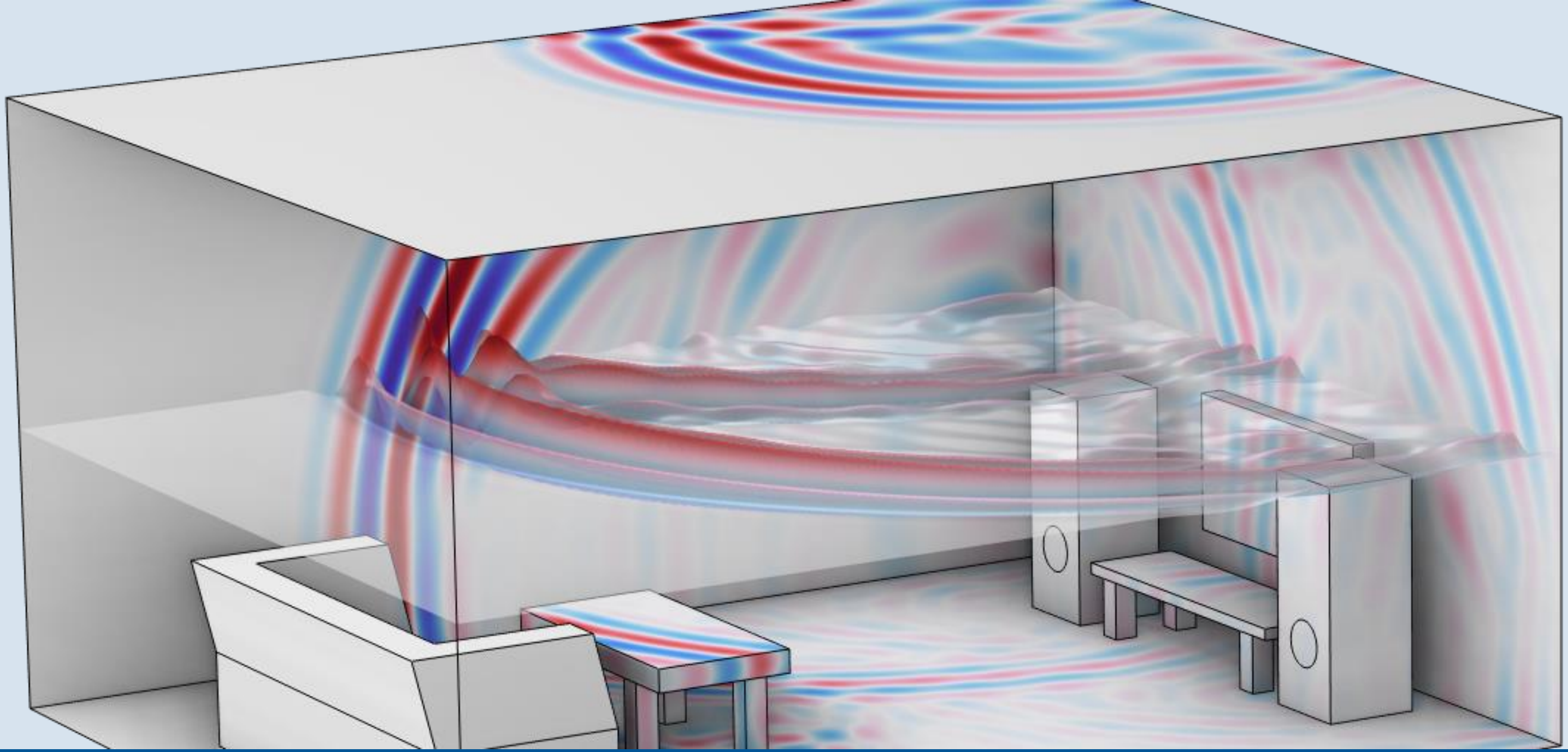


Acoustic Simulations in Buildings:
The Multi-method Approach of COMSOL Multiphysics

Sven Friedel
COMSOL Zurich

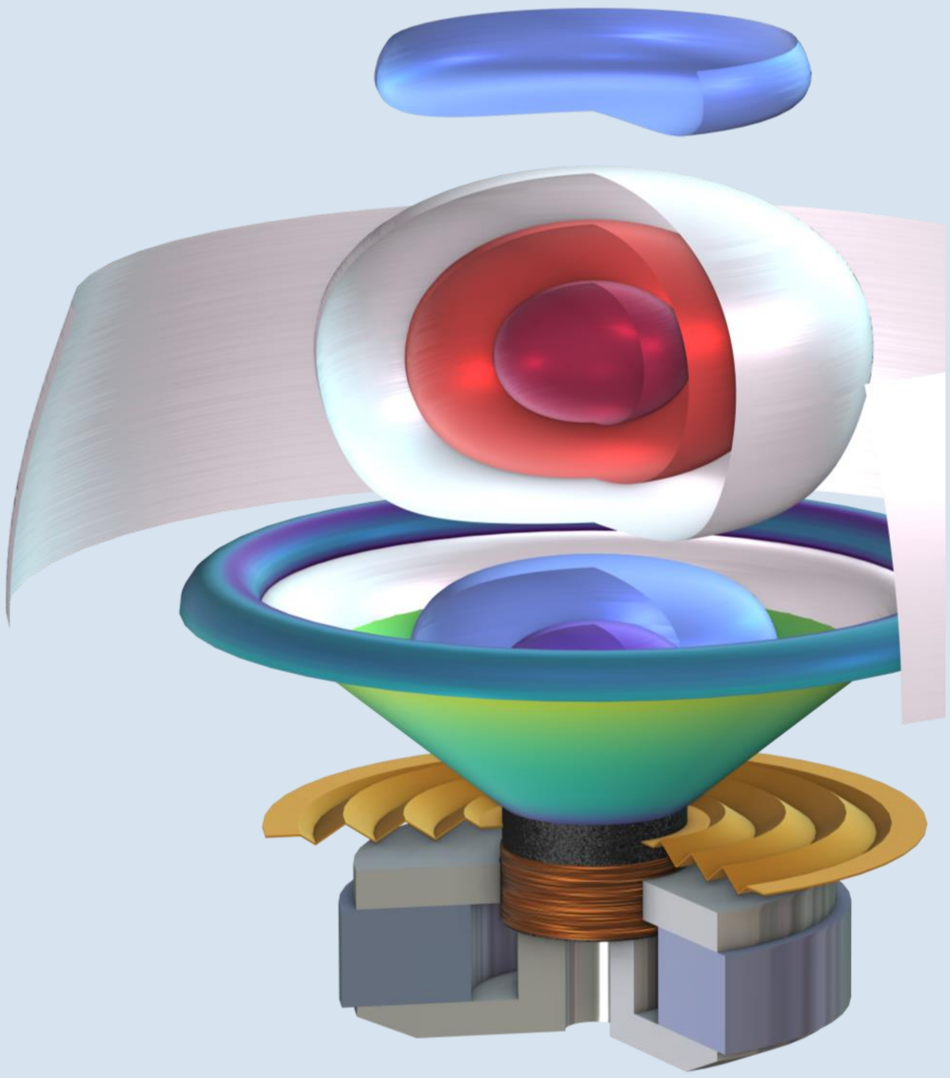
Agenda

- Introduction – The COMSOL Perspective on Acoustics
- Geometric Acoustics
- Wave Acoustics and Hybrid Modeling
- Acoustic-Structure Interaction

COMSOL Multiphysics®

One software environment for any engineering field.

- Provides fully coupled multiphysics and single-physics modeling capabilities.
- Unified User-Interface
- Seamless integration in engineering design workflow
- Allows creation of stand-alone applications



LOUDSPEAKER MULTIPHYSICS

Pressure Acoustics

Sound wave propagates through air

Structural Mechanics

Membrane vibration excited by EM forces.

Electromagnetics

Voice coil driven by voltage interacts with permanent magnet.

COMSOL

Model tree shows sequences of operations

Definitions

Geometry

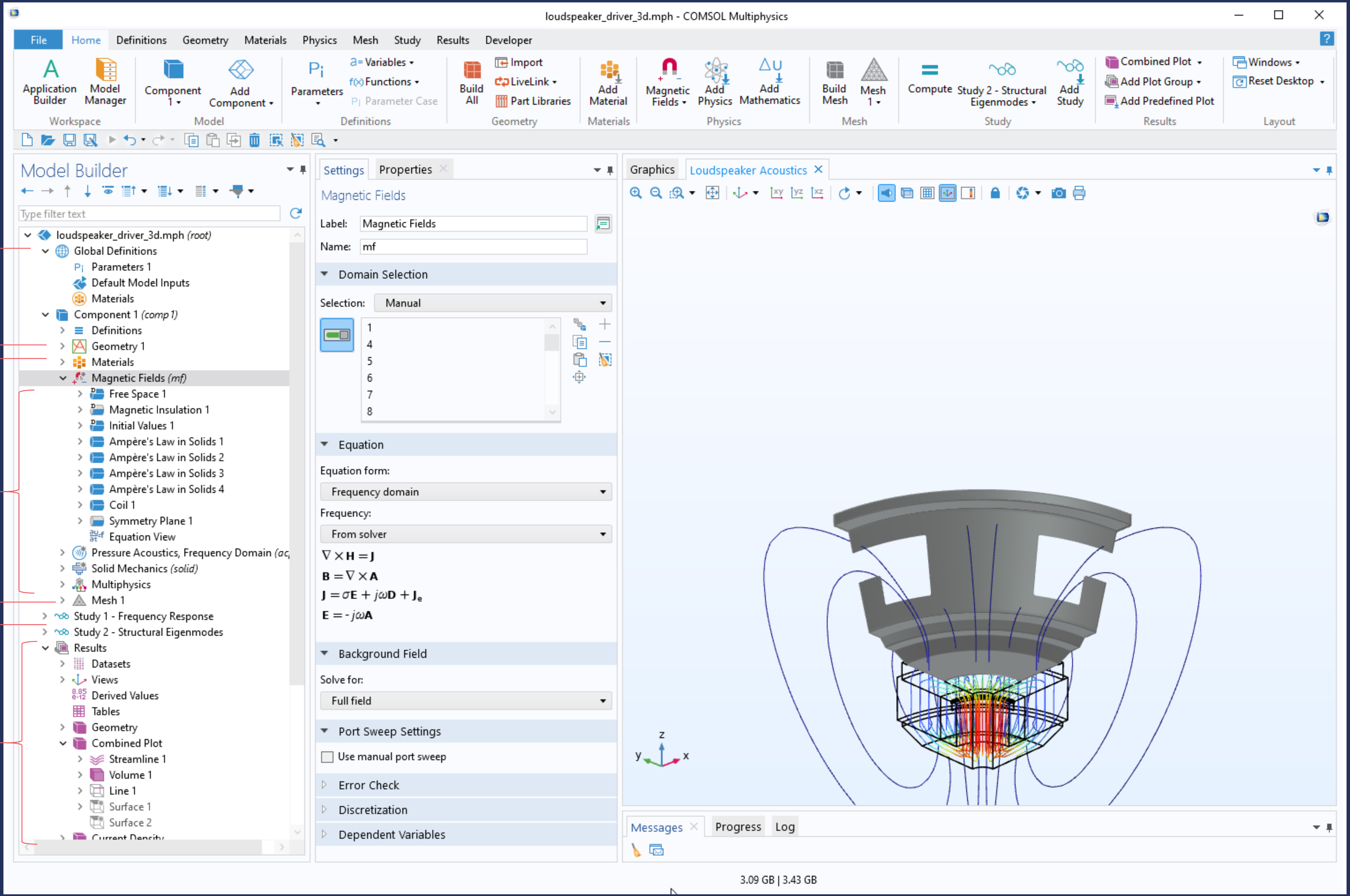
Materials

Physics
Electromagnetics

Mesh

Study

Results



COMSOL

Model tree shows sequences of operations

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Structural Mech.

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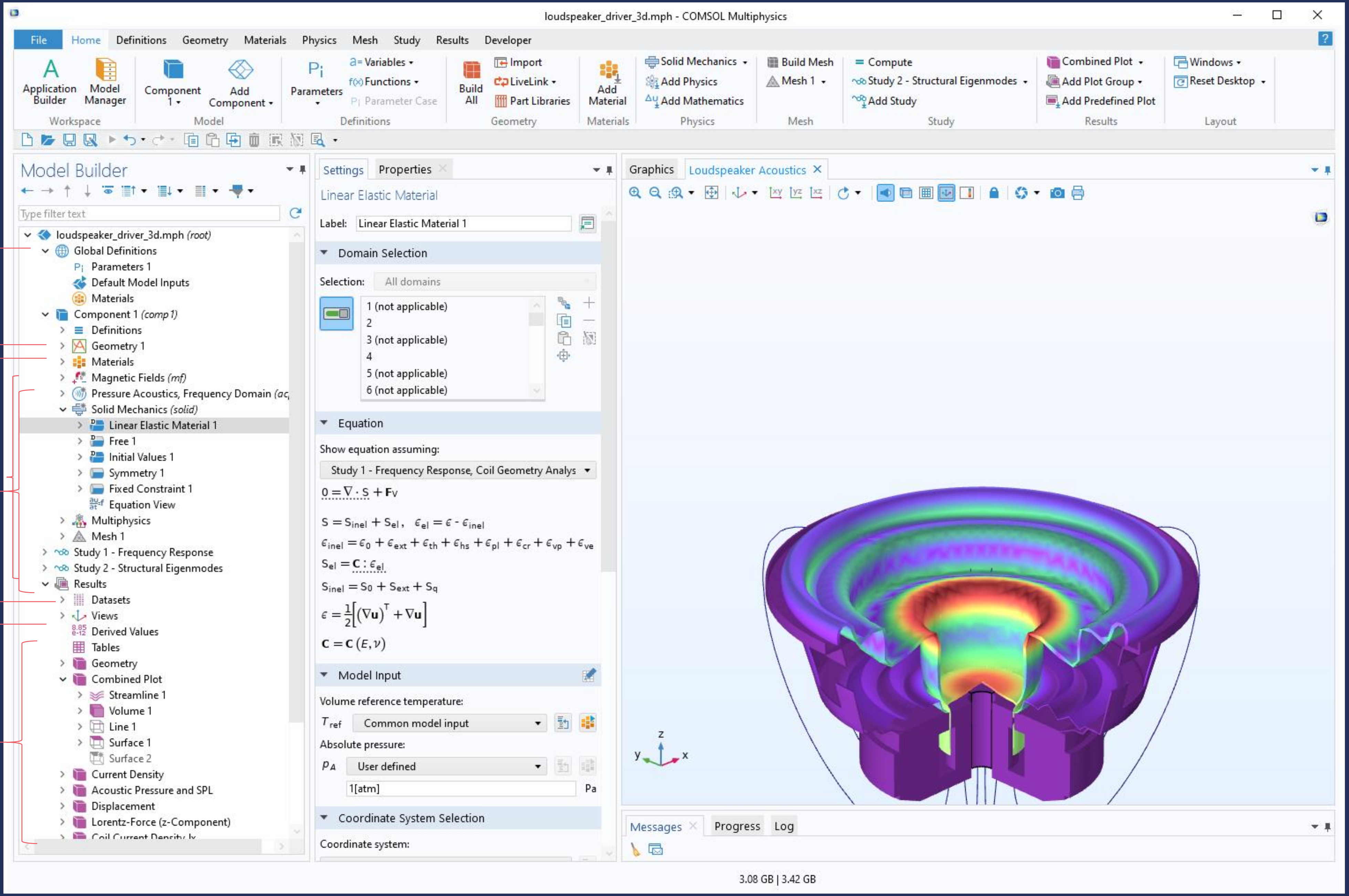

