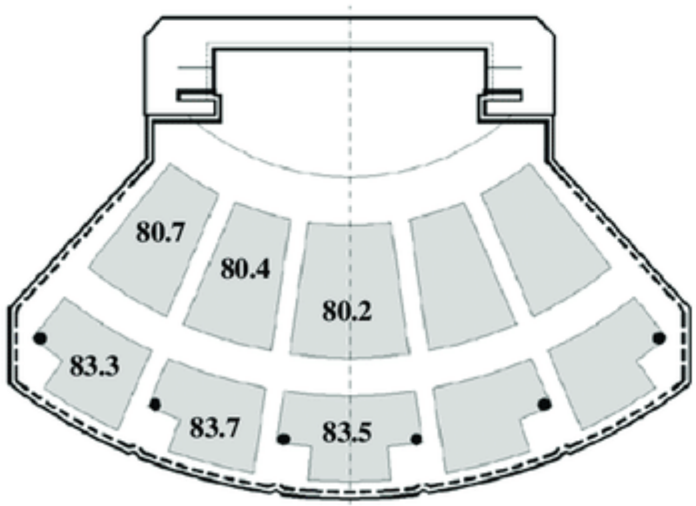


Geometrical room acoustics

- Acoustic design simulations of an auditorium

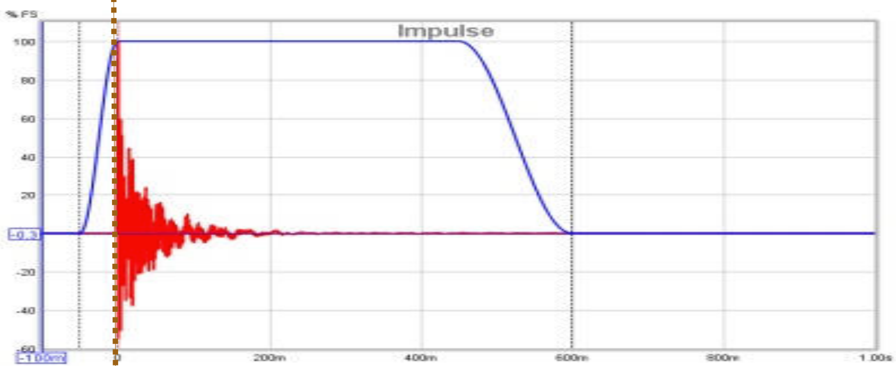


[Odeon software]

