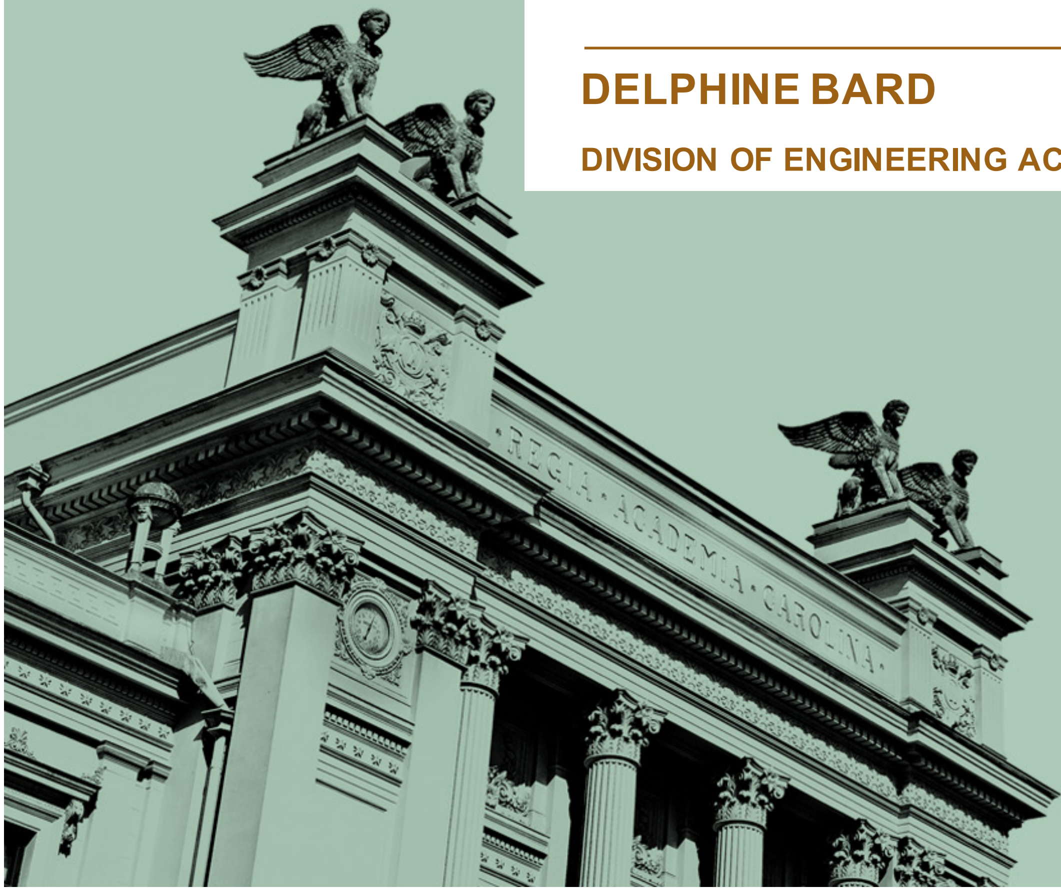
Room Acoustics (2) VTAN01

DELPHINE BARD

DIVISION OF ENGINEERING ACOUSTICS, LUND UNIVERSITY



Parameters: Importance

- T30, EDT: Reverberation
  - T60 = 2*T30
- D50: Clarity of speech
- 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 their geometry, their absorption properties and their diffusivity.
- For the investigation of the sound field three methods are in use

What is Reverberation time?

Efterklangstid: 0 s 0,5 s 1,2 s 2,0 s

Female song

Values for Rt

Bullerhänsyn:

	Litet rum - stort rum
Arbetslokal	T = 0.5 - 1.5 s
Kantin	T = 0.5 - 1.0 s
Kontor	T = 0.4 - 0.8 s

Hänsyn till taluppfattbarhet:

	Litet rum - stort rum
Bio	T = 0.6 - 1.2 s
Bio, THX	T = 0.3 - 1,0 s
Klassrum	T = 0.6 - 0.8 s
Mötesrum	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 behaviour.

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Introduction

- ***Wave based room acoustics***
  - Seeking solutions of the wave equation. The sound propagation is modeled physically correct and considers wave phenomenons such as resonance, interference and diffraction.
  - However analytical solutions are available for a few simple geometries only.
  - In general, specific solutions have to be found with numerical approximations such as the Boundary Element method (BEM) or Finite Element method (FEM). The corresponding computational efforts restricts the application 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. From that follows that the average intensity is 0 everywhere.

