Microsoft Computer Games and Emerging Technologies Research Lab

Sound Propagation in 3D Spaces Using Computer Graphics Techniques

Panagiotis Charalampous and **Despina Michael**

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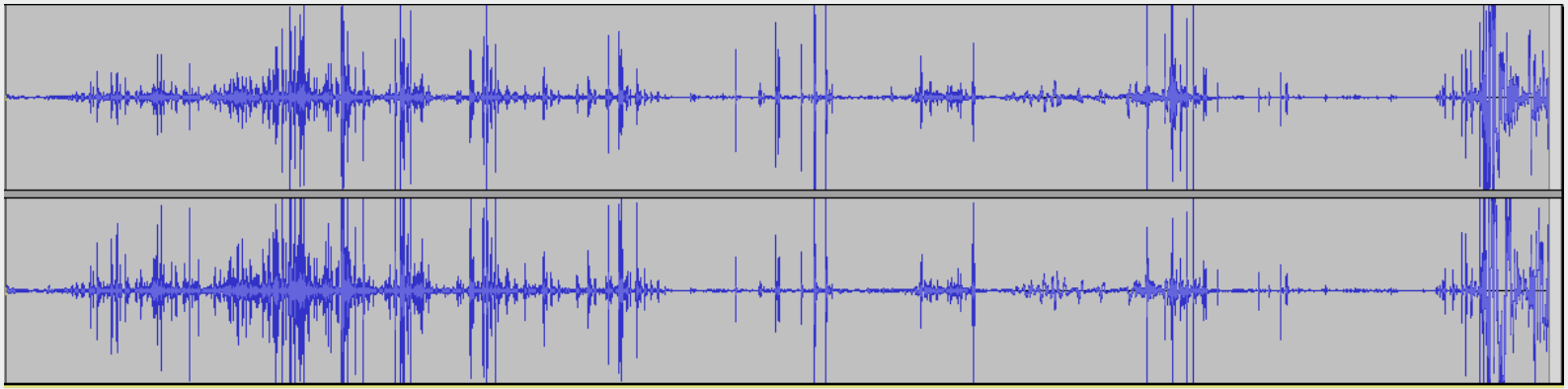
Department of Multimedia and Graphic Arts
Cyprus University of Technology

Sound Vs Light

Similarities	Differences
• Wave phenomena • Similar laws of propagation	• Light is an electromagnetic radiation while sound is the fluctuation of pressure • Light does not require a medium to travel. Sound does. • Sound wavelengths are orders of scale lower that those of light. Wave phenomena like diffraction and interference are more prominent in the case of sound.

Sound Rendering

The process of creating an audible file



$$H|_{left,right} = \sum_{i=1}^{n} P_s * \boldsymbol{IR_i} * HRTF(\theta, \varphi)|_{left,right}$$

Impulse Response Calculation

Geometrical Methods	Numerical Methods
Ray based representation of sound The IR of each ray is a function of distance traveled by the sound ray multiplied by various coefficients which represent acoustical phenomena like reflections, diffractions etc. $$IR = F_f^{-1}\left[\frac{e^{jkR}}{R}\prod_{j=0}^{o} C_o\right](t)$$	**Numerical solutions to the wave equation.** Using element methods, the solution to the wave equation is approximated *Time Domain*: $\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$ *Frequency Domain*: $\nabla^2 A = -k^2 A$

Classification of Techniques

- Geometrical Propagation Techniques
  - Image Sources
  - Beam Tracing
  - Frustum Tracing
  - Ray Tracing
  - Particle Tracing
- Numerical Techniques
  - BEM
  - FEM
  - FDTD
- Hybrid Techniques
- Acceleration Techniques
- Non-graphics Techniques

