Acoustic Simulation

COMP 768 Presentation
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Acoustic Simulation

- Sound Synthesis
- **Sound Propagation**
- Sound Rendering

Goal

- Simulate the propagation of sound in an environment
- Applications: games, virtual environments, architecture
- Examples:
  - Cathedral
  - Soda Hall

Outline

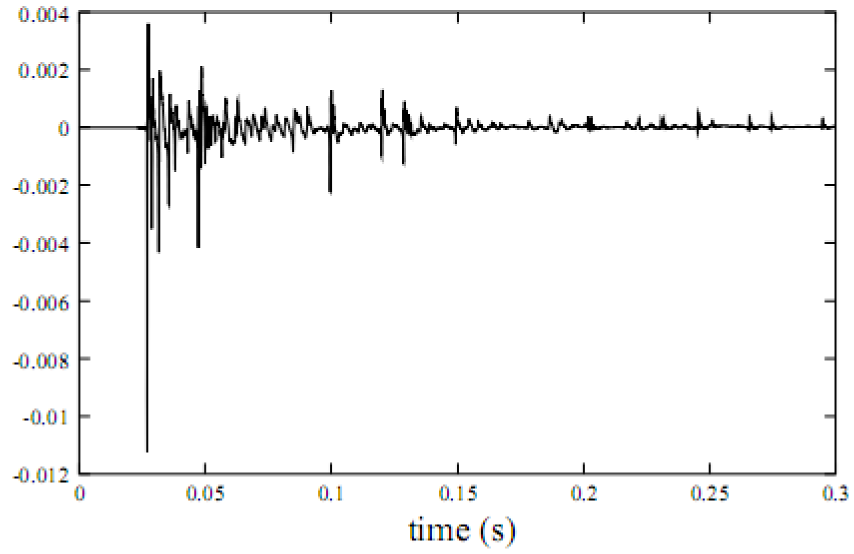
- Introduction
- Numerical Acoustics
- Geometric Acoustics
- Statistical Acoustics
- Hybrid Acoustics

Problem Statement

- Input:
  - Scene geometry
  - Source position(s)
  - Listener position
- Output:
  - Impulse response at listener

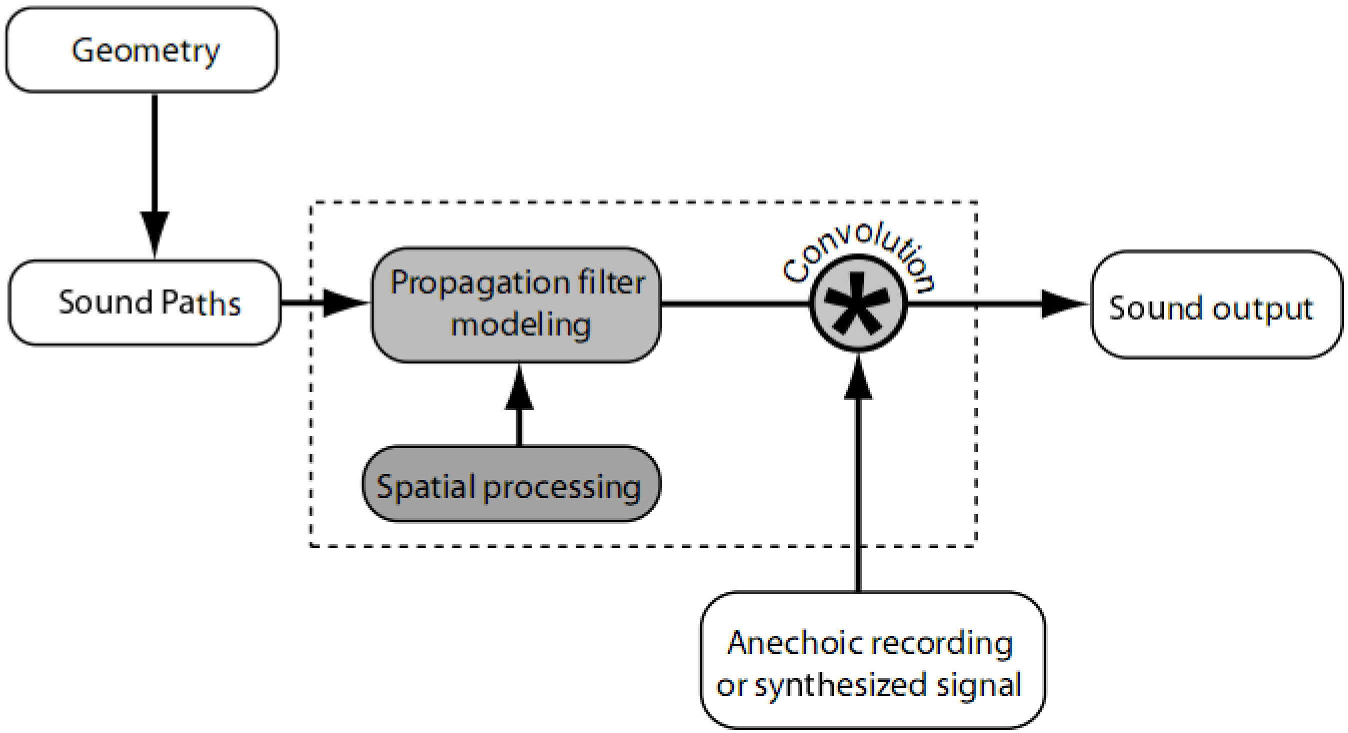
The Impulse Response

- Effect of an "instantaneous" sound at source
- Pressure (or energy) at listener as a function of time



[Funkhouser03]

Auralization



[Funkhouser03]

Acoustic Phenomena

- In reality, sound waves exhibit:
  - Reflection (specular and diffuse)
  - Diffraction
  - Interference
- Any sound propagation technique must try to model as many of these as possible

Solution Approaches

- Numerical
  - Solve a differential equation which describes pressure as a function of time and space
- Geometric
  - Determine sound propagation paths through the scene, locating paths which reach the listener
- Statistical
  - Use macroscopic scene properties (surface area, volume) to estimate acoustic behavior

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Numerical Simulation

- Sound modeled as pressure waves: $P(\mathbf{x}, t)$
- Variation of pressure governed by Helmholtz's Acoustic Wave Equation (a PDE)
- Use a numerical method to solve the PDE and determine pressure as a function of time at listener

[Raghuvanshi09]

Acoustic Wave Equation

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

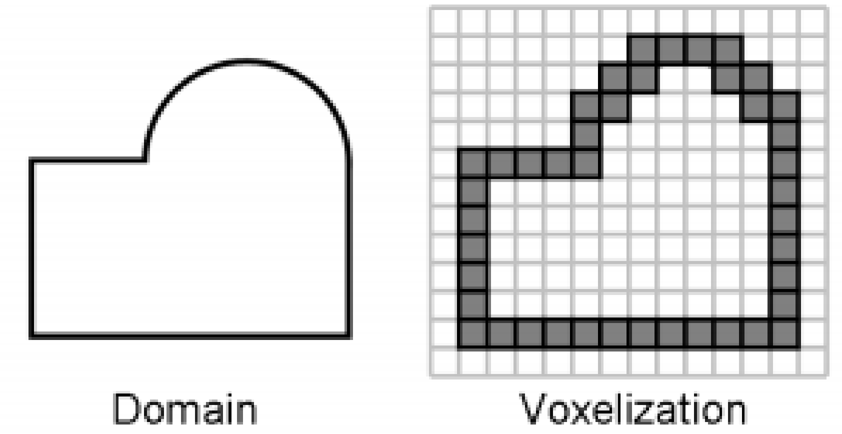
Here:

- *p* is pressure
- *c* is the speed of sound
- *F* is a *forcing term*
  - Accounts for sources, boundary conditions, etc.

