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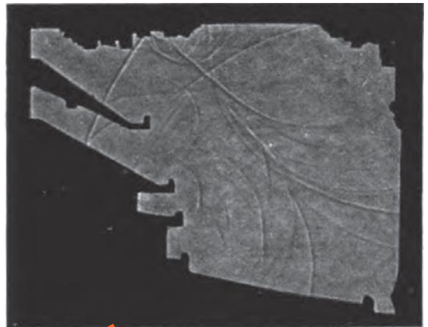
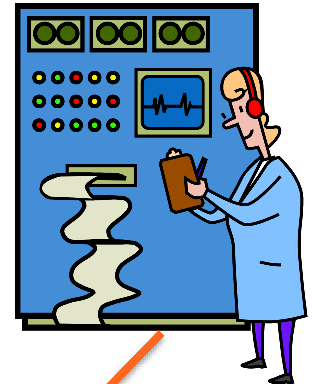
Room Acoustics Modeling

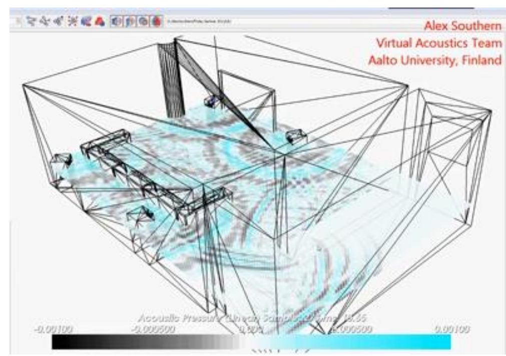
CS-E5530 Virtual Acoustics, 9.1.2019

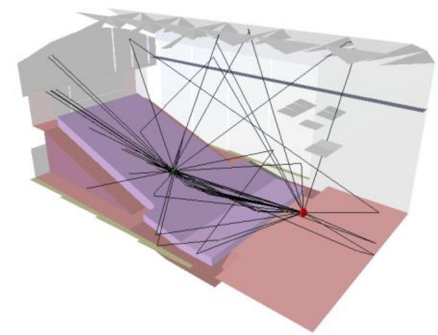
Lauri Savioja, Aalto University

Storyline






Alex Southern
Virtual Acoustics Team
Aalto University, Finland



? ? ?

