

Interactive Sound Rendering

Sound Synthesis
Numerical Acoustic Simulation
Interactive Sound Propagation
Application Demonstration

Themes

- Exploiting analytical solutions using Modal Analysis to accelerate numerical simulation and reducing runtime computation
- Capture only perceptually important auditory cues to perform real-time sound synthesis and acoustic propagation on complex 3D scenes

Overview

- Interactive Sound Synthesis
- Efficient Numerical Acoustic Simulation
- Interactive Sound Propagation
- Conclusion and Future Work

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Overview

- Interactive Sound Synthesis
 - Modal Analysis
 - Perceptually-based acceleration techniques
 - Hundreds of sounding objects
 - Sound from image textures
- Efficient Numerical Acoustic Simulation
- Interactive Sound Propagation
- Conclusion and Future Work

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Physically-based Sound Synthesis

- Aim: Take object geometry and material as input and produce sound
- Current trend: Recorded sounds
- Problems with recorded sounds:
 - Difficult, expensive or dangerous to record (eg. Explosions)
 - Repetitiveness
 - Complex interactions (impact/rolling)



A typical foley studio*

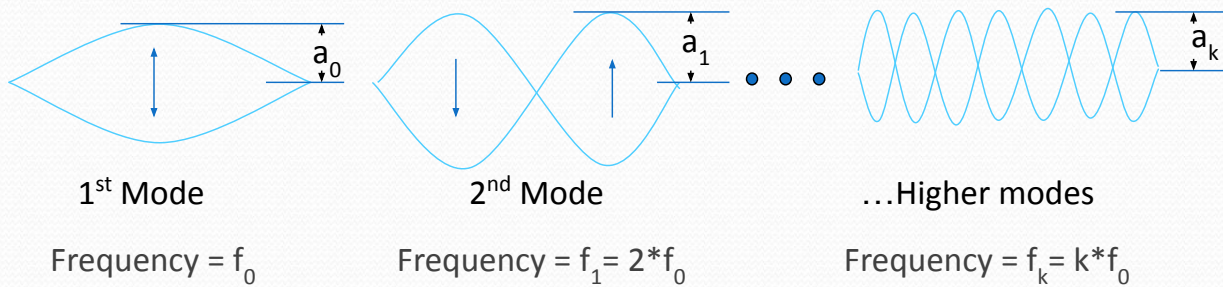
* Image taken from: <http://www.marblehead.net/foley/index.html>

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Physical Simulation

- Elastic deformable model
- Typical simulation time-steps must be $\sim 10^{-5}$ s
- Direct simulation infeasible
- Efficient method: Modal Analysis

Modal Analysis



- Each mode represents a resonant mode of vibration
- Frequency of a mode is fixed
- Applying impulse excites modes of vibration
- Position of impact determines relative amplitude of modes

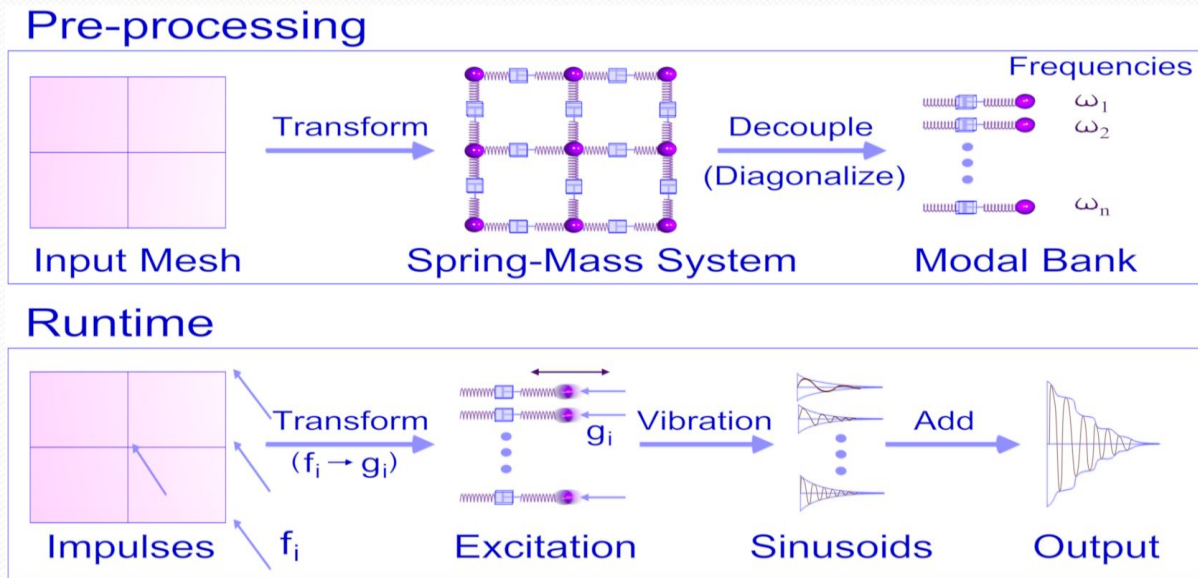
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Previous Work

- FEM deformable simulation
O'Brien et al., SIGGRAPH 2001
- FoleyAutomatic
Doel et al., SIGGRAPH 2001
- Synthesizing Sounds from Rigid-Body Simulation
O'Brien et al., SCA 2003
- Fast modal sounds with scalable frequency-domain synthesis
Bonneel et al., SIGGRAPH 2008

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Overview of Technique



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Approach

- Simpler model: Spring-mass system
- Fast: Supports hundreds of sounding objects
- Runs in real-time, low CPU utilization (~10%), graceful degradation in quality with limited computation
- Exploit human auditory perception
 - Mode Compression
 - Mode Truncation
 - Quality Scaling

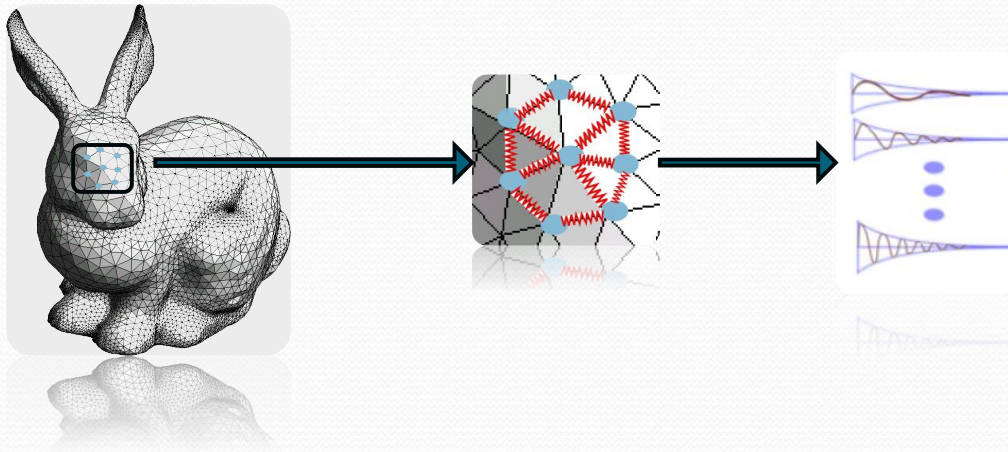
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Modal Analysis

- Deformation modeling
 - Vibration of surface generates sound
 - Sound sampling rate: 44100 Hz
 - Impossible to calculate the displacement of the surface at sampling rate
 - Represent the vibration pattern by a bank of damped oscillators (modes)
- Standard technique for real-time sound synthesis

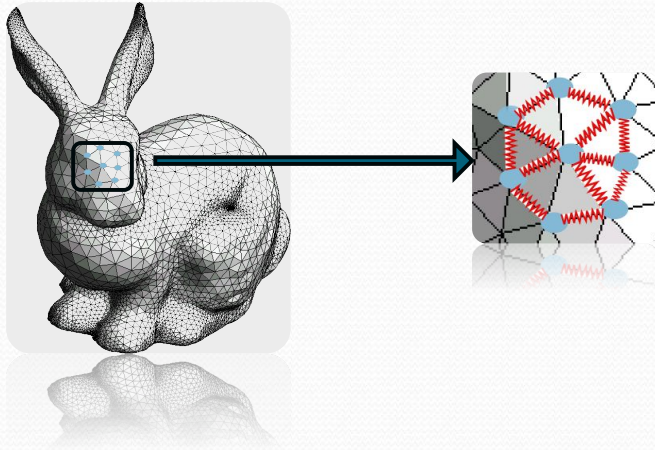
Modal Analysis

- Discretization
 - An input triangle mesh -> a spring-mass system
 - A spring-mass system -> a set of decoupled modes



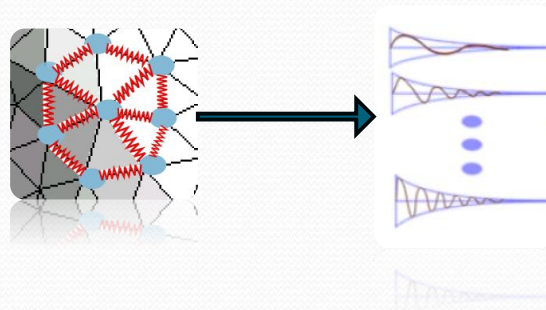
Modal Analysis

- The spring-mass system set-up
 - Each vertex is considered as a mass particle
 - Each edge is considered as a damped spring



Modal Analysis

- Coupled spring-mass system to a set of decoupled modes

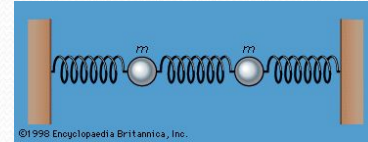


Modal Analysis

- A discretized physics system
 - We use spring-mass system

$$\boxed{K}(d) + \boxed{C}(d, \dot{d}) + \boxed{M}(\ddot{d}) = f$$

Stiffness Damping Mass



- Small displacement, so consider it linear

$$\boxed{K}d + \boxed{C}\dot{d} + \boxed{M}\ddot{d} = f$$

Stiffness Damping Mass

Modal Analysis

- Solve the Ordinary Differential Equation (ODE)

$$Kd + C\dot{d} + M\ddot{d} = f$$

- Rayleigh damping

$$Kd + (\gamma M + \eta K)\dot{d} + M\ddot{d} = f$$

And diagonalizing

$$K = GDG^{-1}$$

- Now, solve this ODE instead

$$DG^{-1}d + (\gamma G^{-1}M + \eta DG^{-1})\dot{d} + G^{-1}M\ddot{d} = G^{-1}f$$

Modal Analysis

- Solve the ODE

$$DG^{-1}\dot{d} + (\gamma G^{-1}M + \eta DG^{-1})\dot{d} + G^{-1}M\ddot{d} = G^{-1}f$$

- Substitute $z = G^{-1}d$ (the modes)

Now, solve this ODE instead

$$Dz + (\gamma M + \eta D)\dot{z} + M\ddot{z} = G^{-1}f$$

Modal Analysis

- General solution

$$z_i = c_i e^{\omega_i^+ t} + \bar{c}_i e^{\omega_i^- t}$$

$$\omega_i^\pm = \frac{-(\gamma\lambda_i + \eta) \pm \sqrt{(\gamma\lambda_i + \eta)^2 - 4\lambda_i}}{2}$$

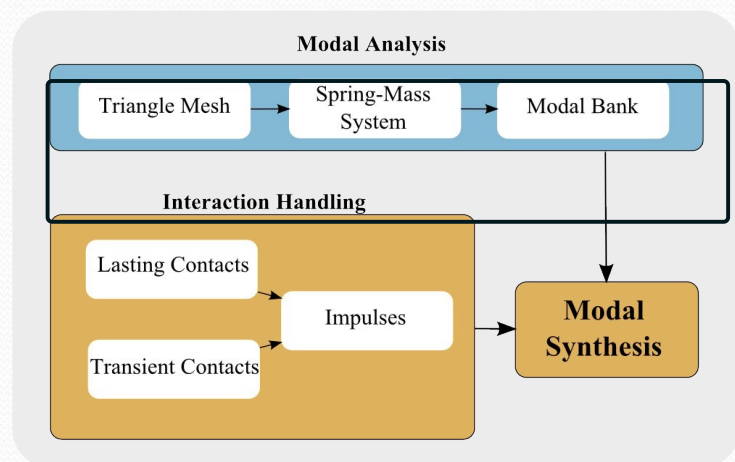
- External excitation defines the initial conditions