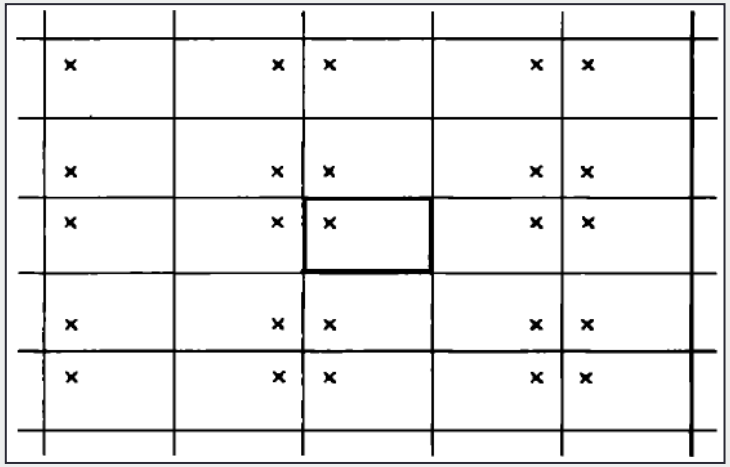
Geometrical Propagation Techniques

- Based on the representation of sound as a ray
- Sound rays are detected in various ways throughout the environment
- After tracing sound rays are calculated and summed to produce the impulse response

Deterministic Tracing	Stochastic Tracing
• Image Sources • Beam Tracing	• Ray Tracing* • Particle Tracing • Frustum Tracing

Image Sources (IS)

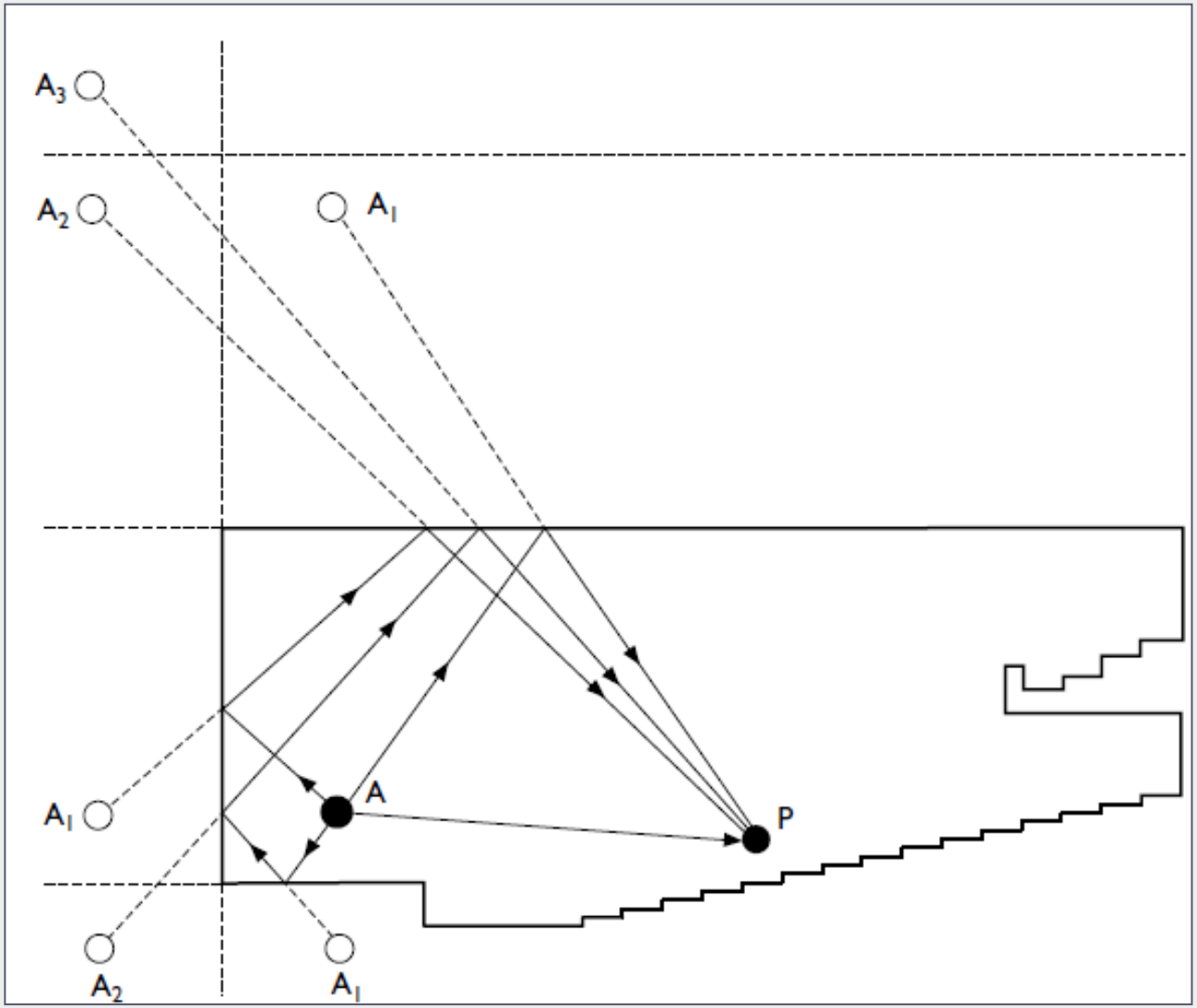
- Image source methods compute virtual sources
- They consider each polygonal surface in the environment as a reflector and mirroring in it, the location of the original source.