Background

Applications and their needs

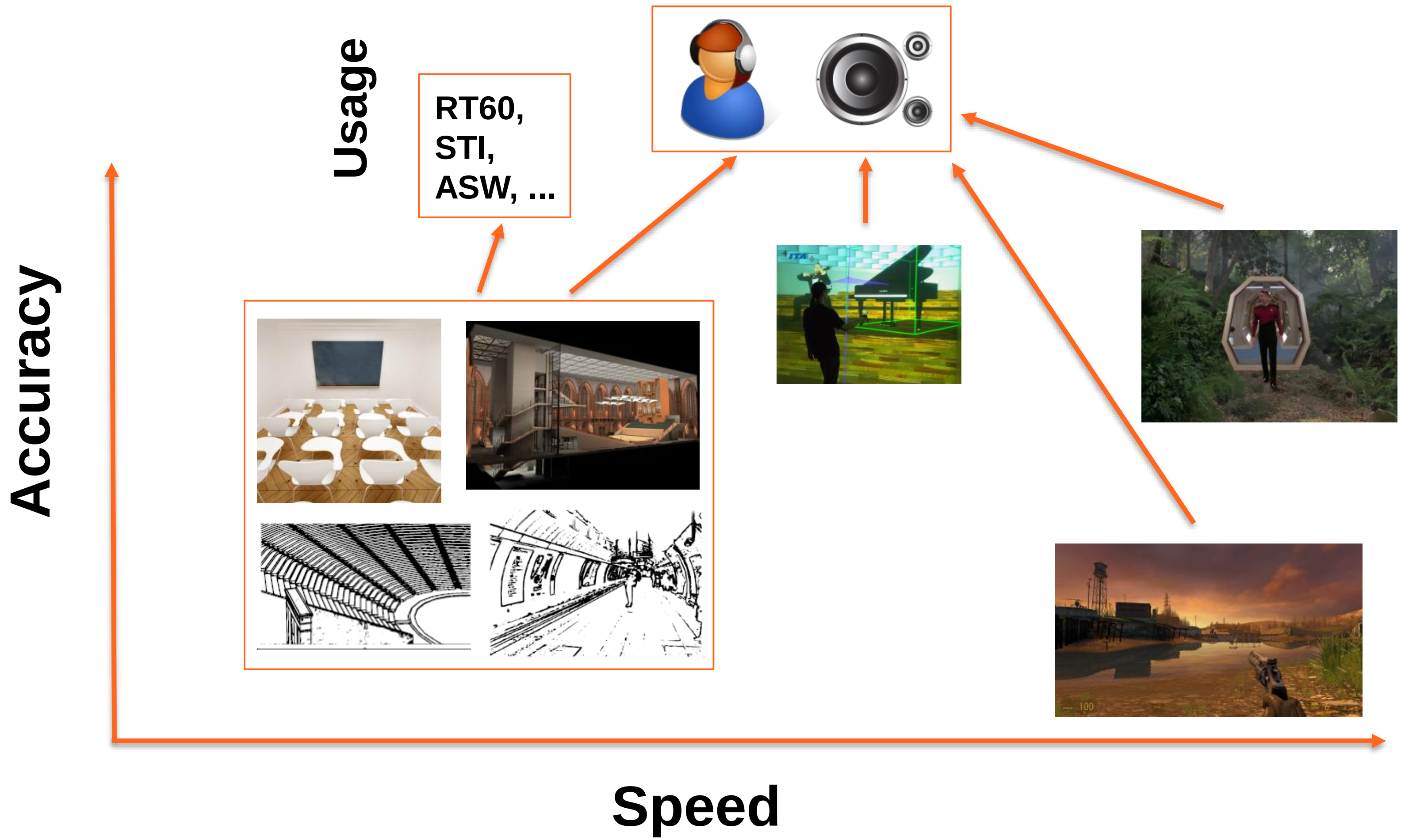


Image sources:
Virtual Acoustics Team, Aalto University
http://gamma.cs.unc.edu/AuralProxies/
http://www.akustik.rwth-aachen.de/Forschung/Projekte/raven
http://en.memory-alpha.org/wiki/File:Riker_Jungle_Holodeck_2364.jpg

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Some basics

What there is to be modeled?

- **Sound source**
- **Room Acoustics**
- **Receiver**

Room Acoustics

- **Sound propagation in the air**
  - Propagation by the linearized wave equation (static medium, constant temperature)
  - Atmoshperic attenuation
  - Atmoshperic scattering

- **Scattering of sound from surfaces**

Scattering from surfaces

- **What happens when a sound wave hits a surface?**
  - Specular reflection from the surface
  - Diffraction from the edges of the surface
  - Sound propagation into the surface (i.e. porous medium)
  - Coupling of the surface and air (i.e. the surface can start to vibrate)
  - Diffuse reflection caused by
    - *Diffraction at edges or by surface structure*
    - *Coupled structure*
    - *Porous medium*

  - And all this is frequency-dependent!

How to describe a material?

- **Basic assumption**
  - Local reaction (vs extended reaction)

- **Material properties**
  - Absorption coefficient in frequency bands
  - Diffusion/scattering coefficient in frequency bands

- **Macroscopic surface structure can be modeled either as part of the geometry or can be approximated by material properties**