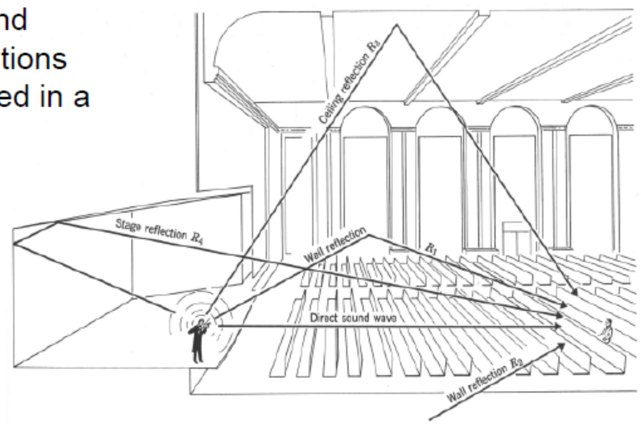


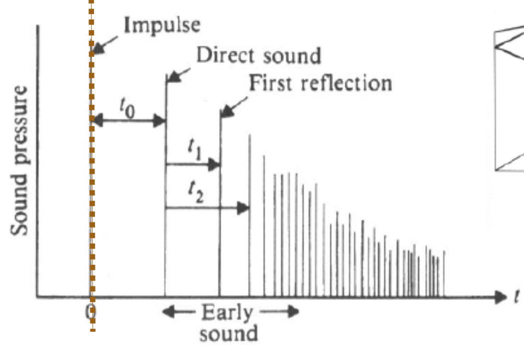
Room acoustics

- Sound field in a room
- Impulse response

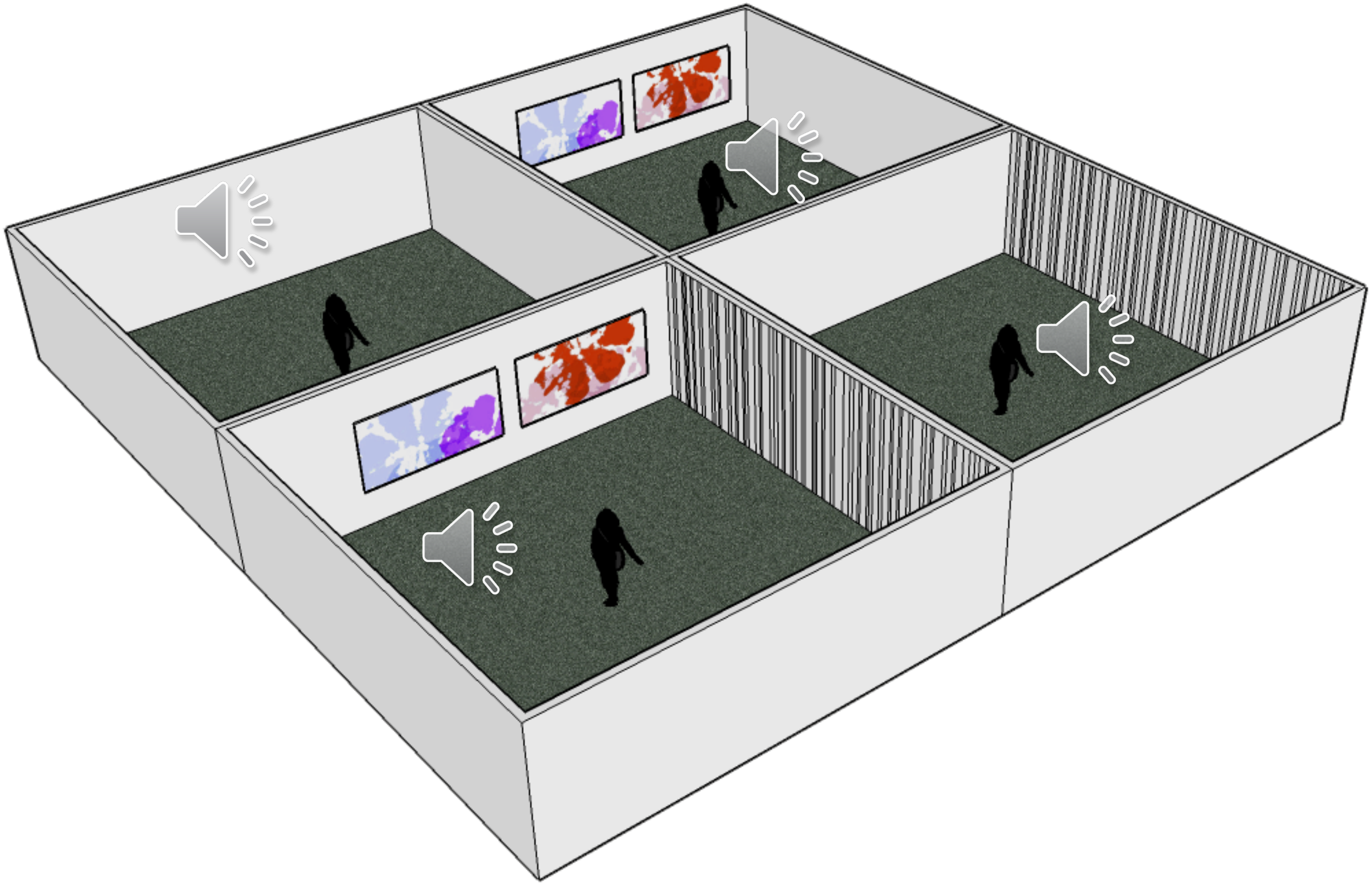


Direct sound, early reflections and reverberant sound and their relations determine how sound is perceived in a space





Sound Example



Reflection at structured surfaces, diffuse reflection and scattering

- ***For λ ≫ structure dimension s***

  → the structure has no effect

  → specular reflection

  at an 'average' plane.