Representative Literature

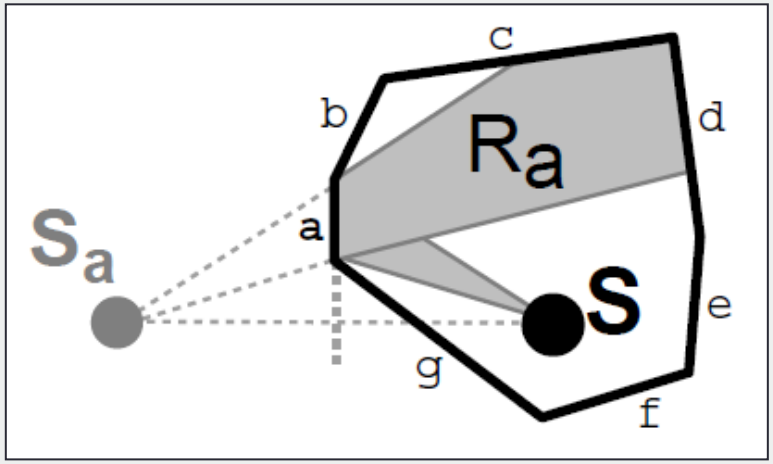
Paper	Method
Alen and Berkley (1979)	IS for rectangular rooms
Borish (1984)	Arbitrary polyhedra
Savioja (1999)	Hybrid method using decay functions
Mechel (2002)	Improved IS algorithm with visibility tests
Shroeder (2006)	IS with BSP acceleration

Image Sources (IS)



Beam Tracing

- Beam tracing is a method of tracing the polyhedral beams within a 3D environment and then casting them to rays for the computation of the impulse response.
- Beam tracing is a method that has been borrowed from graphics

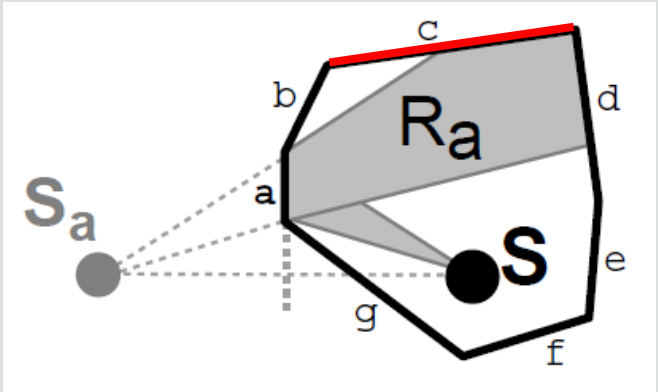
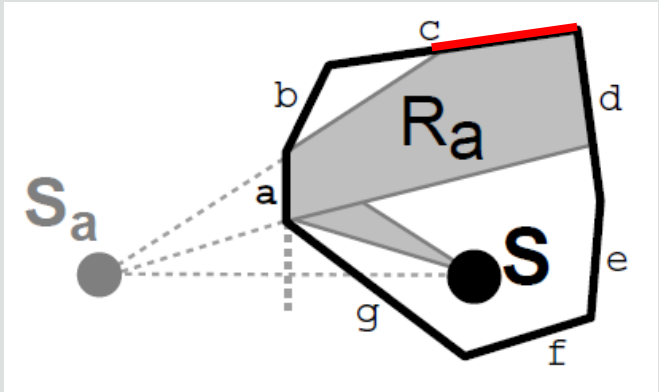