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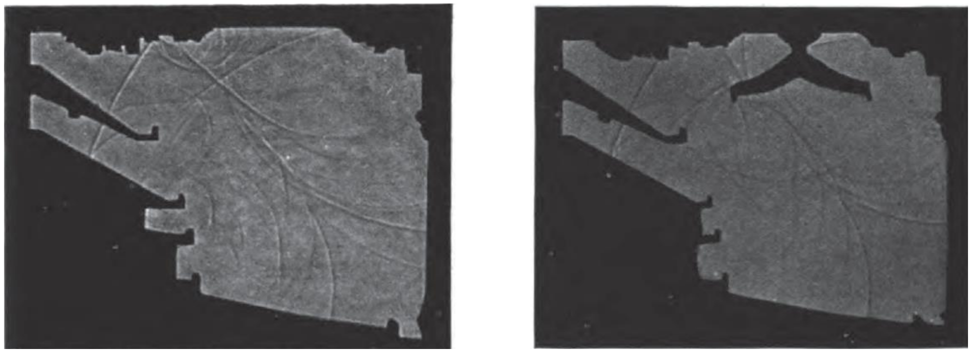
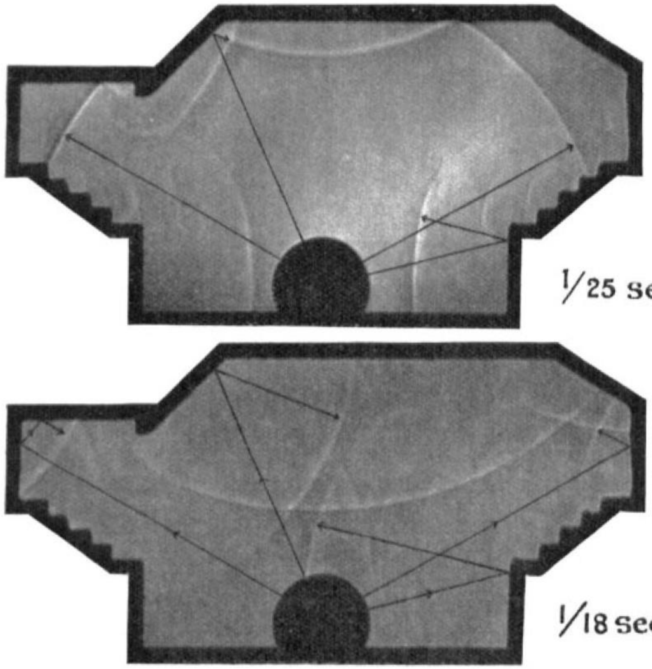
Some history

Schlieren photography



Wallace Clement Sabine, **Collected Papers on Acoustics,** Ch. 7. Theater Acoustics, pp. 163-198, Harvard University Press, 1922



A H Davis and N Fleming, **Sound pulse photography as applied to the study of architectural acoustics,** *J. Sci. Instrum.* **3** 393, 1926

Basic principles

”On one hand, the **practical engineers** usually try to discover the behavior of sound in a room by considering the reflection and absorption of sound energy by the walls along different **sound rays**. On the other hand, most of the **research theorists** insist on considering the normal modes of vibration, or the standing **wave patterns**”

D. Y. Maa. **The Flutter Echoes**. *J Acoust Soc Am*, 13(2):170-178,1941.

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Computing

Computers – 1961

“Digital computers can simulate the transmission of sound in rooms using speech and music as signals. Thus, it is possible to subjectively evaluate and redesign proposed concert halls and theaters prior to construction.”

M. R. Schroeder, **Novel Uses of Digital Computers in Room Acoustics**, *J Acoust Soc Am*, 33:1669, 1961.

Computers - 1968

”The use of a digital computer in room acoustics opens possibilities for the prediction of the acoustical behaviour of halls. Previously, such methods have been of theoretical interest only, due to the required laborious calculations.”

A Krokstad, S Strøm, and S Sørsdal. **Calculating the acoustical room response by the use of a ray tracing technique**. *J Sound Vib*, 8(1):118-125, 1968.

Computers - 1981

“A more realistic auditorium shape … would be feasible but it might cost hundreds of dollars per case.”

E. N. Gilbert. **An iterative calculation of auditorium reverberation.** *J Acoust Soc Am*, 69(1):178, 1981.

Computers - 2012

”... fast GPU sound propagation system for interactive simulation. Our implementation efficiently computes early specular paths and first order diffraction with a multiview tracing algorithm. …The resulting system can render acoustic spaces composed of thousands of triangles interactively.”

M. Taylor, et al., **Guided Multiview Ray Tracing for Fast Auralization**. *IEEE Trans Visualization and Computer Graphics*, 18(11):1797–1810, 2012.

Wave-based models

Techniques

Frequency domain
Helmholz equation

$$\nabla^2 A + k^2 A = 0$$

Elliptic partial differential equation

Time domain
Wave equation

$$\frac{\partial^2 u}{\partial t^2} = c^2 \nabla^2 u$$

Hyperbolic partial differential equation

Analytic solutions available only in rare cases.
Discretization and numerical solution the only real option.