- **For λ ≈ structure dimension *s***

  →the structure acts as a whole

  → diffuse reflection

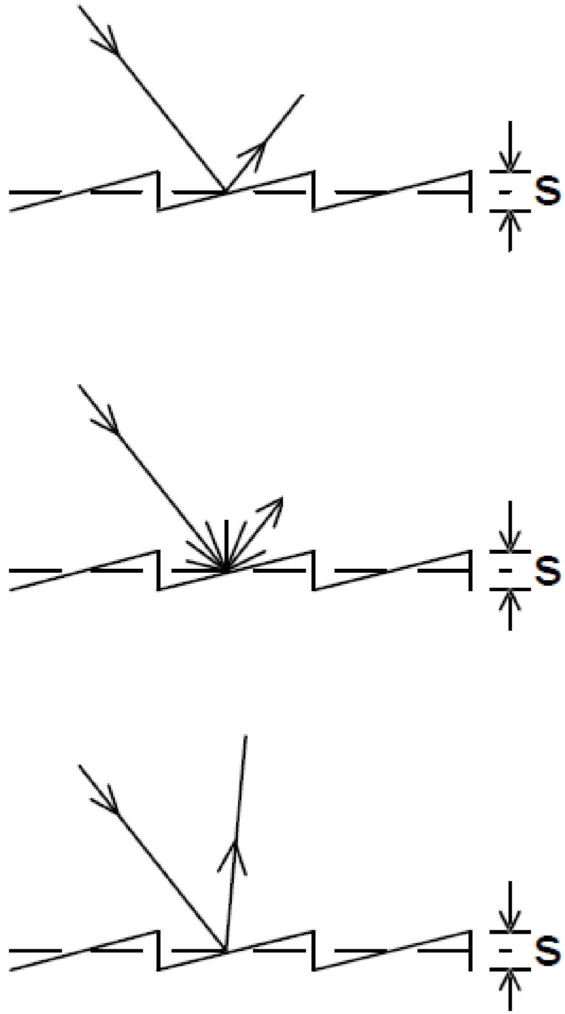
- ***For λ ≪ structure dimension s***

  → the single structure elements

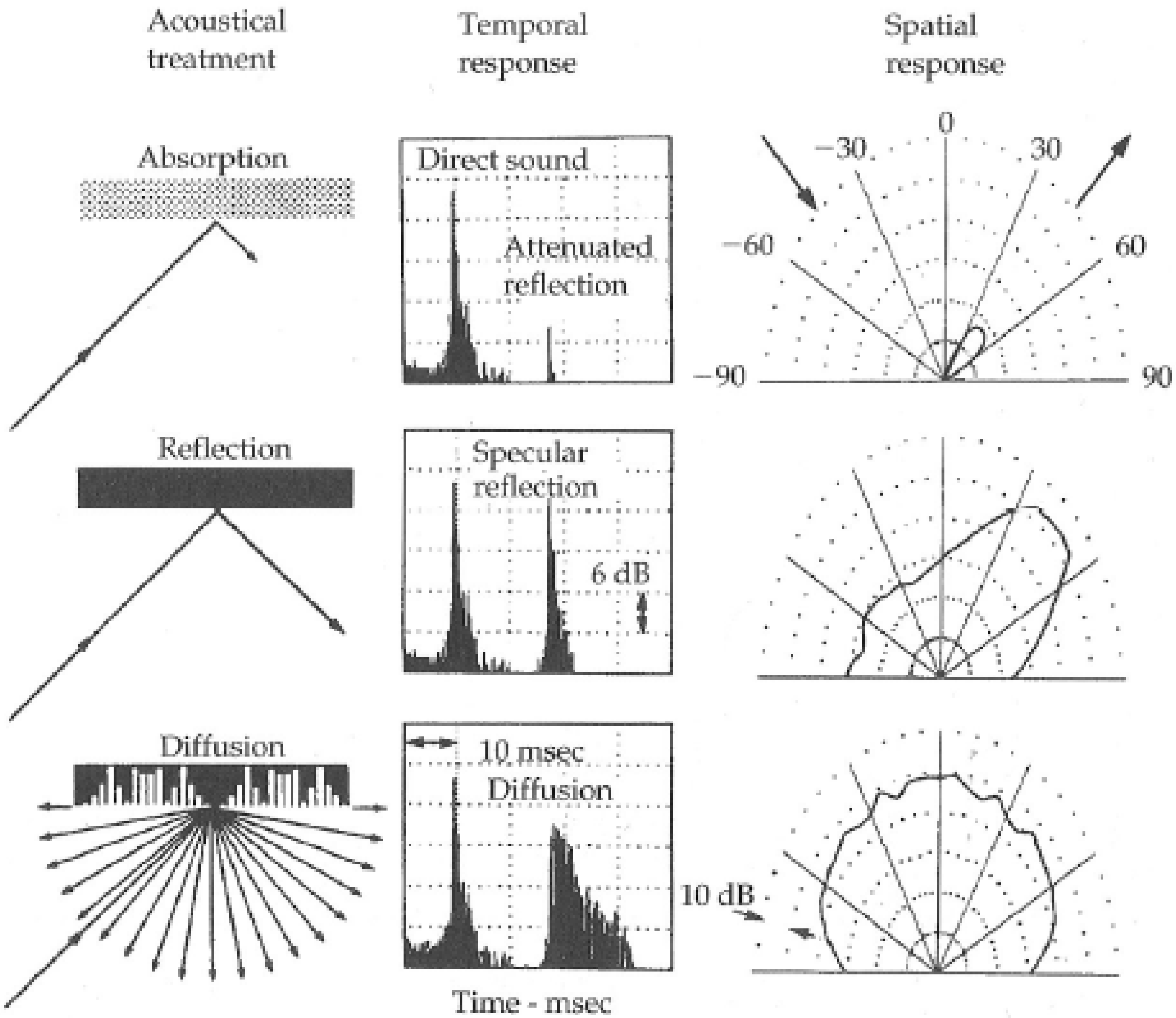
  act as reflectors

  → specular reflection at the

  structure details.

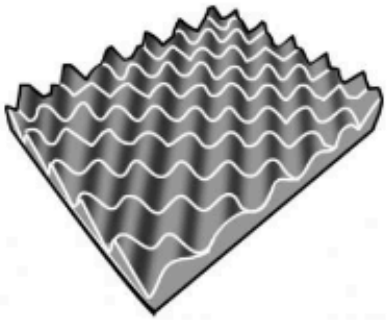


Absorption vs reflections



Room acoustics treatment

- Acoustic design of a music studio

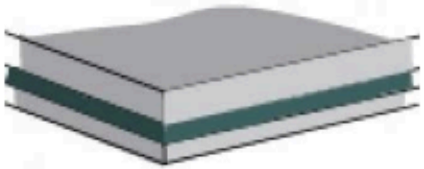


What is soundproofing?

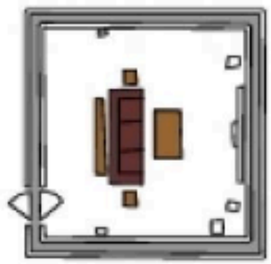
How to soundproof a home

Mechanical resonance

Soundproofing for home theatres



Soundproofing materials



Soundproofing techniques

Room acoustics treatment

- Acoustic design of a music studio

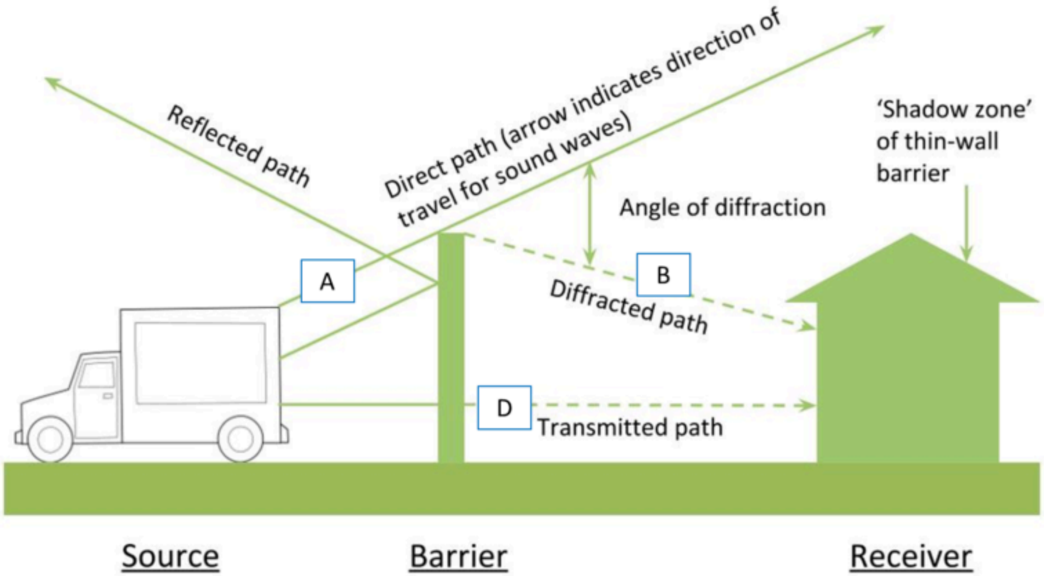
Room acoustics treatment

- Office spaces

[Ecophon solutions]

Outdoor acoustics

- Many geometrical acoustics principles can be applied for open spaces too



[Chuo Expressway Tokyo]

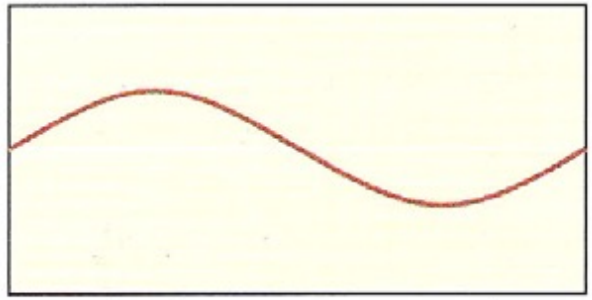
Small rooms

- The sound field in small rooms at low frequencies is dominated by discrete resonances (Eigenfrequencies) with low spectral density.
- Methods of statistical and geometrical acoustics **are not exactly applicable (Schröder frequency).**
- The wave nature of sound has to be considered explicitly with help of wave theoretical room acoustics.