Modal Analysis

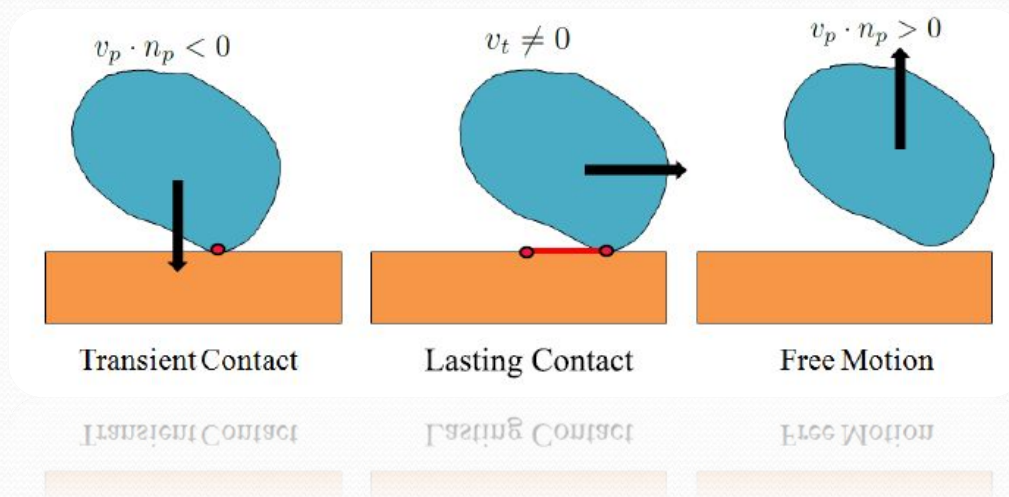
- Assumptions
 - In most graphics applications, only surface representations of geometries are given
 - A surface representation is used in modal Analysis
 - Synthesized sound appears to be “hallow”

Modal Analysis Summary

- An input triangle mesh ->
A spring-mass system ->
A set of decoupled modes



State Detection



State Detection

- Distinguishing between lasting and transient contacts

- In contacts?

$$\begin{cases} v_p \cdot n_p < 0 & \text{in contact} \\ v_p \cdot n_p > 0 & \text{not in contact} \end{cases}$$

- In lasting contacts?

$$\begin{cases} v_t \neq 0 & \text{lasting contact} \\ v_t = 0 & \text{not in lasting contact} \end{cases}$$

Interaction Handling

- Lasting contacts -> a sequence of impulses
- Transient contacts -> a single impulse

Impulse Response

- Dirac Delta function as impulse excitation
 - General solution

$$z_i = c_i e^{\omega_i^+ t} + \bar{c}_i e^{\omega_i^- t}$$

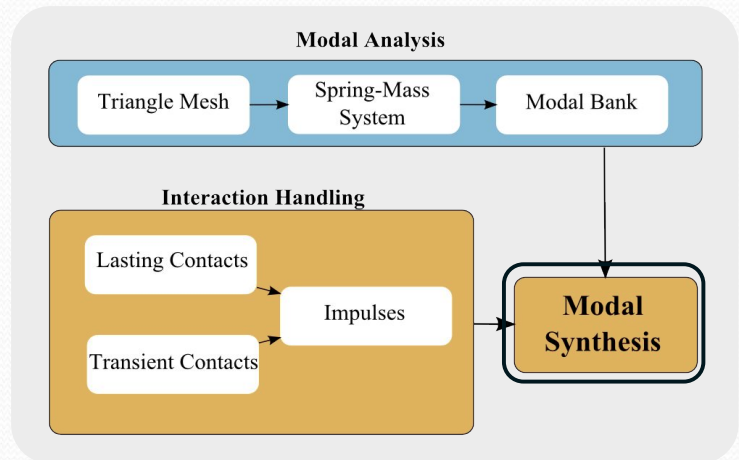
with initial condition given by the impulse,

we have:

$$c_i' = c_i e^{\omega_i^+ t_0} + \frac{g_i}{m_i(\omega_i^+ - \omega_i^-)}$$
$$\bar{c}_i' = \bar{c}_i e^{\omega_i^- t_0} - \frac{g_i}{m_i(\omega_i^+ - \omega_i^-)}$$

Impulse Response

$$z_i = c_i e^{\omega_i^+ t} + \bar{c}_i e^{\omega_i^- t}$$



Handling Lasting Contacts

- The interaction simulation has to be stepped at the audio sampling rate: 44100 Hz
- The update rate of a typical real-time physics simulator: on the order of 100's Hz
- Not enough simulation is provided by the physics engine
- An customized interaction model for sound synthesis

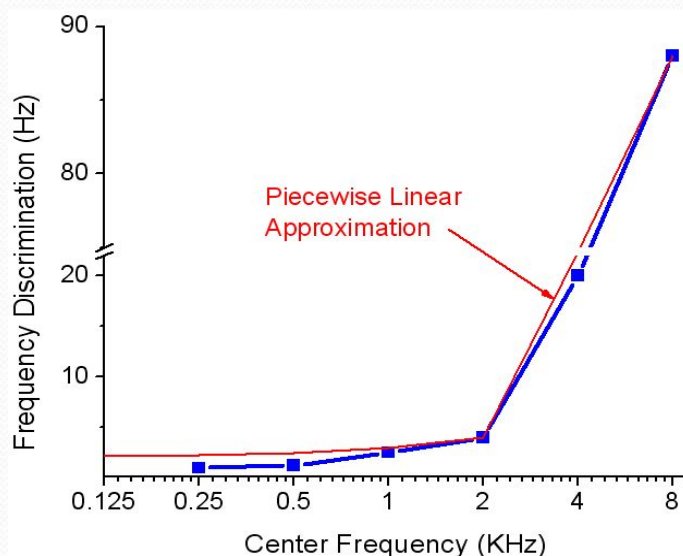
Mode Compression: Principle

- Humans can't distinguish two frequencies arbitrarily close to each other [Sek et. al., 1995*]
- Accuracy in discriminating frequencies depends on the frequency in question
- Different frequencies were played in succession to find if the subject could distinguish between them

*Sek, A., and Moore, B. C. 1995. Frequency discrimination as a function of frequency, measured in several ways. J. Acoust. Soc. Am. 97, 4 (April), 2479–2486.

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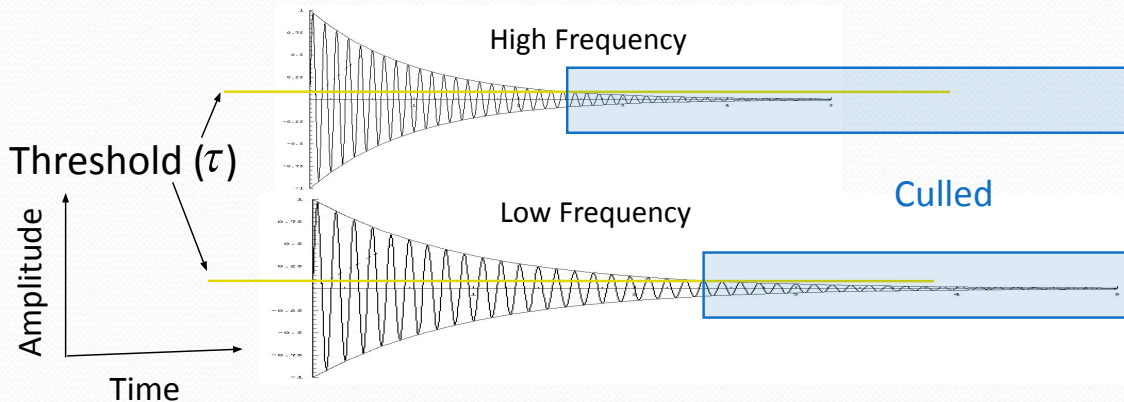
Mode Compression: Auditory Perception



Frequency Discrimination at 2 KHz is about 4 Hz -- We can't tell apart frequencies within the range 1998 - 2002 Hz -> *playing many sinusoids of different frequencies together*

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Mode Truncation



- Impact Sounds: Attack + Decay
- Key Point: Critical to capture attack properly
- Stop mixing mode when its contribution falls below a prescribed threshold, τ (typically -60 to -80 dB of initial level)

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Quality Scaling

- A typical audio scene consists of foreground and background sounds
- *Higher intensity sounds* are considered to be foreground
- Idea: *Give more importance to foreground sounds*
- Provides a graceful way to adapt to variable time constraints

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Implementation Details

- System: 3.4 GHz Pentium 4 Laptop, 1 GB RAM
- Graphics: GeForce 6800 Go, 256 MB
- Sound: Creative Sound Blaster Audigy 2 ZS

- Physics: Pulsk (written by former student: Nico Galoppo),
Rendering: G3D
- Also integrated with NVIDIA PhysX Engine recently

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System Demonstration

VIDEO

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Sound from Image Textures

VIDEO

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Limitations

- Implementation: Model only the surface (not an inherent limitation of the approach)
- More approximate than an FEM-based formulation
 - Some tuning is required
- All sound synthesis techniques relying on Modal Analysis:
Can only use linear damping models

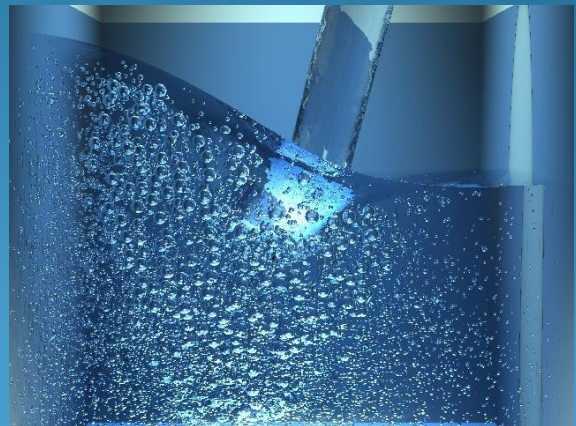
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Sounding Liquids [Moss et al. 2009]

- Work in physics & engineering literature since 1917
 - Sound generated by resonating bubbles
- *Physically-based Models for Liquid Sounds* (van den Doel, 2005)
 - Spherical bubble model
 - No fluid simulator coupling
 - Hand tune bubble profile

Background (Fluid)

- Grid-based methods
- Accurate to grid resolution
 - Bubbles can be smaller
 - Slow
 - Can be two-phase



Background (Fluid)

- Shallow Water Equations
 - Simulate water surface
 - No breaking waves
 - Real time
 - One phase
 - Explicit bubbles



Overview

- Generate sound from existing fluid simulation
 - Model sound generated by bubbles
- Apply model to two types of fluid simulators

- **Particle-Grid-based**

- Extract bubbles
- Process spherical and non-spherical bubbles
- Generate sound

- **Shallow Water Equations**

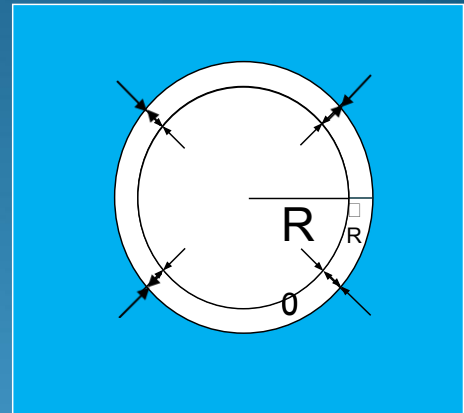
- Processes surface
 - Curvature and velocity
- Select bubble from distribution
- Generate sound