COMSOL

Model tree shows sequences of operations

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Physics
Pressure Acoustics

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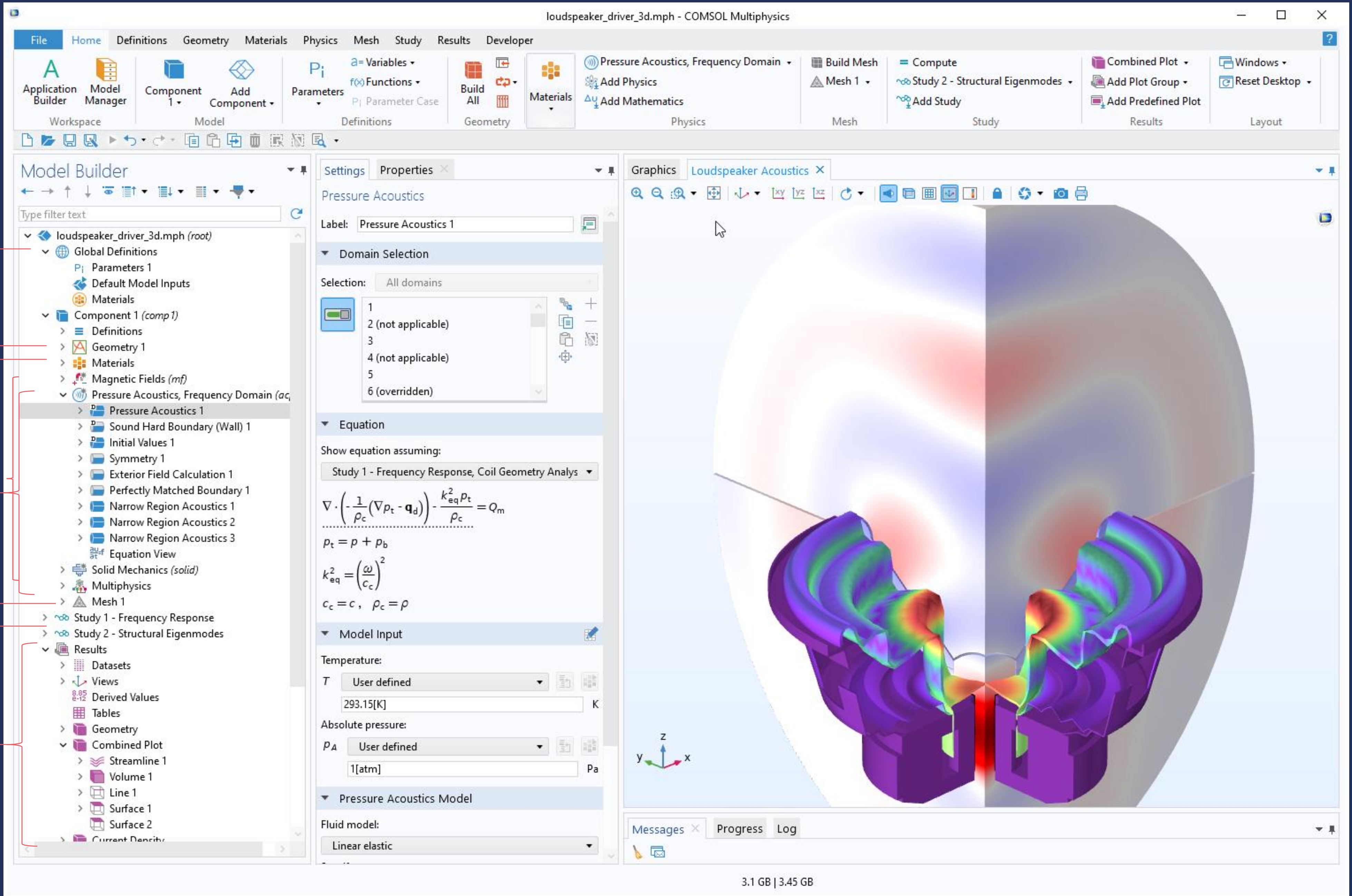
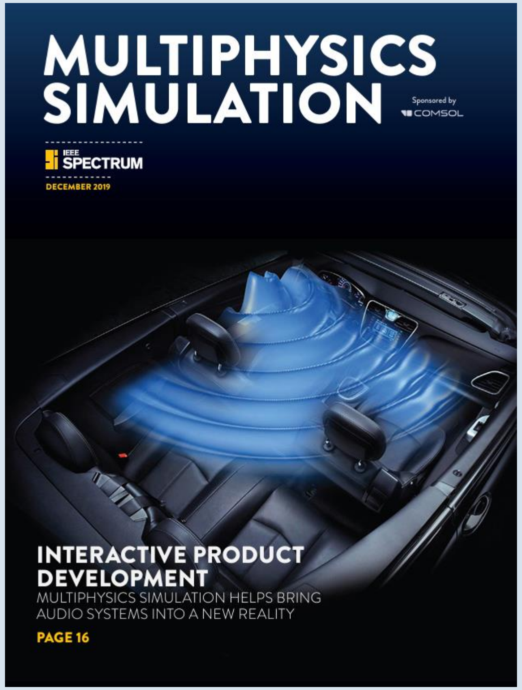
Results

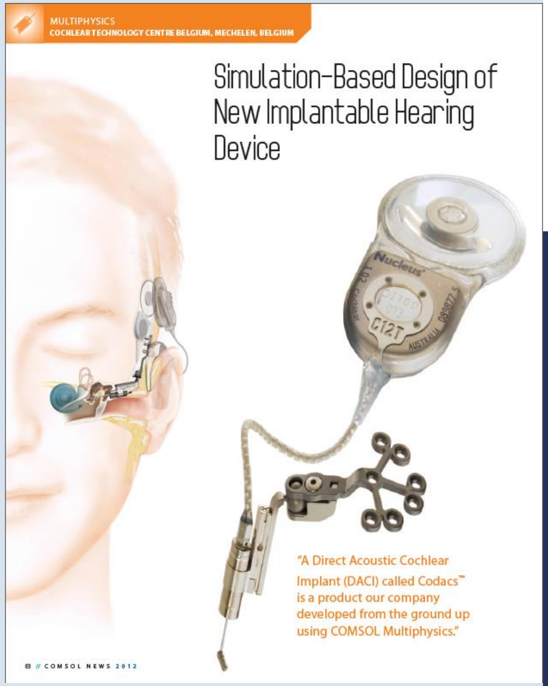


Selected Industrial Applications

Speakers and Headphones



Automotive Acoustics



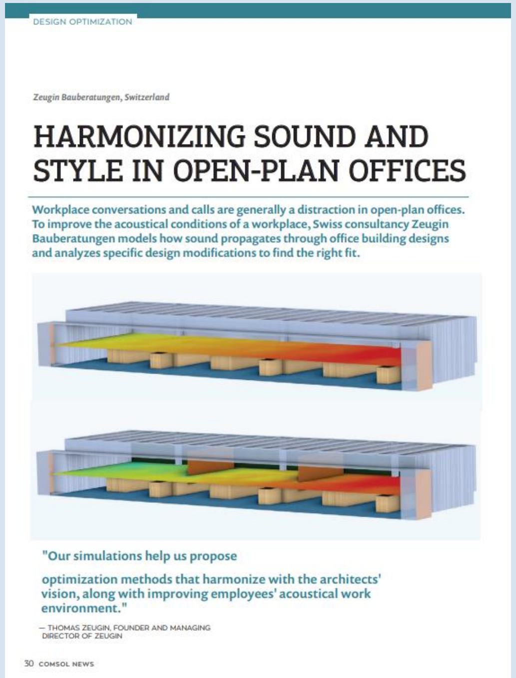
MULTIPHYSICS
COCHLEAR TECHNOLOGY CENTRE BELGIUM, MECHELEN, BELGIUM

Simulation-Based Design of New Implantable Hearing Device

"A Direct Acoustic Cochlear Implant (DACI) called Codacs™ is a product our company developed from the ground up using COMSOL Multiphysics."

COMSOL NEWS 2012

Hearing aids and Implants



DESIGN OPTIMIZATION

Zeugin Bauberatungen, Switzerland

HARMONIZING SOUND AND STYLE IN OPEN-PLAN OFFICES

Workplace conversations and calls are generally a distraction in open-plan offices. To improve the acoustical conditions of a workplace, Swiss consultancy Zeugin Bauberatungen models how sound propagates through office building designs and analyzes specific design modifications to find the right fit.

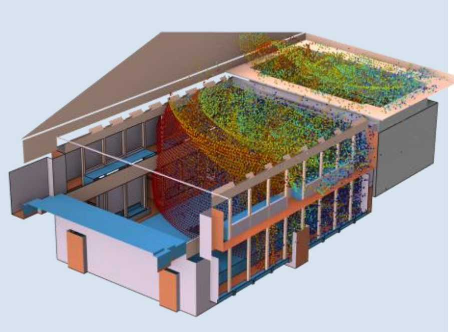
"Our simulations help us propose optimization methods that harmonize with the architects' vision, along with improving employees' acoustical work environment."

— THOMAS ZEUGIN, FOUNDER AND MANAGING DIRECTOR OF ZEUGIN

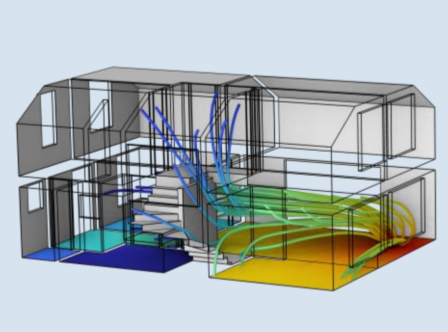
30 COMSOL NEWS

Building Acoustics

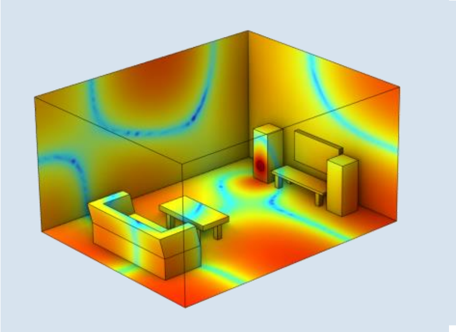
Physics Interfaces for Acoustics in Buildings



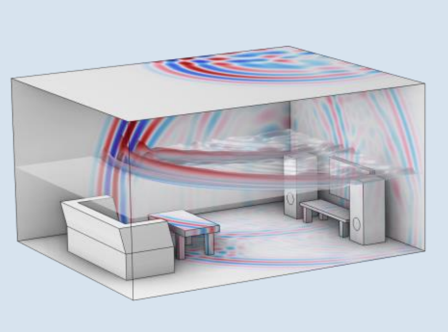
Ray Acoustics



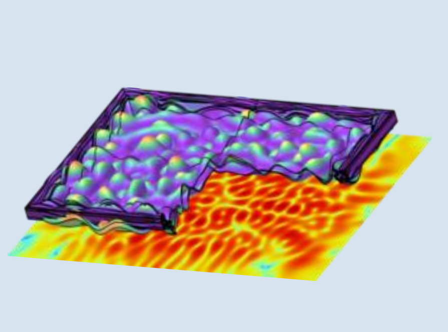
Acoustic Diffusion



Pressure Acoustics, Frequency Domain



Pressure Acoustics, Time Explicit



Acoustic Structure Interaction

Geometric Acoustics

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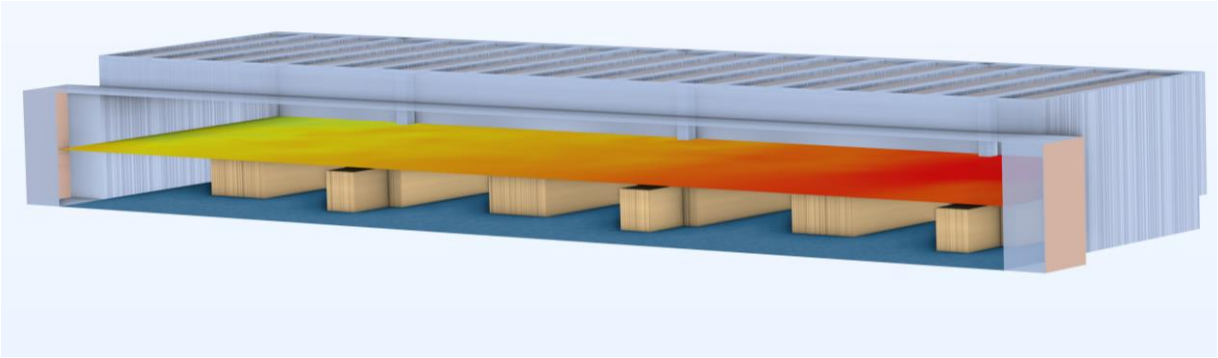
COSTUMER SUCCESS: ZEUGIN BAUBERATUNGEN

Harmonizing Sound and Style in Open-Plan Offices

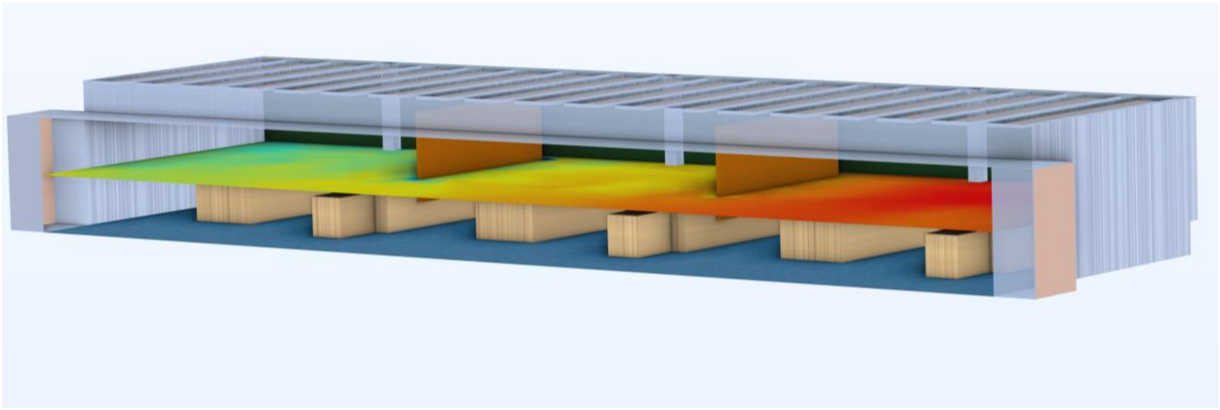
- Project Poststrasse Süd Ostermundingen
- Room acoustic parameters according to EN ISO 3382:2012
- Measures taken:
    1. 80% acoustic floor, hybrid ceiling sail
    2. acoustic curtains
    3. hanging foam plates with 1mm steel inside

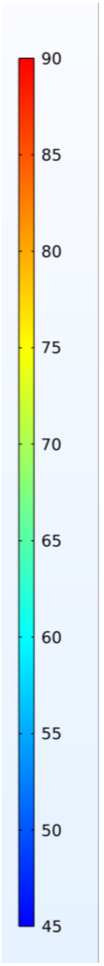
	BEFORE	AFTER
Ablenkungsabstand r_D	7.8 m	4.5 m
Räumliche Abklingrate $D_{2,S}$	4.9 dB	8.7 dB
A-bewerteter SPL bei 4m $L_{P,A,S,4m}$	52.6 dB(A)	46.3 dB(A)

SPL at 1000 Hz original situation (1)



SPL at 1000 Hz with mitigation measures (2) and (3)



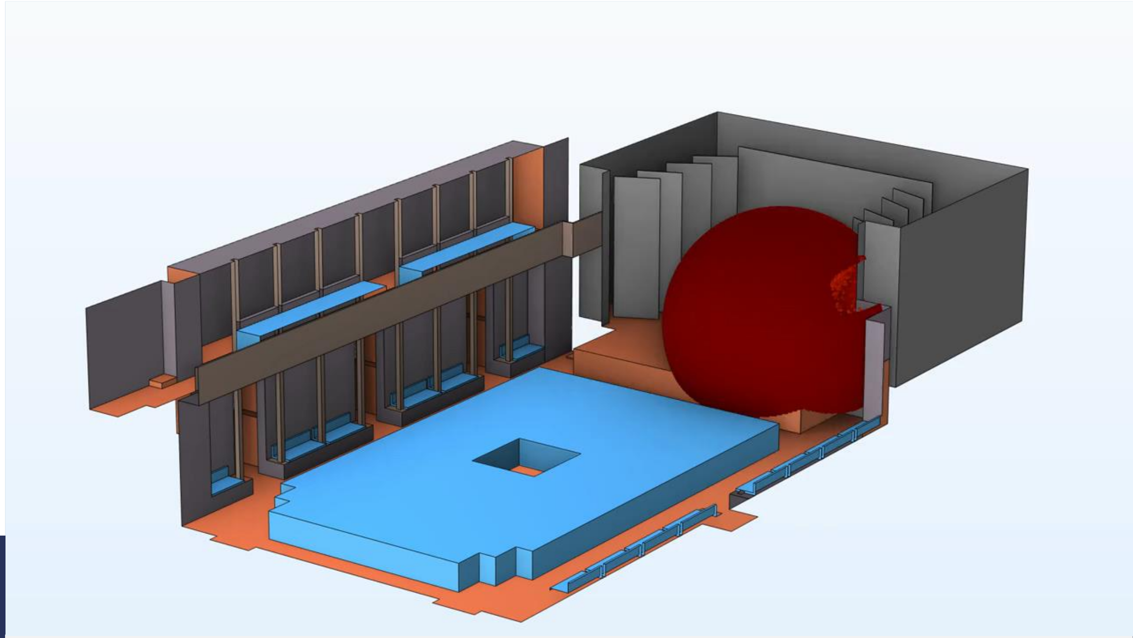


COMSOL TUTORIAL

Validation of Ray Tracing Simulations in Konzerthaus Berlin

Konzerthaus Berlin at Night

- Round robin study: Brinkmann et al. 2019, Aspöck et al, 2020
- Foto: *Ansgar Koreng – Own work. Licensed under* CC BY 3.0 (DE), *via* Wikimedia Commons.