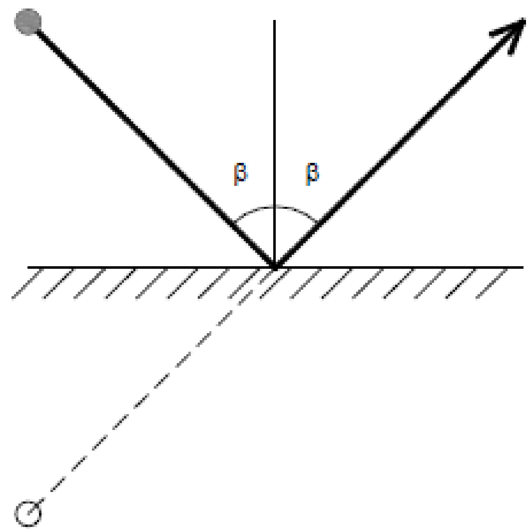
Statistical room acoustics

- 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

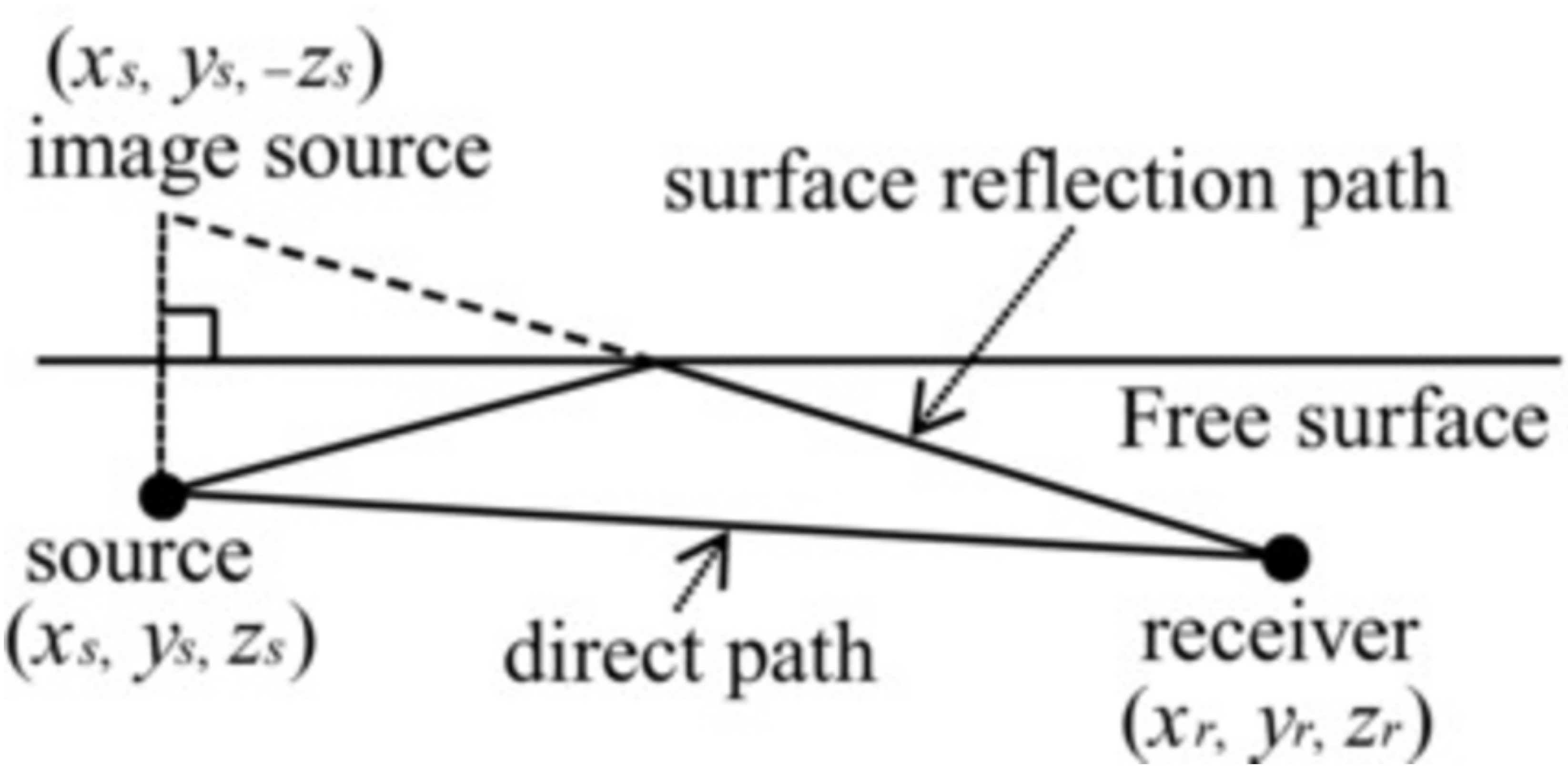
Hz	125	250	500	1000	2000	4000
upholstered seat, row spacing 1.15 m	0,30	0,35	0,50	0,60	0,70	0,70

Reflection at plane surfaces, specular sources

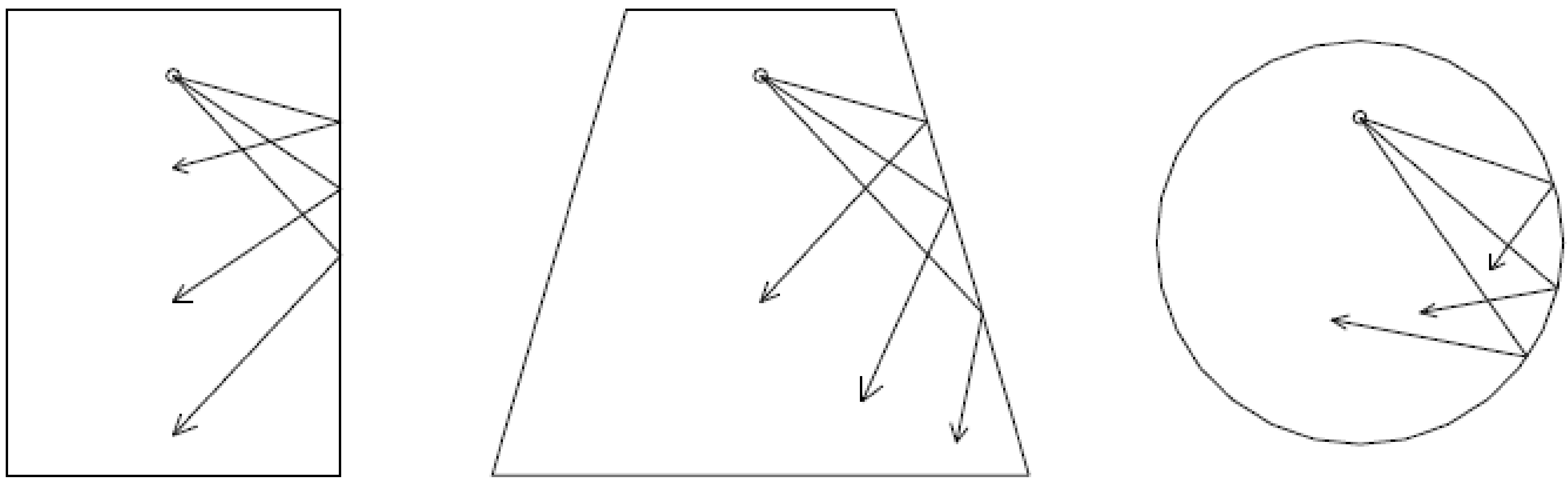
- If a sound ray hits a surface, it looses a certain amount of its energy depending on the absorption coefficient of the corresponding surface.
- The remaining energy is reflected according to the law of reflection
  - angle of incidence = angle of reflection.
- sound path can be determined by construction of mirror sources