[Raghuvanshi09]

Scene Discretization

- Numerical methods require discretization of the scene (spatial and temporal)
- Spatial discretization: uniform grid
  - Grid resolution increases with frequency (Nyquist theorem)
- Temporal discretization: timestep



[Raghuvanshi09]

FDTD Solution

- Use a *difference approximation* to the PDE

$$\frac{d^2 p_i}{dx^2} = \frac{1}{180h^2}\left(2p_{i-3} - 27p_{i-2} + 270p_{i-1} - 490p_i + 270p_{i+1} - 27p_{i+2} + 2p_{i+3}\right) + O\left(h^6\right)$$

$$\frac{\partial^2 P}{\partial t^2} - \frac{c^2}{h^2}KP = F(t)$$

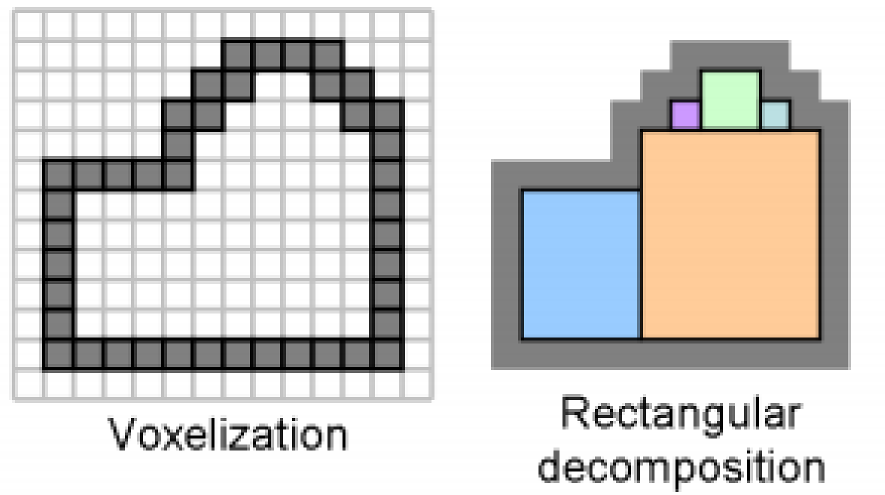
$$P^{n+1} = 2P^n - P^{n-1} + \left(\frac{c\Delta t}{h}\right)^2 KP^n + O(\Delta t^2) + O(h^6)$$

- Issues:
  - Efficiency (too many grid cells)
  - Numerical dispersion

[Raghuvanshi09]

Adaptive Rectangular Decomposition

- Grid cells grouped into large rectangular boxes
- Exact solution of wave equation known for rectangular boxes with reflecting boundaries
- Question: How do we generate the boxes?



[Raghuvanshi09]

Interface Correction

- Interfaces between boxes are not reflecting
- Need to add a correction term
- Correction term based on FDTD difference approximation across the boundary

[Raghuvanshi09]

Boundary Conditions

- Material properties modeled through boundary conditions
- Use *perfectly matched layer* conditions
- Coordinate transform that moves the wave into complex coordinates:

$$dx \to dx\left(1 + \frac{i\sigma}{\omega}\right)$$

[Raghuvanshi09]

Discussion

- Handles:
  - Specular
  - Diffraction
- Advantages:
  - Physically-based, accurate
- Disadvantages:
  - Slow
  - Impractical to simulate high frequencies
  - Boundary voxelization errors

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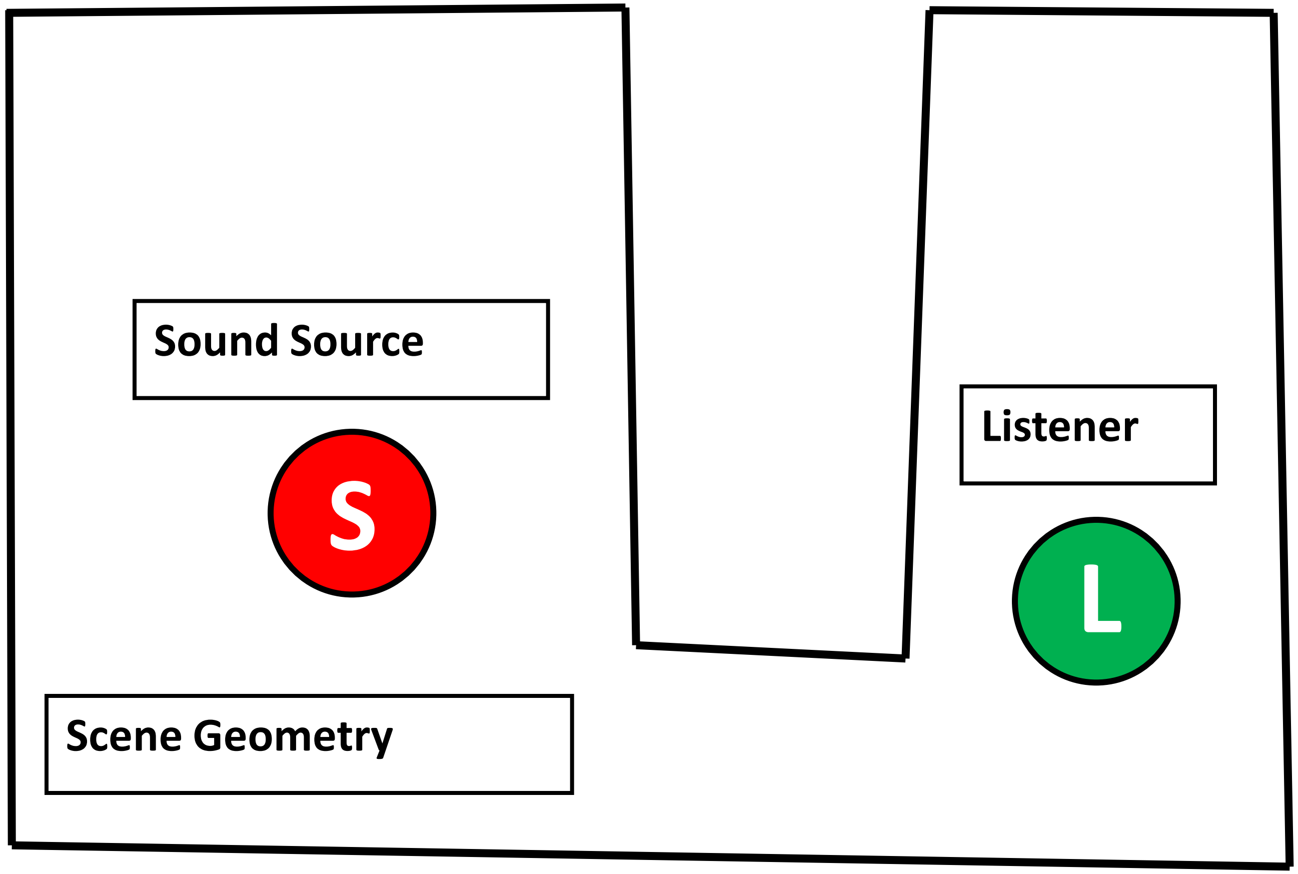
Geometric Propagation

- Similar to geometric optics
- Sound propagates along linear paths
- Paths which reach the listener contribute to the IR
  - Amplitude modified based on path length (attenuation, phase) and absorption coefficients

Ray Tracing

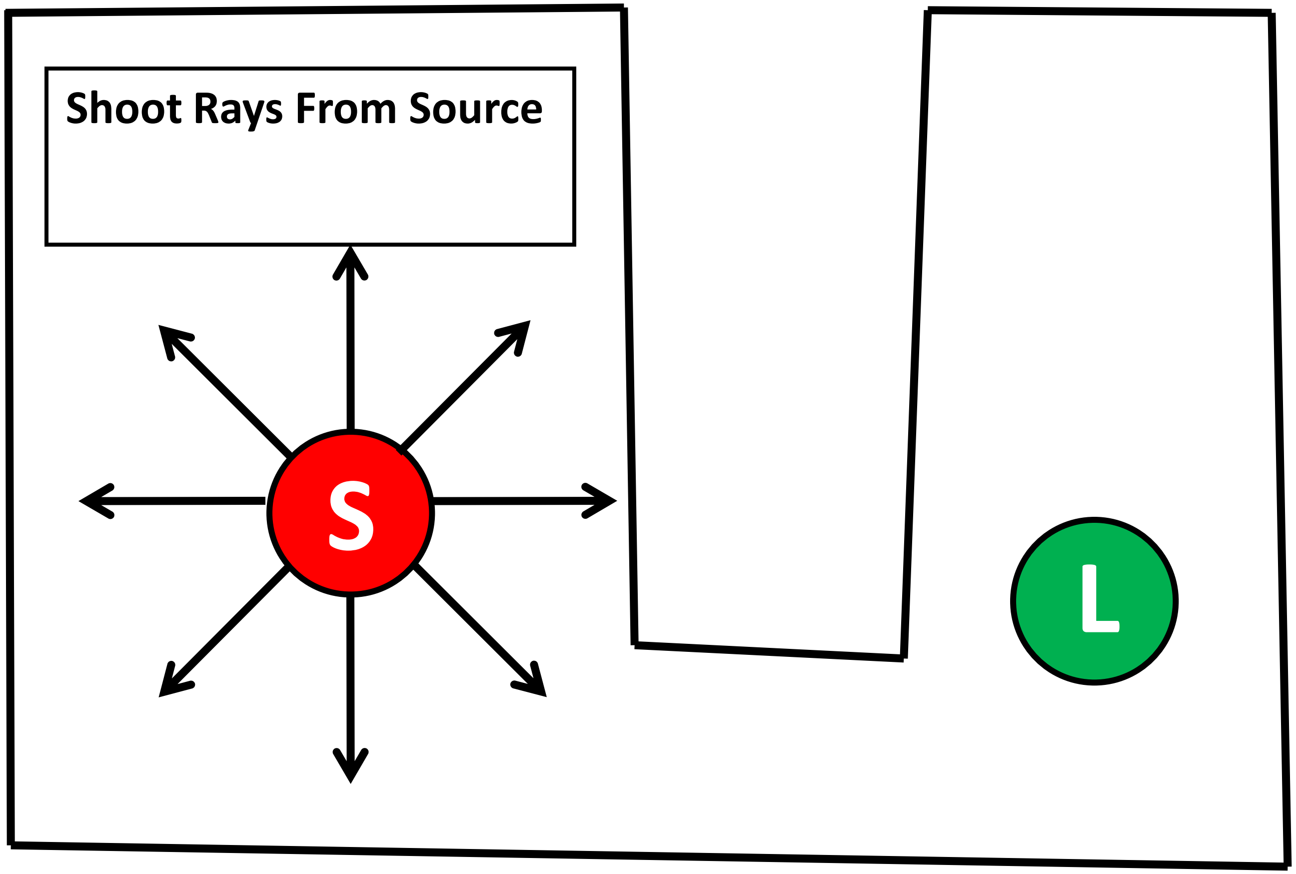
- Classic graphics algorithm, originated in acoustics community
- Trace rays from the source into the scene, reflecting them when they hit geometry