Ray Acoustics Simulation 100 Hz to 5000 Hz

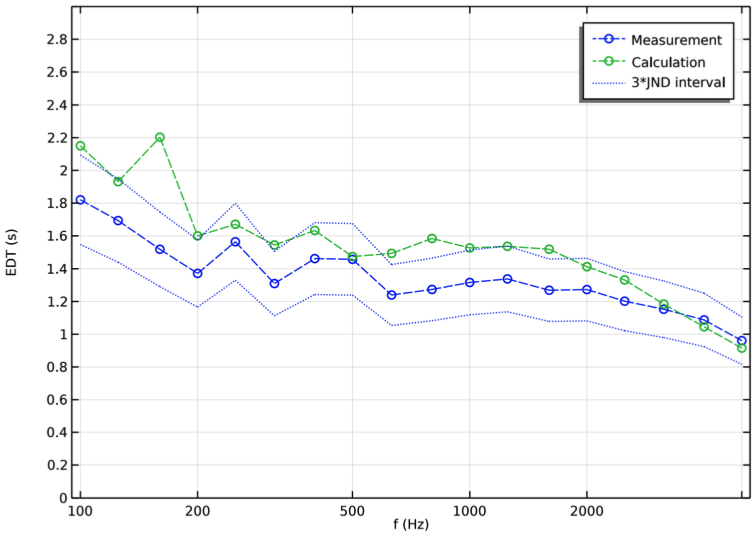
Volume 2350 m^3, A-values of all surfaces, 10 source-receiver pairs, power along each ray, mixed specular and diffuse relection.

COMSOL TUTORIAL

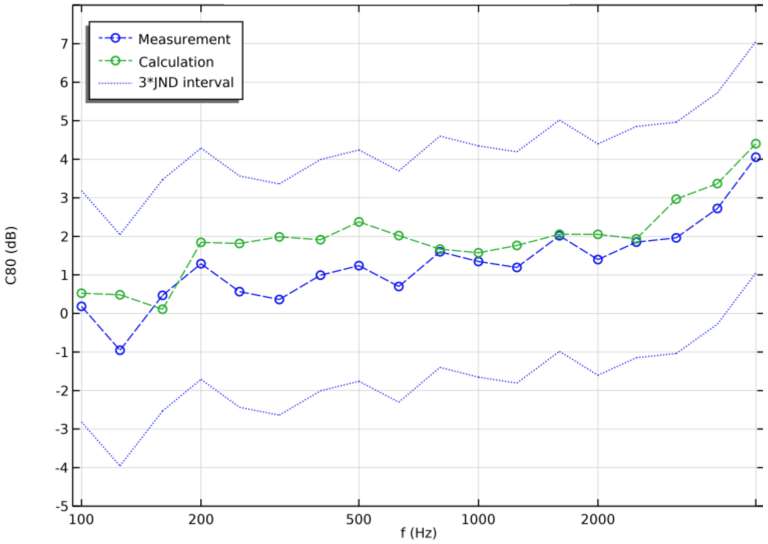
Validation of Ray Tracing Simulations in Konzerthaus Berlin

- Comparison between measurements (blue) and calculated data (green) and 3*JND band
- JND = just noticeable difference

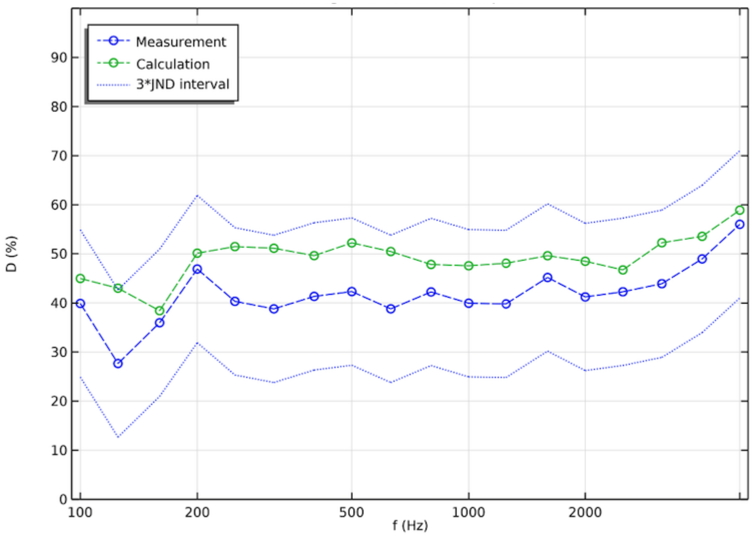
Early decay time (EDT)



Clarity (C80)



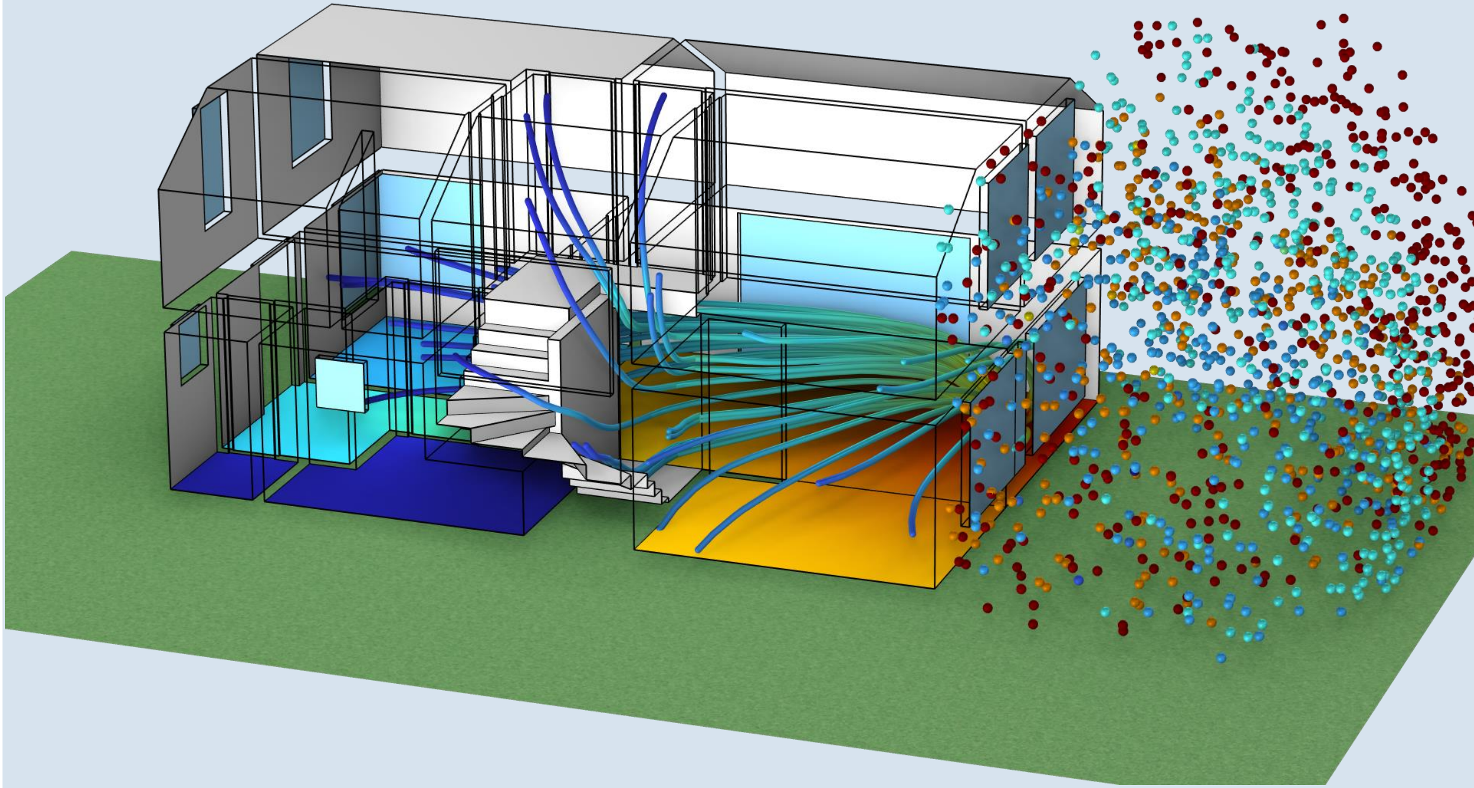
Definition (D)



GEOMETRICAL ACOUSTICS

Acoustic Diffusion Equation

- Fast method to analyze energy decay curves and reverberation time in coupled rooms.
- Uses a diffuse field approximation (no direct sound) useful for high frequencies.
- Diffusion constant is geometry dependent (acoustic mean free path)
- Statistical models: Sabine, Eyring, and Modified Eyring
- Band structure for material parameters and source input



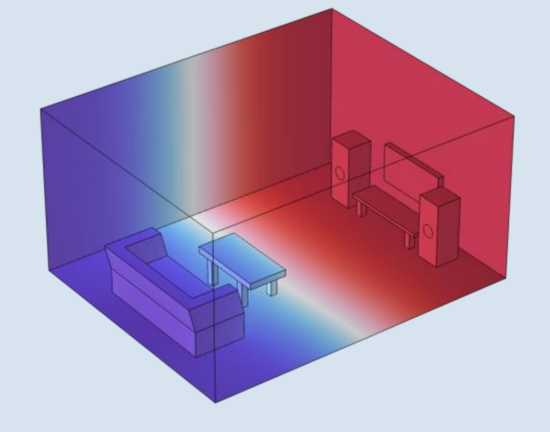
Sound pressure level distribution and energy flux inside a single-family house.

Limitations of Geometrical Acoustics

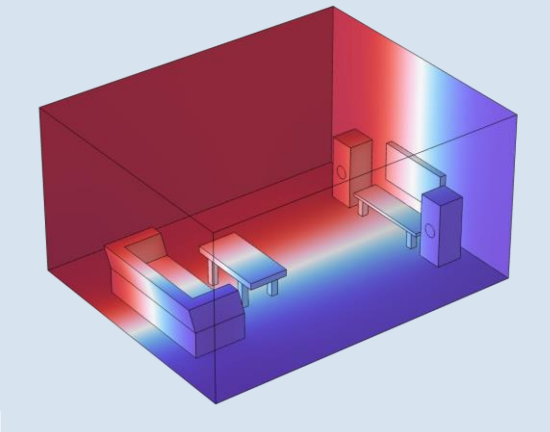
- Low frequency limit: Bad resolution of resonance dominated modal region
- High frequency limit: Wavelength smaller than objects (diffraction)
- No solids: No acoustic Structure interaction
- Simplified Sources: Often modeled as points or simple vibrating surfaces
- Acoustic diffusion: No direct sound, no phase information, no early reflections

Wave Acoustics

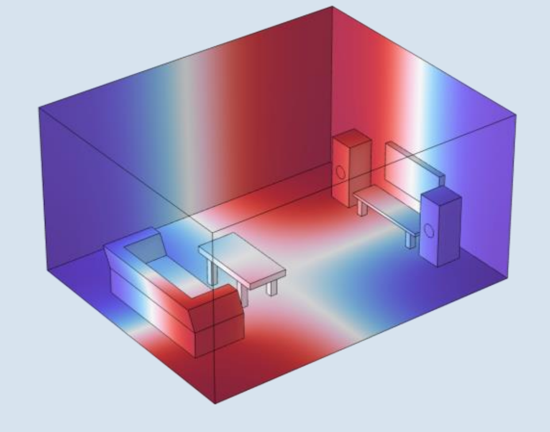
Modal Analysis



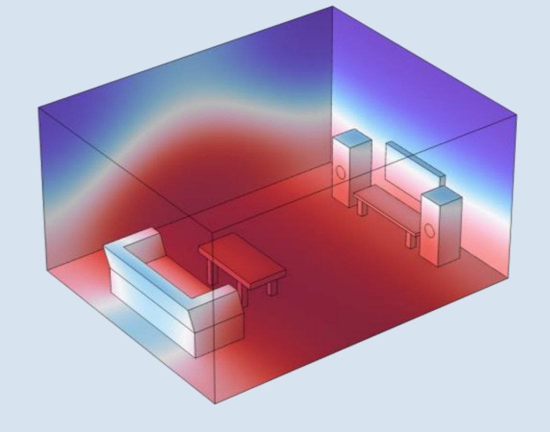
First mode



Second mode



Third mode



Fourth mode

The mode shapes give the locations of pressure nodes and can help identify poor listening positions.