Representative Literature

Paper	Method
Farina (1995)	Pyramid tracing
Funkhouser et al. (1999)	Bidirectional beam tracing, amortized beam tracing
Min, Funkhouser (2000)	Priority based beam tracing
Antonacci et al (2004)	Beam tracing using precomputed visibility diagrams
Laine et al. (2009)	BSP beam tracing
Sikora et al. (2013)	Multi-threaded beam tracing

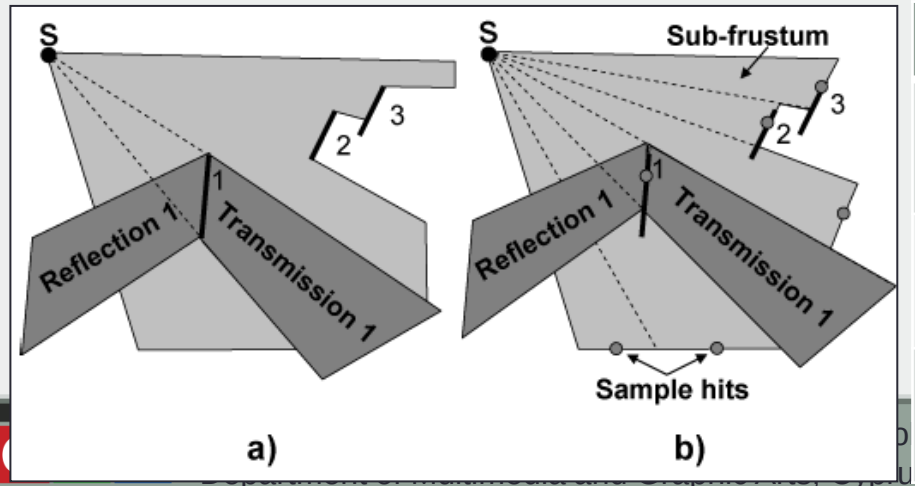
Beam Tracing Vs Image Sources

- Beam Tracing is an extension of the IS method.
- The difference between IS with visibility tests and beam tracing lies in the fact that beams are constructed only for the visible part of the surface, reducing the size of the search tree.

IS with visibility tests	Beam Tracing
	

Frustum Tracing

- Combines the efficiency of interactive ray tracing with the accuracy of tracing a volumetric representation (beam tracing).
- Similar to ray tracing but instead of tracing rays, simple convex polyhedral are traced, like in beam tracing.
- The difference with beam tracing is that instead of performing exact clipping with each primitive in the scene it subdivides the frustum uniformly into smaller sub-frusta to perform discrete clipping.
- It keeps track of intersections at the level of those sub-frusta avoiding maintaining a full list of clipped edges or faces of the beam (beam tracing).

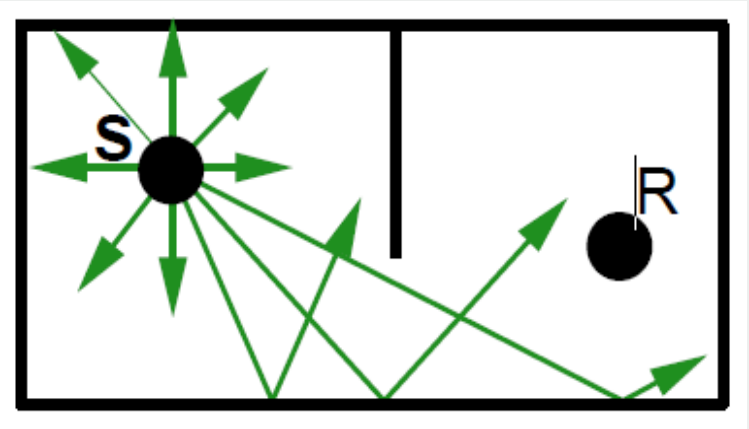


Representative Literature

Paper	Method
Lauterbach et al. (2007)	Frustum tracing
Chandak et al. (2008)	Adaptive frustum tracing
Taylor et al. (2009)	Frustum tracing with sound diffraction