Ray Tracing



(figures courtesy Anish Chandak)

Ray Tracing



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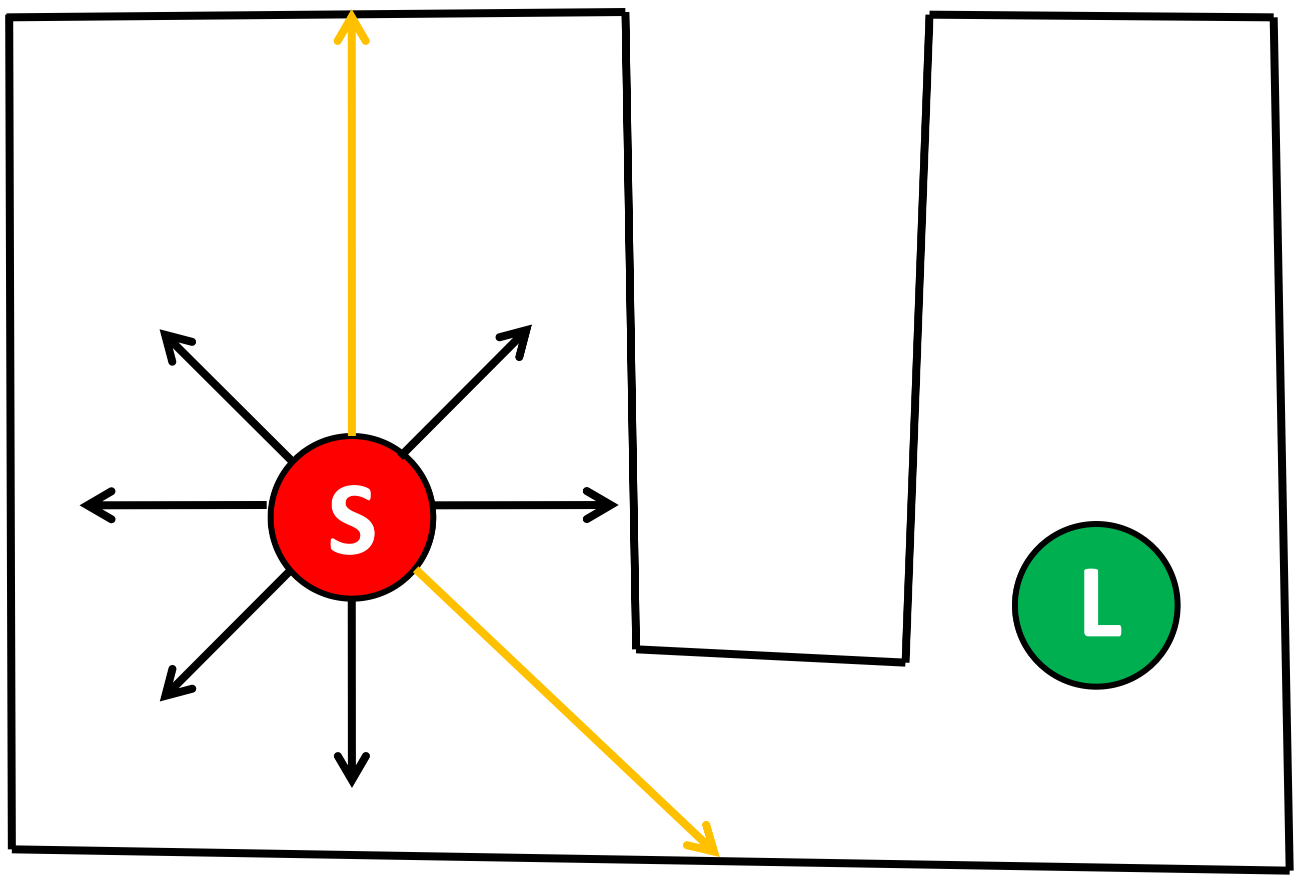
Ray Tracing



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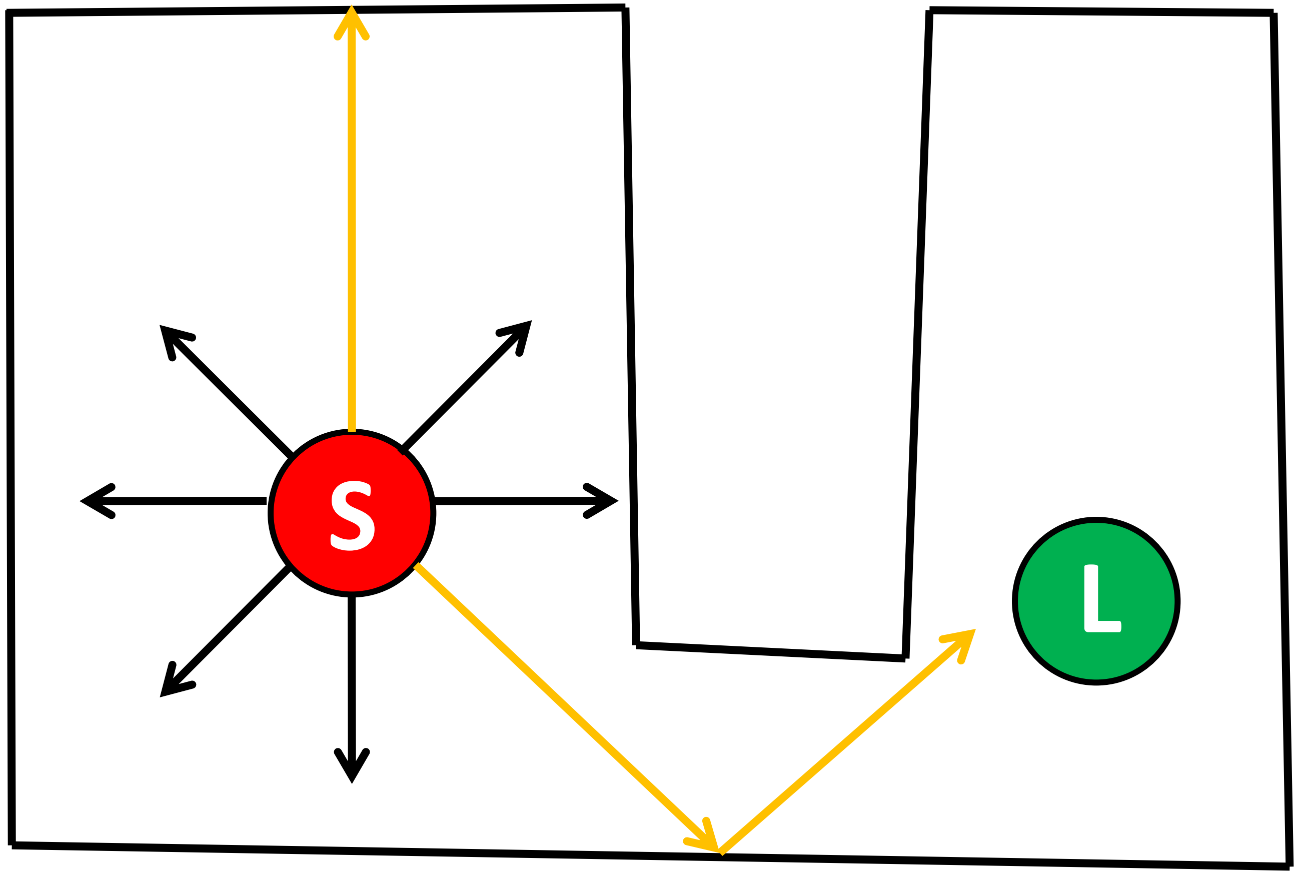
Ray Tracing