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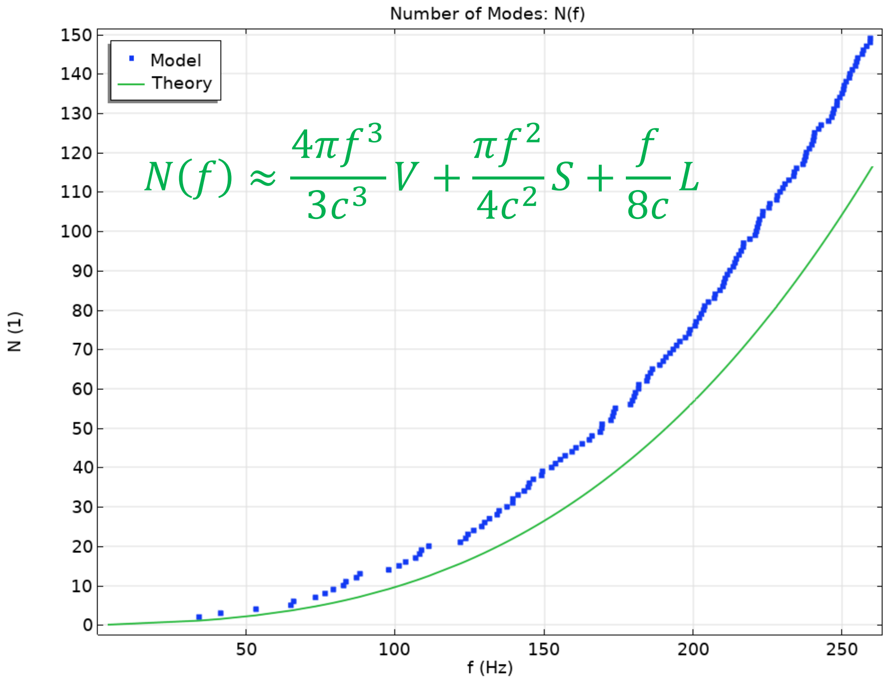
Statistics: Number of Modes

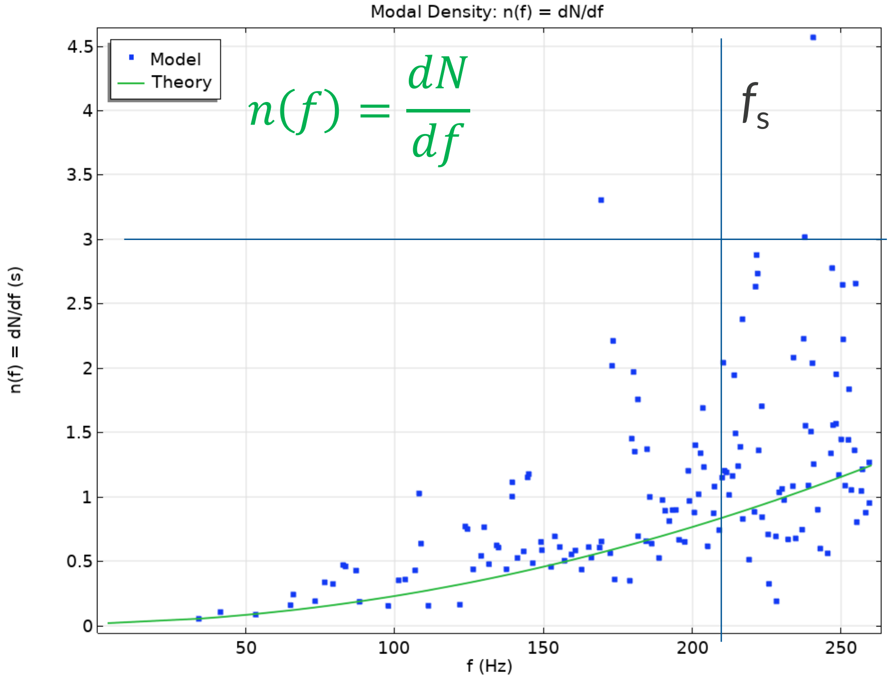
- Compare modal statistics with the theoretical predictions

$$L = \text{room volume}$$
$$S = \text{total surface area}$$
$$L = \text{total edge lengths}$$
$$N(f) = \text{number of modes}$$
$$n(f) = \text{modal density}$$

$$f_s \approx 2000\sqrt{\frac{T_{60}}{V}} = \text{Schroeder Frequency}$$

- The frequency domain analysis contains already much more information than simple theoretical predictions.



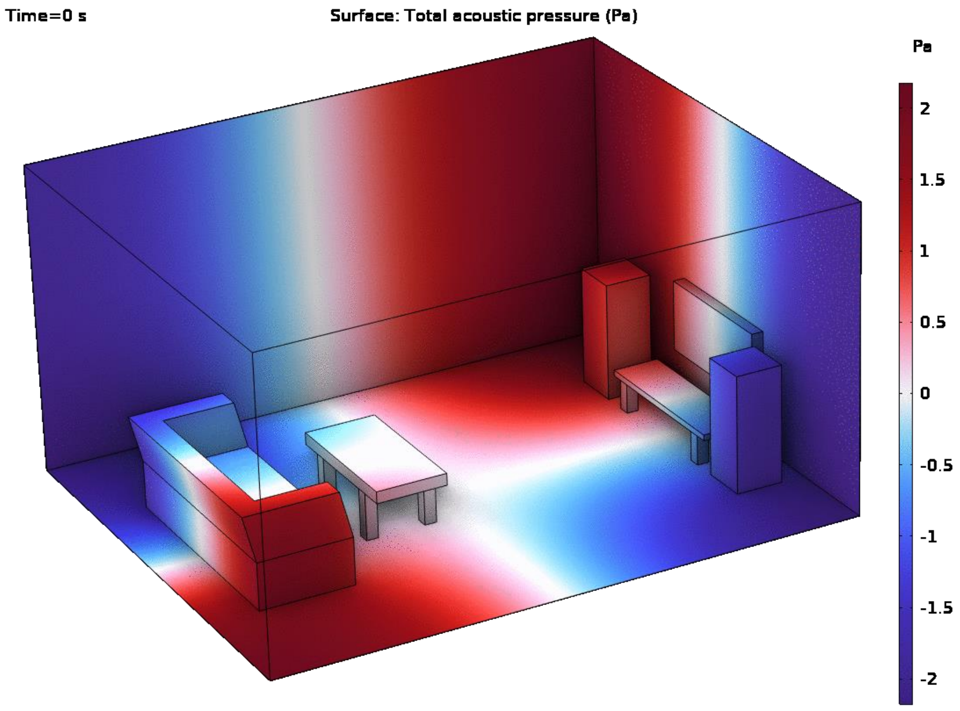


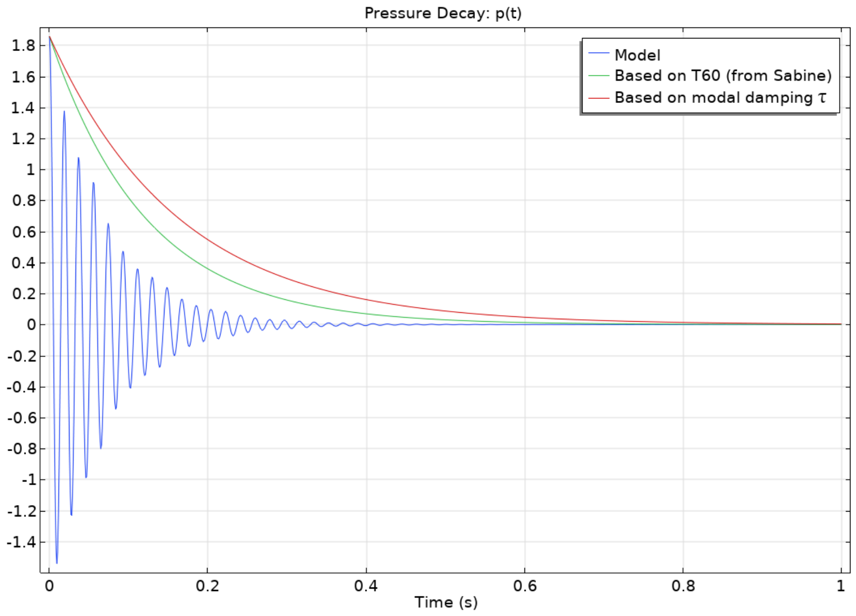
Single Mode Reverberation Time: Transient

- Modal analysis also yields information about decay of modes, when ***impedance boundary conditions*** are used (floor, sofa, ceiling) → complex eigenfrequency:
- f = (53.3 + 0.013i) Hz

$$p(t) = p_0 \exp\left(-\frac{t}{\tau}\right)\cos(\omega t)$$
$$\approx p_0 \exp\left(-\frac{3\log(10)}{T_{60}}t\right)\cos(\omega t)$$

$$\tau = 2\alpha = 4\pi Re(f)$$
$$\omega = 2\pi Imag(f)f$$

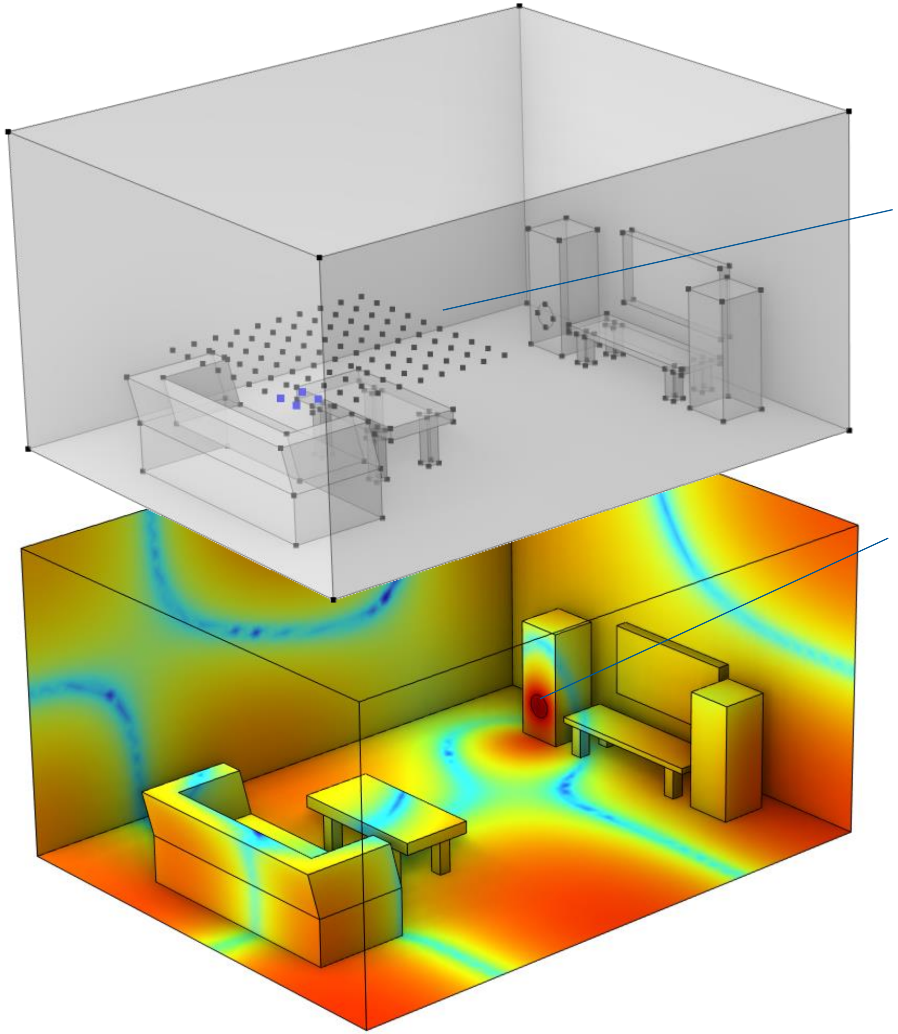




Time-Harmonic Analysis

- Compute response of room in the frequency domain
- Full–wave analysis
- Analyze transfer functions
- Room impulse response from IFFT

- **Detailed boundary conditions**



TS	Value
Re	3.5 ohm
Le	0.45 mH
BL	6 Tm
Rms	1.5 kg/s
Cms	1.4 mm/N
Mms	18.5 g

Impedance Boundary Condition and Porous Materials

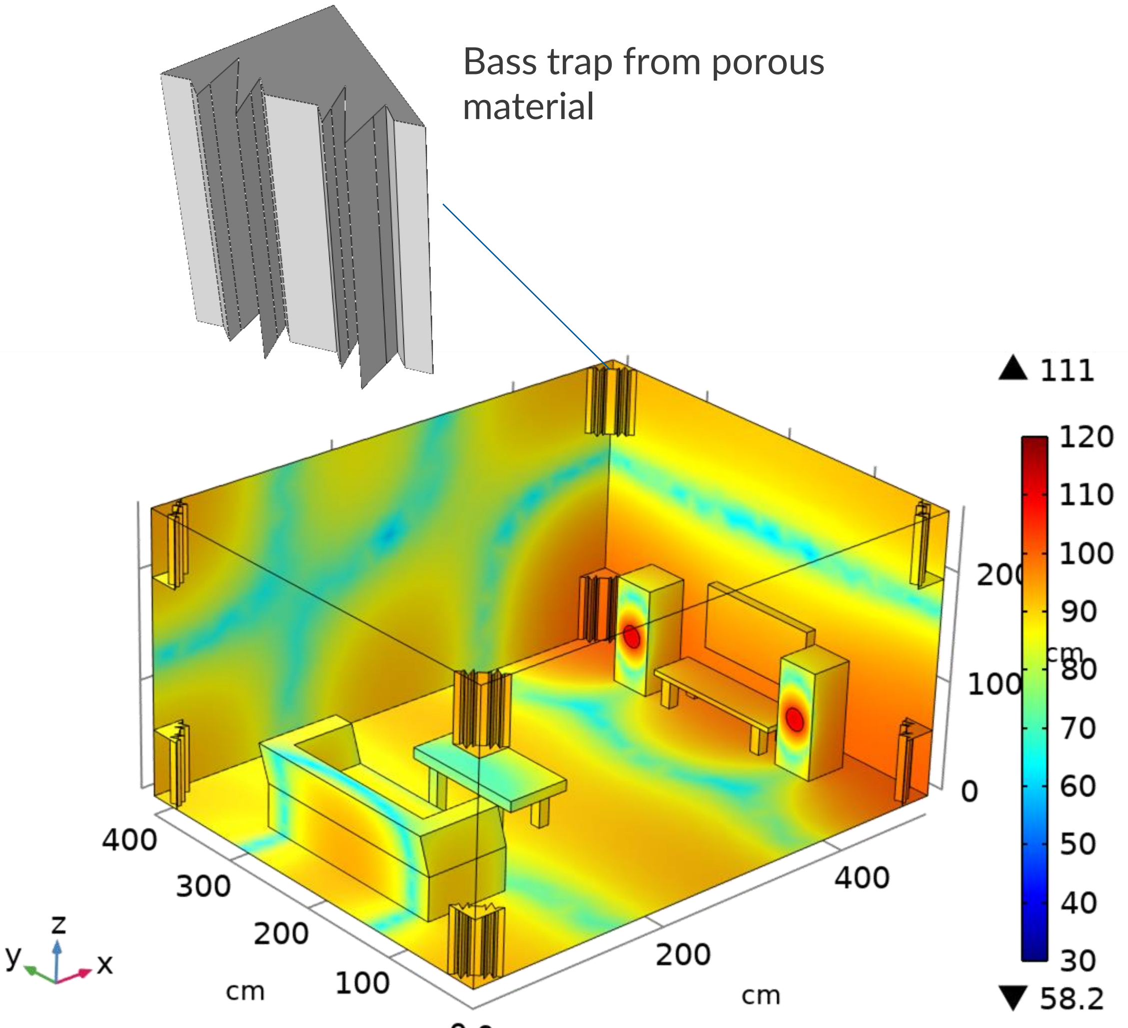
- In ***Pressure Acoustics*** impedance boundary conditions (IBC) describe the damping at surfaces.

$$\boldsymbol{u} \cdot \boldsymbol{n} = \frac{p}{Z_n}$$

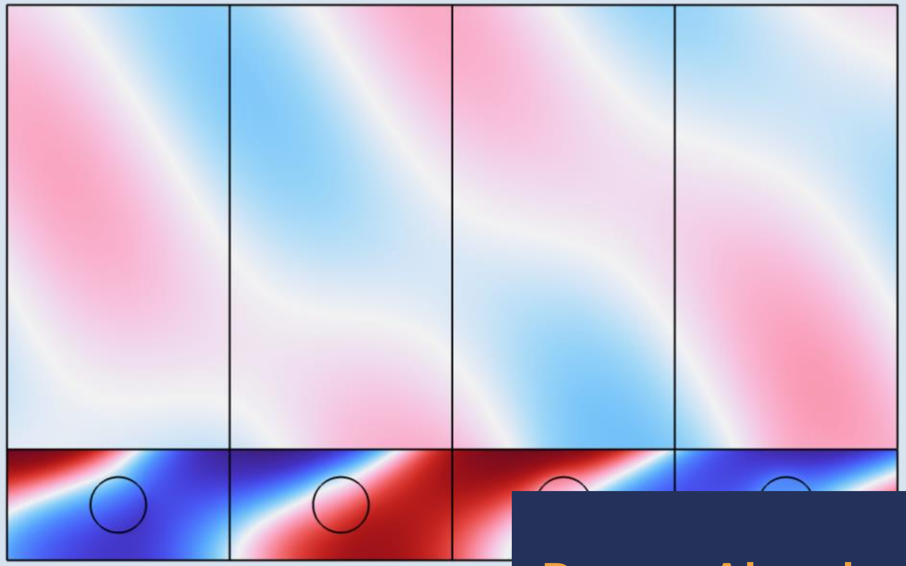
- Unlike in Ray Tracing only the normal component of the impedance is accounted for, whereas in reality it depends on the angle of incidence.