Reflection at plane surfaces, specular sources



Effect of basic reflections

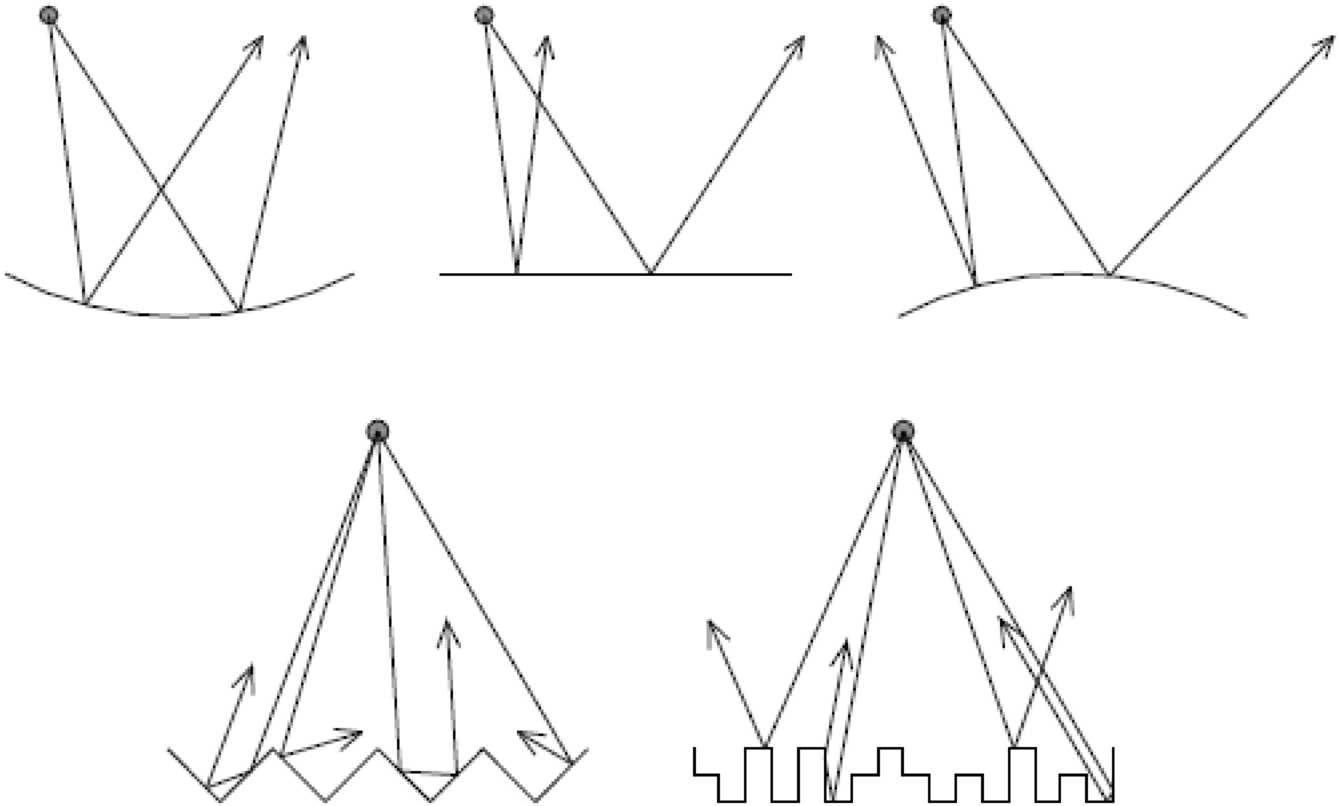


Rectangle:
Lateral reflections occur in the entire space

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

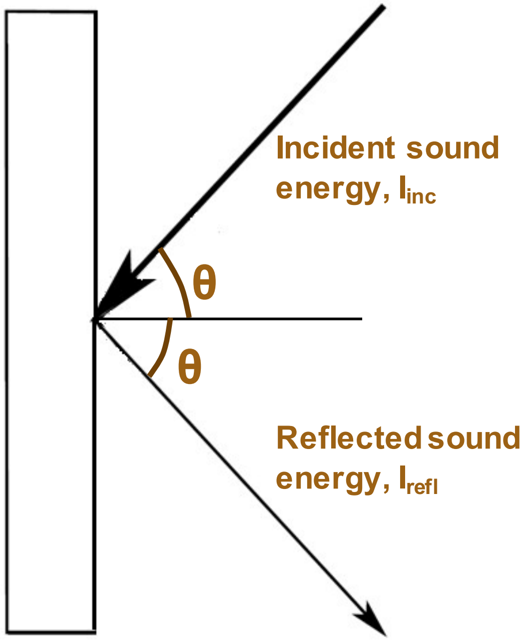
Round:
Reflections from concave surfaces cause sound to strongly focus on some parts of the space

Effects of shapes



Reflection from a surface

- Specular reflection: Angle of reflection equals angle of incidence

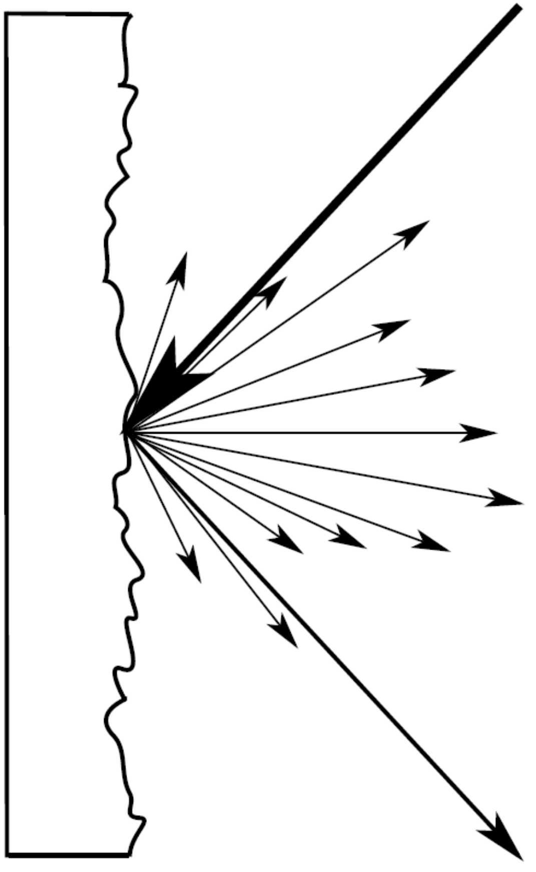


Absorption coefficient:

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

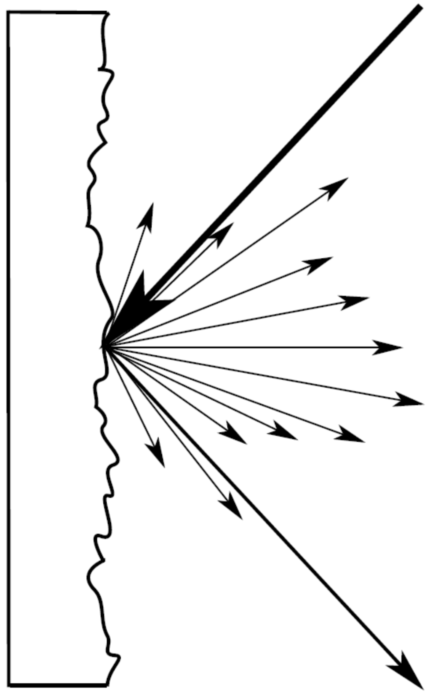
Reflection from a surface

- Diffuse reflection
  - Scattered in many directions

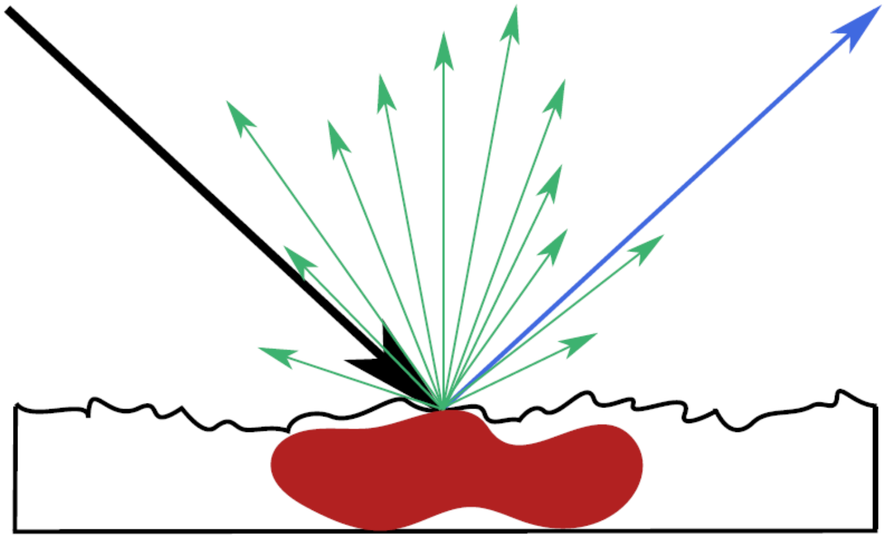


Reflection from a surface

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



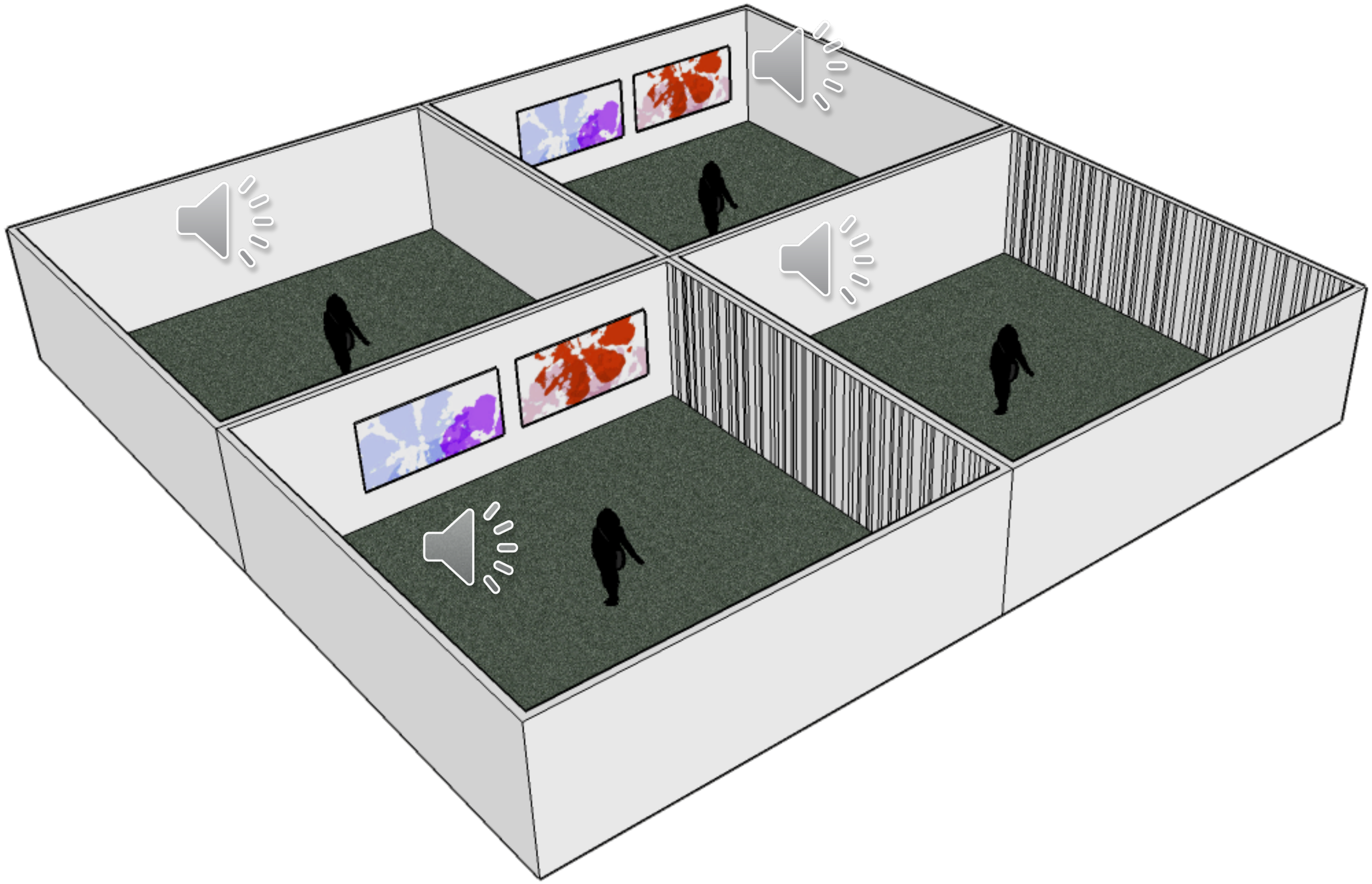
Absorption and scattering



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

absorbed **specularly reflected** **diffusely reflected**

Sound Example



Reflection at structured surfaces, diffuse reflection and scattering

- *For $\lambda \gg$* structure dimension *s*

→ the structure has no effect

→ specular reflection

at an 'average' plane.