Techniques

Frequency domain

- Finite Element (FEM)
- Boundary Element (BEM)

Time stepping

- Finite-Difference Time-Domain (FDTD)
- Pseudo-spectral methods such as Adaptive Rectangular Decomposition (ARD)

Solving partial differential equations

"most researchers will agree that there is no one superior method except, of course, the one they happen to be using in their current problem. ”

FDTD

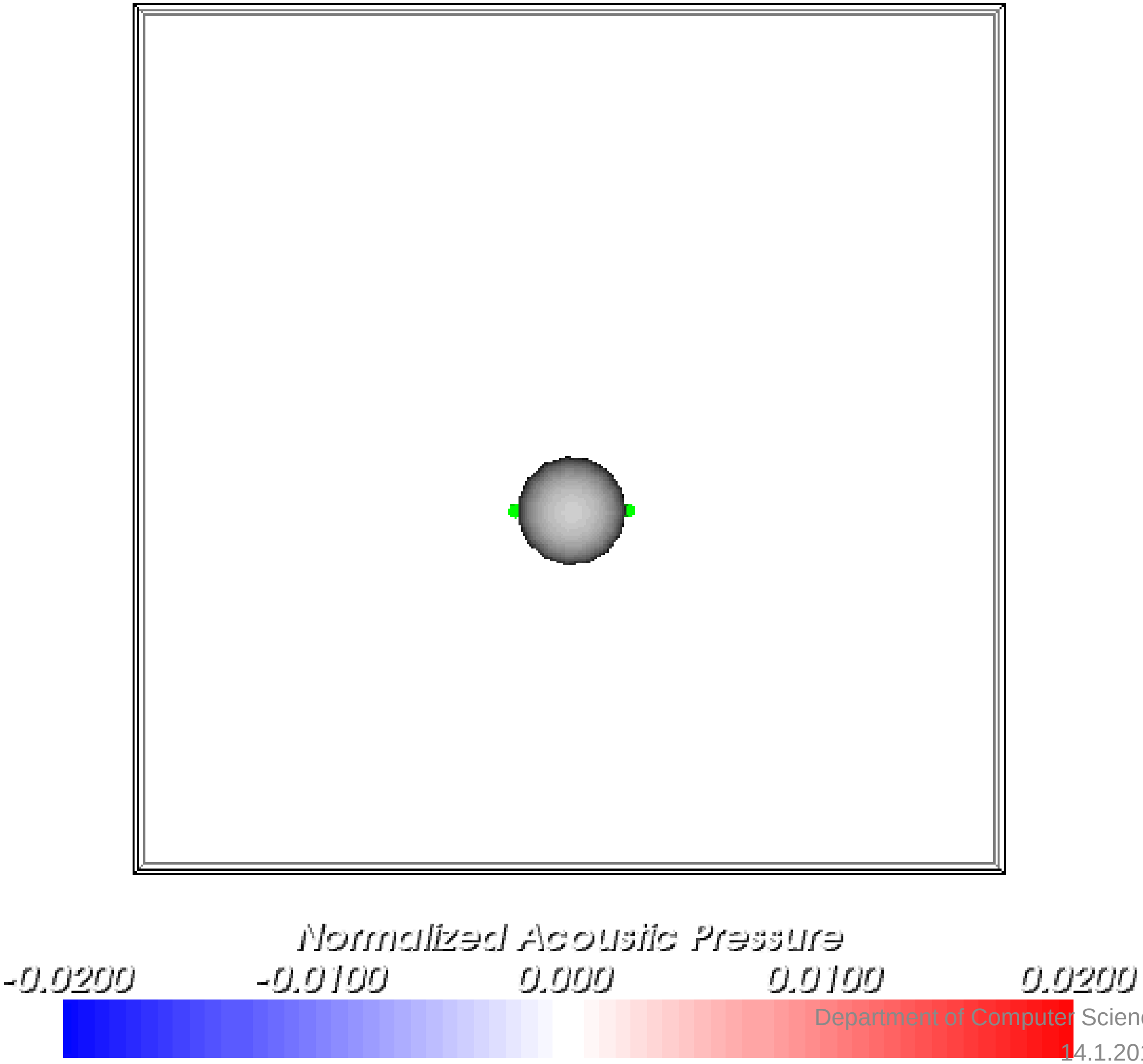
$$p(n+1) = \frac{1}{N}\sum p_{neigh}(n) - p(n-1)$$

(N = dimensionality)

Why wave-based models instead of geometrical acoustics?