Mathematical Formulations

- Spherical Bubbles

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{3\gamma p_0}{\rho R_0^2}}$$

$$\tau(t) = A \sin(2\pi f(t)t) e^{-dt}$$



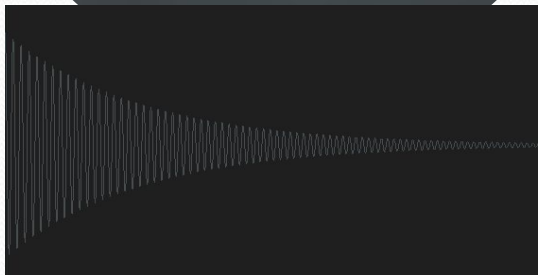
- Non-spherical bubbles

- Decompose into a spherical harmonics

$$f_n^2 \approx \frac{1}{4\pi^2} (n-1)(n+1)(n+2) \frac{\sigma}{\rho R_0^3}$$

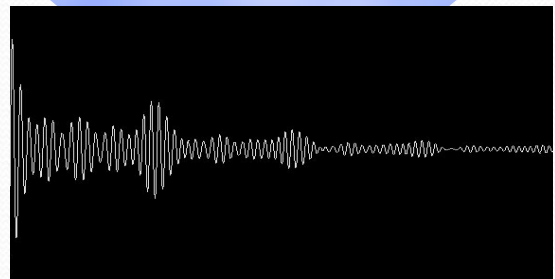
Without

Spherical Harmonics

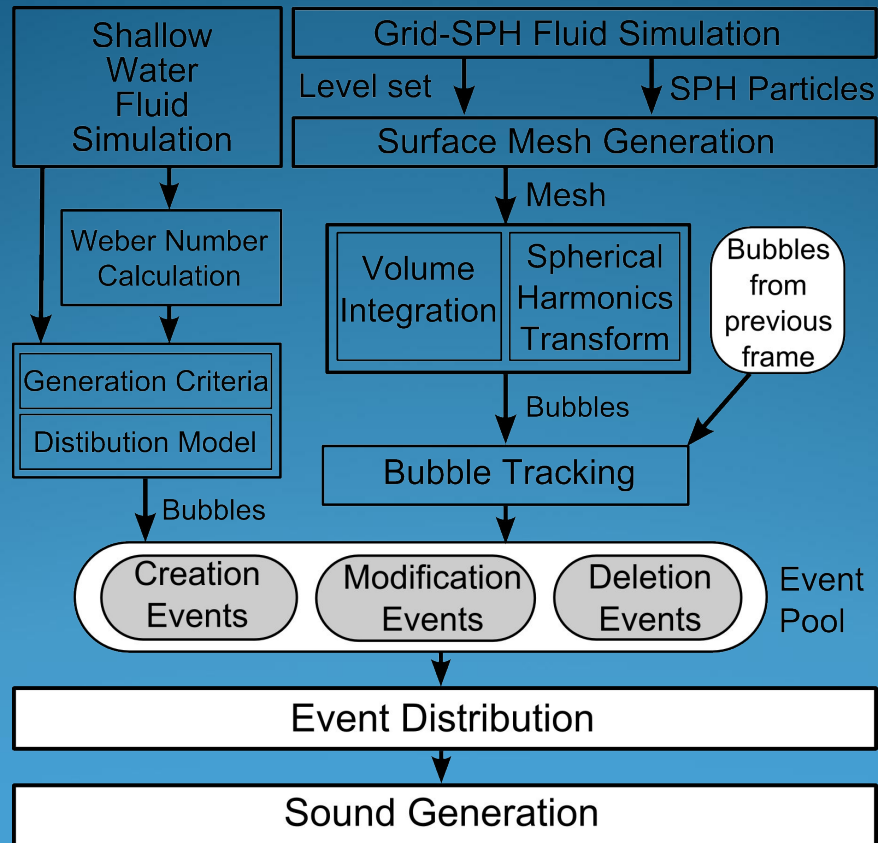


With

Spherical Harmonics

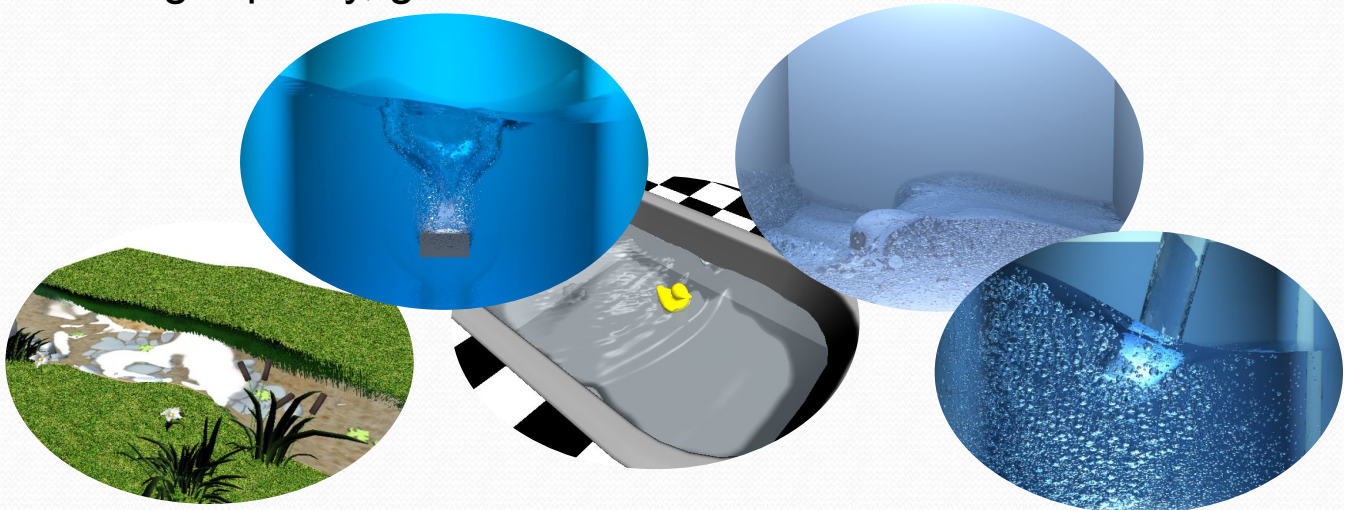


System Overview



Summary

- Simple, automatic sound synthesis
- Applied to two fluid simulators
 - Interactive, shallow water
 - High-quality, grid based



Video Demonstration

VIDEO

Overview

- Interactive Sound Synthesis
- Efficient Numerical Acoustic Simulation
- Interactive Sound Propagation
- Conclusion and Future Work

Overview

- Interactive Sound Synthesis
- Efficient Numerical Acoustic Simulation
 - Novel technique based on 3D Adaptive Rectangular Decomposition
 - Hundred times faster than Finite Difference Time Domain
- Interactive Sound Propagation
- Conclusion and Future Work

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Acoustics: Governing Equation

- Solve the Linear Wave Equation:

$$\frac{\partial^2 p}{\partial t^2} - c^2 \nabla^2 p = F(\mathbf{x}, t)$$

∇^2 is the Laplacian operator in 3D

c is the speed of sound in air

p is the pressure field to solve

- The RHS is the forcing term, corresponding to volume sound sources in the scene

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State of the art: Room Acoustics

- Geometric Techniques (e.g. Ray/Beam/Frustum Tracing) combined with explicit diffraction modeling
- Auralization software (e.g. ODEON, CATT): Hybrid image-source and ray-tracing along with (upcoming) explicit diffraction modeling
- Numerical acoustic simulation for complex 3D scenes has been explored only since mid-2000 (~2006)

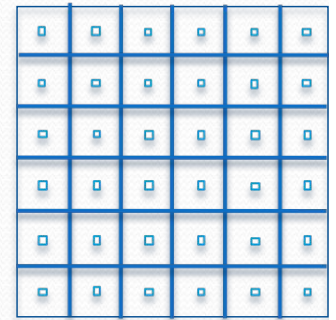
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Acoustics for Interactive Applications

- Geometric Approaches
 - Beam Tracing (Funkhouser et. al.)
 - Phonon Tracing (Bertram and Deines et. al.)
 - Frustum Tracing (Chandak et. al.)
-
- Advantages: Efficient, easy to understand
-
- Difficulties: Diffraction / Scattering, high-order reflections

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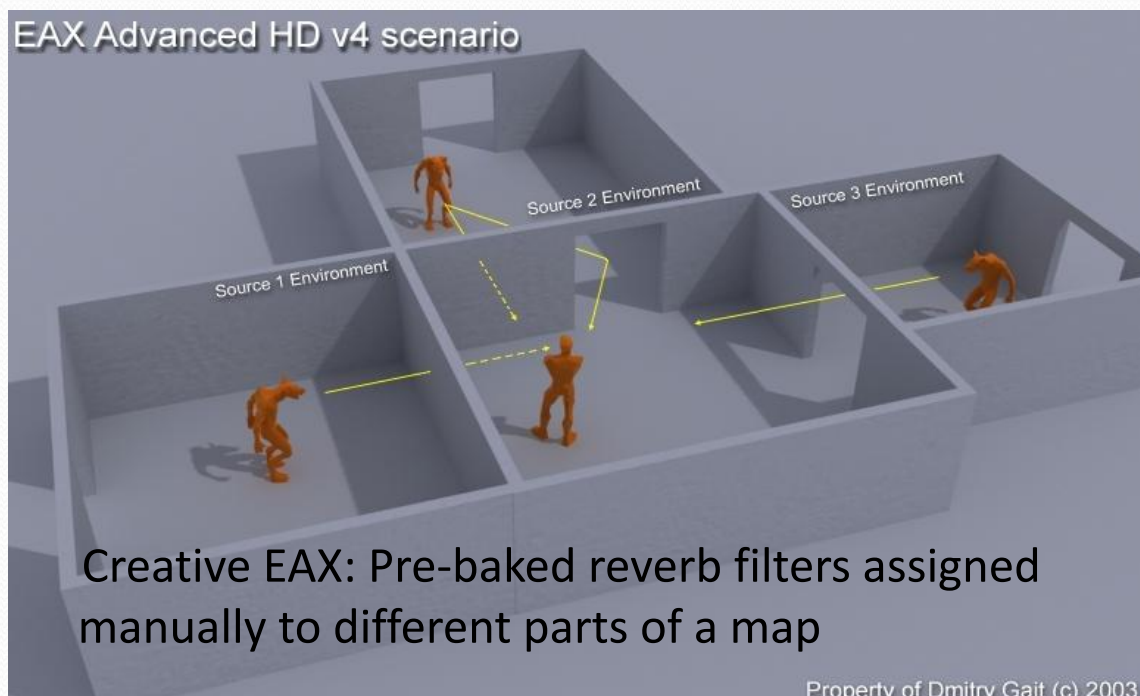
Numerical Acoustics



- Discretize and solve Wave Equation on a grid
- Explored for complex 3D scenes (eg. auditoria) only recently (2004 – 2006) by Sakamoto et. al.
- Disadvantage: Slow and memory-intensive
 - Simulations are band-limited
 -
- Advantages: Diffraction / Scattering, high-order reflections

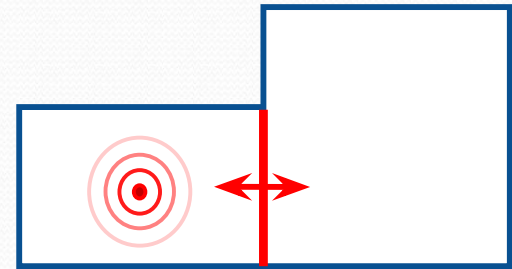
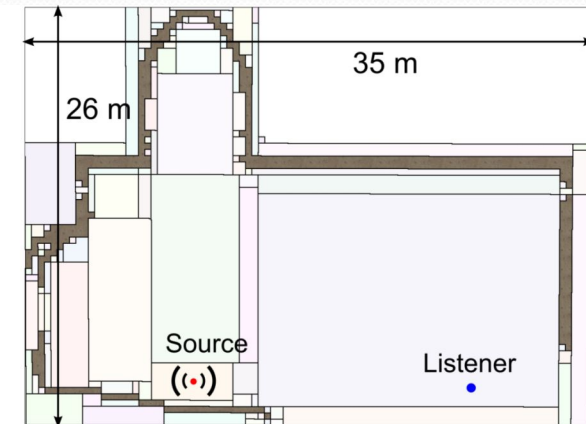
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Acoustics in Games



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Adaptive Rectangular Decomposition



Interface Handling

- Numerical Simulation of the Wave Equation
- Rectangular Decomposition of a 3D scene
- Exploit analytical solutions on rectangular spaces
- 6th order Finite Difference for interface transmission

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Solution on a Rectangular Domain

- Rectangular space in 3D with size (l_x, l_y, l_z) , and perfectly reflective boundary
- Modal Analysis can be done **analytically** –

$$p(x, y, z, t) = \sum_{i=(i_x, i_y, i_z)} m_i(t) \Phi_i(x, y, z)$$

$$\Phi_i(x, y, z) = \cos\left(\frac{\pi i_x}{l_x} x\right) \cos\left(\frac{\pi i_y}{l_y} y\right) \cos\left(\frac{\pi i_z}{l_z} z\right)$$