- For $\lambda \approx$ structure dimension *s*

→the structure acts as a whole

→ diffuse reflection

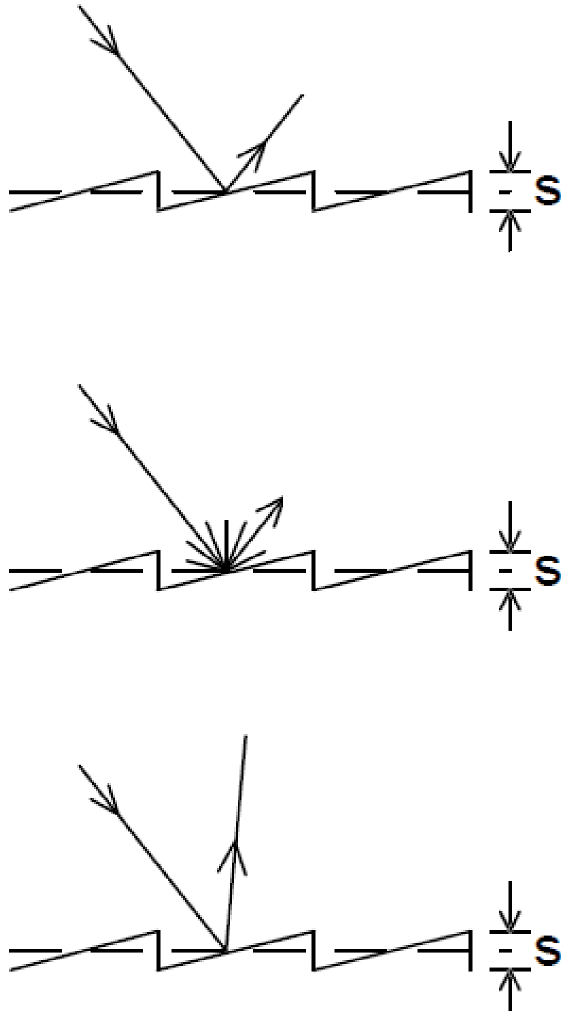
- *For $\lambda \ll$* structure dimension *s*

→ the single structure elements

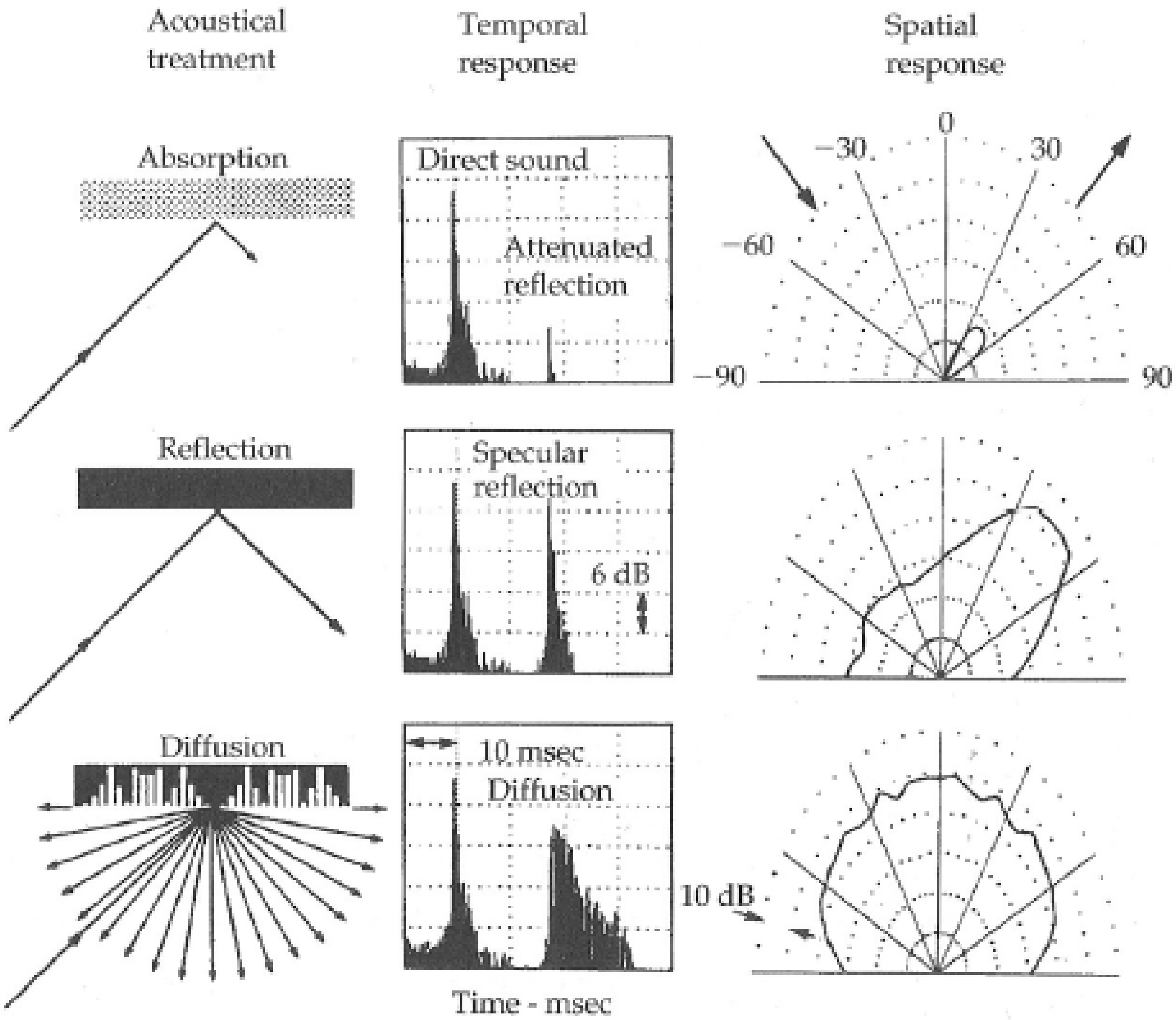
act as reflectors

→ specular reflection at the

structure details.