Acoustical Ray Tracing

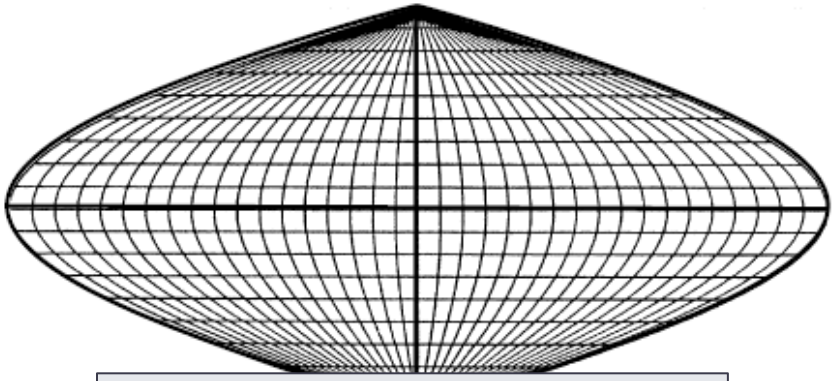
- Ray tracing is a technique where a sound path is traced throughout the 3D environment
- The various effects that occur in when a ray encounters an obstacle are calculated.



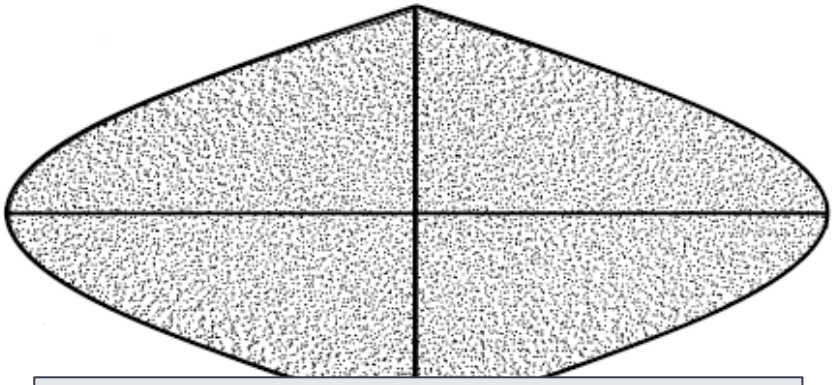
Representative Literature

Paper	Method
Krodstad (1968)	Ray tracing for acoustics
Kulowski (1985)	Ray tracing for arbitrary room shapes
Vorlander (1989)	Hybrid IS and ray tracing method
Taylor et al (2009)	Hybrid ray tracing and frustum tracing method
Taylor et al (2012)	Multiview ray tracing
Dreher (2012)	Ray tracing using acceleration structures