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Leveraging GPU for Acoustics

- Solution of Wave Equation within each rectangle can be done using a 3D Discrete Cosine Transform (DCT)
- DCTs can be computed using FFT
- Use efficient FFT implementation on GPU
 - Govindaraju, N. K., Lloyd, B., Dotsenko, Y., Smith, B., and Manferdelli, J. **High-Performance Discrete Fourier Transforms on Graphics Processors.** In the *Proc. of 2008 ACM/IEEE Supercomputing*

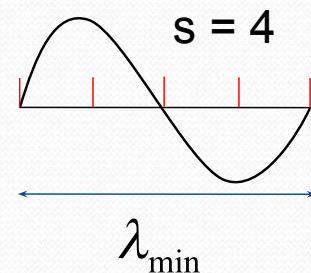
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Computational Efficiency

- For a scene of size L in 3D and simulation duration T –

$$\text{Memory : } \left(\frac{L s v_{\max}}{c} \right)^3$$

$$\text{Time : } T \left(\frac{L}{c} \right)^3 (s v_{\max})^4$$



- Nyquist Limit: $s \geq 2$
- FDTD: $s = 10$. My approach: $s = 2.6$
- Speedup with my technique : $(10 / 2.6)^4 > 100$

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Demo

Video

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Performance Comparison

Scene Name	Volume (m ³)	Time: FDTD (CPU)	Time: My Technique (GPU)	Speedup
Corridor	375	365 min	4 min	~ 90x
House*	1,275	3.5 days	24 min	~ 200x
Cathedral	13,650	1 week (estimated)	29 min	~ 300 x

● Quad-core 2.8GHz Intel Xeon CPU with 8GB RAM, NVIDIA GeForce GTX 280

* This simulation was band-limited to 2 kHz, instead of 1 kHz

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Summary

- Adaptive Rectangular Decomposition yields 100x improvement in performance over FDTD and consumes 10x less memory
- Source of Speedup: Modal Analysis of rectangular spaces as well as GPU-DCT
- Can feasibly simulate acoustics for large, complex scenes, such as a Cathedral

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Limitations

- Stair-casing errors near boundary (similar to FDTD)
 - A smooth, slanted wall acts as a diffuse reflector for highest frequencies on grid
- Current implementation doesn't handle frequency-dependent absorption

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Overview

- Interactive Sound Synthesis
- Efficient Numerical Acoustic Simulation
- Interactive Sound Propagation
- Conclusion and Future Work

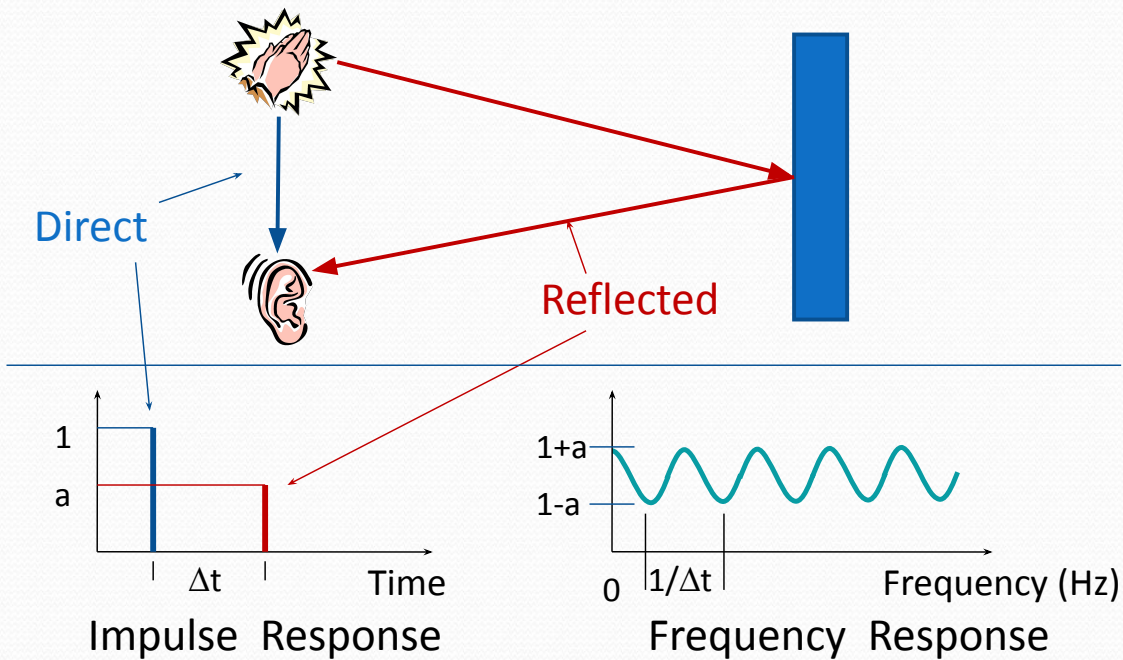
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Overview

- Interactive Sound Synthesis
- Efficient Numerical Acoustic Simulation
- Interactive Sound Propagation
 - Perceptual aspects of acoustics
 - Novel perceptually-motivated techniques
 - Interactive auralization system: moving sources and listener
- Conclusion and Future Work

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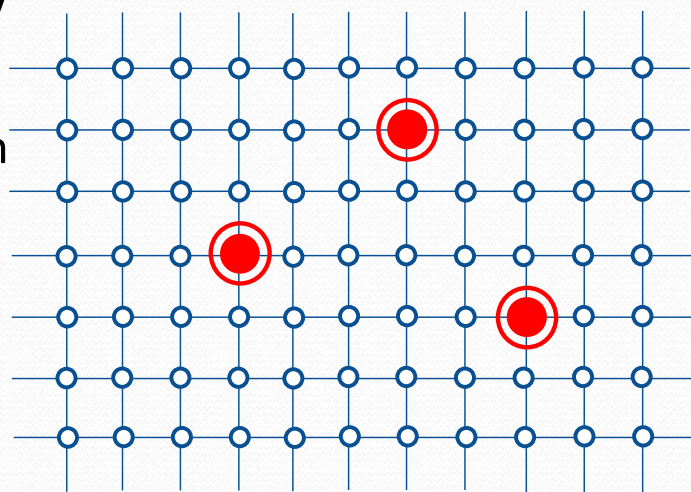
Impulse Response (IR)



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Challenges

- Direct approach is costly
- Days of simulation (even with fast simulator)
- Terabytes of storage



- Source locations
- Listener locations

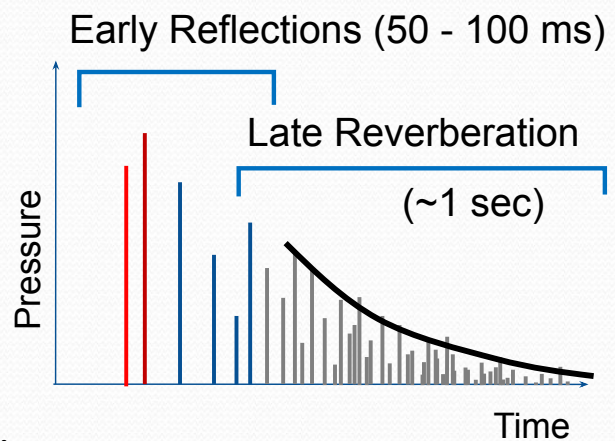
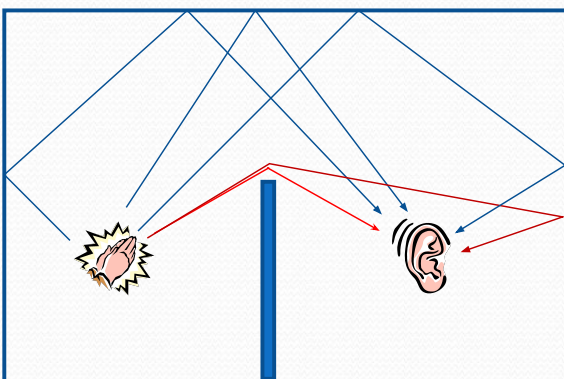
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Contributions

- Approach –
 - Sample data at lower resolution in space (~1 m)
 - Novel perceptually-based scheme: Store each Impulse Response compactly
 - Spatially-interpolate Impulse Responses
- Audio engine that uses fast frequency-domain convolutions

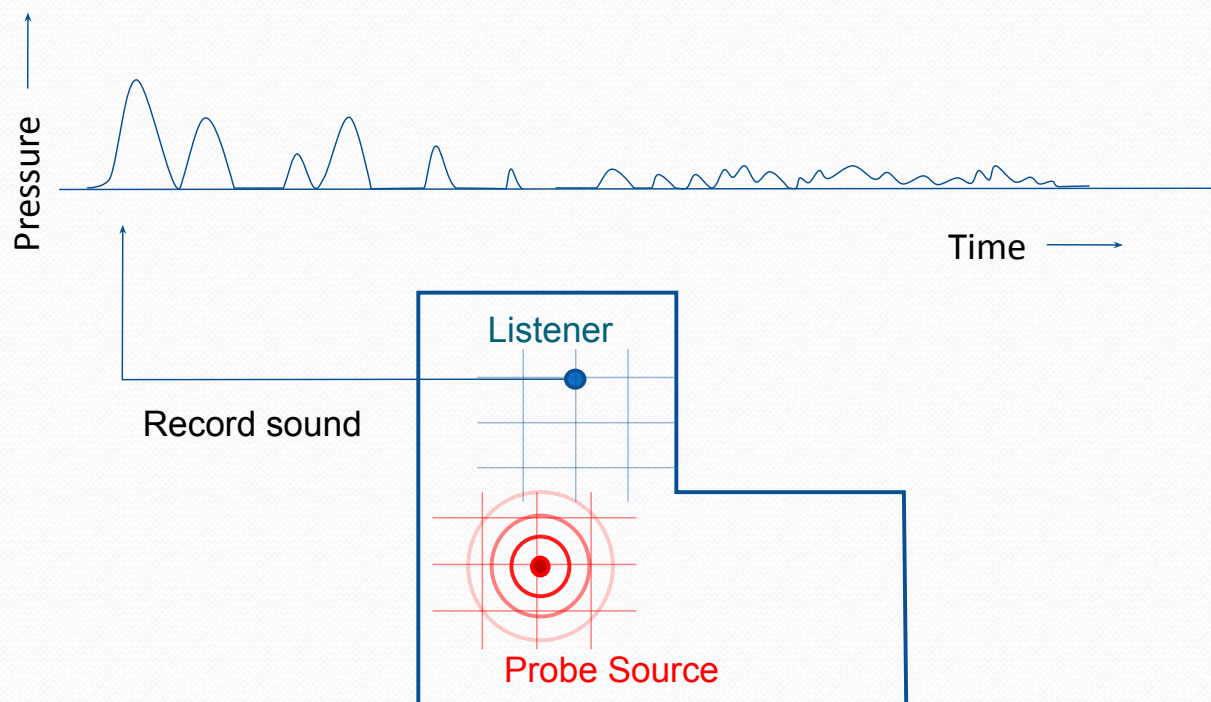
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Auditory perception of acoustic spaces



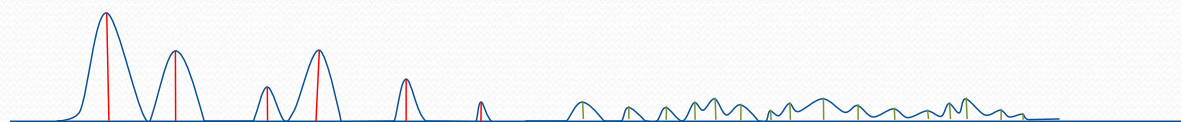
- Direct Sound: Sense of direction
- ER: Loudness, Timbre, “Envelopment”. Perceivable spatial variation.
- LR: Only statistical properties perceivable – Decay Time (RT60), Periodicities (Flutter echoes)

IR Factoring (1)



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IR Factoring (2)