Absorption vs reflections



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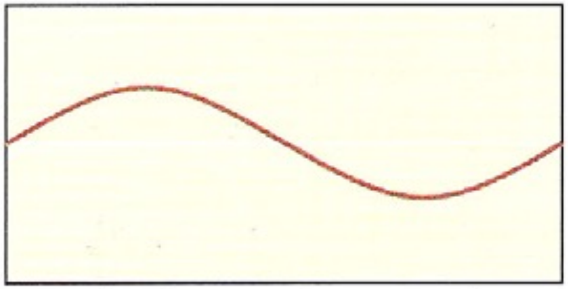
Small rooms

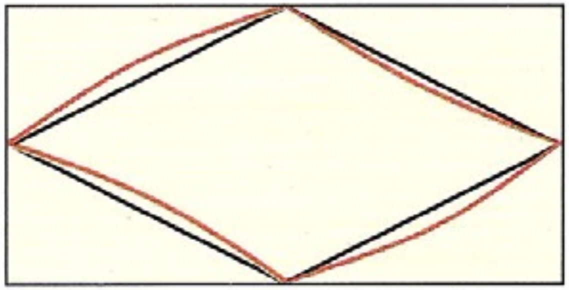
- The sound field in small rooms at low frequencies is dominated by discrete resonances (Eigenfrequencies) with low spectral density.
- Methods of statistical and geometrical acoustics **are not applicable.**
- The wave nature of sound has to be considered explicitly with help of wave theoretical room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

Room Modes

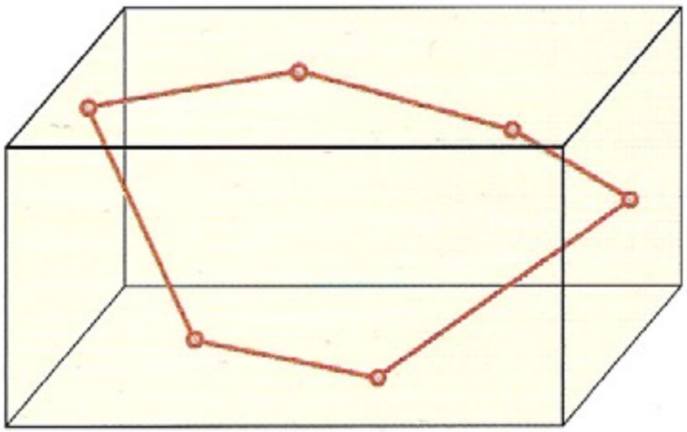
- Sound field within a room is comprised of room resonances, called room modes
- **Room mode = characteristic resonance of the room**
- Three types of modes: axial, tangential, oblique
- The amount and spacing of room modes changes with frequency
- At low frequencies there are only a few room modes and the modes are sparsely spaced, as a result of which 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 are so close to one another, that single room modes cannot be distinguished
  - sound field approaches the idealisation of **diffusivity**



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:

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

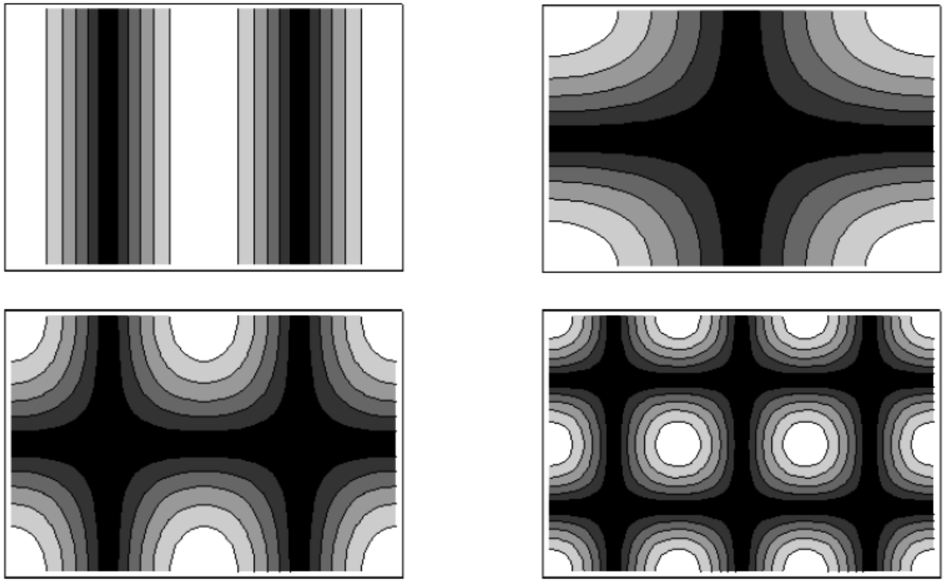
- Example, typical dewlling room: T = 0,5 s ja V = 30 m^3 → f_s = 260 Hz
- The room modes of a rectangular room can be calculated based on the dimensions of the room (L_x, L_y, L_z):

$$f_{lmn} = \frac{c}{2}\left[\left(\frac{l}{L_X}\right)^2 + \left(\frac{m}{L_Y}\right)^2 + \left(\frac{n}{L_Z}\right)^2\right]$$

where l, m, n are integers

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

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

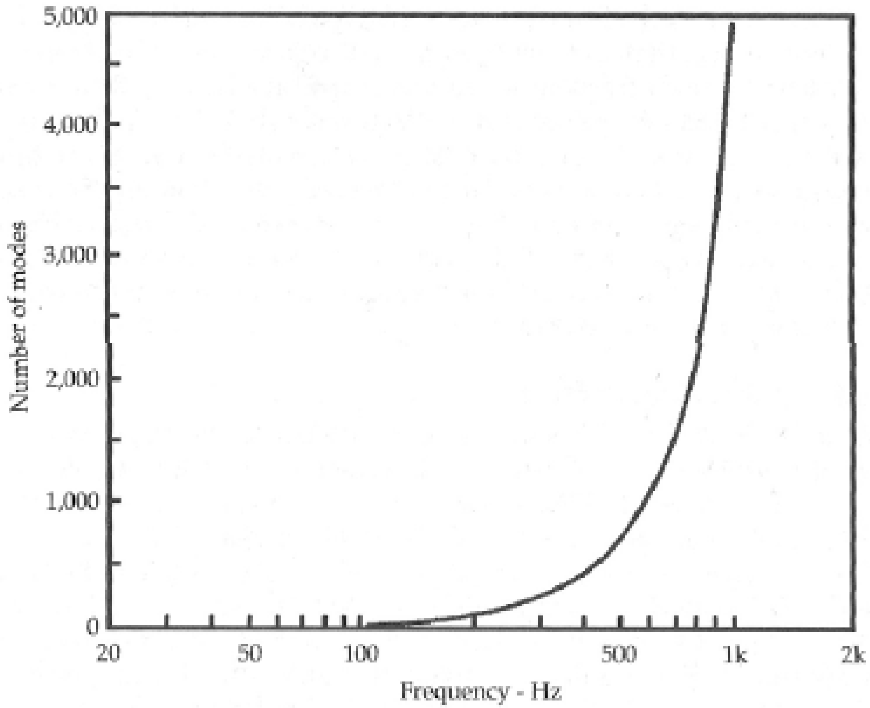
$$N_f \approx \frac{4\pi}{3} V \left(\frac{f}{c}\right)^3$$

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

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

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 acoustical 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. These effects are irrelevant if there is no other contribution stronger than -15 dB relative to the direct sound within 20 ms after the direct sound .
- 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.						