- **Wave-based models are more accurate and inherently model:**
  - Everything related to wave-nature of sound
    - *Such as edge diffraction*
  - Everything related to the phase of sound (phase is part of wave-nature, I know)
    - *Such as interference*

FDTD video


Normalized Acoustic Pressure
-0.0200
-0.0100
0.000
0.0100
0.0200

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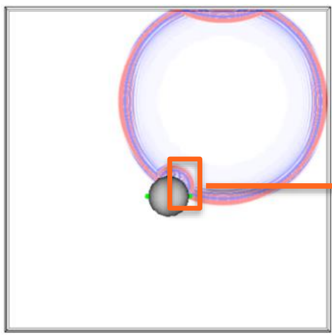
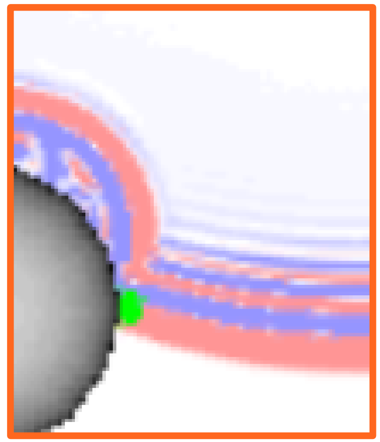
Challenges in modeling

Reflections





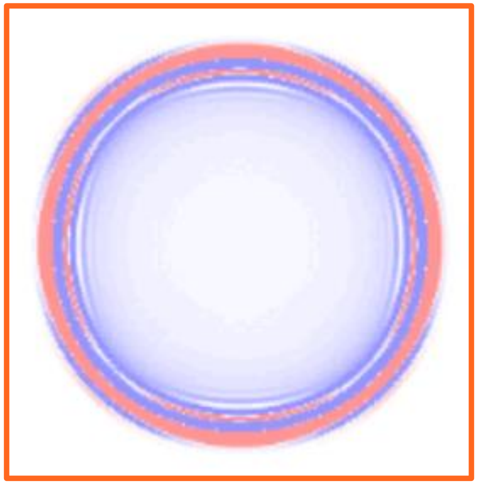
Acoustic impedance (local reactions) vs. extended reaction ?

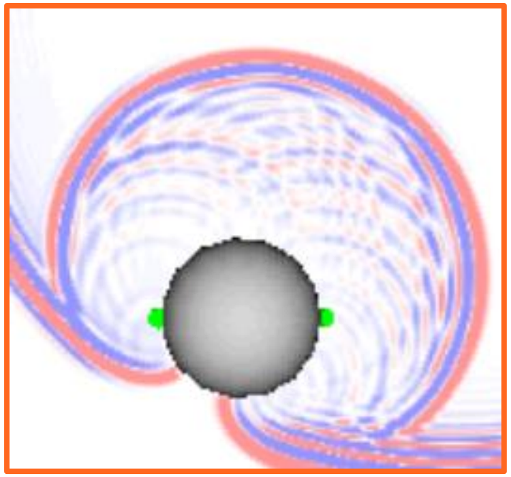
Diffuse reflections ?

Transmission ?

Coupled structures ?