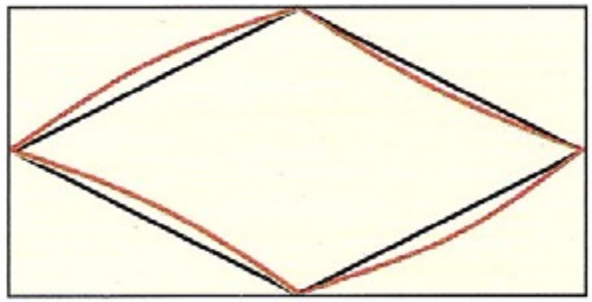
Room modes

- The sound field within a room is comprised of room resonances, called room modes
  - **Room mode = characteristic resonance of the room**
  - Three types of modes: axial, tangential, oblique
  - The amount and spacing of room modes changes with frequency
- At low frequencies there are only a few room modes, sparsely spaced.
  - So the reverberation time and sound level can vary considerably in different points in the room (consider the placement of a subwoofer in a living room)
- At high frequencies the number of room modes gets so high and their frequencies so close to one another
  - indistinguishable resonances
  - sound field approaches the ideal **diffusivity**

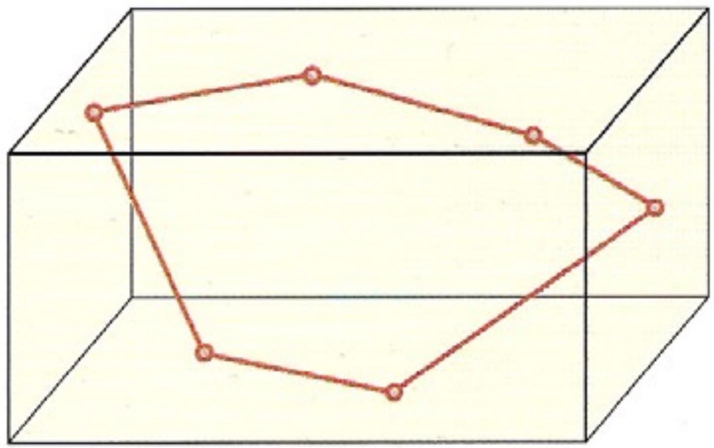
Room modes



Axial – one dimensional



Tangential – two dimensional



Oblique – three dimensional

Room modes

- The frequency, below which the sound field in a room is not diffuse (so-called Schröder frequency) depends on reverberation time and volume:

$$f_s = 2000\sqrt{\frac{T}{V}}$$

- Example, typical dewlling room: T = 0,5 s ja V = 30 m^3 → f_s = 260 Hz
- The room modes of a rectangular room can be calculated based on the dimensions of the room (L_x, L_y, L_z):

$$f_{n_x,n_y,n_z} = \frac{c}{2}\sqrt{\left(\frac{n_x}{L}\right)^2 + \left(\frac{n_y}{B}\right)^2 + \left(\frac{n_z}{H}\right)^2}$$

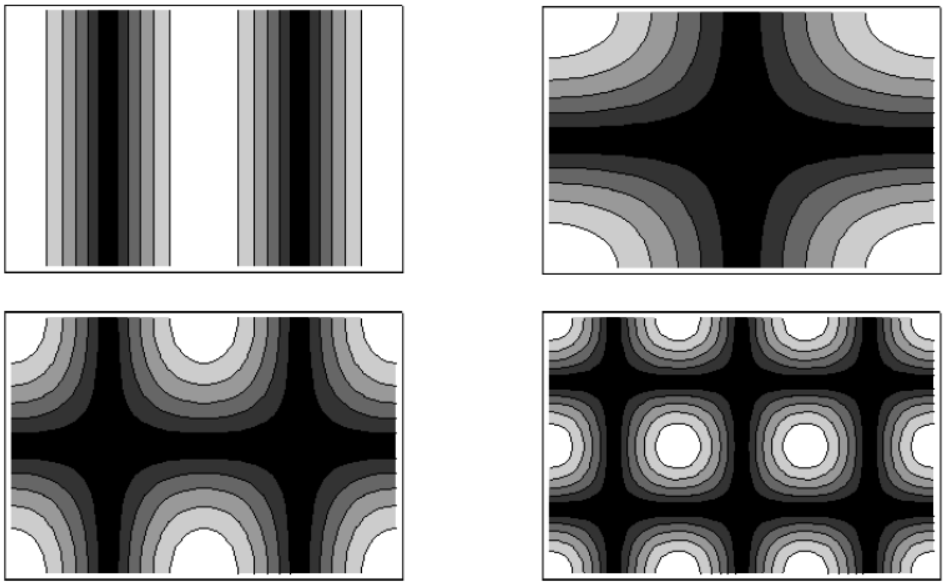
where n_x , n_y , n_z are integers and
L, B, H are the length, width (breadth) and height of the room,
or also denoted L_x , L_y , L_z

Room modes: Rectangular rooms

Sound pressure amplitude distribution in a rectangular room for a few modes. The amplitude is gray-scale coded where white stands for maximum and black for minimum amplitudes.