$$Z_n = Z_n(f, \theta)$$

- If in doubt: model the porous layers or parts **explicitly**

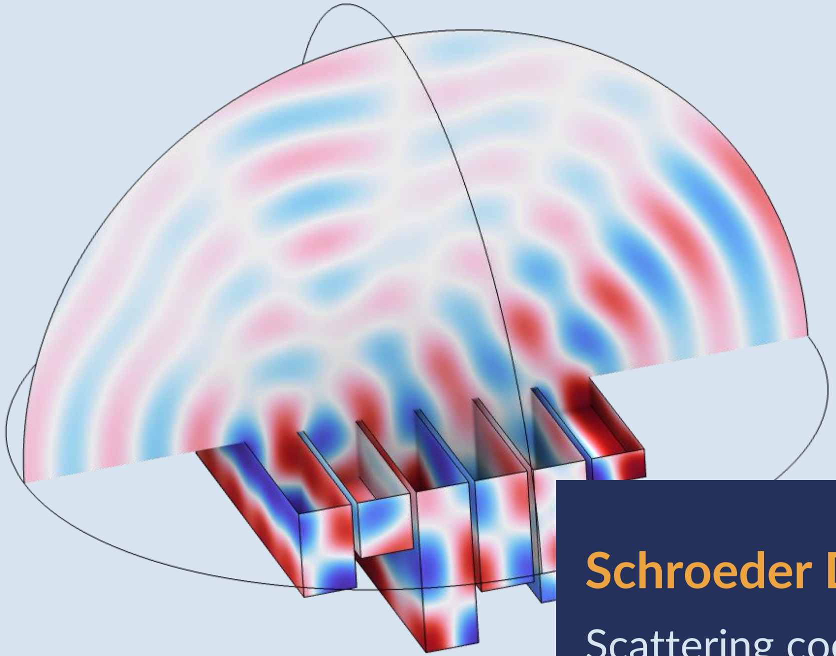


Sub-Modeling of Building Elements



Porous Absorber

Absorption and reflection coefficients, surface impedance



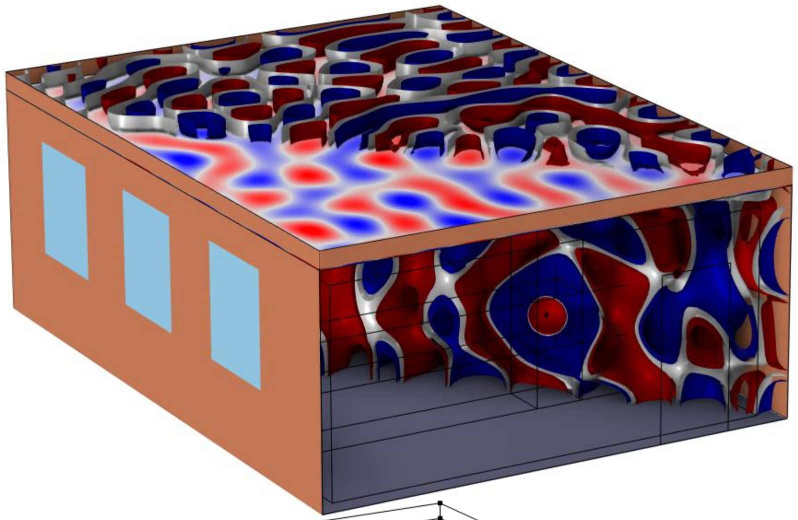
Schroeder Diffuser

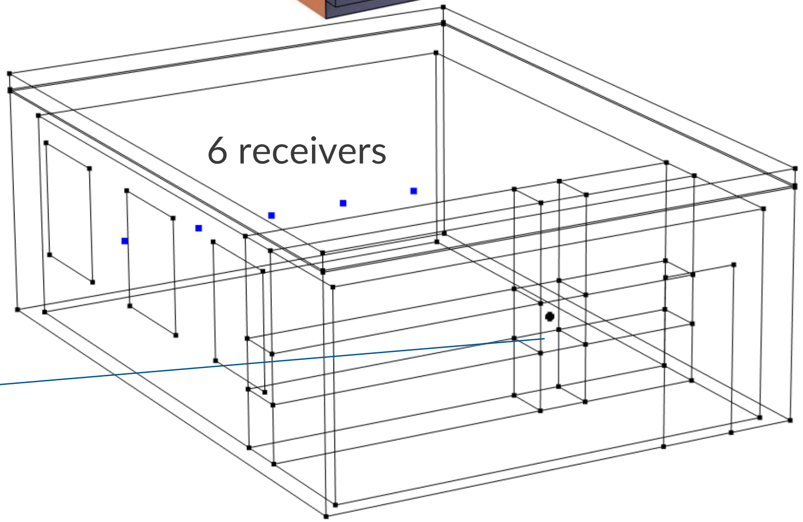
Scattering coefficient for single, multiple, or infinite arrangement(s)

Classroom with Low Ceiling: Transfer Function

- Vol = 144 m^{3},
- 20 Hz to 400 Hz,
- 1Hz resolution
- 55 min,
- 7 GB RAM

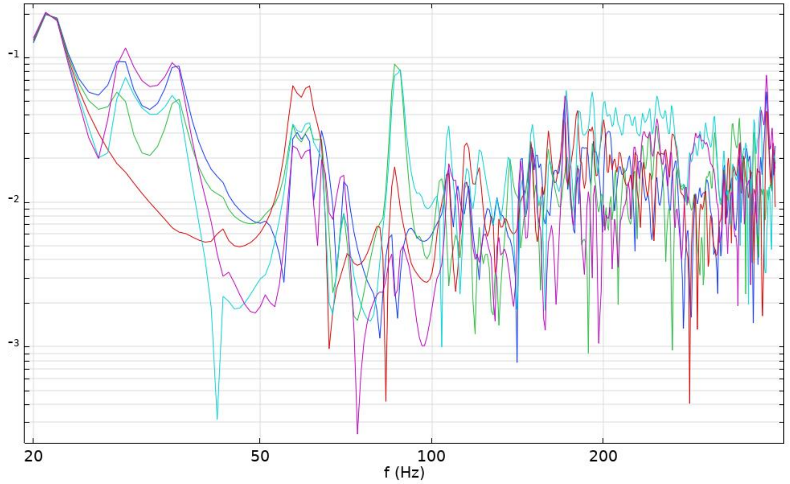
- Inverse Fourier Transformation with window

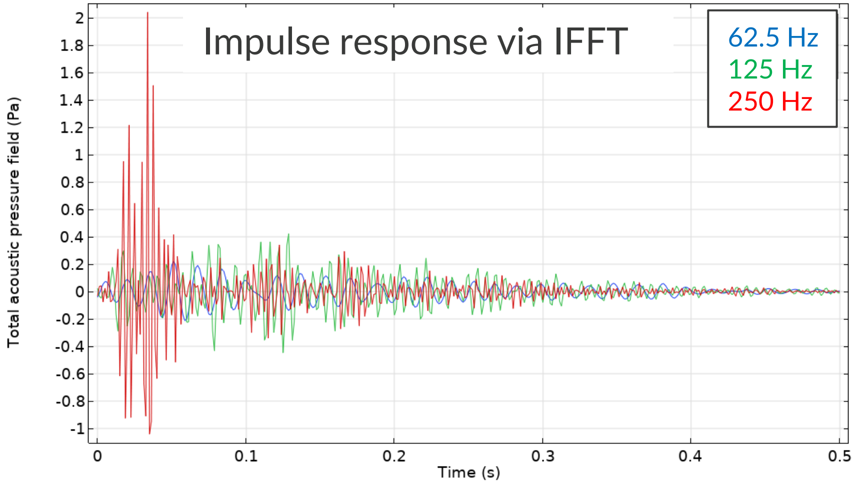




Point source

Transfer function 20 Hz – 400 Hz





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FEM at Higher Frequencies and in Large Rooms?

The Problem

- The *computational expense* raises linearly with volume *V but* exponentially with the frequency:

$$N_{DOF} = \frac{V(fN_\lambda)^3}{c^3}$$

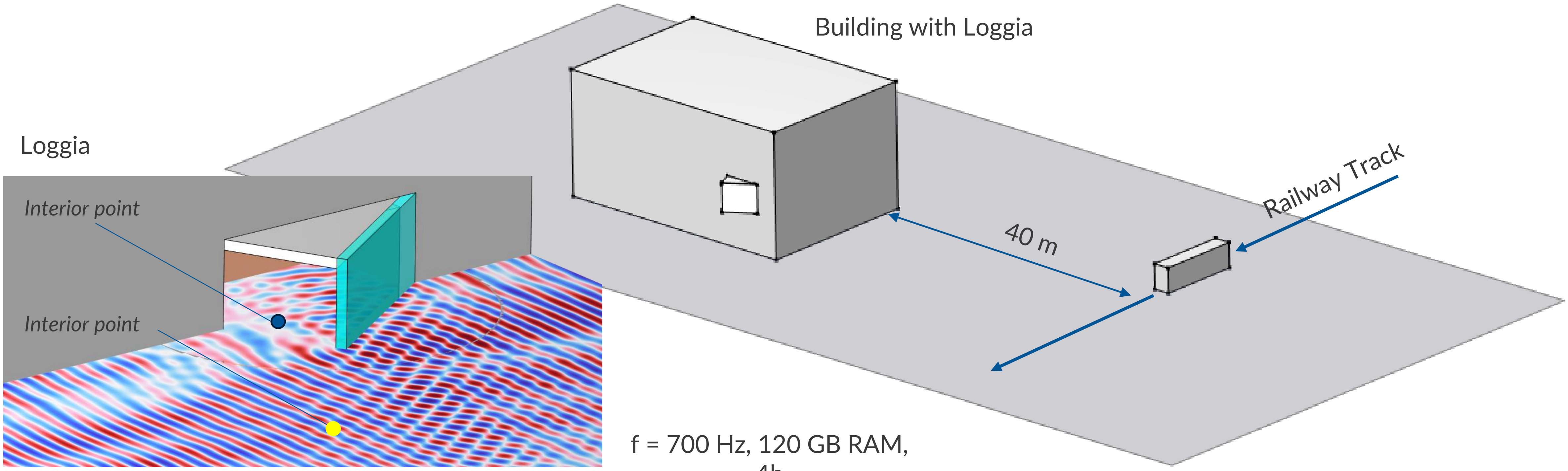
N_λ = number of mesh cells per λ
N_{DOF} = number degrees of freedom

The Solutions

- ***Hybrid Methods:*** use full-wave FEM only where it is needed and combine with ray tracing where it is possible:
  - FEM – BEM coupling
  - FEM – Ray coupling
  - FEM – Ray hybrids in frequency ranges
- ***Lean FEM methods:*** higher order discretization and time-explicit.
  - Discontinuous Galerkin

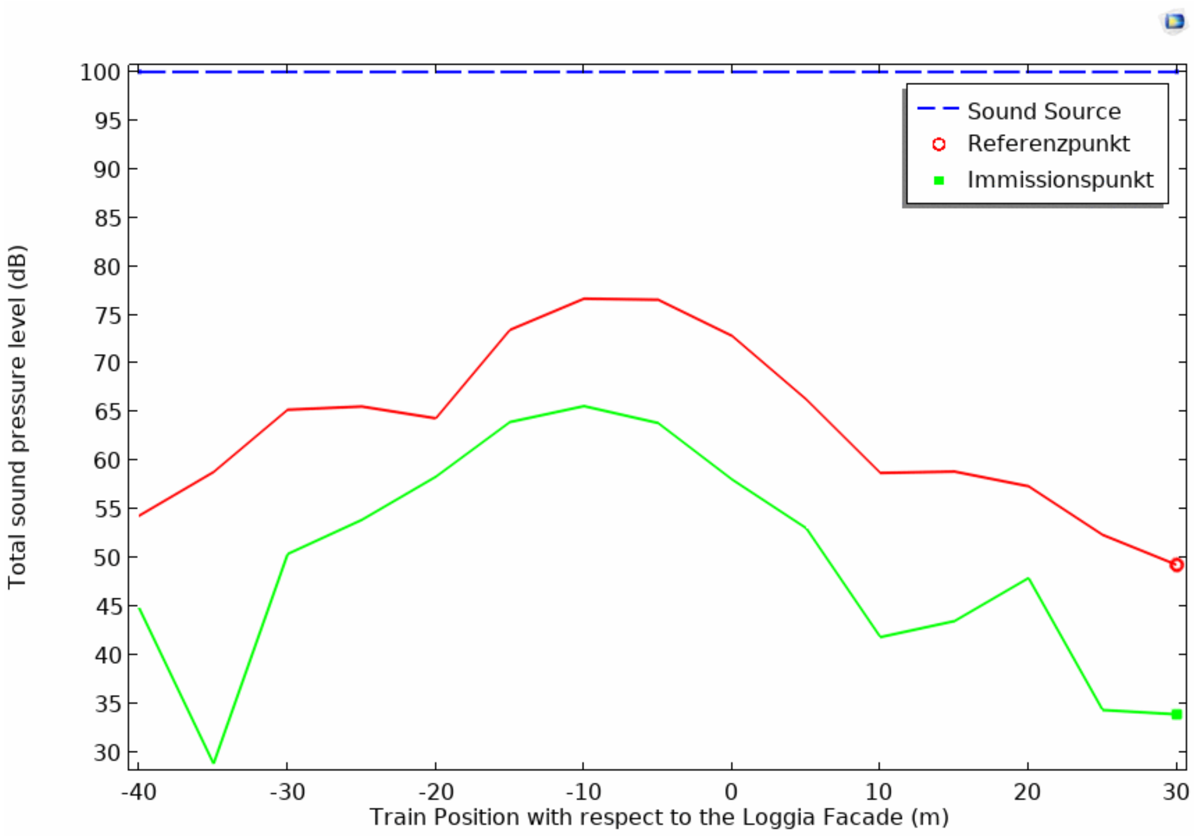
The Loggia Example – FEM-BEM Coupling

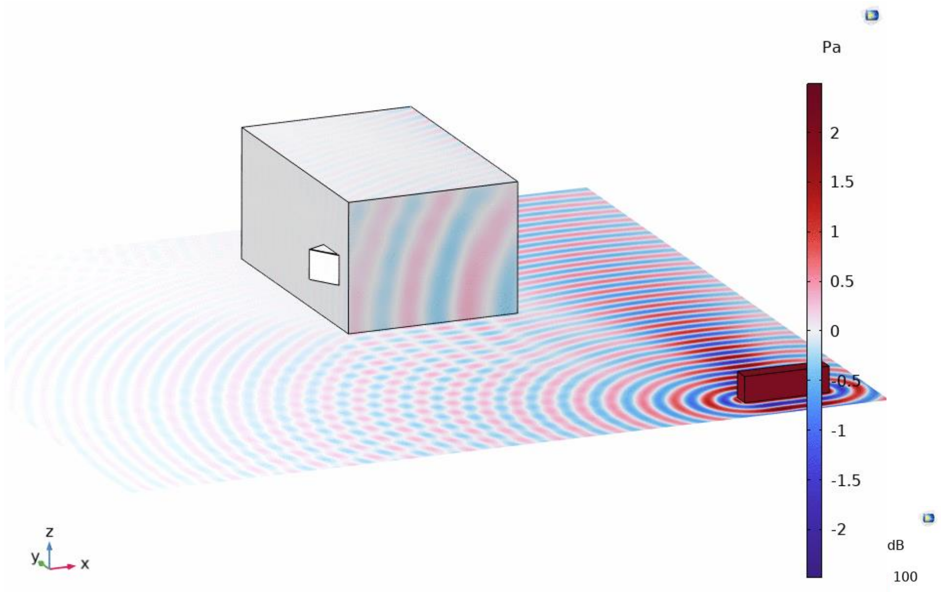
- Client wants to know the insertion loss between points inside and outside the loggia. The desired frequency 4 kHz across a distance of >40 m would require a classical FEM to solve for 125 Mio DOFs: solution model incident field with BEM