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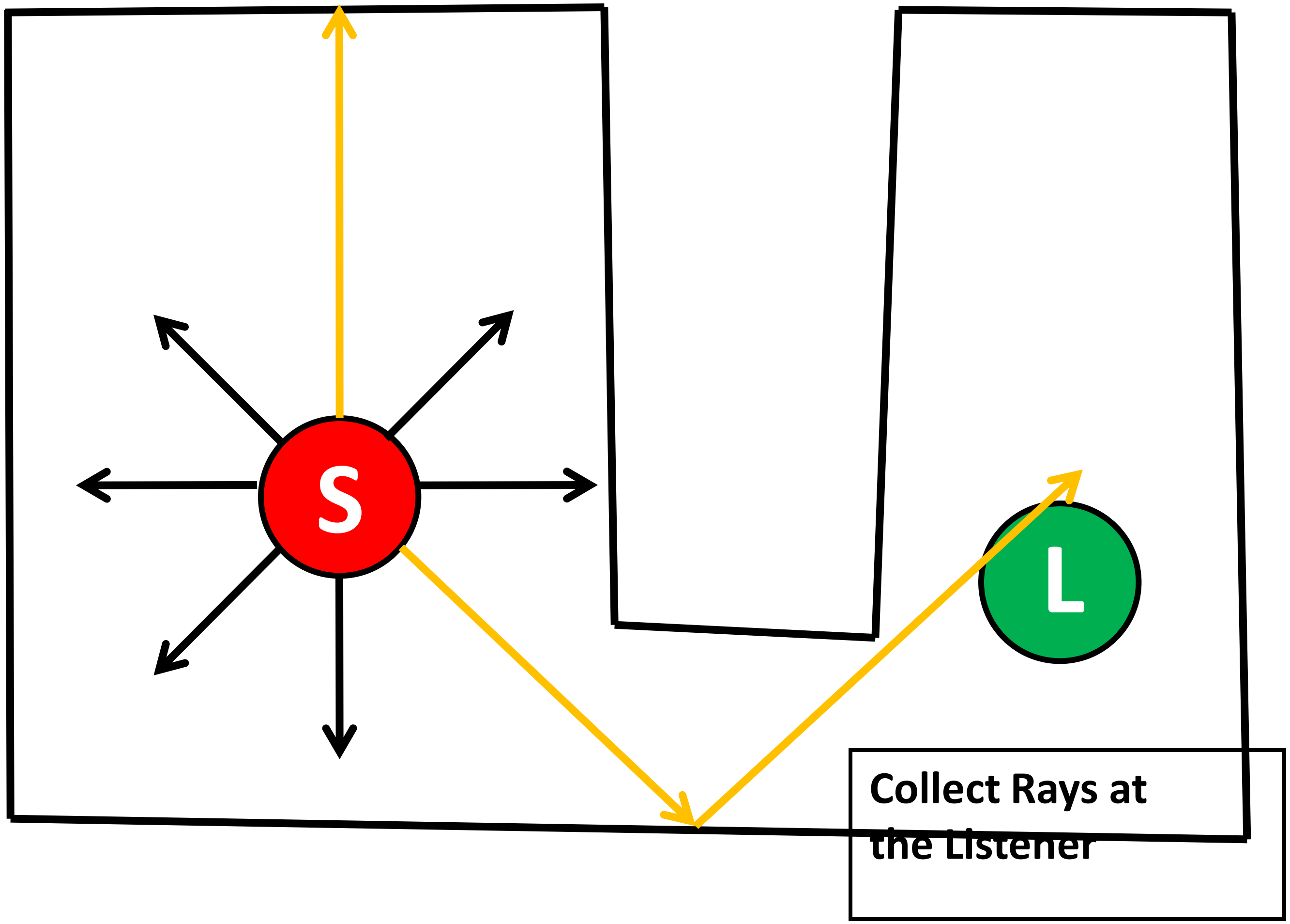
Ray Tracing

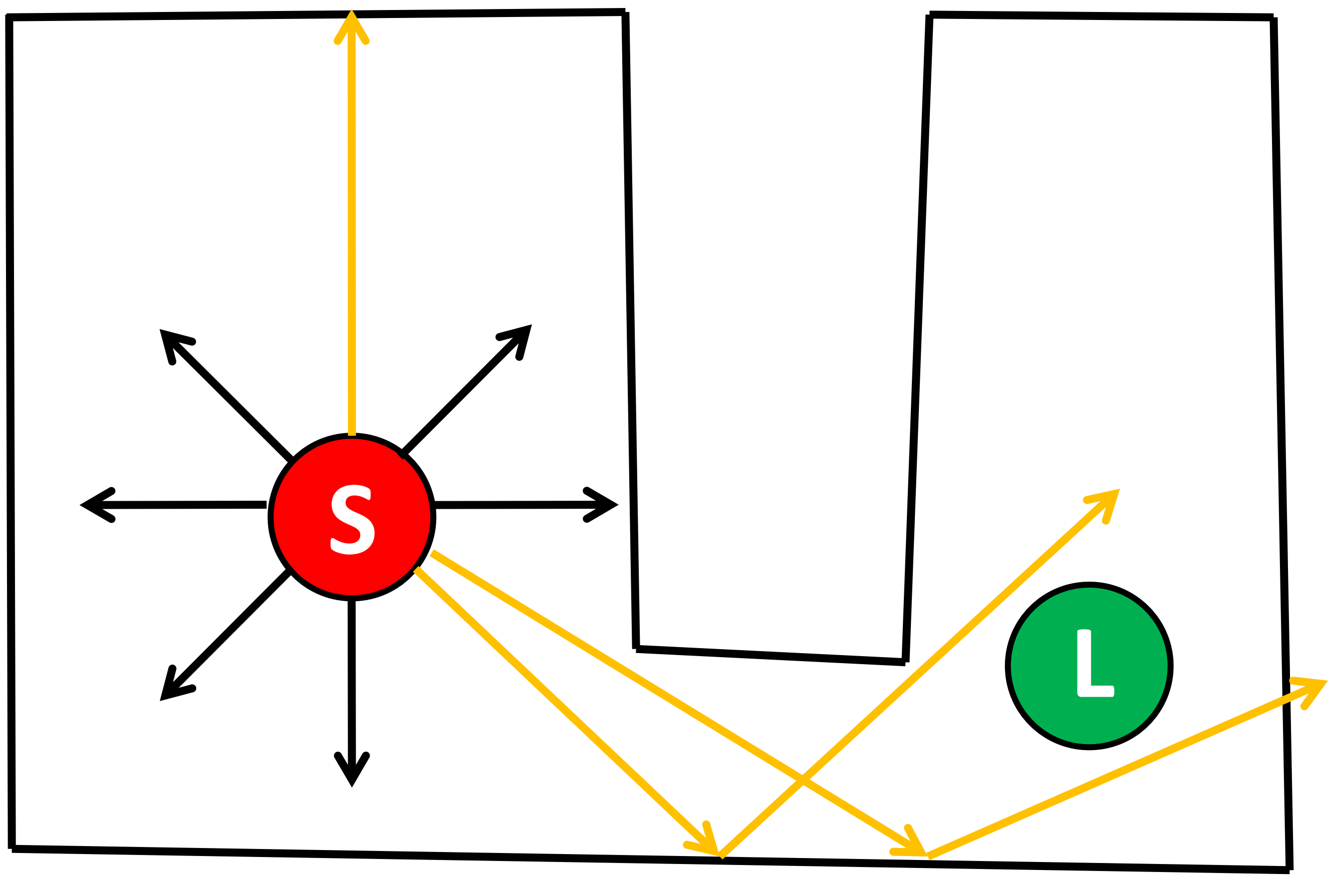


(figures courtesy Anish Chandak)

Ray Tracing

- Issues:
  - Many rays need to be traced for accuracy
  - Sampling/aliasing errors