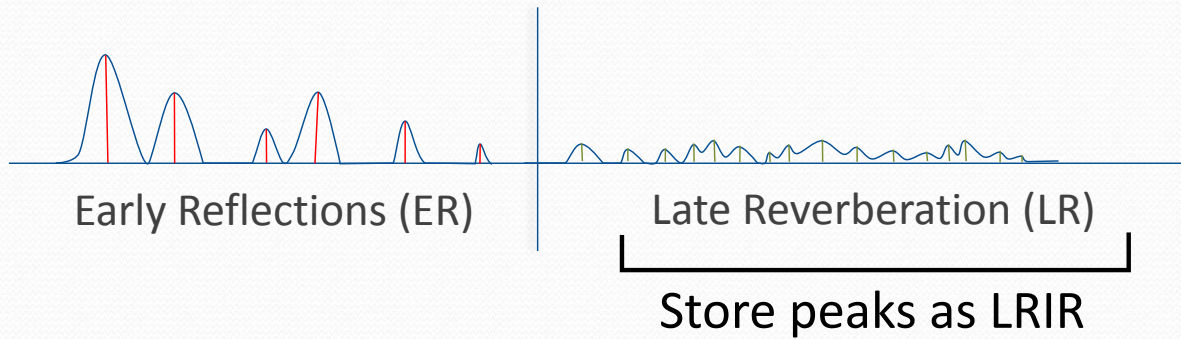


Peak Detection

- Finds peak delays and amplitudes

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IR Factoring (3)

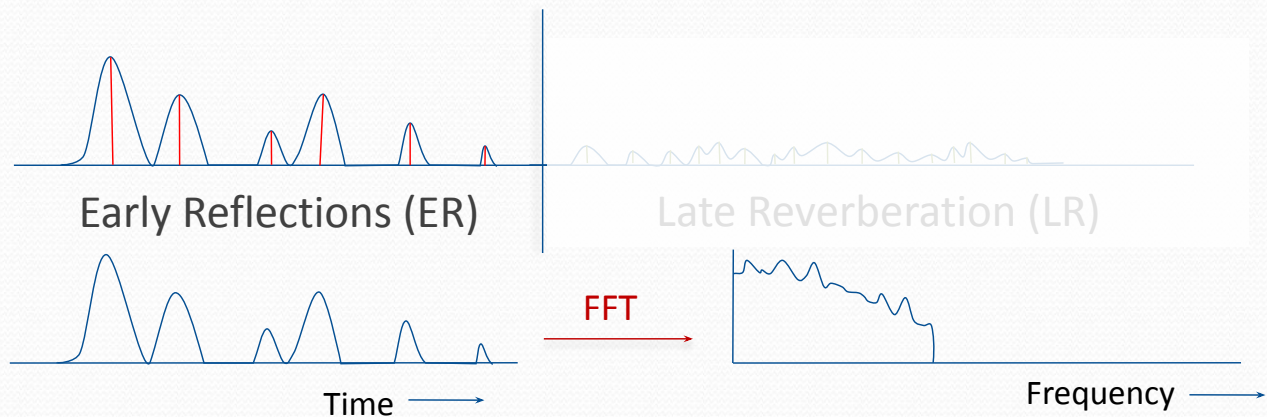


ER - LR Decomposition

- Compute and store only one Late Reverberation filter per room
- Reduces pre-computation time and runtime memory usage by 10 times

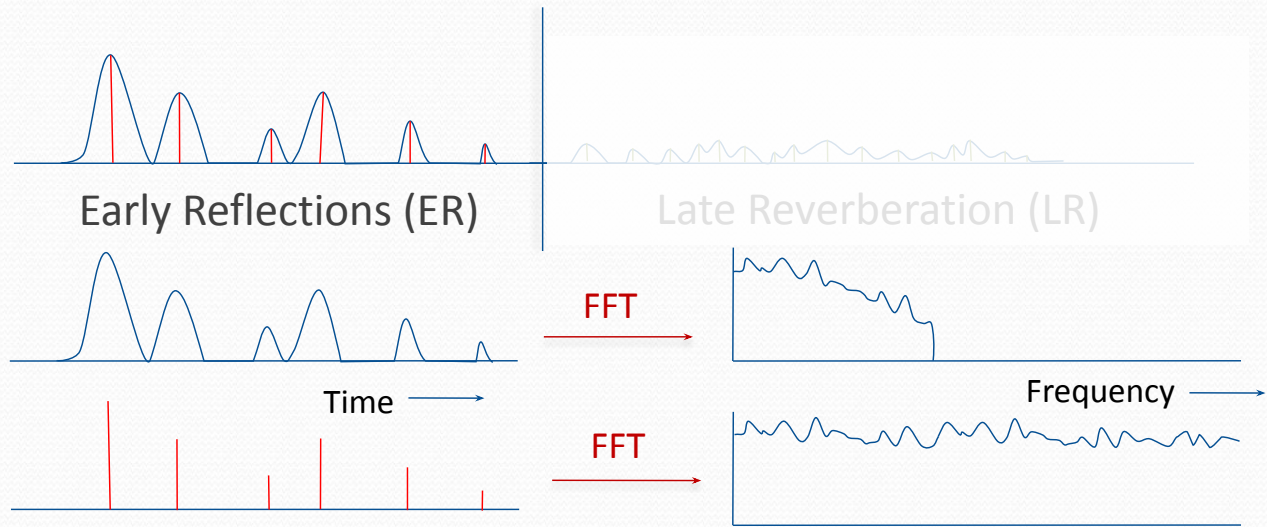
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IR Factoring (4)



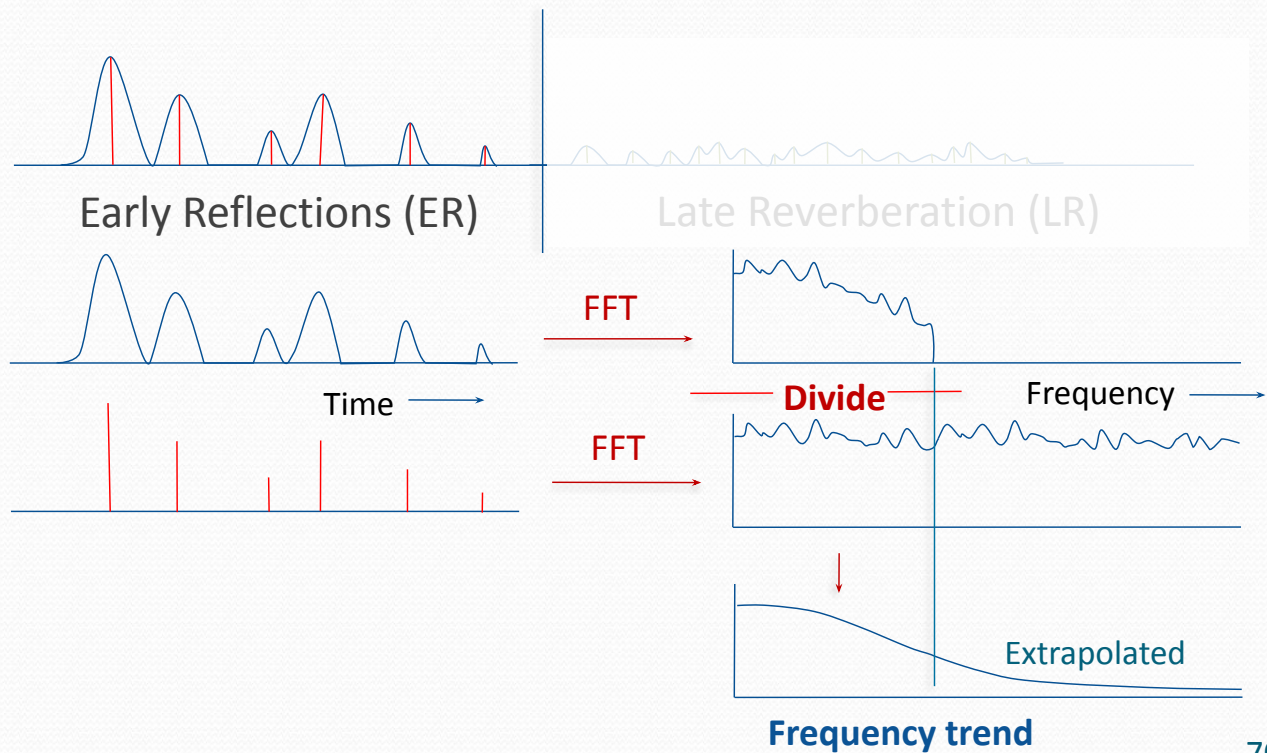
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IR Factoring (5)



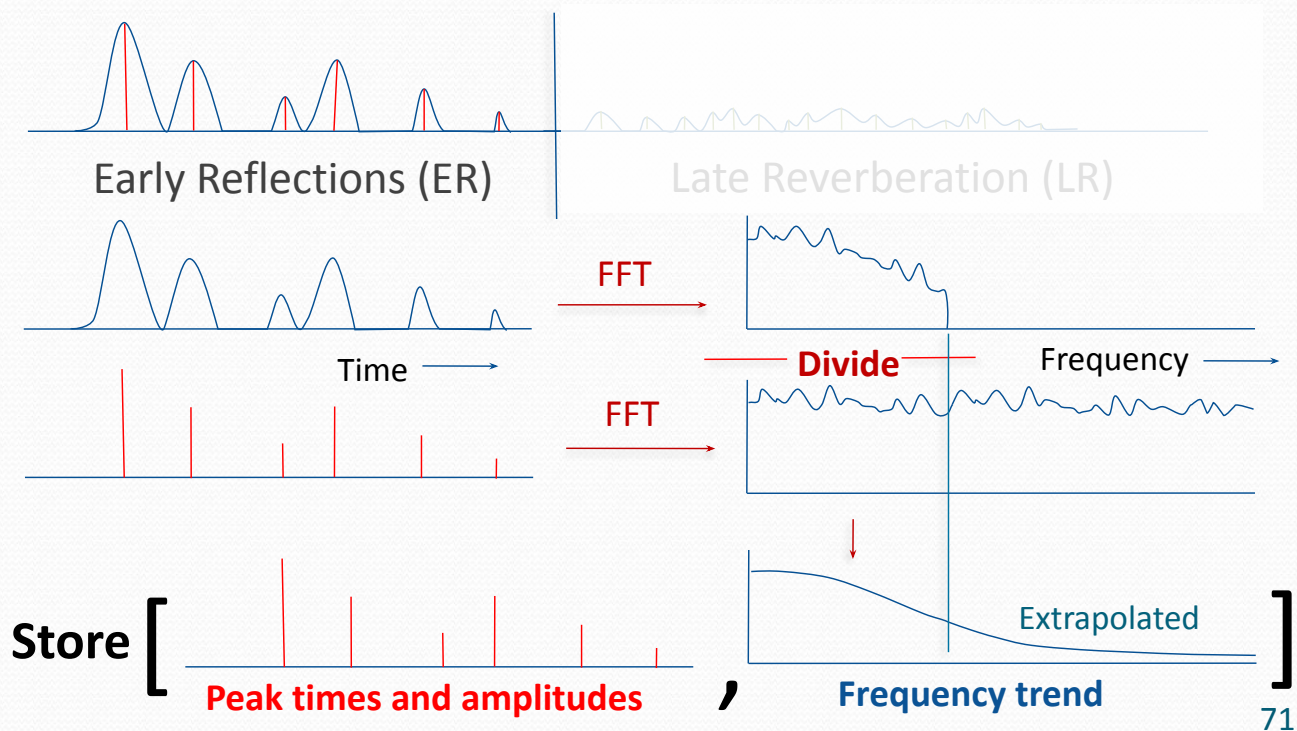
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IR Factoring (6)



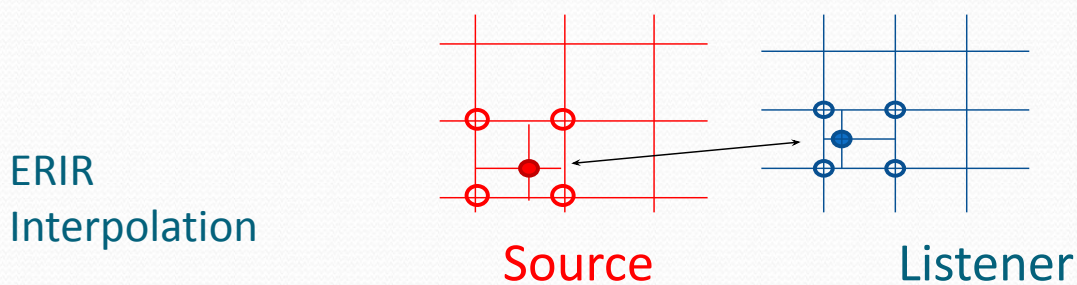
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IR Factoring (7)