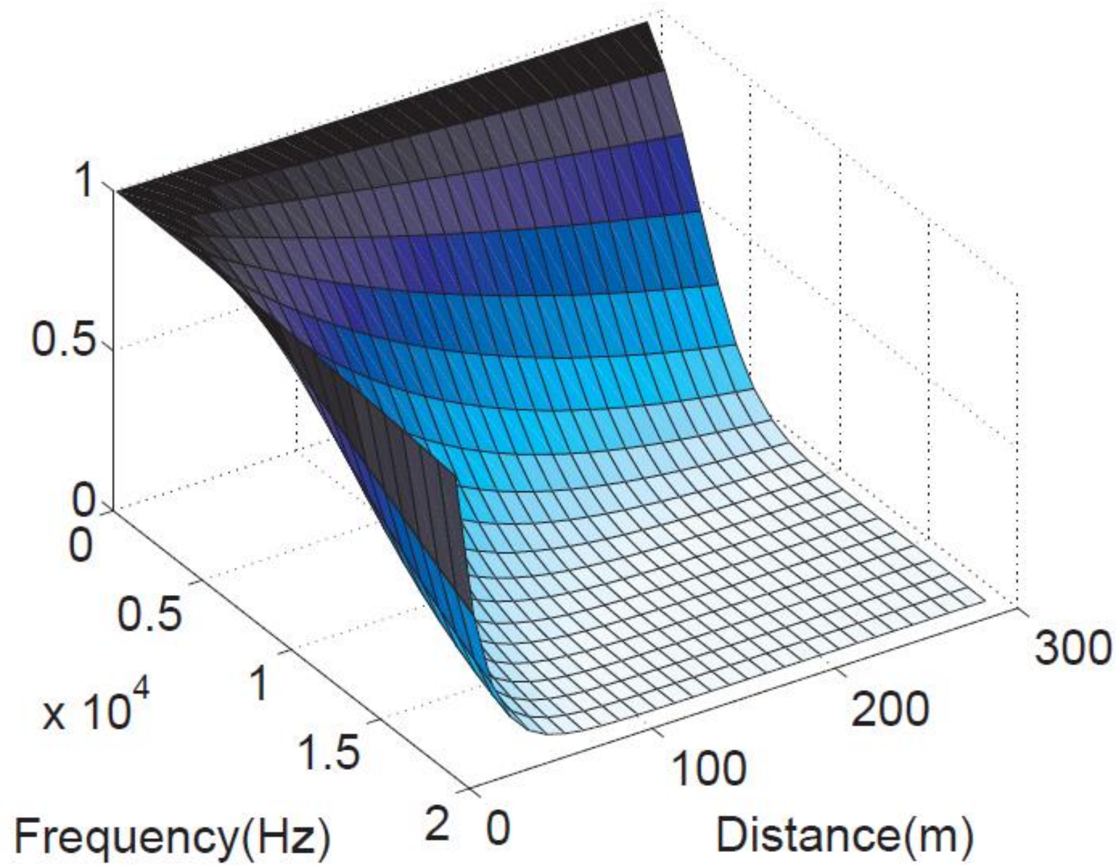
Source and receiver directivity



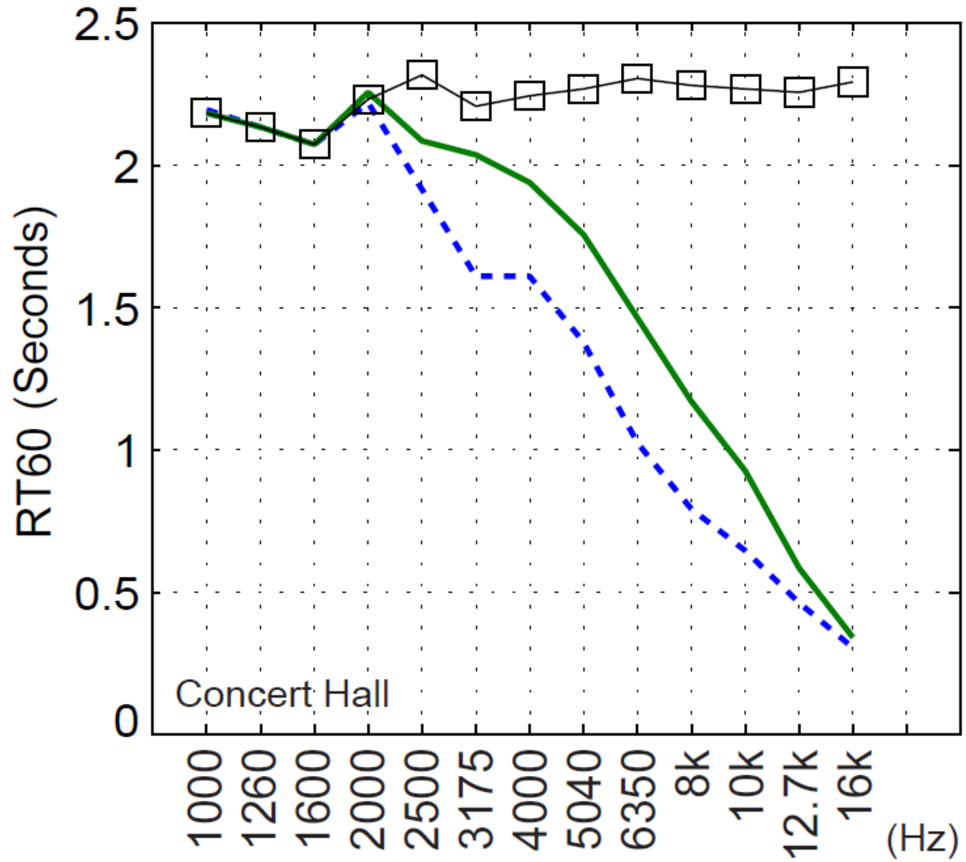


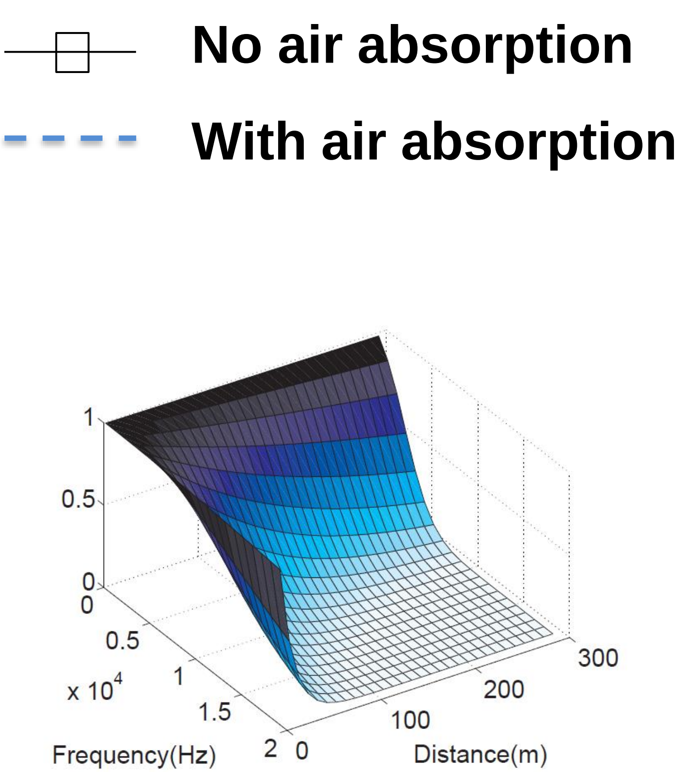
Omnidirectionality is a poor approximation of reality!

Modeling air absorption



Modeling air absorption





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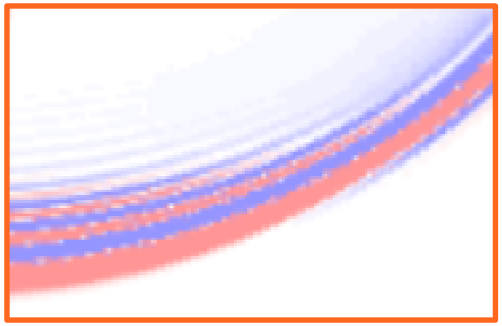
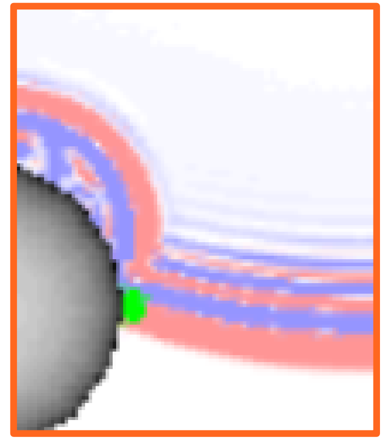
Challenges in computation