Ray Tracing



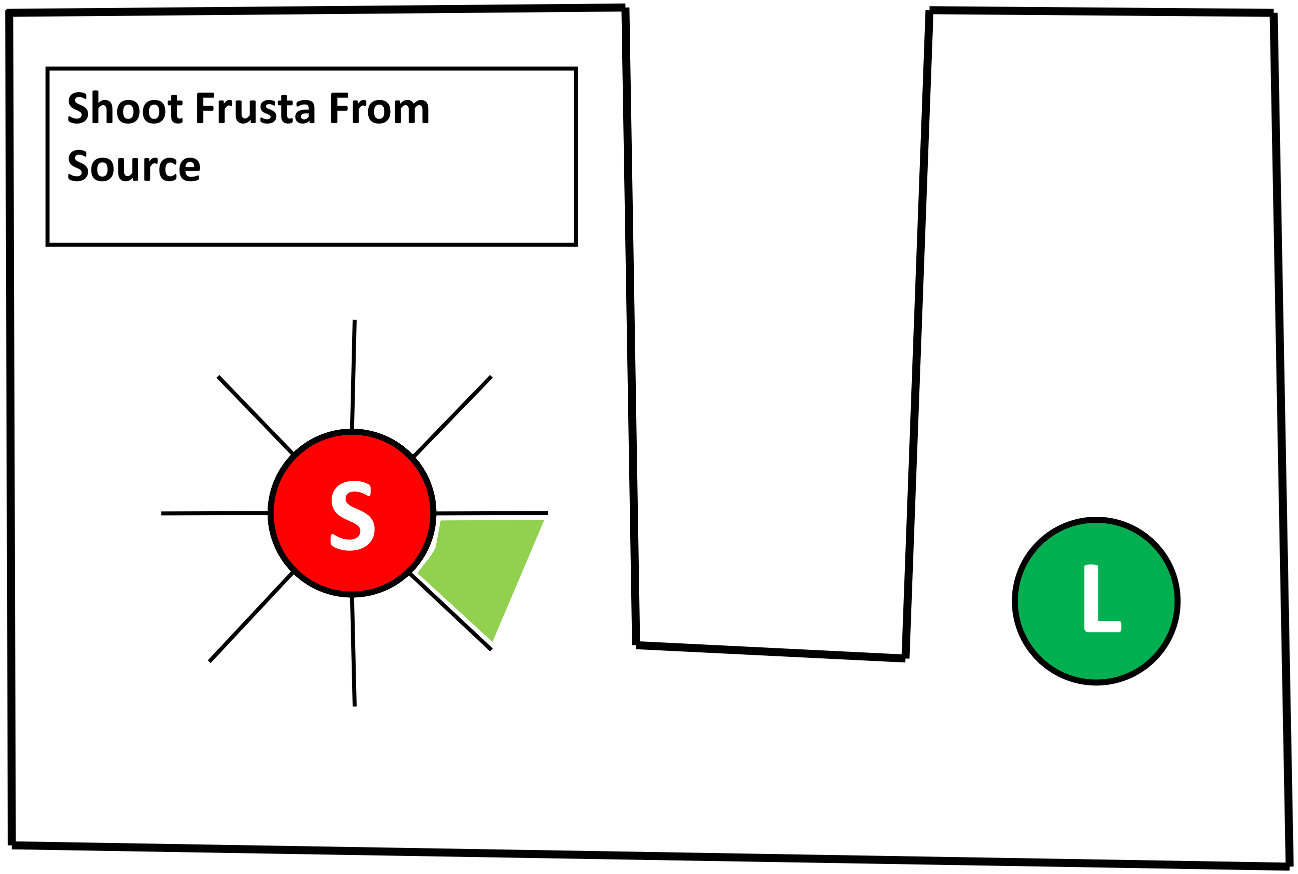
(figures courtesy Anish Chandak)

Frustum Tracing

- Trace volumetric frusta into the scene, reflecting them when they hit geometry
- Fewer scene traversals than ray tracing
- Frusta which reach the listener contribute to the IR

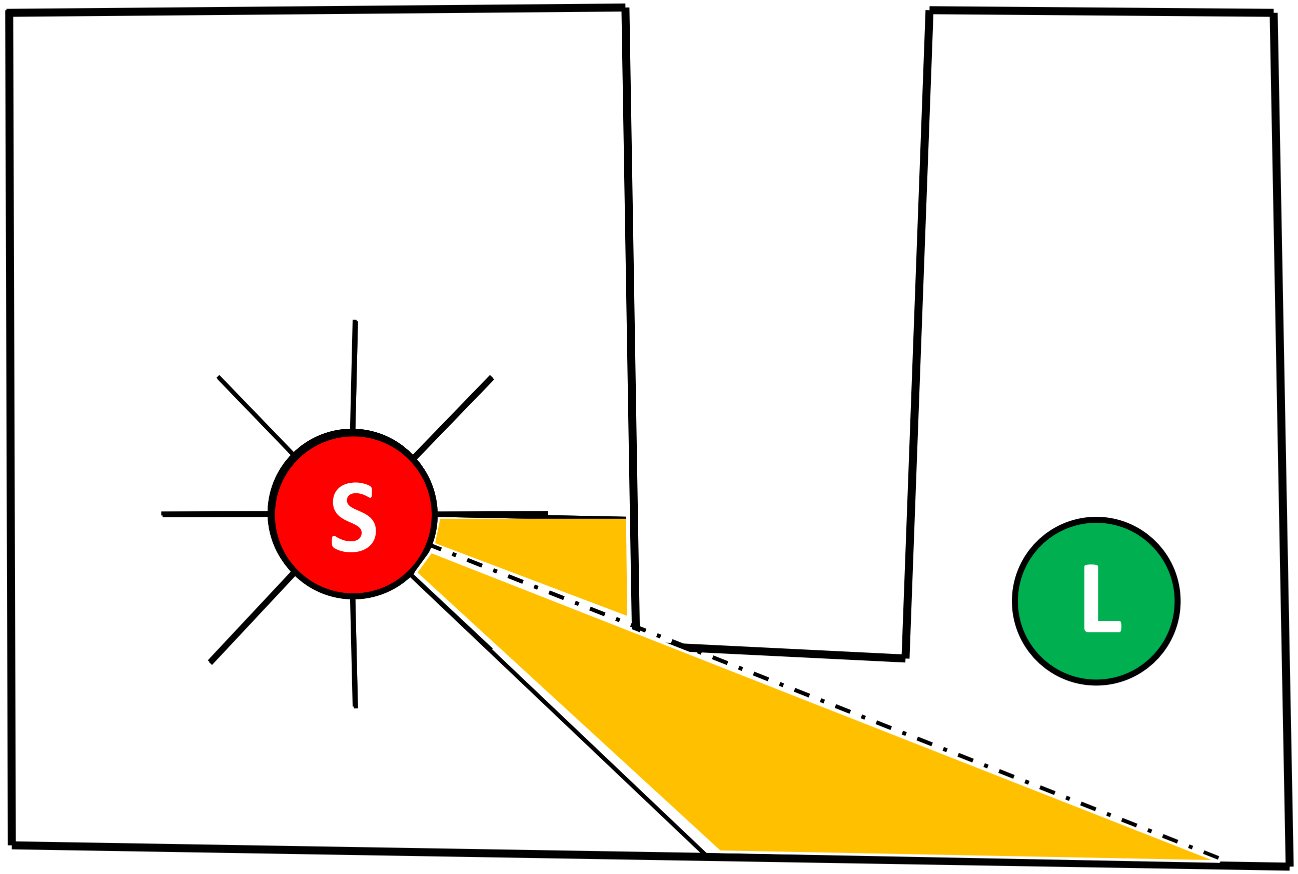
[Chandak08]