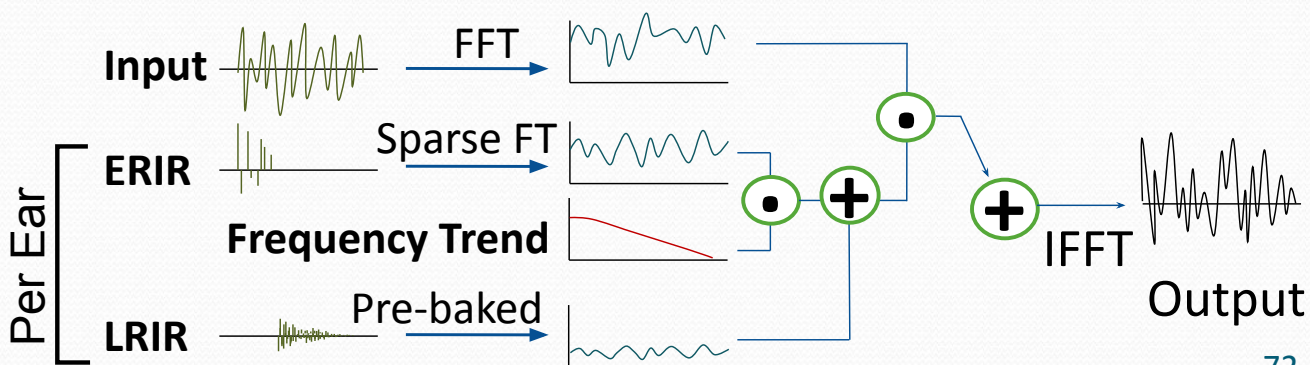


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Runtime Processing



Auralization



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Performance

- Pre-processing times typically a few hours
- Can handle about 10 sound sources in real-time on a Quad-core Xeon system with 4 GB RAM
- Bottleneck: 1D FFT
 - Auralization system maps well to parallel processors

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Walkthrough: Game Scene

- “Citadel” Scene from the game Half-Life 2
- Large Size: 3,500 m³
- Complex geometry (fin-like structures)

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System Demonstration

Video

<http://www.youtube.com/watch?v=MQt1jtDBNK4>

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Summary

- The first interactive sound propagation system that leverages numerical simulation
- Can render important acoustic effects like Late Reverberation and Diffraction low-pass filtering in real-time
- Can handle multiple moving sound sources and listener
- Works for large, complex 3D scenes

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Limitations

- Uniform sampling – Can use importance-based sampling instead
 - Need quantitative measures of when 2 Impulse responses sound the same – complex psycho-acoustic question
- Scaling with scene size
 - Room-portal decomposition
- Static Scenes
 - Include limited dynamic geometry

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Overview

- Sound Synthesis
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- Interactive Sound Propagation
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Summary

- Interactive Sound Synthesis
 - Perceptually-motivated optimizations enabling hundreds of sounding objects in real-time
- Efficient Numerical Acoustics
 - A simulator 100 times faster than Finite Difference Time Domain for constant wave speed simulations
- Interactive Sound Propagation
 - Leverage fast numerical acoustics
 - Exploit auditory perception
 - Render wave-based acoustics for multiple moving sources and listener in real-time

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Conclusion

- Physically-based Sound: Complex underlying physical processes require a lot of computational power
- Combination of efficient algorithms, perceptually-motivated optimizations and fast hardware

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Recent Work: Sound Synthesis

- **Ultimate goal:** Virtual Worlds with physically-based sounds for collisions, rolling, sliding, creaking, cloth, gunshots, water, automobiles, and so on
- Infer audio materials from video
- Virtual Musical Instruments using next-gen UI
- Mobile Musical Instruments

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Recent Work: Sound Propagation

- Acoustics for Games and Virtual Worlds
- Accurate numerical predictions in auditorium design
- Efficient numerical solvers for high-performance computing applications
- Combine Sound Synthesis and Acoustics for a completely physically-based auralization system

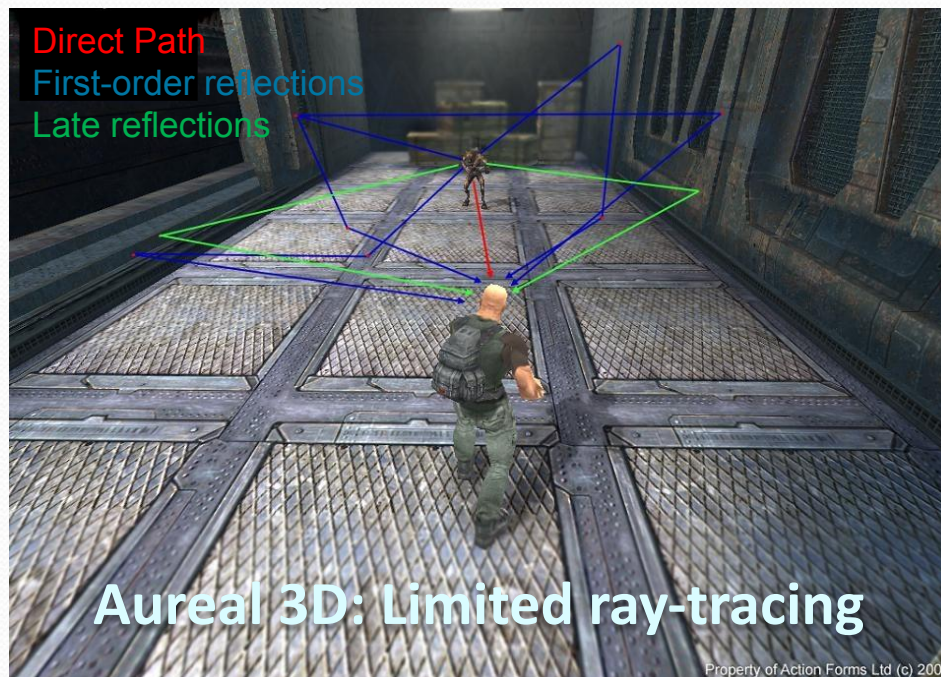
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References

- Nikunj Raghuvanshi and Ming C. Lin. **Interactive Sound Synthesis for Large Scale Environments**. In SI3D '06: Proceedings of the 2006 symposium on Interactive 3D graphics and games, 2006.
- Nikunj Raghuvanshi, Nico Galoppo, and Ming C. Lin. **Accelerated Wave-based Acoustics Simulation**. In SPM '08: Proceedings of the 2008 ACM Symposium on Solid and physical modeling, 2008.
- Nikunj Raghuvanshi, Rahul Narain, and Ming C. Lin. **Efficient and Accurate Sound Propagation using Adaptive Rectangular Decomposition**. IEEE Transactions on Visualization and Computer Graphics, December 2009.
- Nikunj Raghuvanshi, Brandon Lloyd, and Ming C. Lin. **Efficient Numerical Acoustic Simulation on Graphics Processors Using Adaptive Rectangular Decomposition**. Proc. EAA Symposium on Auralization, 2009.

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Acoustics in Games

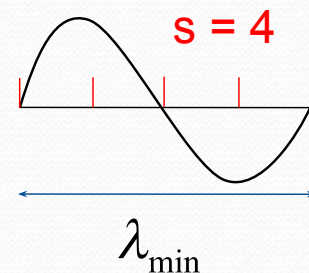


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Computational Challenges (1)

- Need sufficient spatial resolution to resolve smallest wavelength of interest

$$h \sim \frac{\lambda_{\min}}{s}, \quad s > 2$$



- Also, need sufficiently small time-step to resolve highest frequency

$$dt < \frac{1}{sV_{\max}}$$

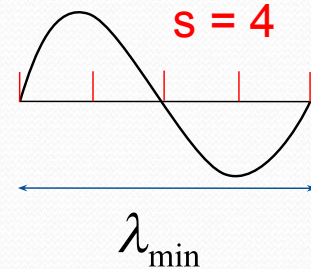
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Computational Challenges (2)

- For a scene of size L in 3D and simulation duration T –

$$\text{Memory : } \left(\frac{L s v_{\max}}{c} \right)^3$$

$$\text{Time : } T \left(\frac{L}{c} \right)^3 (s v_{\max})^4$$



- For a medium-sized room – $L = 10$ m, $T = 1$ s,
 $c = 340$ m/s, $s = 10$, $v_{\max} = 10,000$ Hz

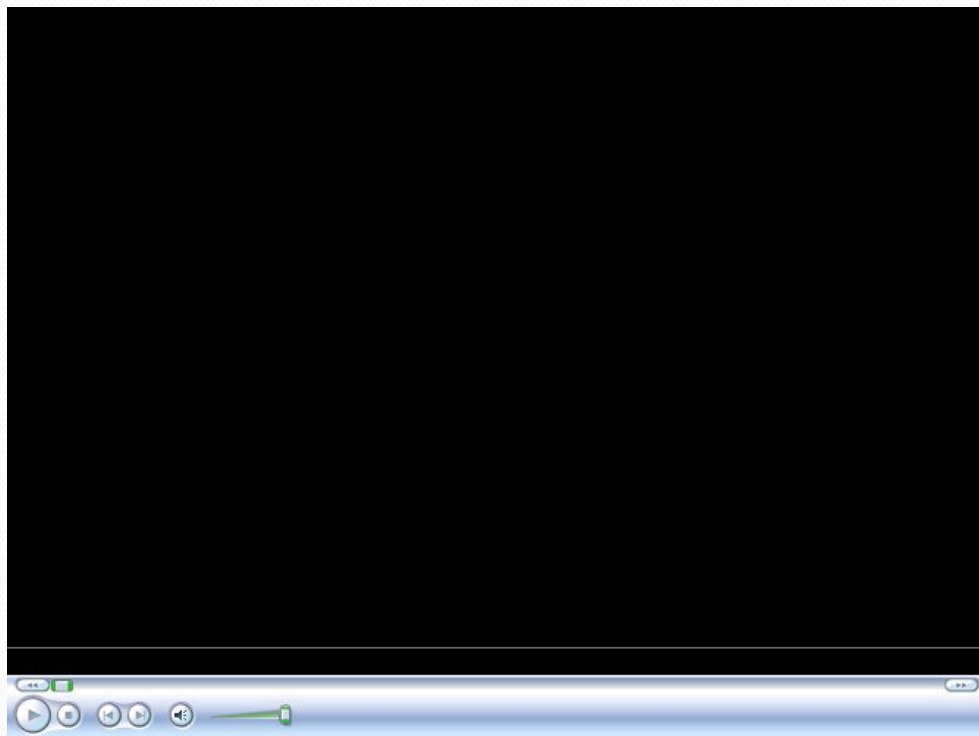
Memory : **~100 GB** Time: **6 days**, at 100 GFLOPS

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Bass Boost in small spaces

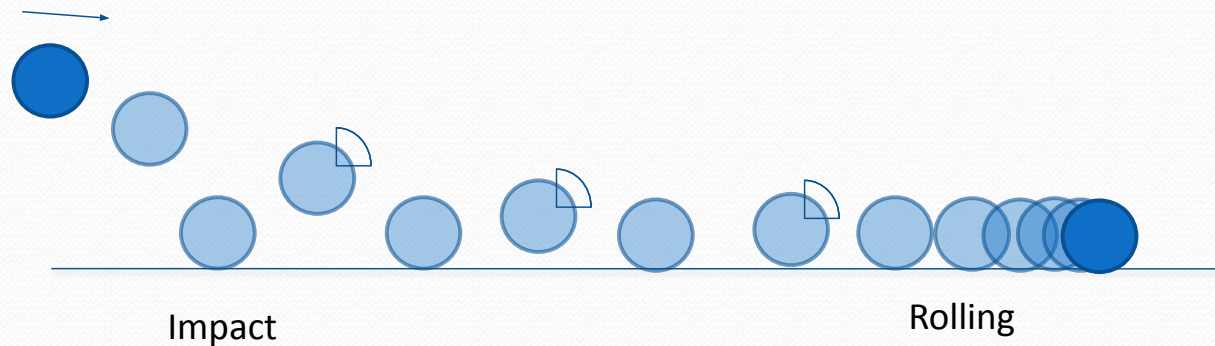


Input



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A typical scenario



- How do you handle this with recorded sounds?