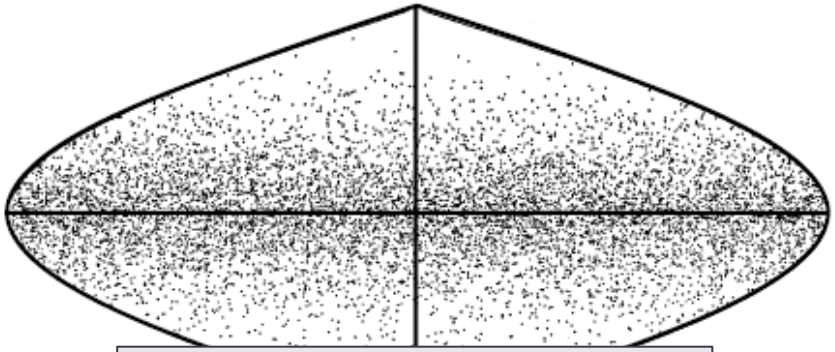
Ray Tracing Distribution Types



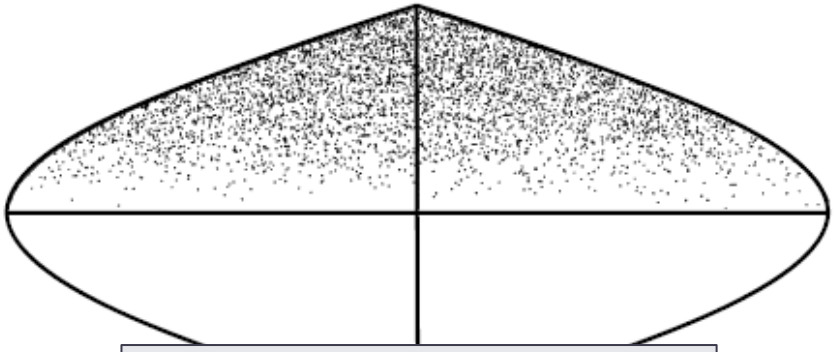
Variants of ray sources



Uniform random distribution



Concentration of rays at the equator

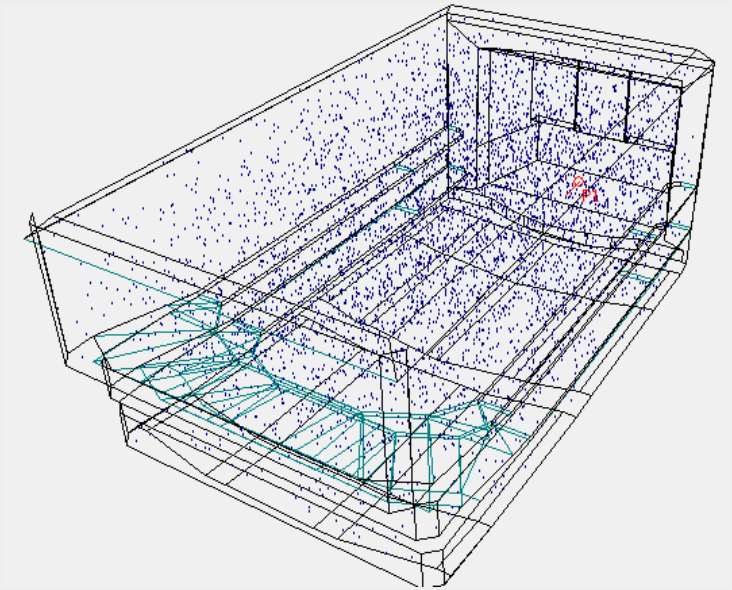


Concentration of rays at the north pole

spherical coordinate system between source and listener

Particle Tracing

- Particle tracing is a variation of the acoustical ray tracing technique. It is inspired by the photon tracing technique used in computer graphics.



Representative Literature

Paper	Method
Bertram et al (2005)	Phonon tracing
Kapralos (2006)	Sonel Mapping

Numerical Techniques

- Based on the subdivision of an environment to elements. Similar to radiosity techniques used in computer graphics.

Types	
Time Domain	Frequency Domain
FDTD	BEM FEM Radiant approaches

Representative Literature

Paper	Method
Kirkup and Wu (2000)	BEM in Acoustics
Thompson (2006)	FEM in Acoustics
Siltanen et al (2007)	The acoustics rendering equation
Raghuvanshi (2010)	ADR FTDT
Mehra et al. (2012)	GPU time domain solver
Mehra et al. (2013)	Equivalent Source Method

Hybrid Techniques

- Synthesize a variety of approaches for the generation of the impulse responses.