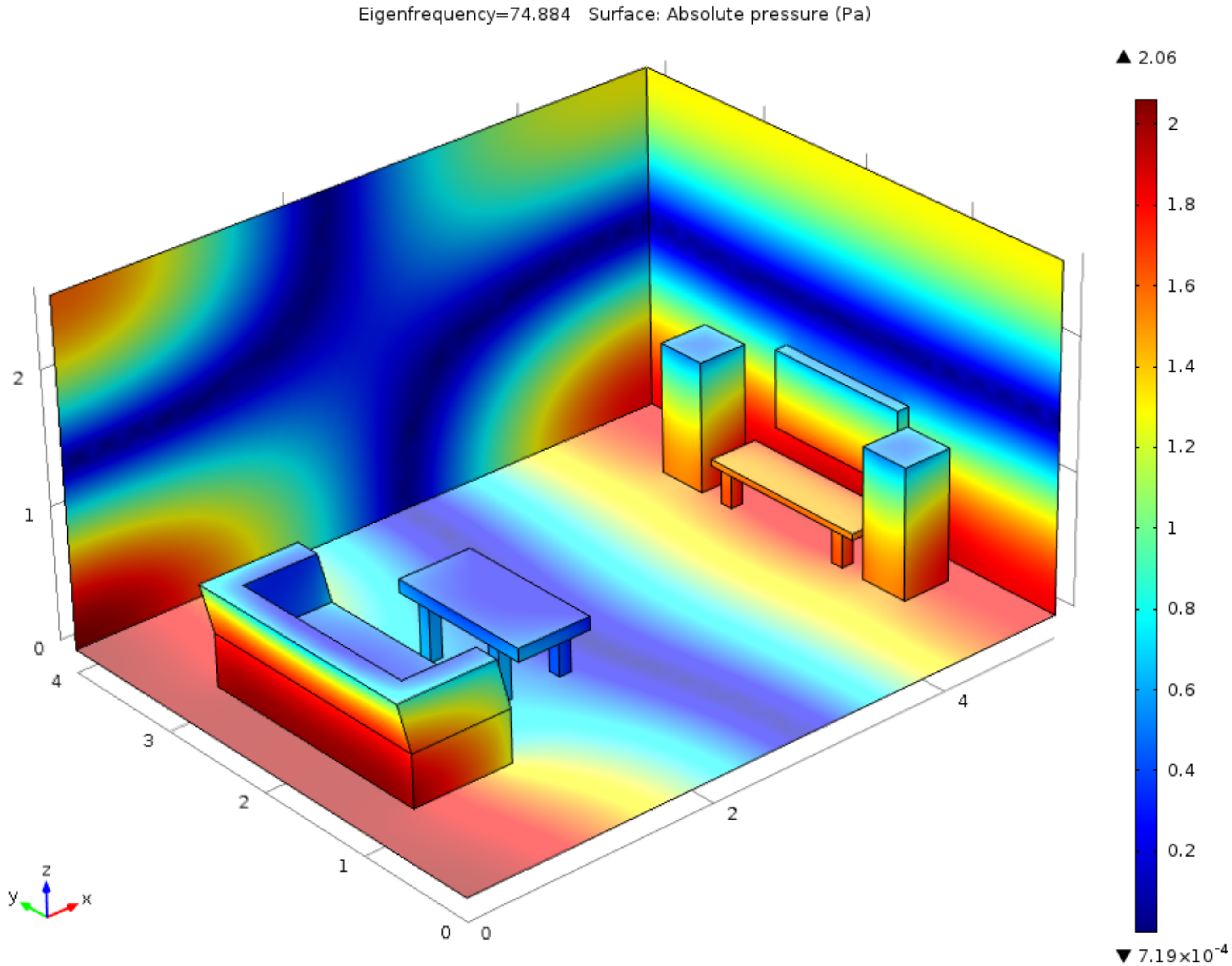
From left to right and top to bottom:

mode (2,0,0), mode (1,1,0), mode (2,1,0), mode (3,2,0).



Eigenfrequency [Hz]	n_x	n_y	n_z
36.2	1	0	0
41.5	0	1	0
54.8	0	0	1
55.0	1	1	0
65.7	1	0	1
68.6	0	1	1
72.3	2	0	0
77.7	1	1	1
82.9	0	2	0
83.4	2	1	0

Room modes: Rectangular rooms



[COMSOL software]

Rectangular rooms

The frequency differences between the adjacent Eigenfrequencies are quite large at the low frequency end. For increasing frequency these differences become smaller. The number N_f of Eigenfrequencies between 0 and the frequency f [Hz] in a rectangular room of volume V [m3] is estimated as

$$N_f \approx \frac{4\pi}{3} V \left(\frac{f}{c}\right)^3$$

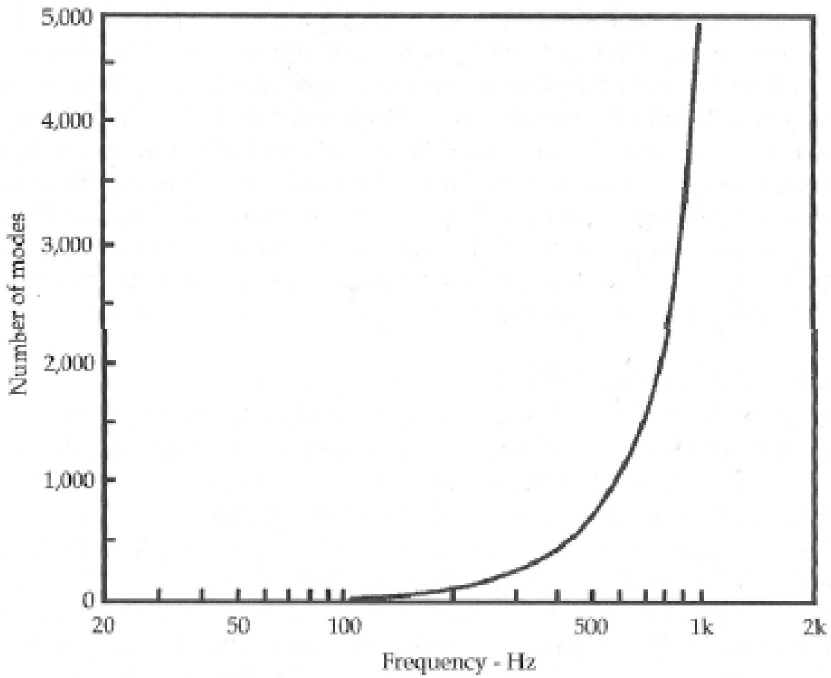
The density $\frac{dN_f}{df}$ (number of Eigenfrequencies per Hz) at frequency f is then