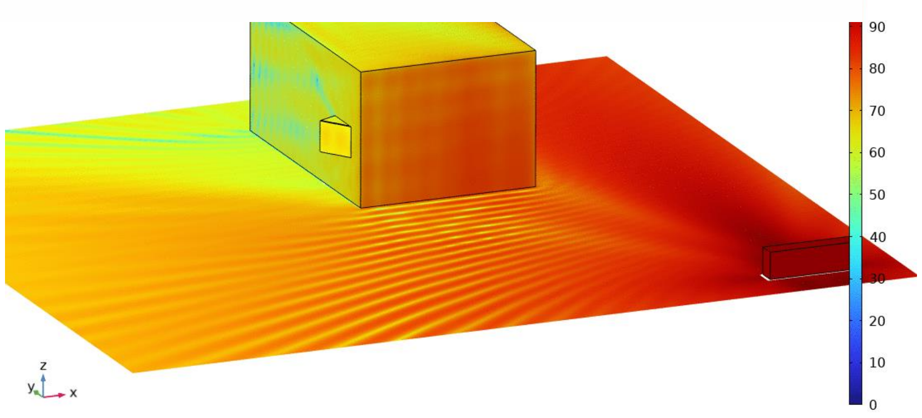


f = 700 Hz, 120 GB RAM, 4h

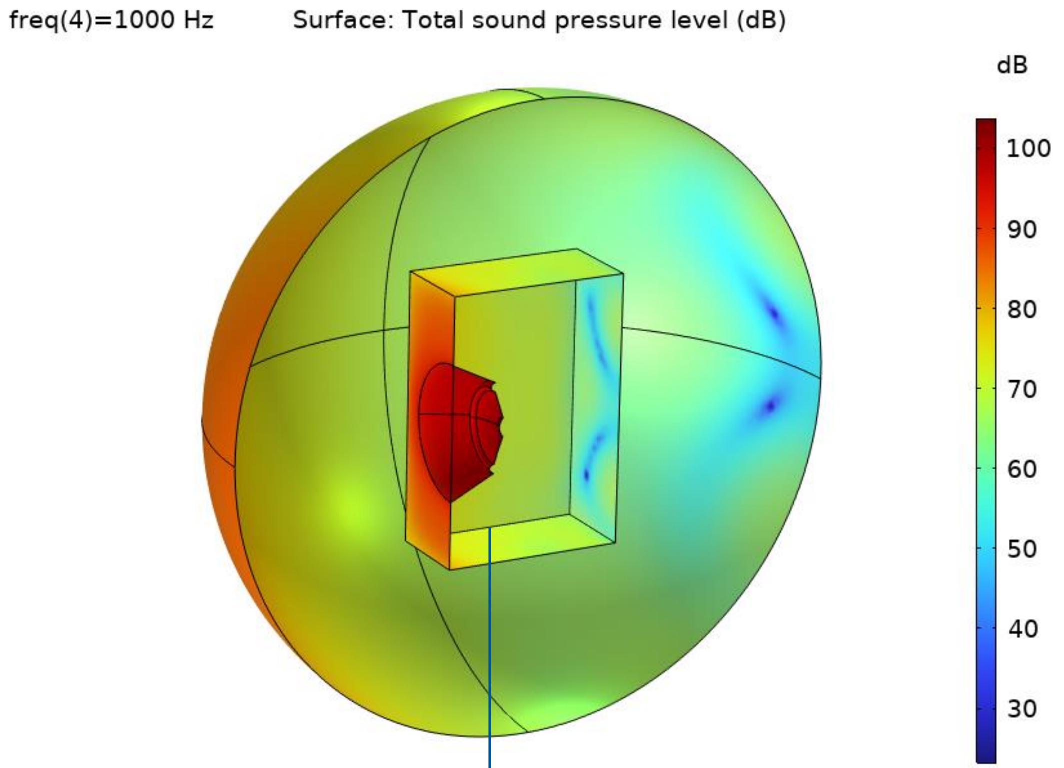
Insertion Loss vs. Sound Source Position (100 Hz, FEM-BEM)

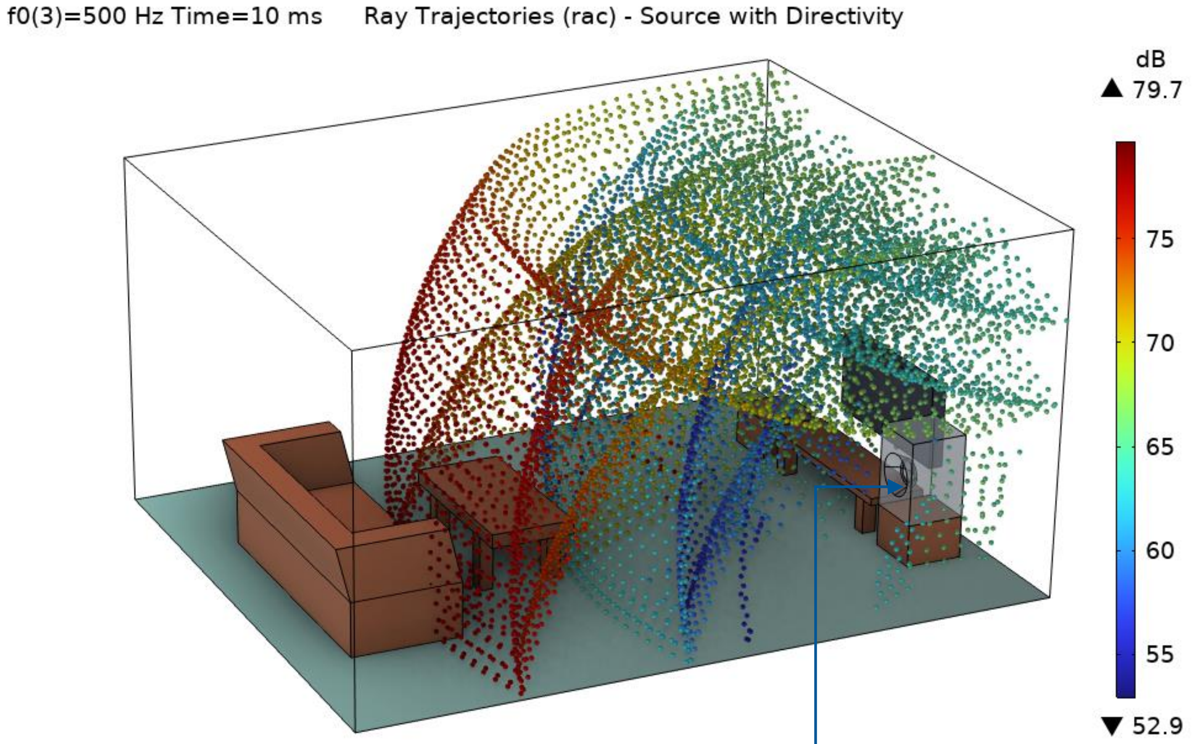






FEM-Ray Coupling: Near-field and far-field

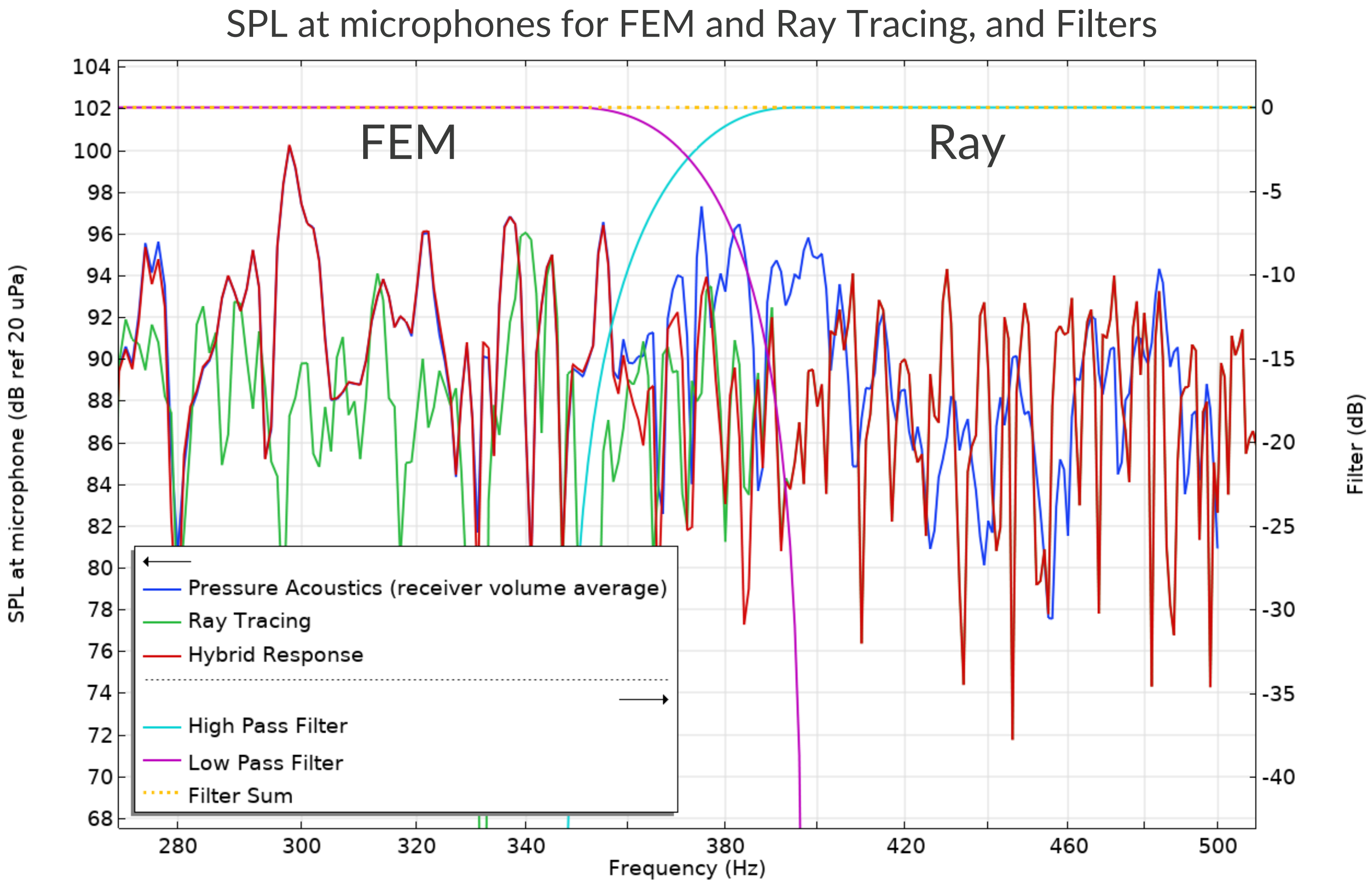


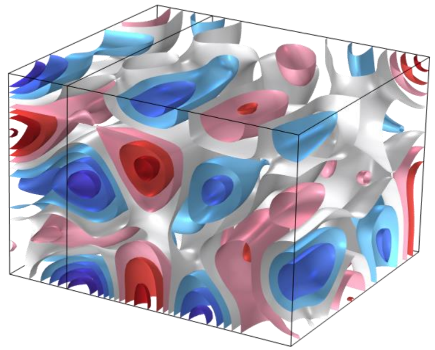


FEM to Ray Coupling for Source

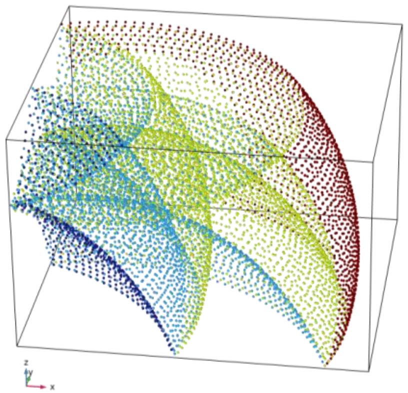
Read More in the *blog*.