Numerical errors



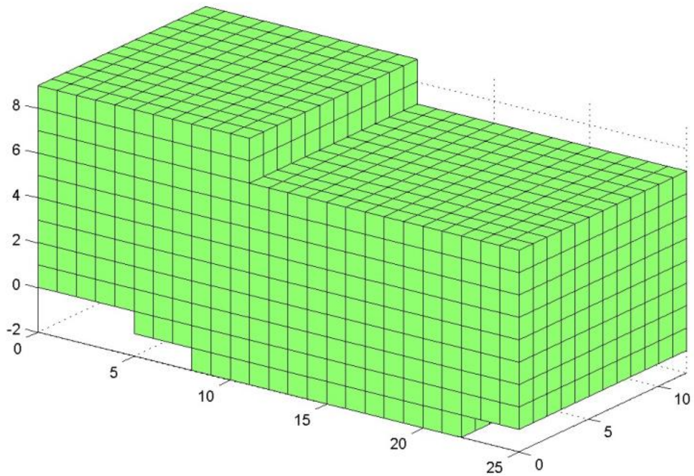


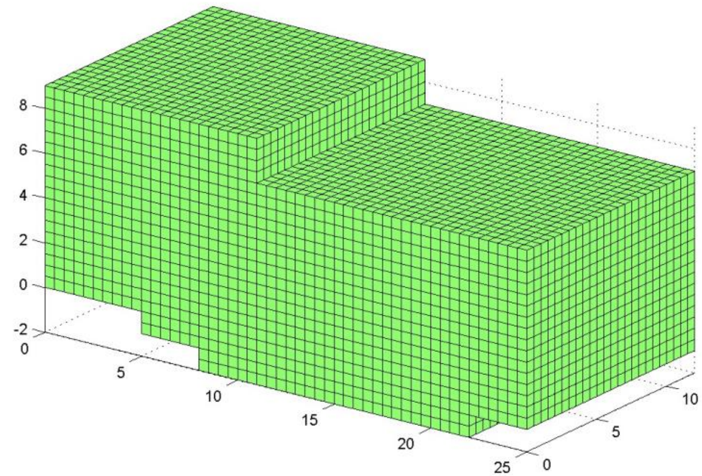
Dispersion error

Staircased boundaries

Numerical instabilities

Performance

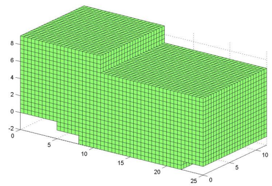


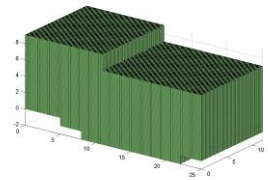


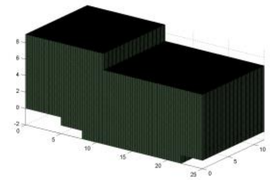
Δx = 100cm
$f_s = c\sqrt{3}/\Delta x \approx 600$Hz
Nodes: ***N***
Time steps: ***M***
Computation: ***NM***

Δx = 50cm
$f_s \approx 1.2$kHz
Nodes: **$2^3N=8N$**
Time steps: **2*M***
Computation: **16*NM***

1s impulse response by FDTD, volume 3 300 m^3
Computer performance 1.4TFLOPS

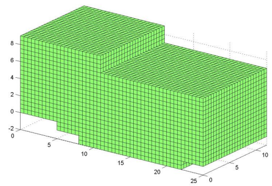
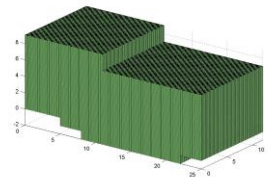
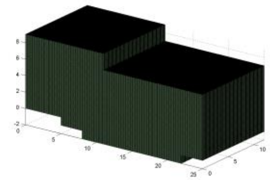






Δx	50 cm	12.5 cm	3.1 cm	8 mm
f_s	1.2 kHz	4.8 kHz	19 kHz	76 kHz
Nodes	3.3×10^3	1.7×10^6	108×10^6	6.9×10^9
Memory	422 kB	27 MB	1.7 GB	111 GB
Operations	251 MFLOPs	64 GFLOPs	16 TFLOPs	5 PFLOPs
Time	0.2 ms	46 ms	12 s	50 min

1s impulse response by FDTD, volume 3 300 m³
Memory bandwidth 288GB/s

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f_s	1.2 kHz	4.8 kHz	19 kHz	76 kHz
Nodes	3.3×10^3	1.7×10^6	108×10^6	6.9×10^9
Memory	422 kB	27 MB	1.7 GB	111 GB
Transfer	1 GB	257 GB	66 TB	17 PB
Time	3.5 ms	0.89 s	3min 48s	16h 15min

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Some room acoustic attributes

Reverberation time formulae

- **Sabine:** $\boldsymbol{T60 = 0.161\,\frac{V}{A} = \frac{0.161\,V}{S\alpha}}$
  - Diffuse sound field
  - Low absorption
  - Absorption evenly distributed in the room

- **Eyring:** $\boldsymbol{T60 = \frac{0.161\,V}{-S\,ln(1-\alpha)}}$
  - For higher absorption values

Objective parameter: Strength

$$G = \frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10m}^2(t)dt}$$

Objective descriptor: Early/late ratios

Clarity:

$$C_{80} = 10Log\left(\frac{\int_{0ms}^{80ms} p^2 dt}{\int_{80ms}^{\infty} p^2 dt}\right) dB \qquad C_{80} = 10LOG\left(\frac{E(0,80ms)}{E(80,\infty ms)}\right) dB$$

Deutlichkeit or Definition D_{50}:

$$D_{50} = \left(\frac{E(0,50ms)}{E(0,\infty ms)}\right)$$

Geometrical Acoustics … next week

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