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

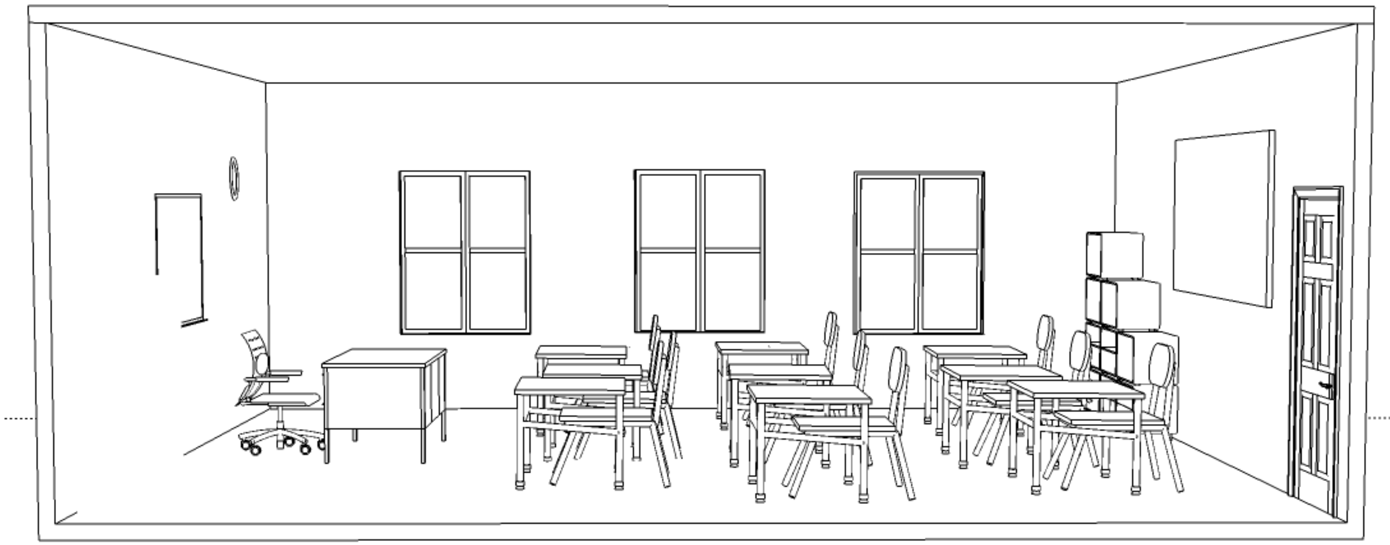
Array of objects	Sound absorption coefficient α_s in octave bands, centre frequency in Hz					
	125	250	500	1 000	2 000	4 000
chairs in a row at 0,9m – 1,2m; wood/plastic	0,06	0,08	0,10	0,12	0,14	0,16
chairs in a row at 0,9m – 1,2m; upholstered; typical minimum	0,10	0,20	0,30	0,40	0,50	0,50
chairs in 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

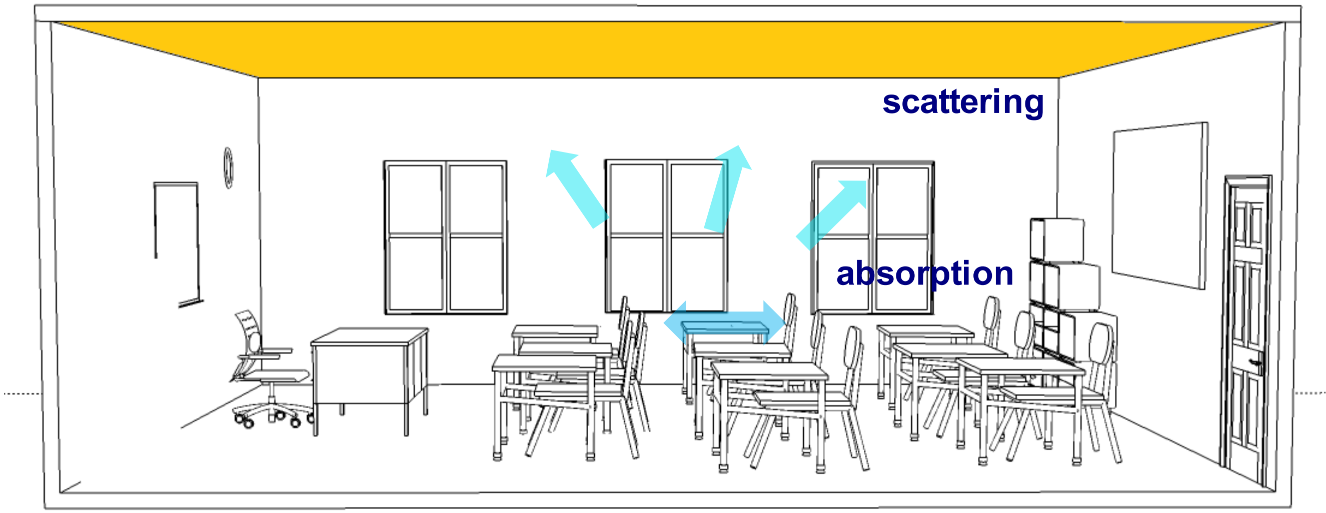
Diffusers

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.