$$\frac{dN_f}{df} \approx 4\pi V \left(\frac{f^2}{c^3}\right)$$

Lund University

Room modes: Rectangular rooms

- The number of modes (mode density) increases with increasing frequency, at low frequencies mode density is low
- From room acoustics point of view, room modes are the more problematic the smaller the size of the room
- Room modes must be considered in the design of, e.g.
  - Control rooms
  - Recording studios



Acoustical design of small rooms

- In small undamped rooms the following difficulties are typical:
  - At low frequencies the transfer function is very uneven due to the low density of resonances.
  - At mid and high frequencies strong reflections lead to comb filter distortions and errors in the stereo image.
  - At all frequencies the reverberation is too large which leads to low transparency of the acoustical image.

Acoustical design of small rooms

There are two fundamental strategies:

» installation of absorbers

» installation of diffusers

Absorbers

Low frequency absorbers for the low frequency range are typically realized as plate or membrane absorbers. To obtain a broad frequency band of absorption, different modules are necessary with adjusted resonance frequency. In the mid and high frequency range porous absorbers can be used.

Absorption data from EN 12354-6

Table B.1 — Typical values for the absorption coefficient

Material	Sound absorption coefficient α_s in octave bands, centre frequency in Hz					
	125	250	500	1 000	2 000	4 000
concrete, plastered brick	0,01	0,01	0,01	0,02	0,02	0,03
brickwork, unplastered	0,02	0,02	0,03	0,04	0,05	0,07
hard floor coverings (e.g. PVC, parquet) on heavy floor	0,02	0,03	0,04	0,05	0,05	0,06
soft floor covering on heavy floor; ≤ 5 mm	0,02	0,03	0,06	0,15	0,30	0,40
soft floor covering on heavy floor; ≥ 10 mm	0,04	0,08	0,15	0,30	0,45	0,55
wooden floor, parquet on battens	0,12	0,10	0,06	0,05	0,05	0,06
windows, glass facade	0,12	0,08	0,05	0,04	0,03	0,02
doors (wood)	0,14	0,10	0,08	0,08	0,08	0,08
net curtain; 0 mm - 200 mm in front of hard surface[1]	0,05	0,04	0,03	0,02	0,02	0,02
curtain, < 0,2 kg/m^2; 0 mm – 200 mm in front of hard surface; typical minimum [1]	0,05	0,06	0,09	0,12	0,18	0,22
curtain, woven material ≈ 0,4 kg/m^2; folded or ruffled > 1:3, 0-200 mm in front of hard surface; typical maximum	0,10	0,40	0,70	0,90	0,95	1,00
large openings (smallest dimension > 1 m)	1,00	1,00	1,00	1,00	1,00	1,00
air grid, 50 % open area	0,30	0,50	0,50	0,50	0,50	0,50

NOTE These data are based on publications used in Austria, Denmark and the Netherlands.

1 in front of a window the values of the combination can increase to the values for such a window alone.

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Absorption data from EN 12354-6

Table C.1 — Typical values for the equivalent absorption area for some common objects

Object	Equivalent absorption area A_{obj} in octave bands, centre frequency in Hz					
	125	250	500	1 000	2 000	4 000
single chair, wood	0,02	0,02	0,03	0,04	0,04	0,04
single chair, upholstered	0,10	0,20	0,25	0,30	0,35	0,35
single person in a group, sitting or standing, 1 per 6 m^2 area; typical minimum	0,05	0,10	0,20	0,35	0,50	0,65
single person in a group, sitting, 1 per 6 m^2 area; typical maximum	0,12	0,45	0,80	0,90	0,95	1,00
single person in a group, standing, 1 per 6 m^2 area; typical maximum	0,12	0,45	0,80	1,20	1,30	1,40
NOTE These data are based on publications used in Austria, Denmark and the Netherlands.						

Table C.2 — Typical vales for the sound absorption coefficient for some common specified arrays of objects