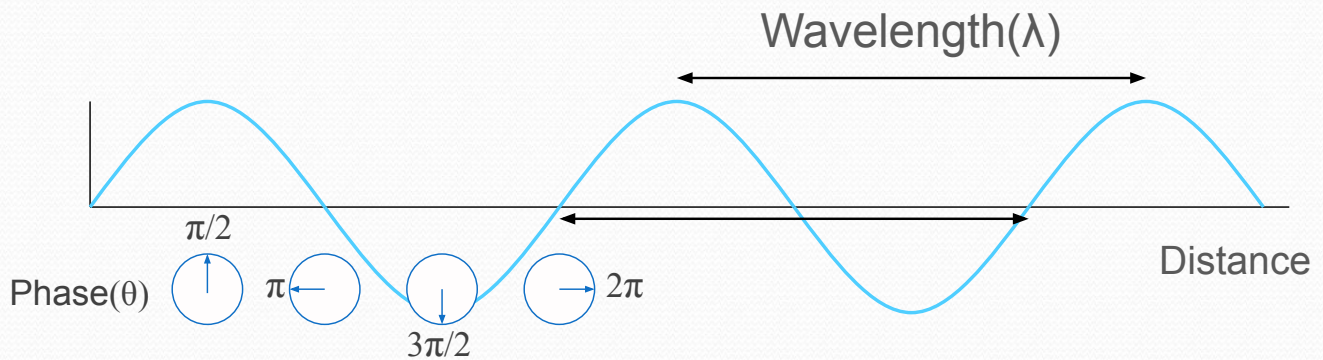
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Related/Future Work

- Model-based Synthesis
 - Current work with Naga K. Govindaraju, Brandon Lloyd, Guy Whitmore and Christopher Melroth
- Sliding Sounds
 - Past work in SIGGRAPH by Doel et. al.
 - Current work being done by Zhimin Ren at UNC
- Liquid Sounds
 - Recent paper on “Harmonic Fluids” by Doug James at Cornell
 - Also, some work at UNC by Yero Yeh
- Cloth Rustling

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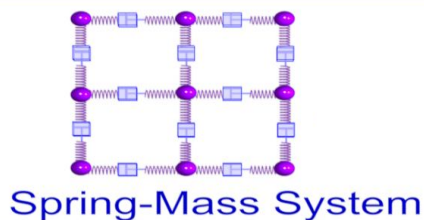
Quick primer on waves



- Phase (θ): Measures the progression of wave between crest and trough
- Frequency: ν , Wavelength: λ
- Wave Speed , $c = \nu\lambda$

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Equation of Motion

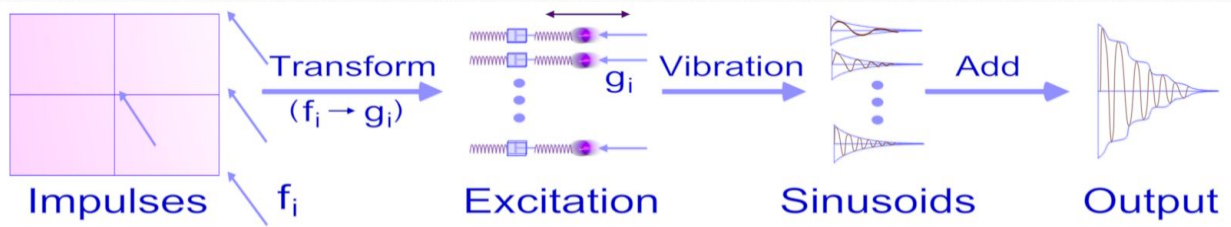


- Equation of motion (linear system of coupled ODEs):

$$\underbrace{M \frac{d^2 r}{dt^2}}_{\text{Inertia}} + \underbrace{(\gamma M + \eta K) \frac{dr}{dt}}_{\text{Damping}} + \underbrace{Kr}_{\text{Elasticity}} = \underbrace{F(t)}_{\text{Force}}$$

γ, η : Fluid and Viscoelastic Damping constants

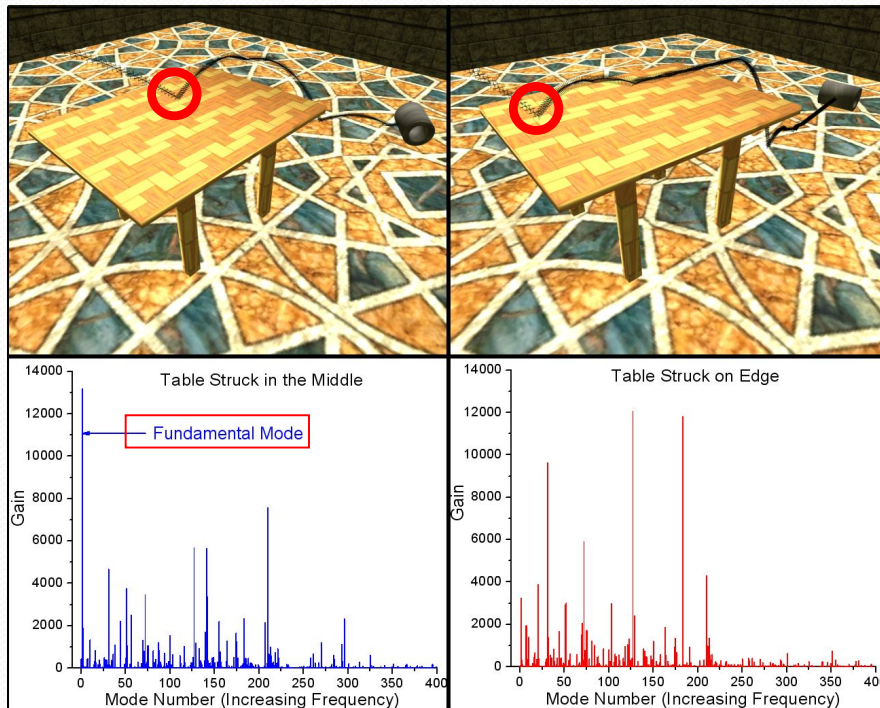
Sound Synthesis



- Rigid Body Simulator provides impulses
- Transform to mode gains
- Sound synthesized by adding the modes' sinusoids
- Advantage: Adding damped sinusoids is very fast

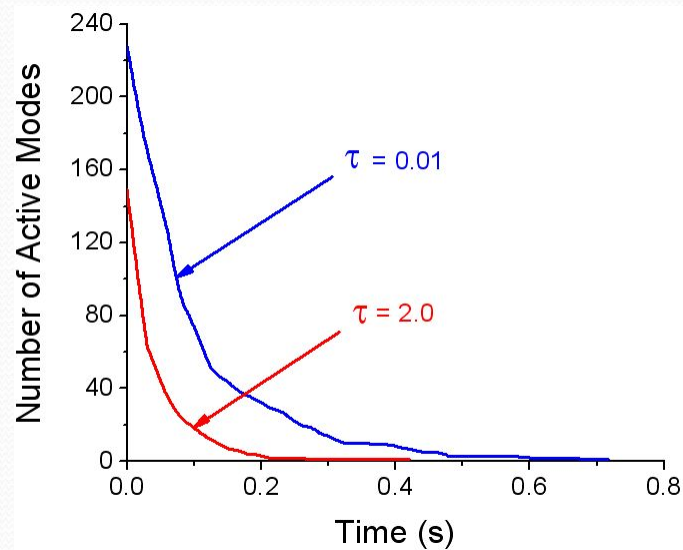
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Position Dependent Sounds. Analysis



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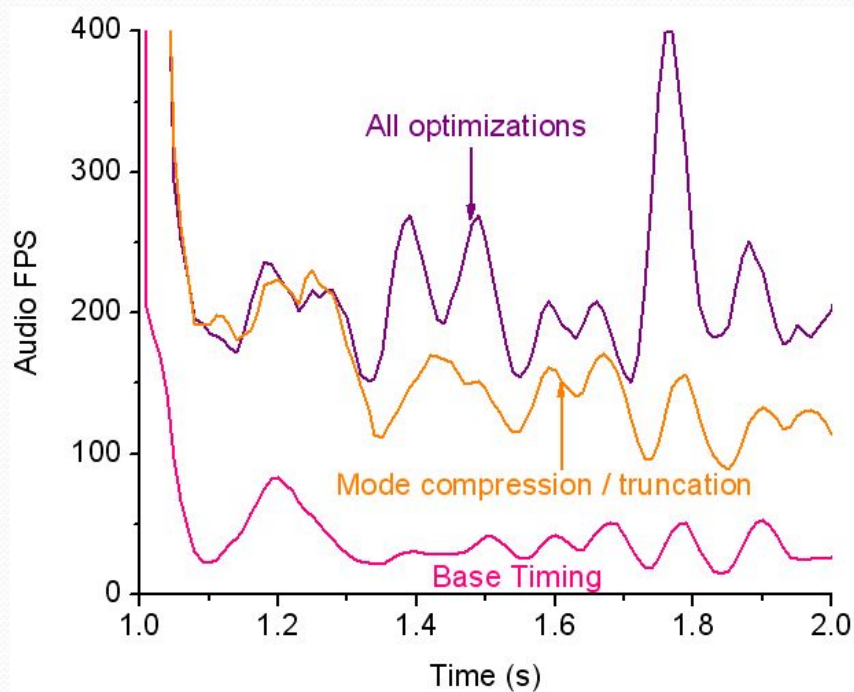
Mode Truncation: Performance



- Xylophone bar struck in the middle
- Higher value of τ : Modes fall off more quickly
- Very little perceptual difference

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Efficiency: Analysis



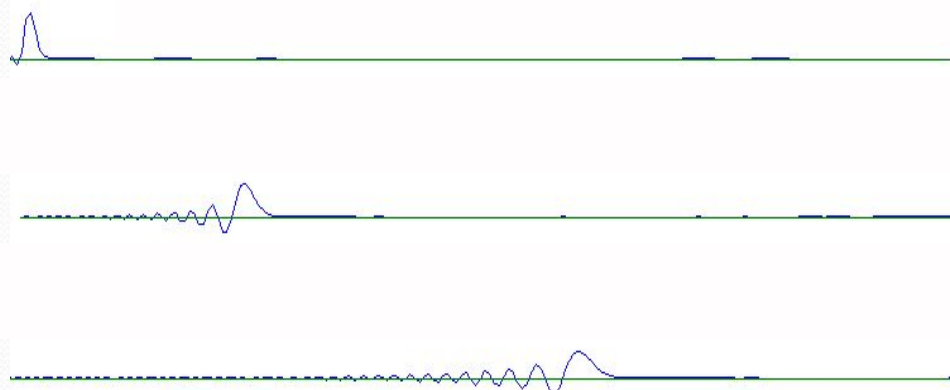
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Acoustics: Computational Challenges

- Multiple reflections are audible: Full time domain solution required, unlike lighting
- Interference is important eg. Dead spots in auditoria
- Diffraction is observable for sound and must be captured properly

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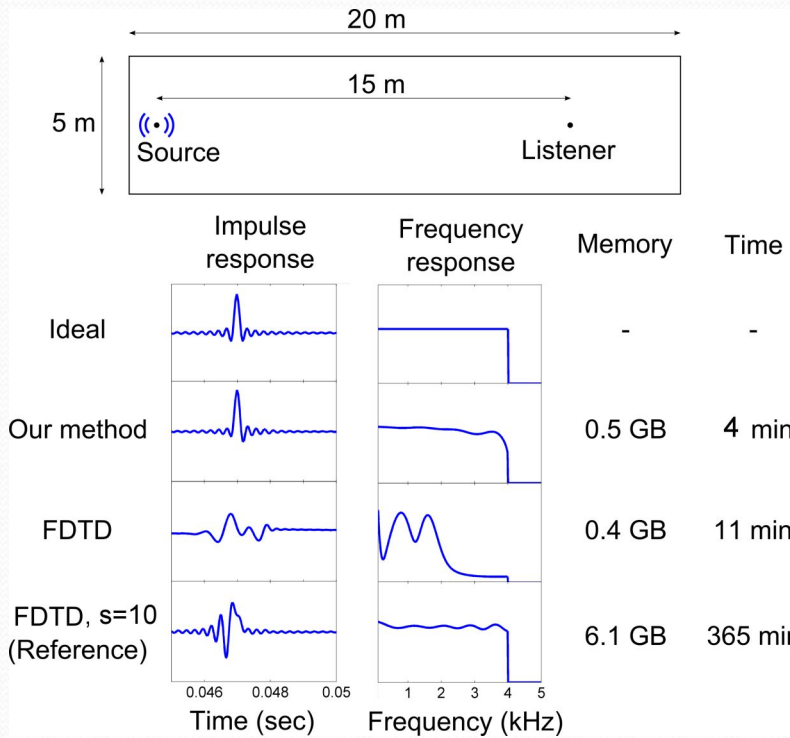
Errors in FDTD: Numerical Dispersion