Frustum Tracing



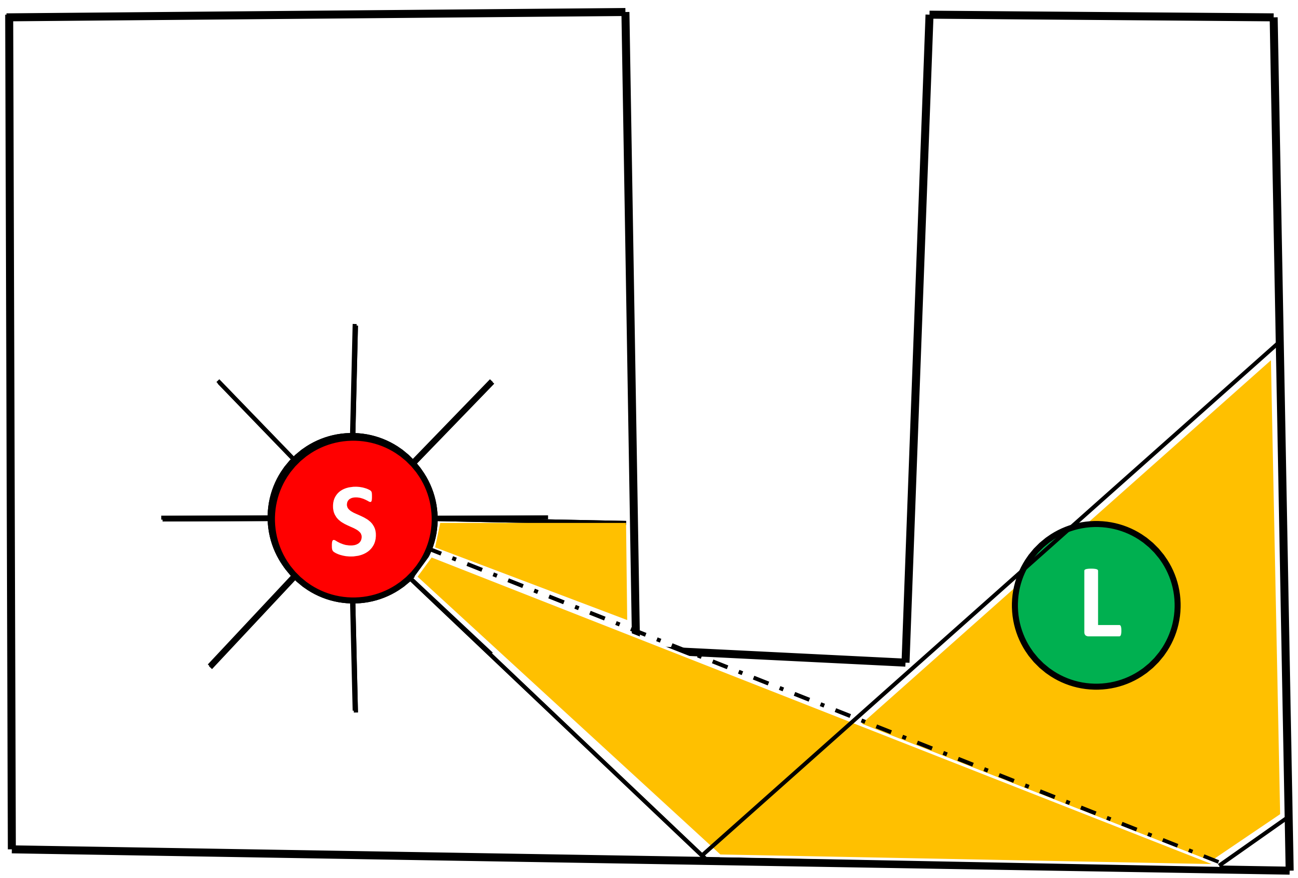
[Chandak08]

Frustum Tracing



[Chandak08]

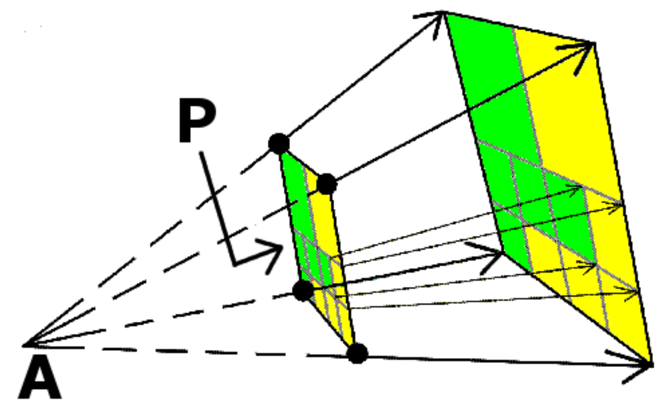
Frustum Tracing



[Chandak08]

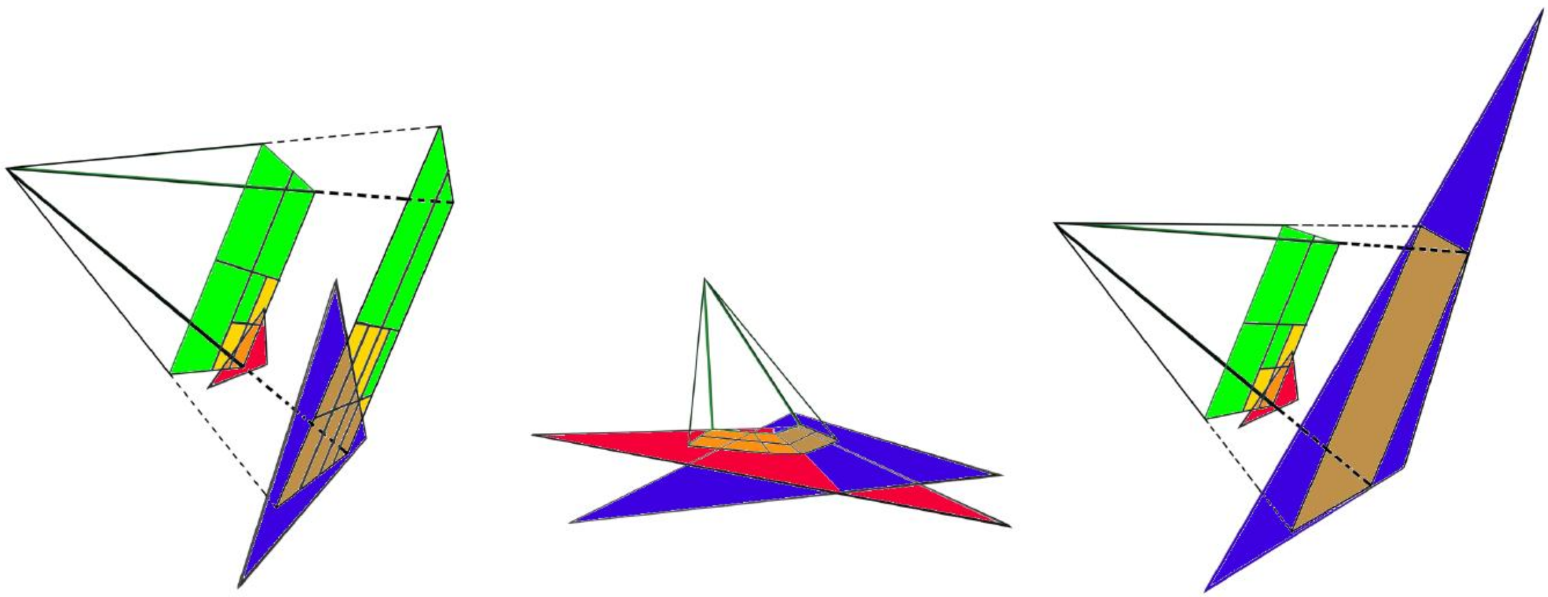
Frustum Subdivision

- Frusta which partially intersect geometry are subdivided
- Conservative approximation to exact intersection
- Can lead to errors in IR



[Chandak08]