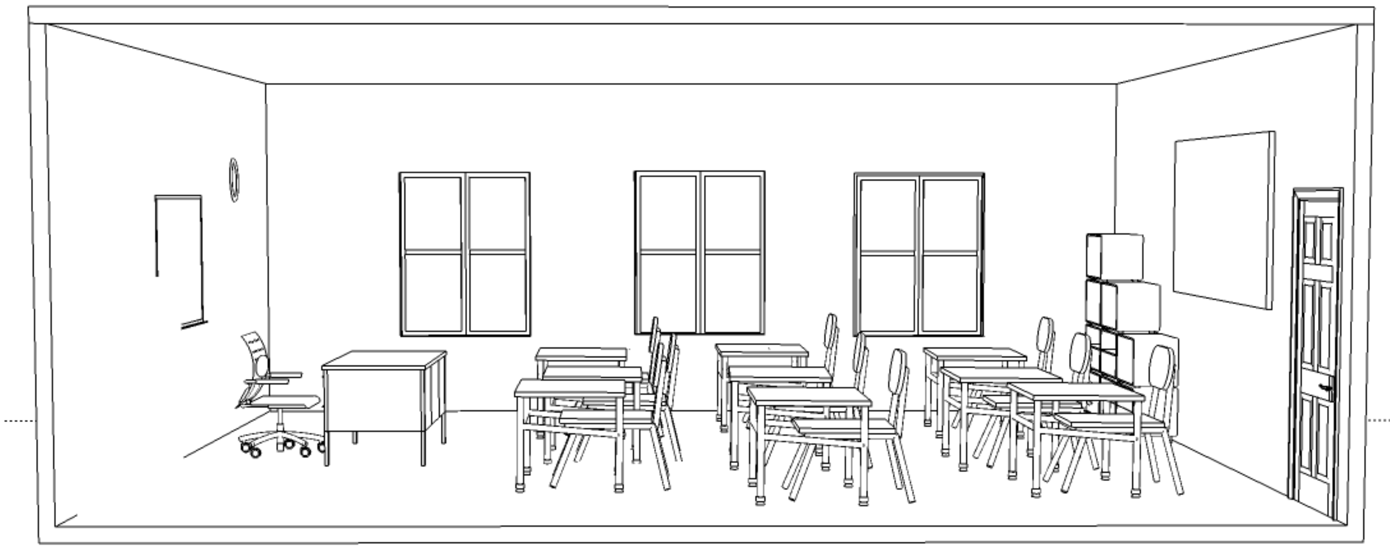
Array of objects	Sound absorption coefficient α_s in octave bands, centre frequency in Hz					
	125	250	500	1 000	2 000	4 000
chairs in a row at 0,9m – 1,2m; wood/plastic	0,06	0,08	0,10	0,12	0,14	0,16
chairs in a row at 0,9m – 1,2m; upholstered; typical minimum	0,10	0,20	0,30	0,40	0,50	0,50
chairs in a row at 0,9m – 1,2m; upholstered; typical maximum	0,50	0,70	0,80	0,90	1,0	1,0
persons sitting in a row at 0,9m – 1,2m (audience); typical minimum	0,20	0,40	0,50	0,60	0,70	0,70
persons sitting in a row at 0,9m – 1,2m (audience); typical maximum	0,60	0,70	0,80	0,90	0,90	0,90
children in a hard furnished class room, 1 per m^2 area	0,10	0,20	0,25	0,35	0,40	0,40
NOTE These data are based on publications used in Austria, Denmark and the Netherlands.						

Acoustical design of small rooms

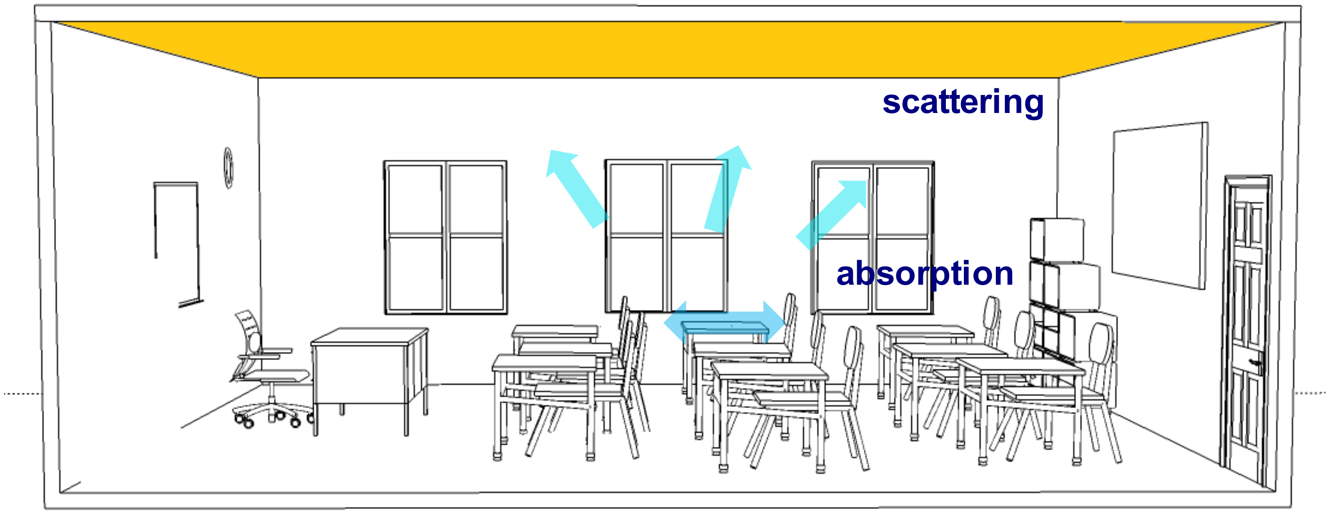
Diffusers

- The use of diffusers aims at replacing reflections by scattering .
- In the best case the scattered sound energy is equally distributed in all directions.
- In small rooms, scattering may help to avoid room resonances. In order to create diffuse reflections a surface has to introduce locally inhomogeneous reflection conditions. This inhomogeneity can be realized by phase or amplitude variation.