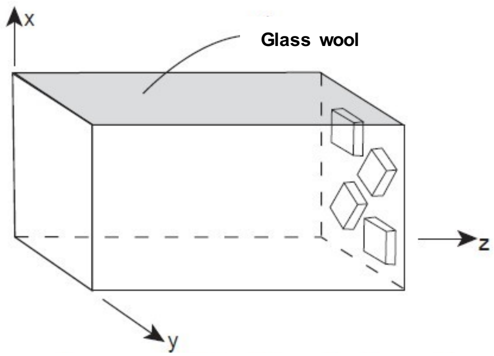
Typical classroom

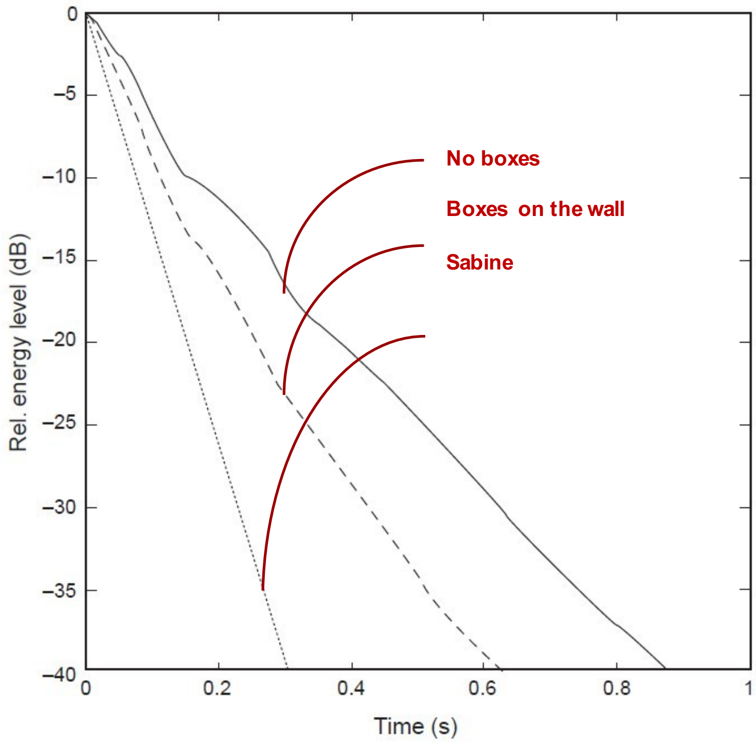


Effect of furniture



Scattering – why is it important?





Furniture absorption

T_0 empty room

T_{furn} furnished room

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

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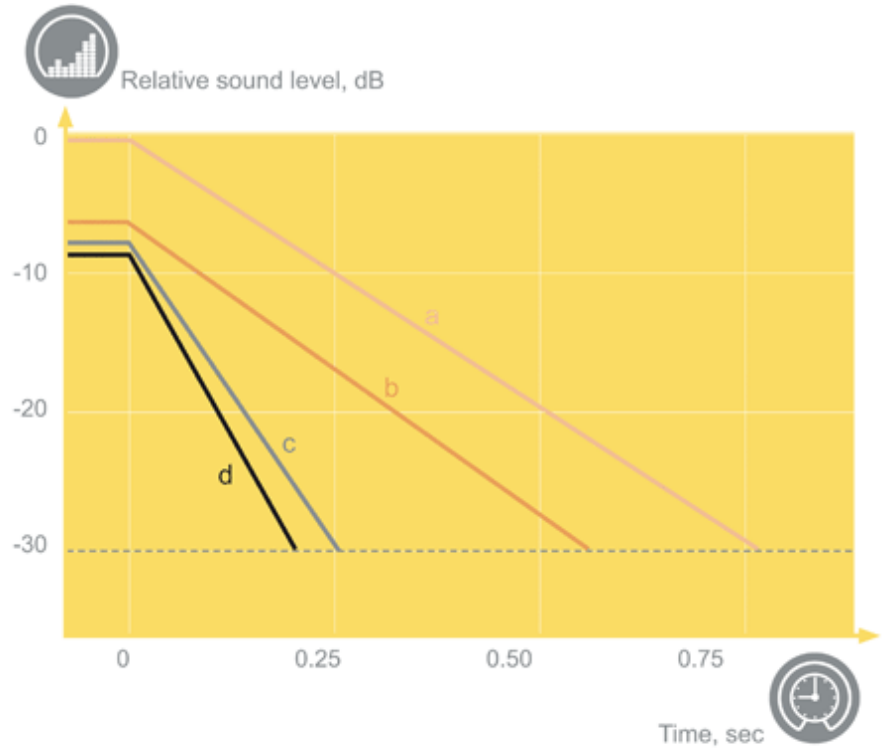
Effects of furniture



The reverberation curve in a classroom for

a) empty room

b) a + an absorbent ceiling

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

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

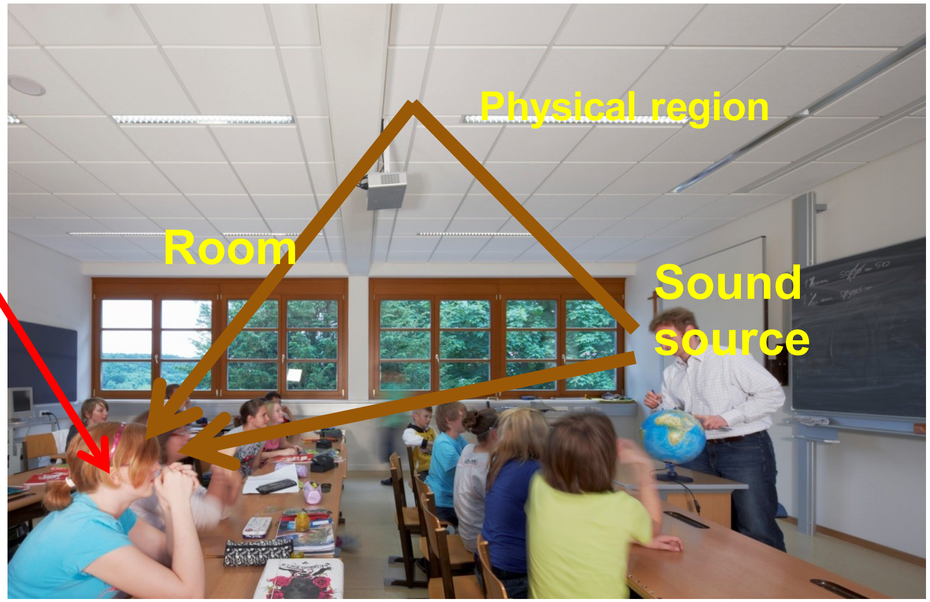
Assessment of sound in rooms

Physiological and psychological region

Sensation

- Sound strength
- Clarity
- Sharpness
- …

Preference



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