Frustum Subdivision

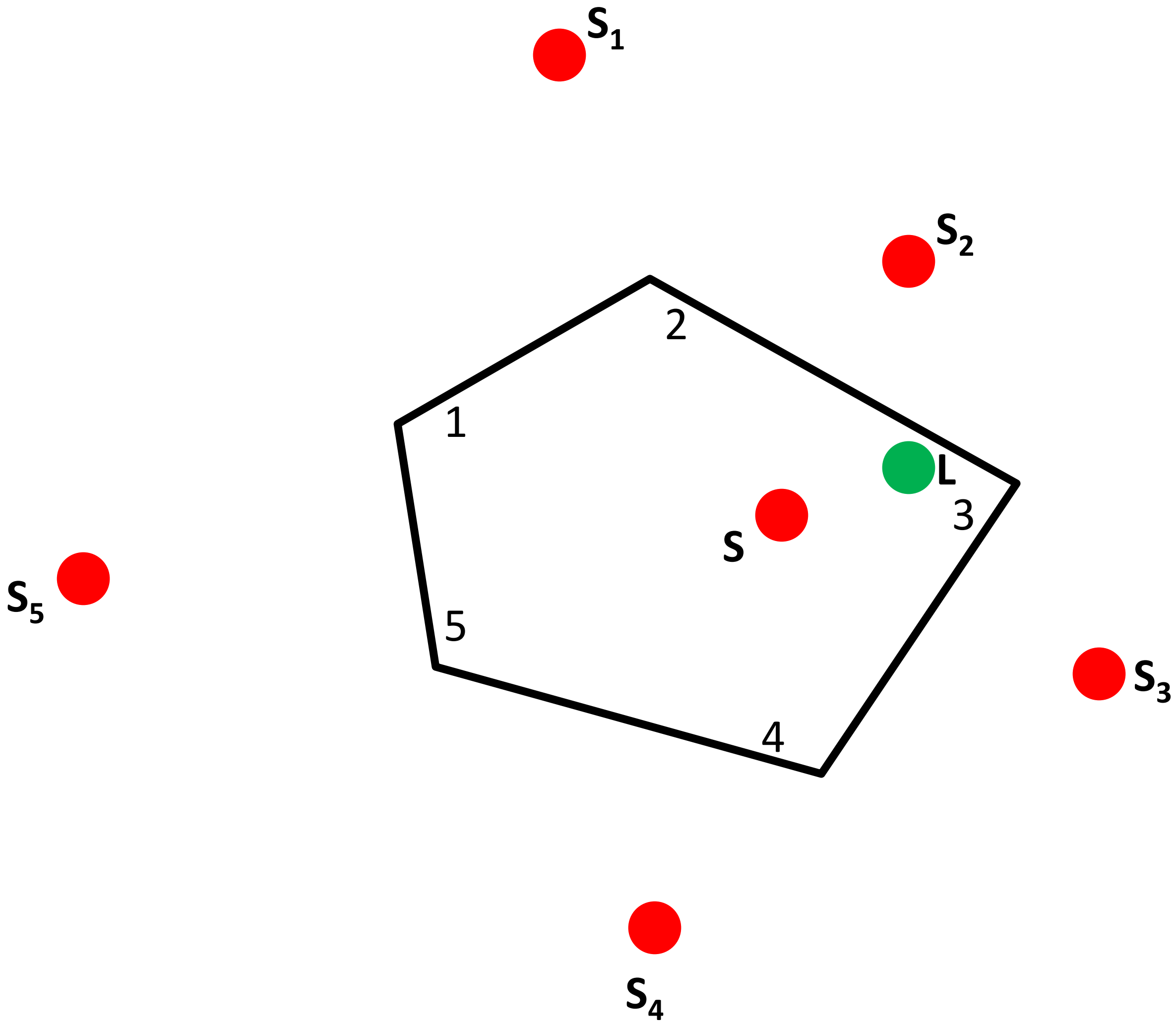


[Chandak08]

Image Source Method

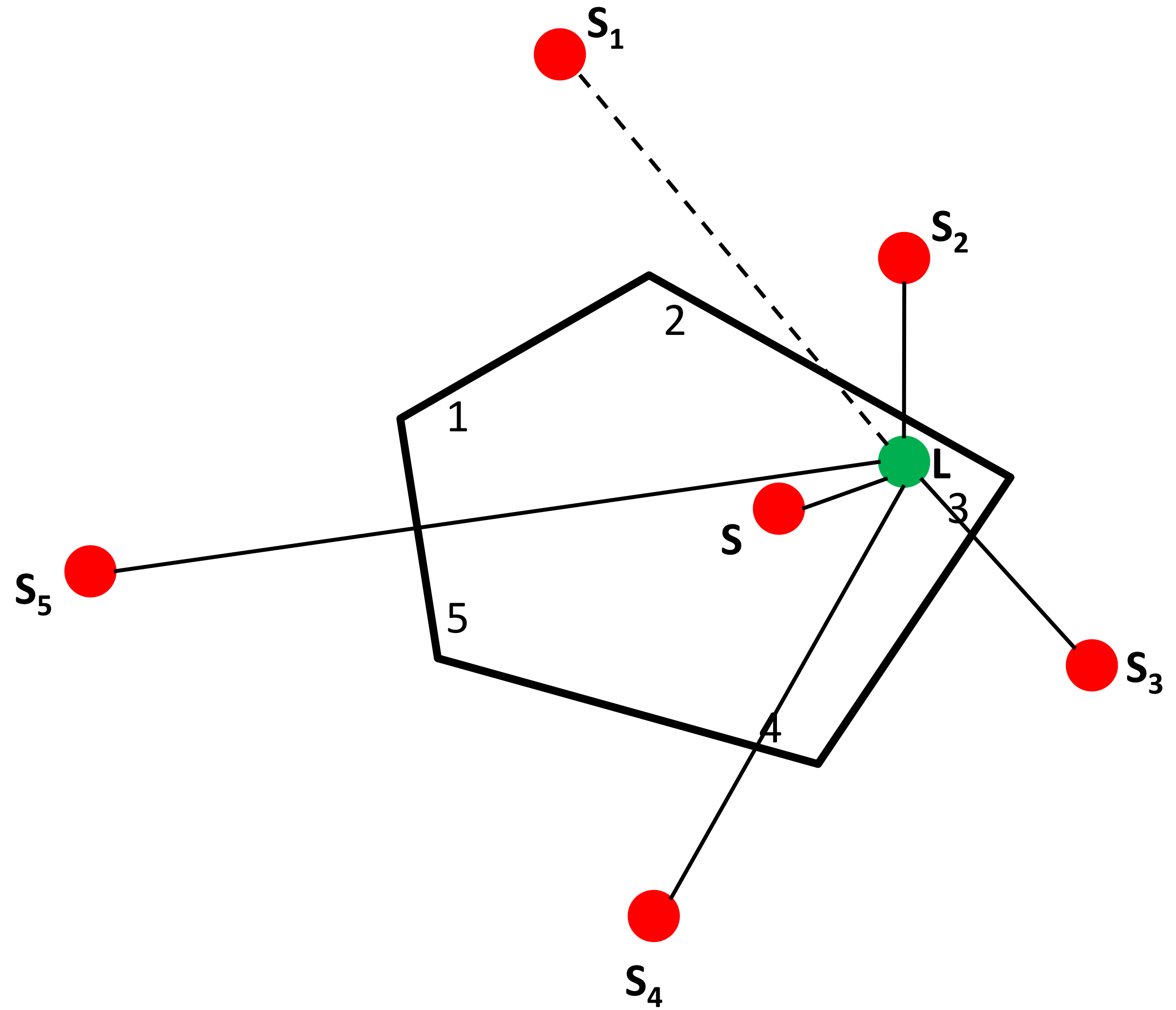
- Reflections modeled as direct propagation from “images” of source
- Given a scene and source, compute all image sources
- Perform direct propagation from image sources (accounting for material properties)

Image Source Method



(figures courtesy Anish Chandak)

Image Source Method

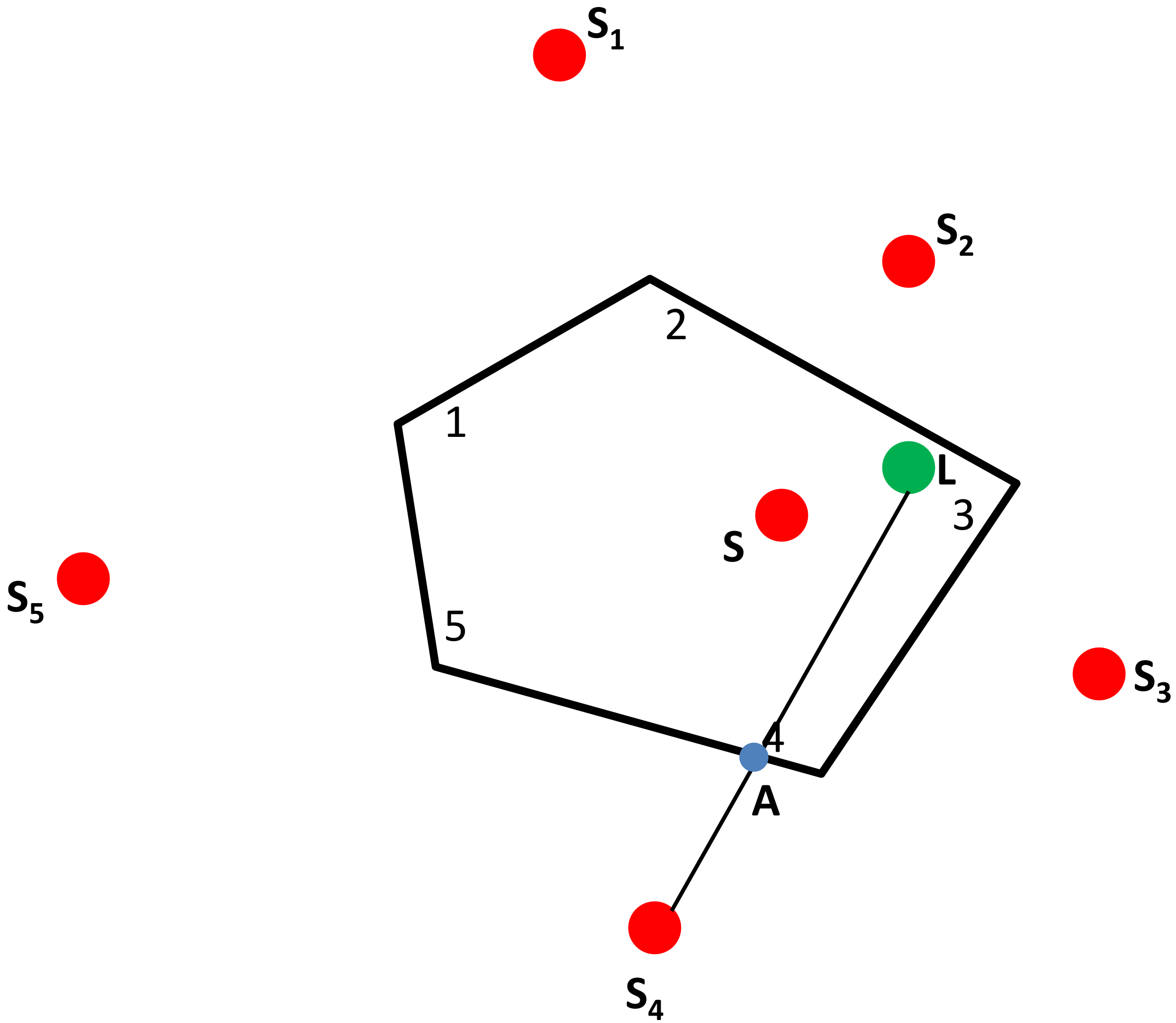


(figures courtesy Anish Chandak)