FEM-Ray Hybrid: Low frequency and High frequency





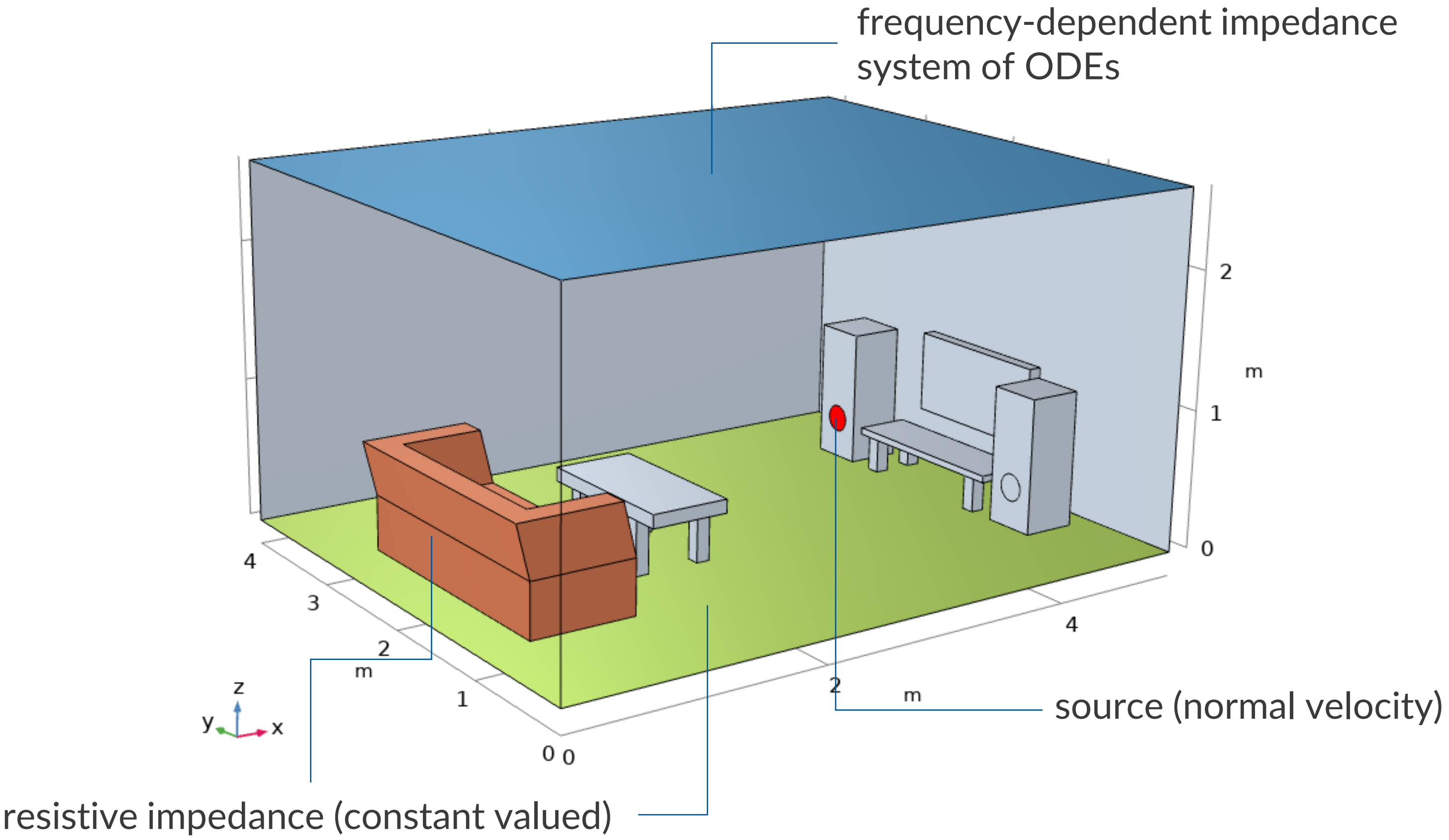
FEM

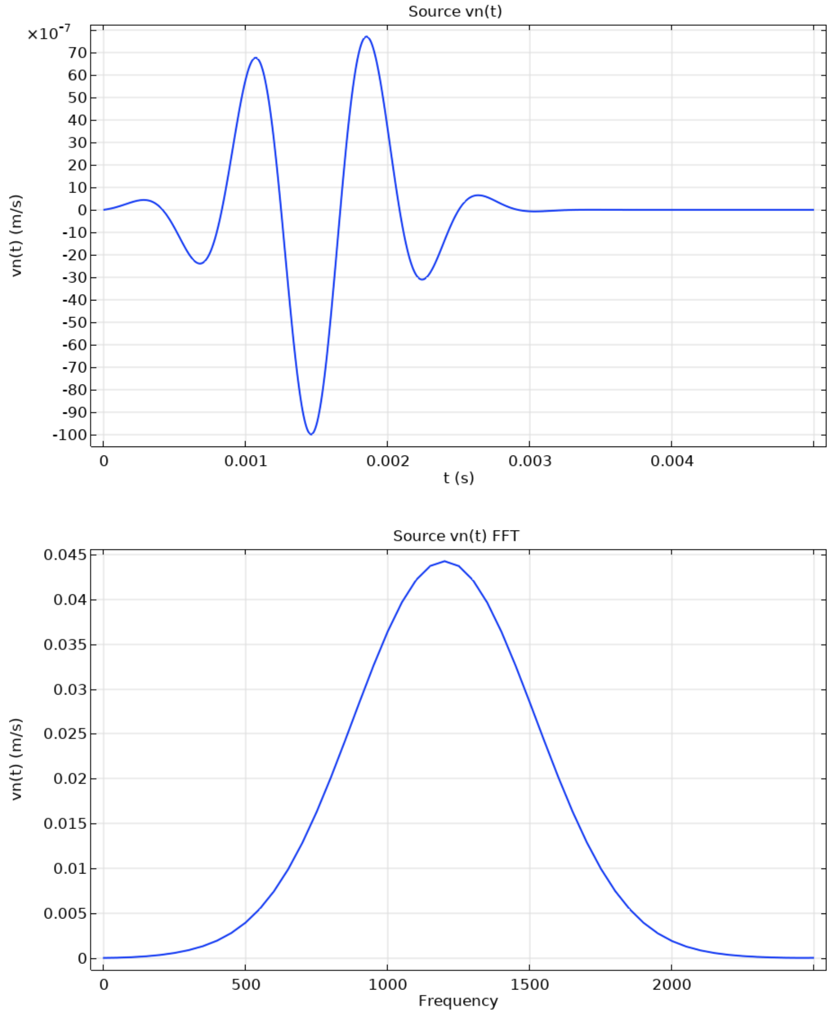


Ray

Read More in the *blog*.

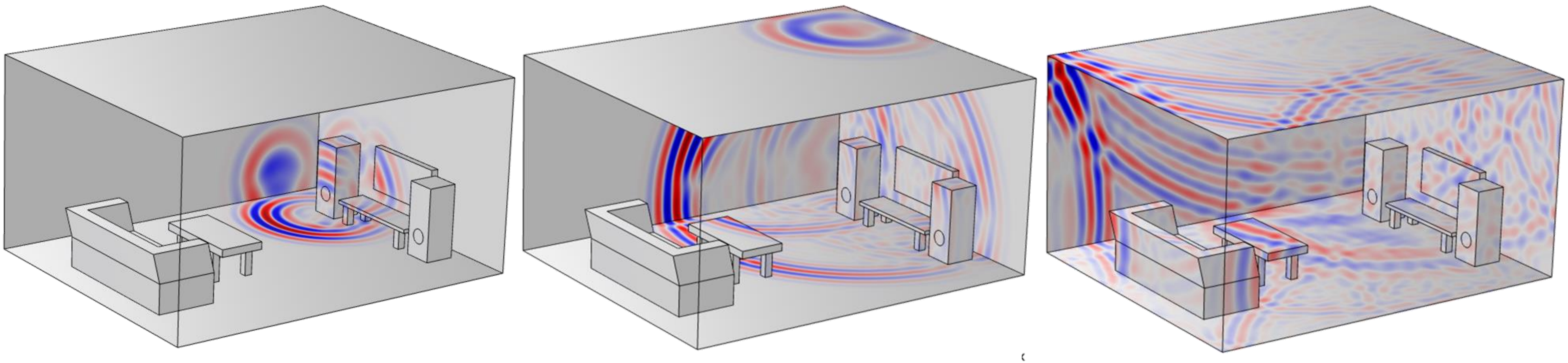
Full Wave Room Acoustics with DG-Time Explicit Method





Full Wave Room Acoustics with DG-Time Explicit Method

- Model volume 51 m^3 , 700 Hz, 0.04s = 30*T0 : computation time on single workstation 25h
- Discontinuous Galerkin (dG) method well suited for distributed computing on a cluster architecture / cloud.

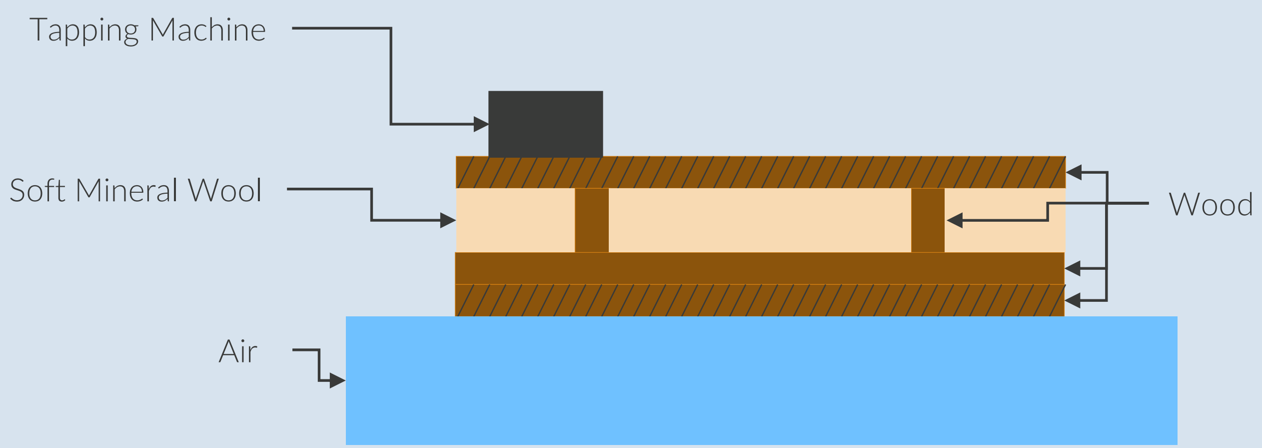


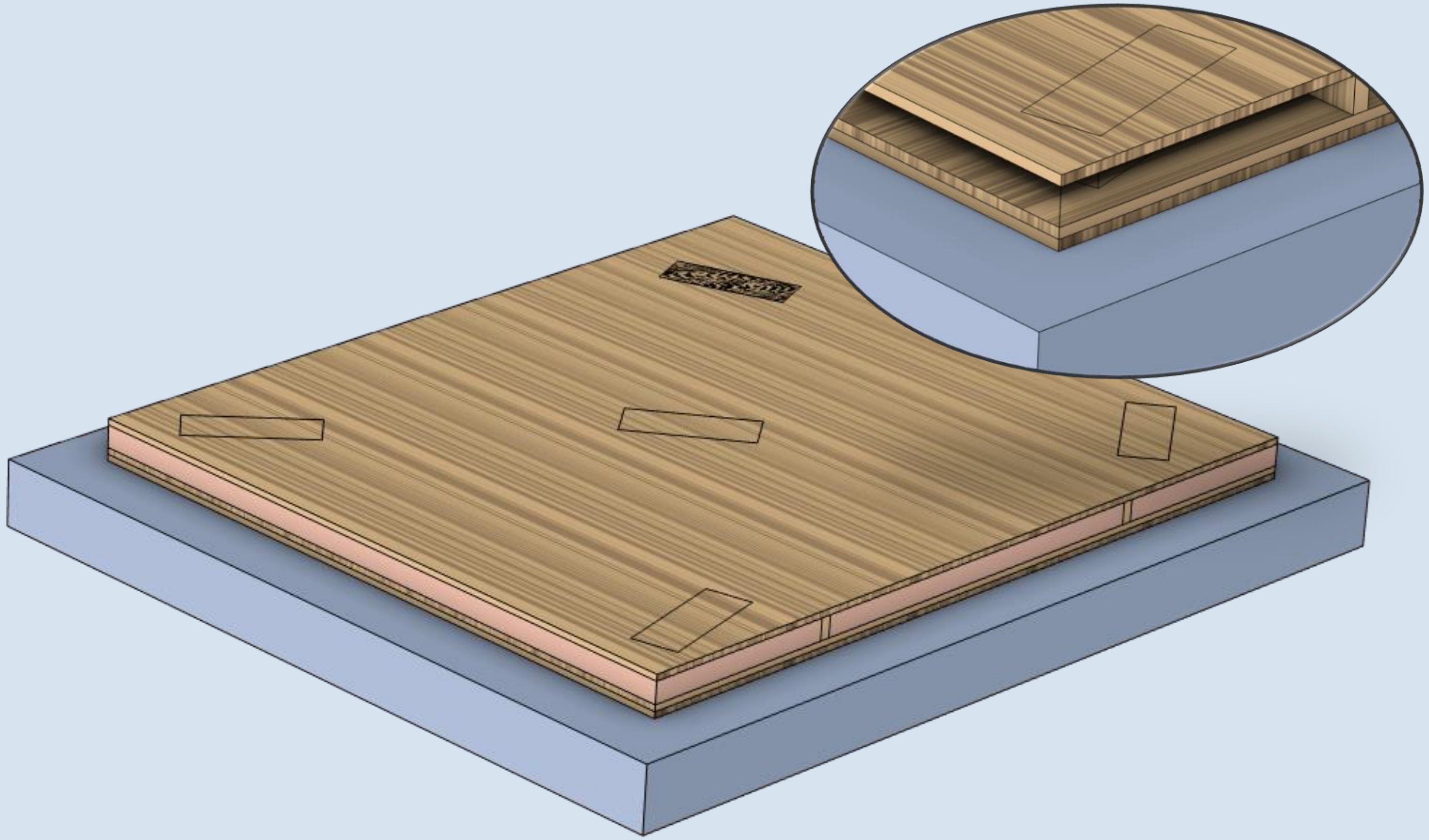
Acoustic Structure Interaction

Tapping Machine on Wooden Floor

- Impact of an ISO tapping machine B&K 3402 Tapping machine
- Floor made of three layers and two beams of anisotropic wood separated with a soft mineral wool.
- Wood fixed at sides.
- Air domain underneath surrounded by PML (not shown)

- *Model courtesy of Chloé Balmes (DTU, COMSOL DK) made in Nov 2023*

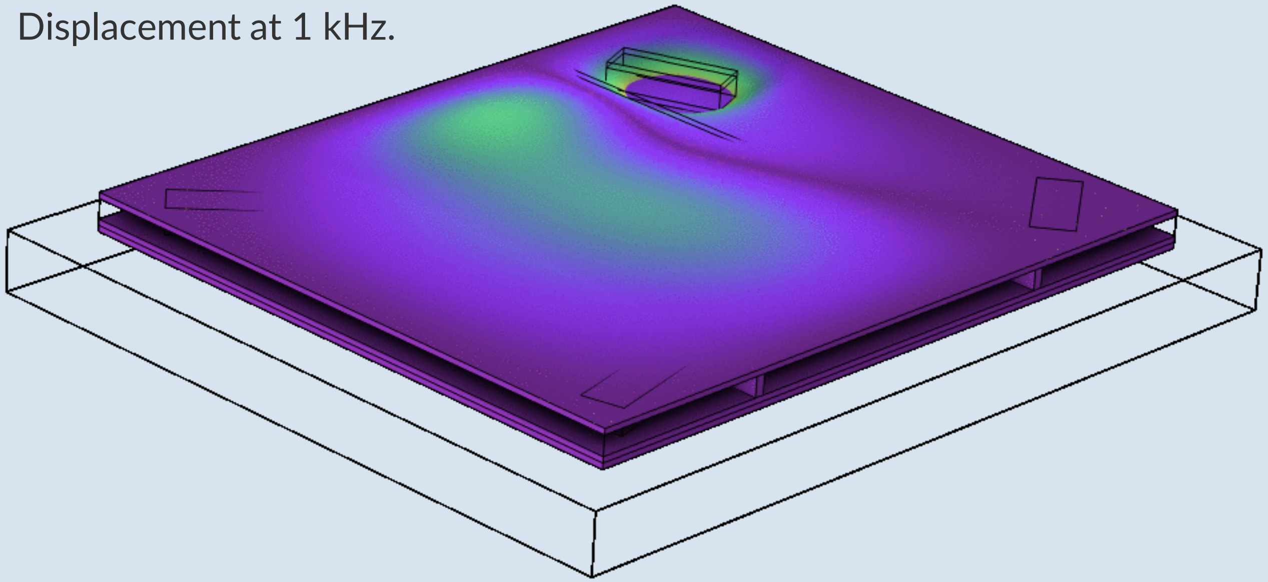




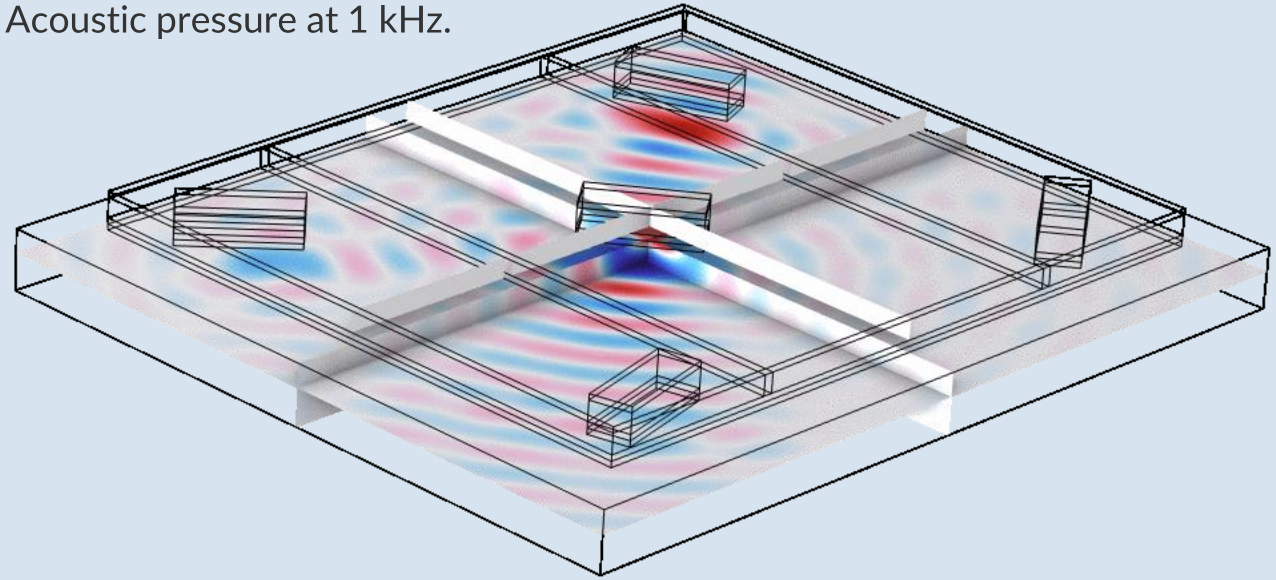
Tapping Machine on Wooden Floor

- Frequency domain response calculated for 14 Frequencies between 50 Hz and 1 kHz.
- Computational Expense:
  - 15 GB RAM
  - 15 min compute time per source

Displacement at 1 kHz.