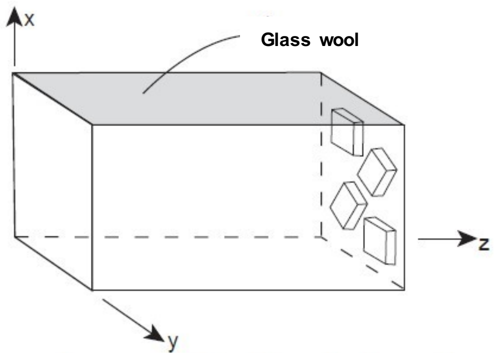
Typical classroom

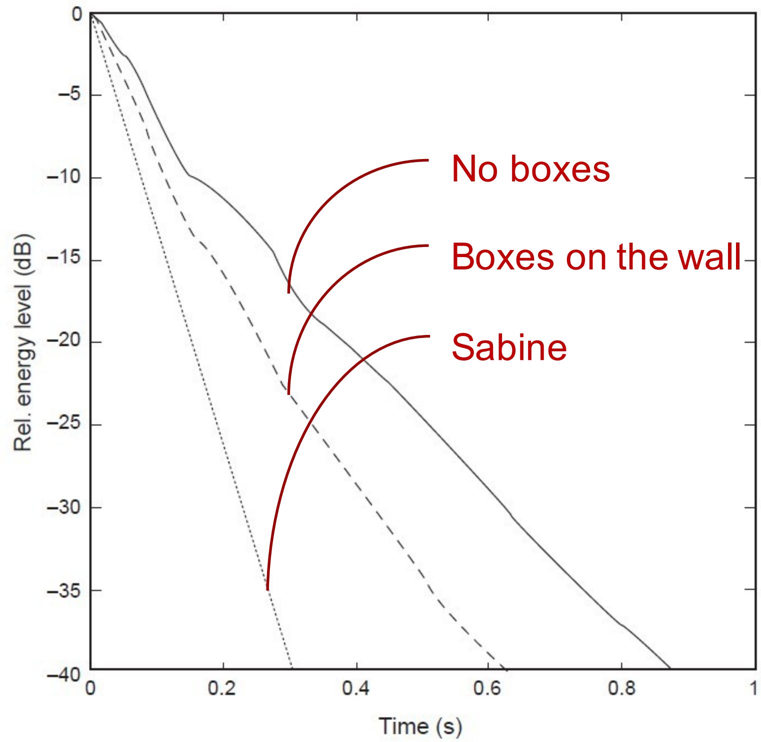


Effect of furniture



Scattering – why is it important?





Furniture absorption

T_0 empty room

T_{furn} furnished room

$$A_{furn} = 0{,}163V \left(\frac{1}{T_{furn}} - \frac{1}{T_0}\right)$$

Effects of furniture

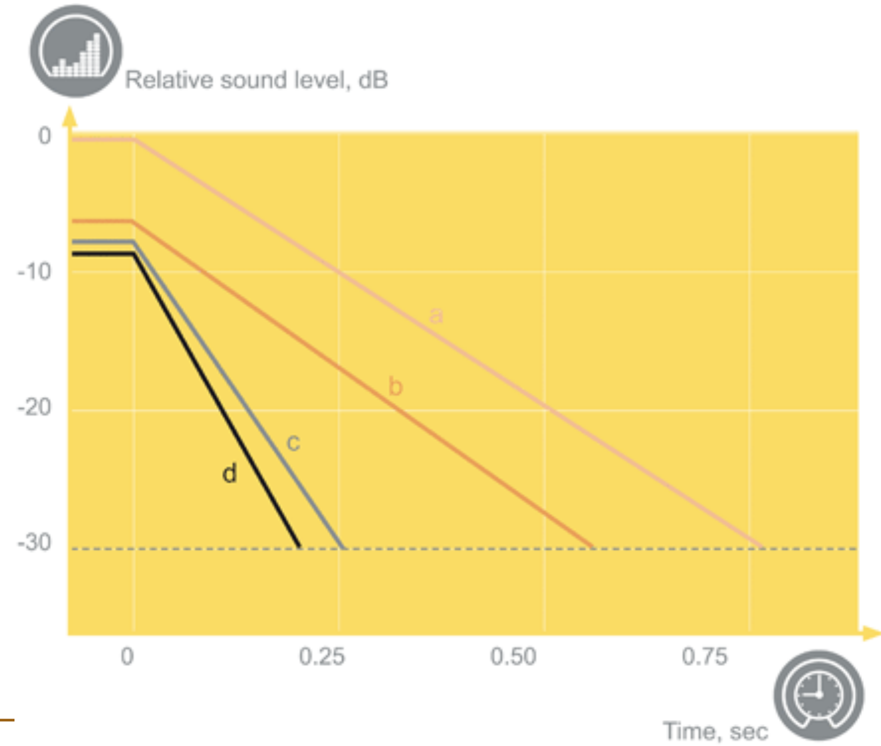
The reverberation curve in a classroom for

a) empty room,

b) empty room + an absorbent ceiling,

c) b + shelves, cupboards and furnishings along the walls,

d) c + pupil stations, consisting of a chair and small table, distributed across the floor.



Assessment of sound in rooms

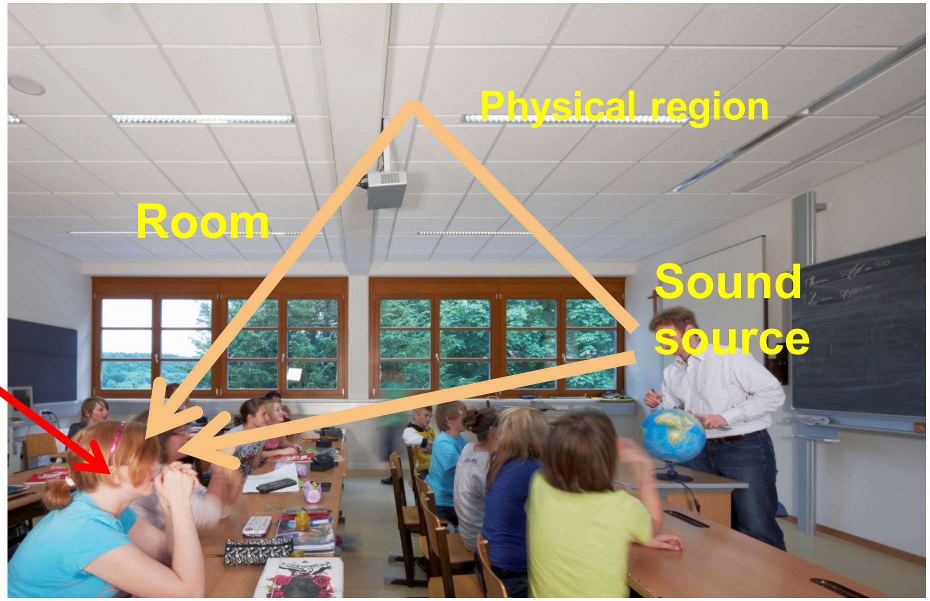
Psychoacoustics:
Physiological and psychological region

Sensation

- Sound strength
- Clarity
- Sharpness
- …

Perception

Preference



Thank you for your attention!

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