Image Source Method

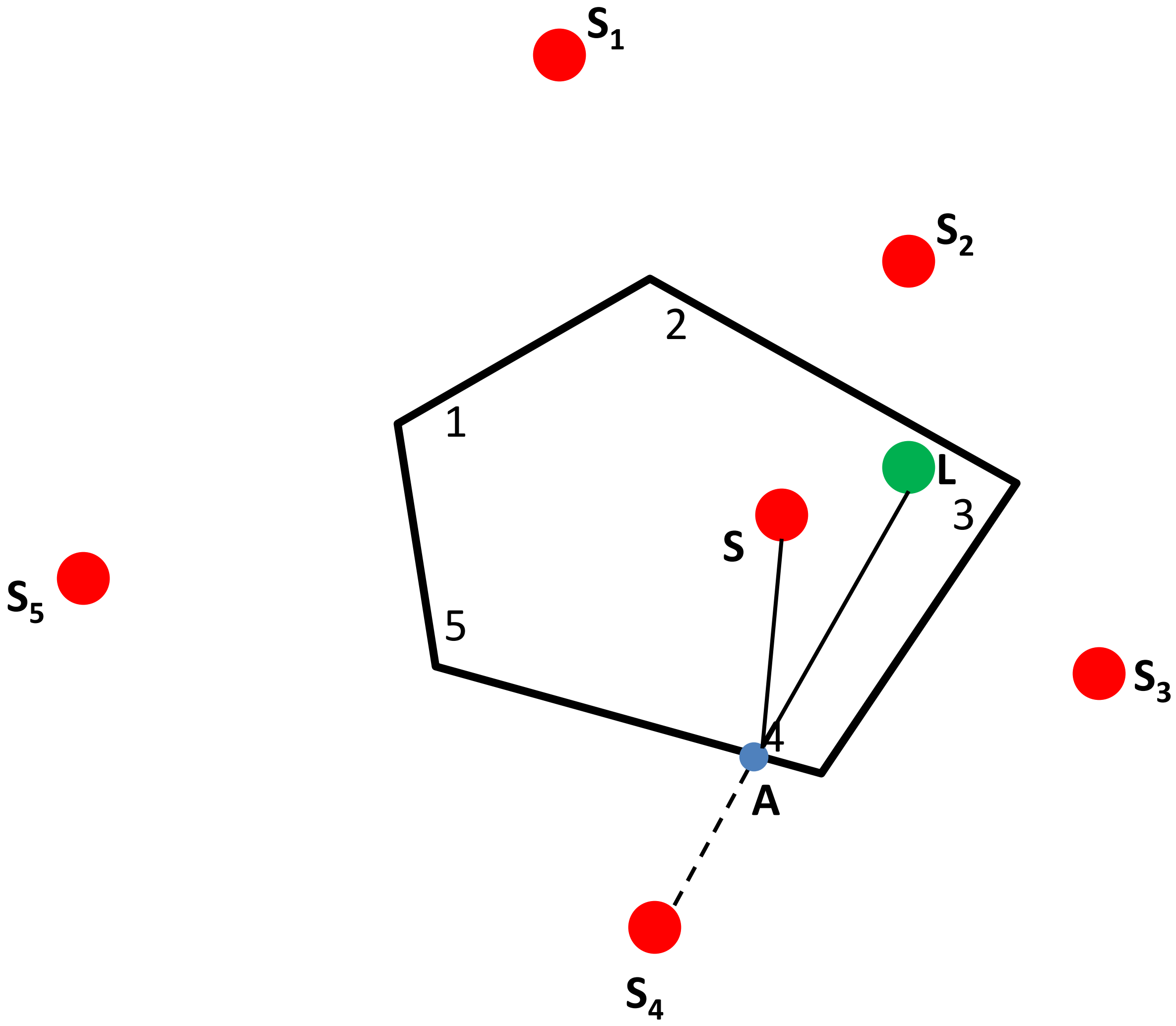
- Not all image sources correspond to reflections which reach the listener
- Need to determine “valid” image sources
- Path computation can be expressed as a visibility problem
- Visibility can be computed using:
  - Beam tracing
  - Frustum tracing

Image Source Method



(figures courtesy Anish Chandak)

Image Source Method



(figures courtesy Anish Chandak)

Diffraction

- Diffraction needs to be explicitly modeled in geometric acoustics methods
- Edge diffraction with frustum/beam tracing requires estimation of diffraction paths
- Edge diffraction with image sources corresponds to from-region visibility
- (details covered by Paul Calamia, skipping)

Discussion

- Handles:
  - Specular
  - Diffuse (sort of)
  - Diffraction (not accurate)
- Advantages:
  - Fast
  - Can handle high frequencies
- Disadvantages
  - Not very accurate
  - Issues with handling diffuse reflections, diffraction

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Sabine's Equation

- Models relation between room sizes and acoustic energy decay

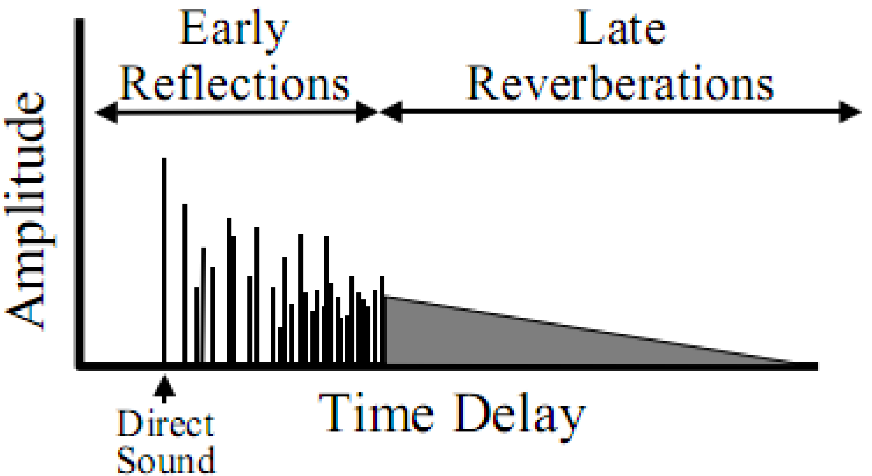
$$RT_{60} = \frac{cV}{Sa}$$

- Here:
  - V is the room volume
  - S is the room surface area
  - a is the average absorption coefficient
  - RT_{60} is the time taken for energy to decay by 60 dB

[Summers03]

Reverberation

- Given room properties, RT_{60} can be estimated
- This can be used to fit an energy decay curve
- This curve can be sampled to get IR



$$E(t) = E_0 e^{\frac{cS}{4V} t \log(1-a)}$$

Discussion

- Advantages:
  - Simplicity
  - “Sounds good”
- Disadvantages
  - Doesn’t take into account the actual scene
  - Computing surface area and volume is error-prone

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Frequency-based Hybridization

- Numerical methods are good at low frequencies, geometric methods at high frequencies
- Run:
  - Numerical simulation on a coarse grid
  - Geometric method for a few orders of reflection
- Combine the resulting IRs

[Savioja95]

Combining IRs

- We want low frequency contributions from numerical IR, high frequency contributions from geometric IR
- Use high-pass/low-pass filters with sum of squared magnitude (energy) = 1
- The numerical component gives us diffraction for free

[Savioja95]

Adding Diffuse Reflections

- Ray tracing can handle diffuse reflections
- Radiosity has also been used for acoustics
- Hybrid techniques have been attempted which combine radiosity with:
  - Ray tracing [Tenenbaum07]
  - Beam tracing [Lewers93]

Distance-based Hybridization

- It may not make sense to run a full-blown simulation for distant/unimportant parts of the scene
- It may be worth investigating simulation LOD methods for sound propagation

Discussion

- Handles:
  - Specular, diffuse, diffraction
- Advantages:
  - Combines advantages of both numerical and geometric methods: reasonably fast and accurate
- Disadvantages:
  - IRs need to be combined carefully

References

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