- All frequencies don't travel with the same numerical speed
- Need $s = 10$ for this

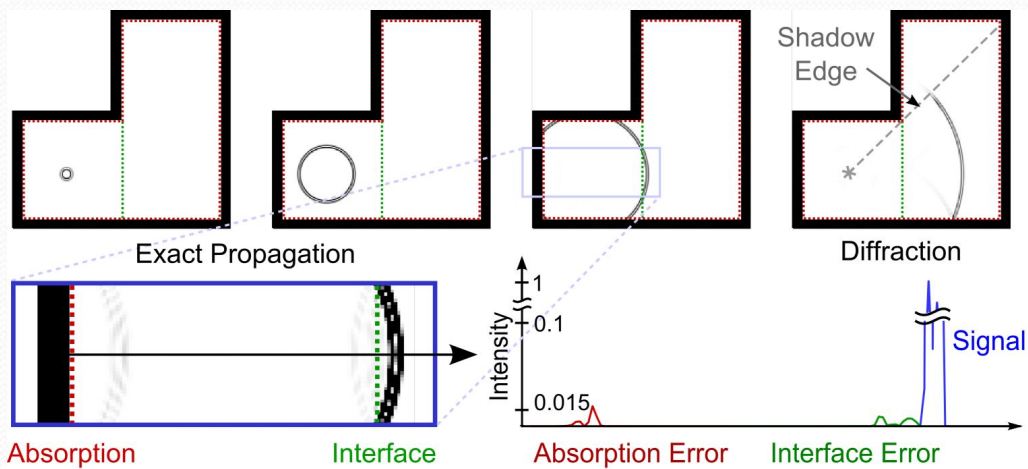
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Error comparison with FDTD



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Interface Errors



Frequency	Interface error	Absorption error
250 Hz	-54 dB	-21 dB
500 Hz	-42 dB	-26 dB
750 Hz	-36 dB	-26 dB
1000 Hz	-28 dB	-32 dB

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Solution on a Rectangular Domain

- Rectangle in 3D with size : (l_x, l_y, l_z) , with sound-hard boundary
- Represent pressure in Modal basis for Laplacian on the rectangular domain:

$$p(x, y, z, t) = \sum_{i=(i_x, i_y, i_z)} m_i(t) \Phi_i(x, y, z)$$

$$\Phi_i(x, y, z) = \cos\left(\frac{\pi i_x}{l_x} x\right) \cos\left(\frac{\pi i_y}{l_y} y\right) \cos\left(\frac{\pi i_z}{l_z} z\right)$$

$m_i(t)$ are time-varying mode coefficients

Φ_i are eigen-functions of Laplacian

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Solution in Spectral Basis using DCT

- The transformation from real space and spectral space can be done using 3D DCT and inverse DCT

$$\{m_i\} = DCT\{p_i\}, \quad \{p_i\} = iDCT\{m_i\}$$

- Wave Equation in spectral space (decoupled):

$$\frac{\partial^2 m_i}{\partial t^2} + c^2 k_i^2 m_i = iDCT(F(t)),$$

- Analytical solution in time:

$$k_i^2 = \pi^2 \left(\frac{i_x^2}{l_x^2} + \frac{i_y^2}{l_y^2} + \frac{i_z^2}{l_z^2} \right)$$

$$M_i^{n+1} = 2M_i^n \cos(\omega_i \Delta t) - M_i^{n-1} + \frac{2\widetilde{F}^n}{\omega_i^2} (1 - \cos(\omega_i \Delta t))$$

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Modeling partially absorbing surfaces

- Numerical absorbers for Wave Equation is a tough challenge
- Perfectly Matched Layer (**PML**) was developed in the Electromagnetic simulation community
- We adapt a time-domain formulation described in
 - Y. S. Rickard, N. K. Georgieva, and W.-P. Huang, "Application and optimization of pml abc for the 3-d wave equation in the time domain," *Antennas and Propagation, IEEE Transactions on*, vol. 51, no. 2, pp. 286-295, 2003

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Summary (contd..)

- Automatically handles interference and diffraction
- Parallelizable at multiple granularities: Source positions, Partitions, DCT
- Axis-aligned simulation grid, easy to obtain using voxelization

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Current Progress

- Compression scheme is nearly finished, can handle a medium-sized Lecture hall
- Extracting diffraction information still needs to be tested and tweaked
- Late reverb interpolation needs to be implemented
- Real-time auralization system is also near completion. IR interpolation needs to be tested properly.

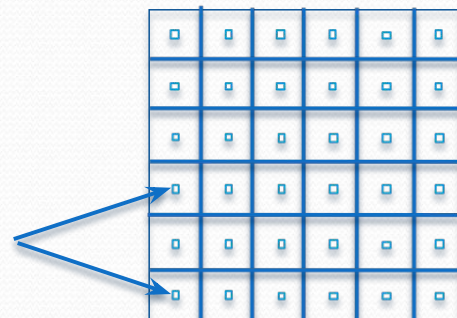
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Finite Difference Time Domain (FDTD)

- Discretize continuum derivative operators:

$$\frac{P_{t+dt} - 2P_t + P_{t-dt}}{dt^2} + KP_t + O(h^6) + O(dt^2) = F_t$$

- Spatial cell size: h , time-step: dt
- Works on a uniform Cartesian grid
- Pressure sampled at cell centers



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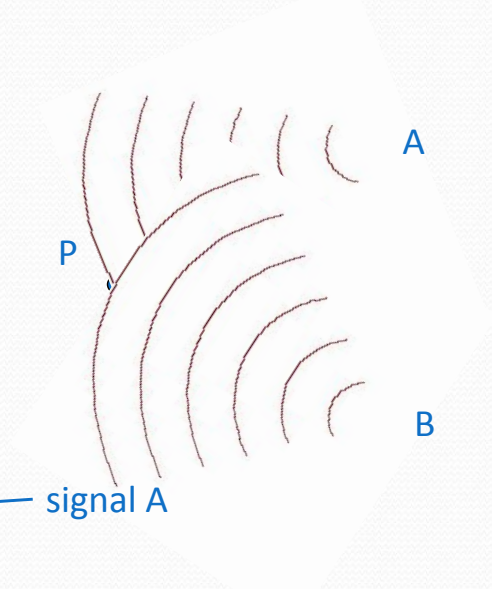
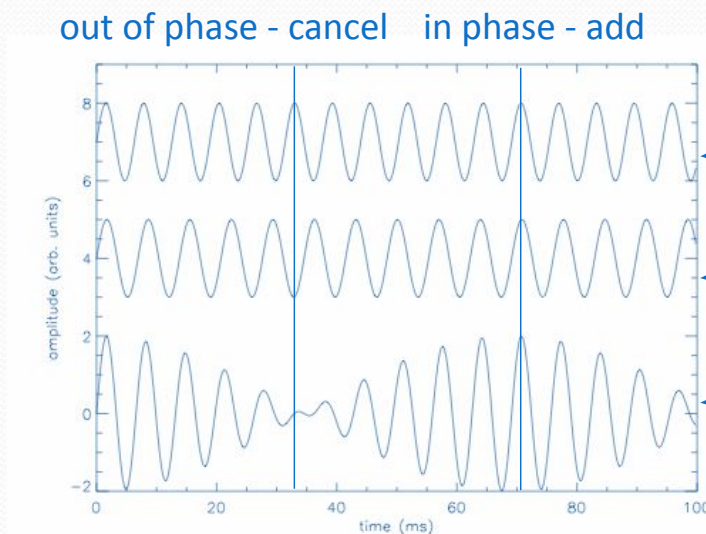
Summary

- Simple formulation and easy to implement
- Works on arbitrary surface meshes
- Acceleration techniques exploiting auditory perception
 - Mode Compression
 - Mode Truncation
 - Quality Scaling
- Well suited for large-scale, real-time applications with stringent time constraints, like games

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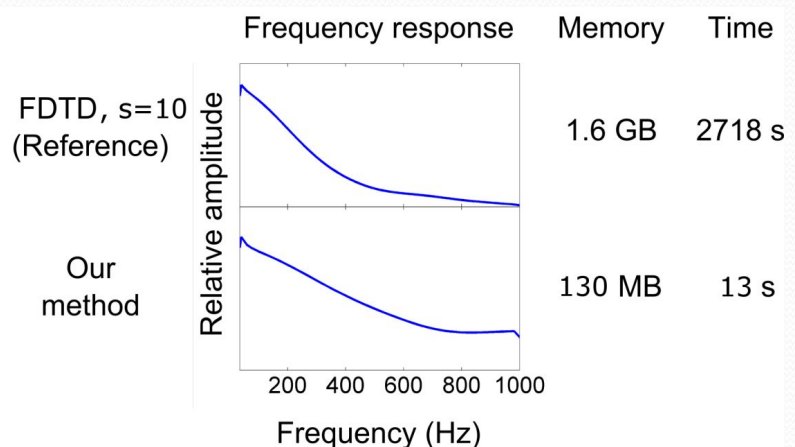
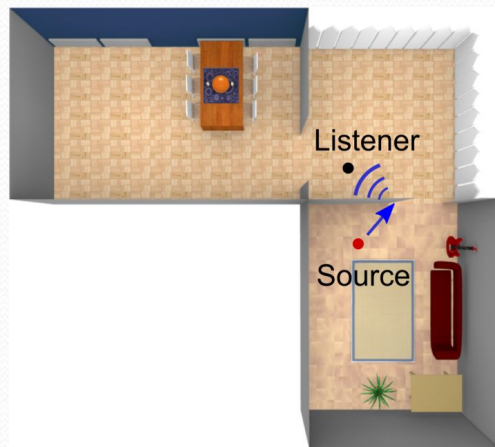
Interference

- The resultant pressure at P due to two waves is their sum
- Phase is crucial



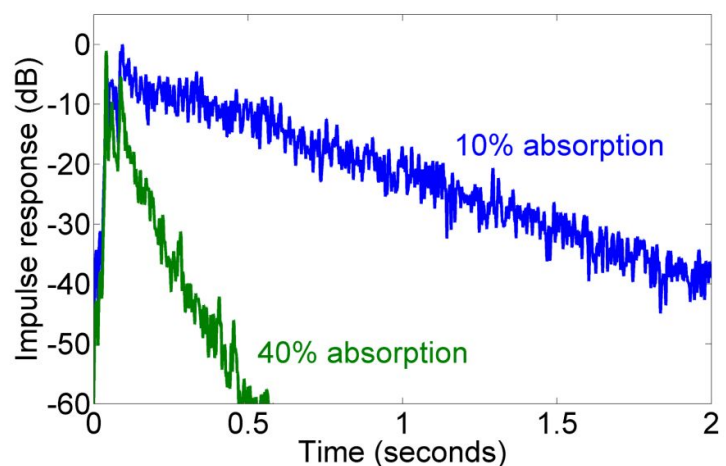
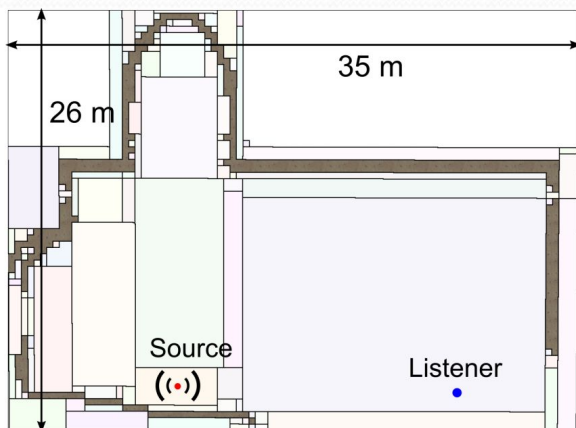
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Performance: House



- Dimensions: 17m x 15m x 5 m
- Auralization: 24 minutes to generate a .4 second long Impulse Response (< 2 kHz)

Performance: Cathedral



- Dimensions: 35m x 15m x 26 m
- 29 minutes to generate a 1-second long Impulse Response (< 1 kHz)