Acoustic pressure at 1 kHz.



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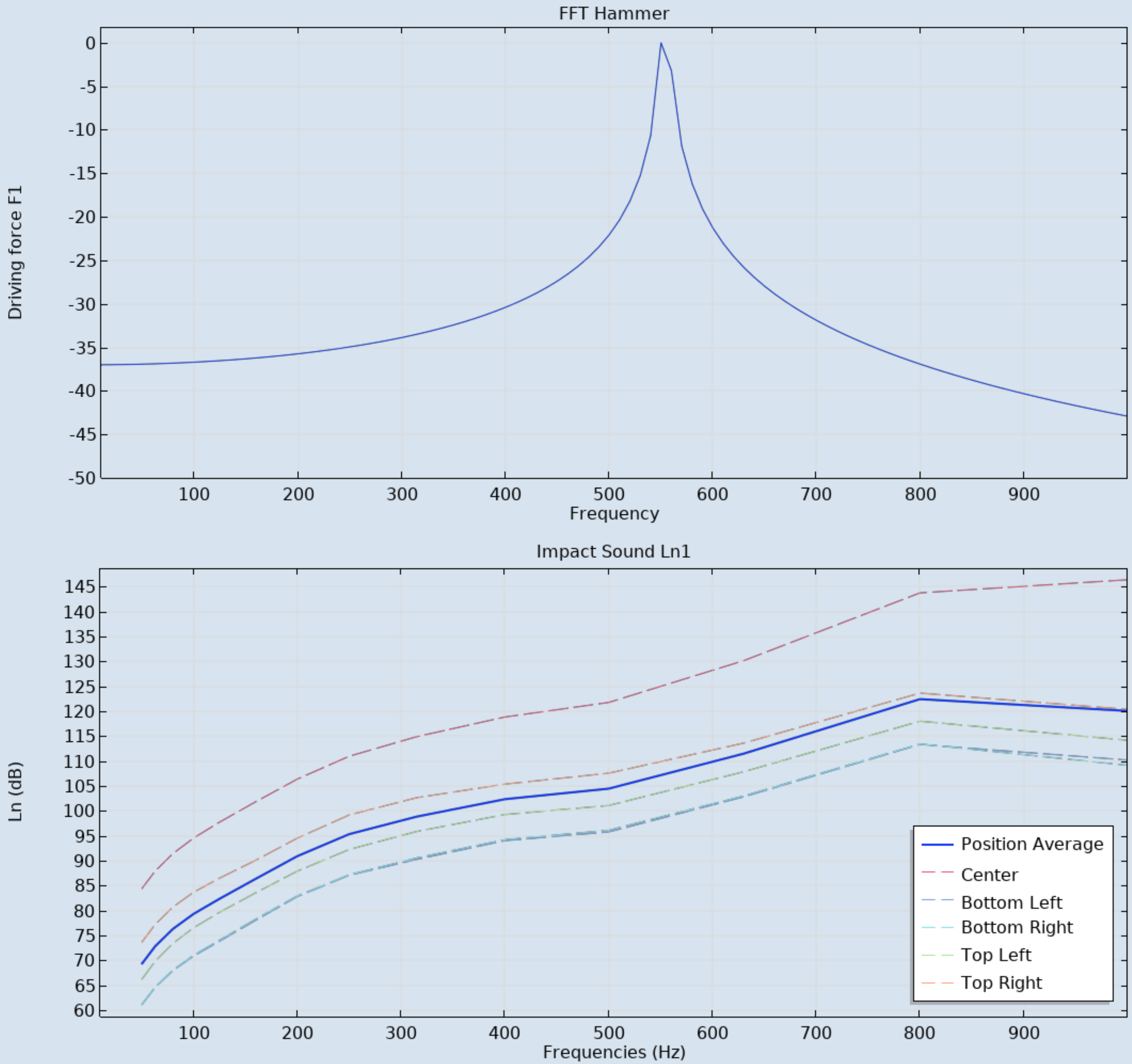
Tapping Machine on Wooden Floor

- Tapping source modeled in response to floor stiffness (Brunskog & Hammer, 2003).

- Simulation ***validated*** on a 5-layer wooden floor measured in the anechoic room of DTU (Technical university of Denmark), data available after publication.

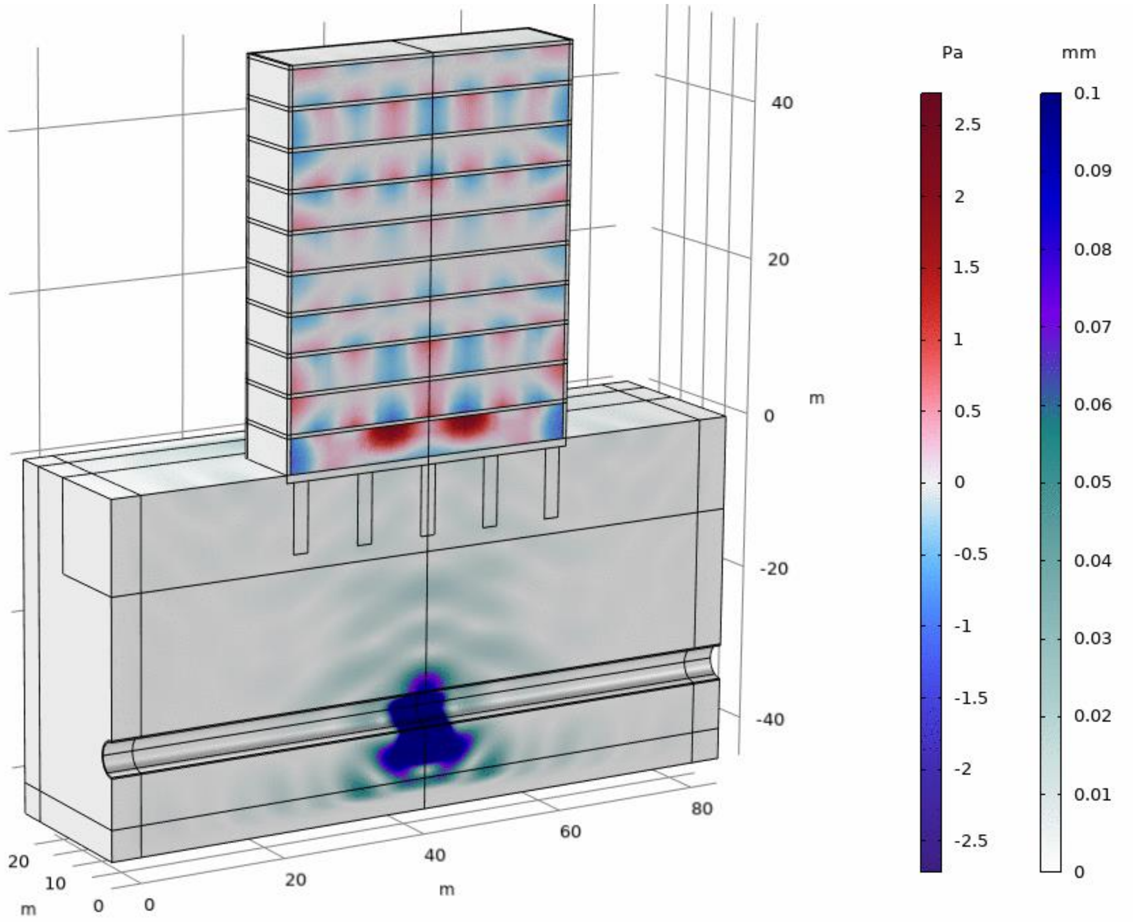


COMSOL

COMSOL TUTORIAL

Underground Train-Induced Noise in Urban Buildings

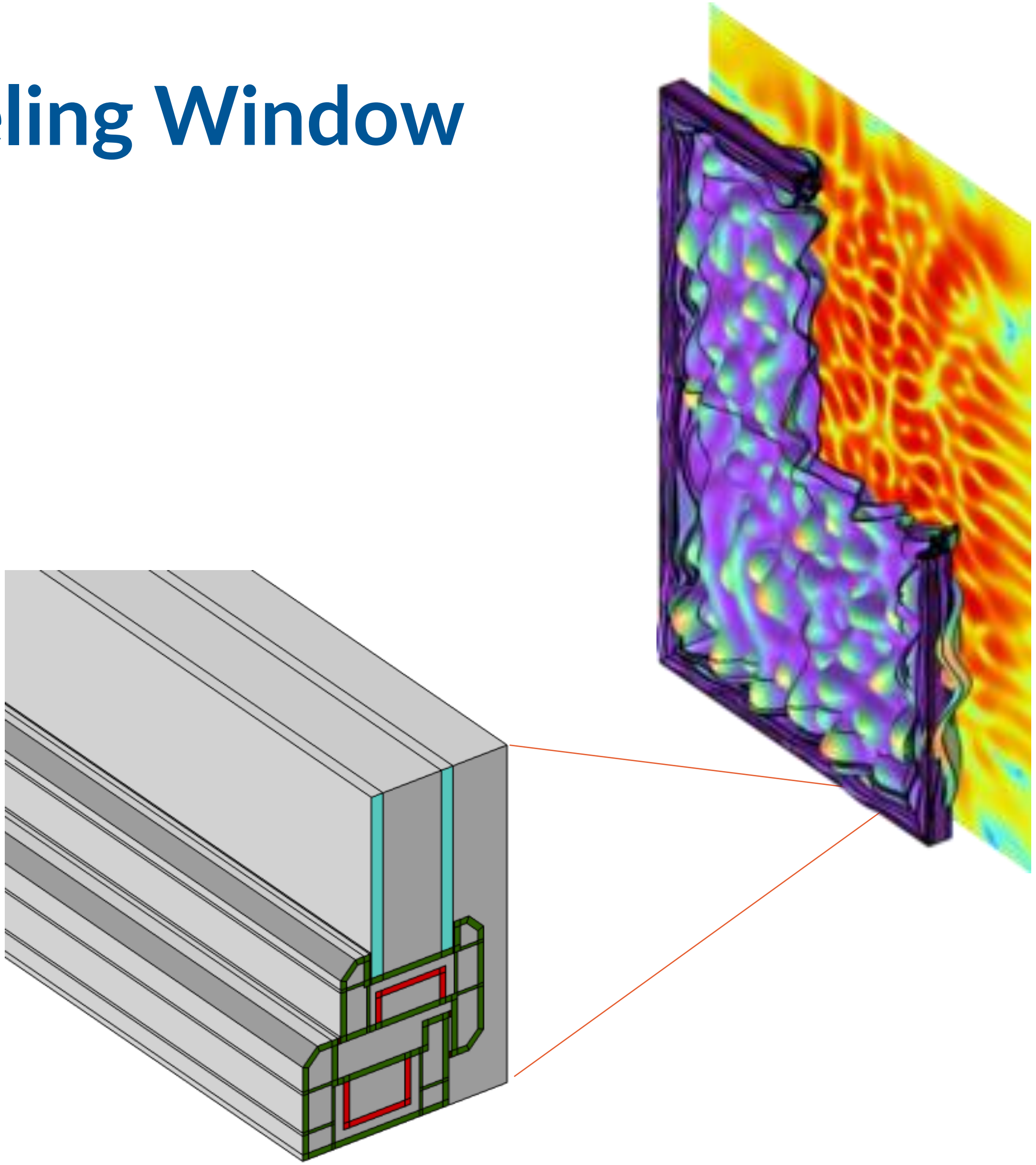
- Fully-coupled Acoustics-Structure
- Damping in soil and concrete materials
- Elastic waves in the soil can leave the computational domain without any reflection, using the *Perfectly Matched Layers*
- Underground Train-Induced Noise in Urban Buildings



COMSOL TUTORIAL

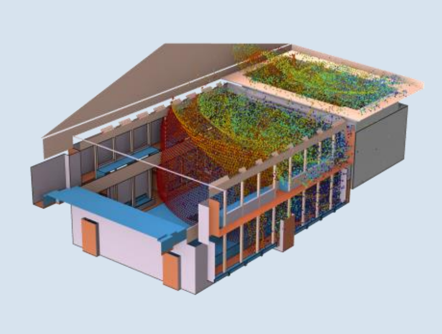
Sound Transmission Loss Modeling Window

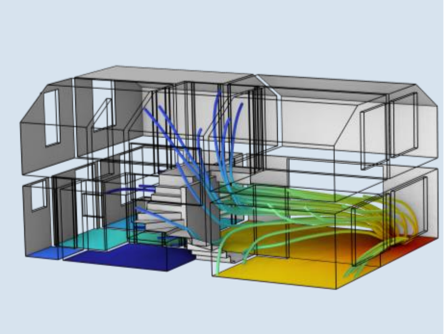
- The loggia glazing can be modeled by the *Elastic Waves* physics interface
  - A fully coupled acoustics-structure interaction
- Resources:
  - Sound Transmission Loss Through a Window
  - Sound Transmission Loss Through a Concrete Wall
  - Technical Papers and User’s Presentations

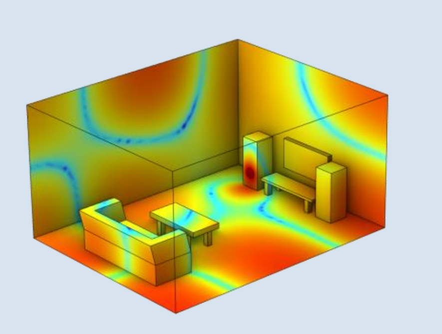


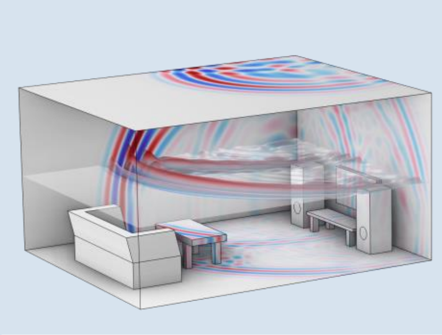
Summary: Multimethod Building Acoustics in COMSOL

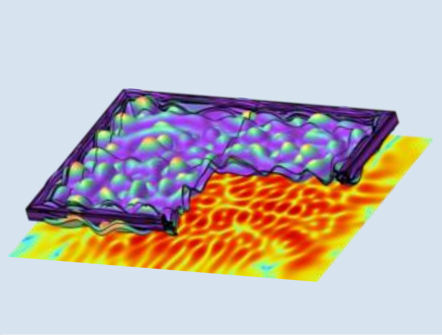
- COMSOL offers a wide spectrum of modeling tools for acoustics in rooms and buildings.
- *Traditional ray-acoustics* has limitations in modal and diffraction regions.
- *Full-wave modeling* offers more information but becomes computationally expensive at high frequencies and in large rooms.
- *Hybrid approaches* available in a homogenized GUI can compensate the shortcomings and combine the virtues of each method.

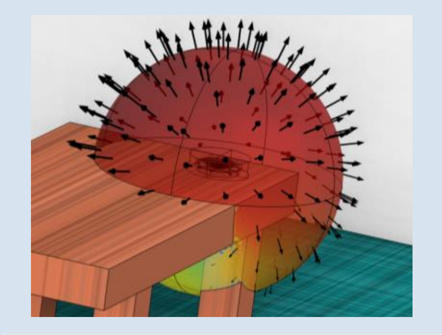

Ray Acoustics


Acoustic Diffusion


Pressure Acoustics, Harmonic


Pressure Acoustics, Transient


Acoustic Structure Interaction


Hybrid Methods