Representative Literature

Types	
Frequency Decomposition	Low frequencies with numerical methods High frequencies with geometrical acoustics
Spatial Decomposition	Near source area with numerical methods Far from the source with geometrical acoustics

Paper	Method
Murphy et al. (2008)	Digital Wavequide Mesh
Southenrn et al. (2011)	FTDT, beam tracing and acoustic radiance transfer
Aretz (2012)	FEM, image source and ray tracing
Barbone et al. (1998)	FEM, ray tracing
Hampel et al. (2008)	BEM, ray tracing
Yeh et al. (2013)	Two way pressure coupling technique

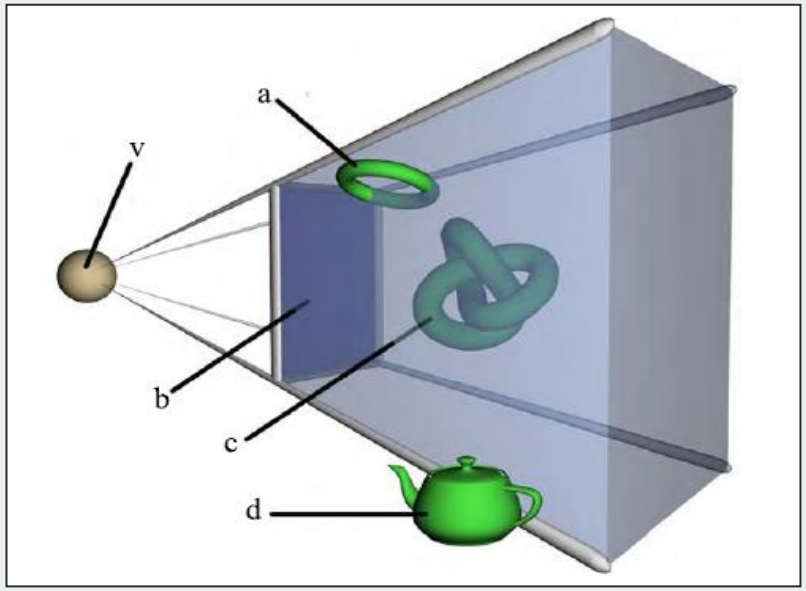
Acceleration Techniques

- Acceleration techniques is a number of complementary techniques developed for the acceleration of tracing techniques.

- The most prominent types of acceleration techniques are the following
  - Visibility computations
  - Precomputations
  - Hardware Acceleration

Visibility Computations

- Techniques used to reduce the geometrical primitives under consideration



Representative Literature

Paper	Method
Nirenstein (2003)	Algorithms for visibility culling
Cohen et al. (2003)	Review of visibility culling techniques
Chandak el al. (2011)	Geometric sound propagation using visibility computations

Precomputations

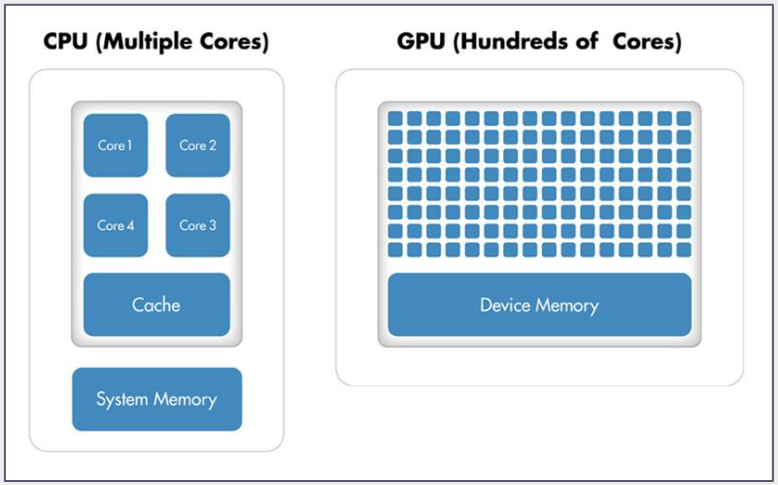
- Precomputation techniques are used to precompute information before the rendering begins.
- **Limitation:** Precomputations are limited to static parameters in the scenes. Changes will require a new computation of the precomputed data.

Representative Literature

Paper	Method
Tsingos (2009)	Precomputing reverberation effects
Foale et al. (2007)	Precomputing sound propagation calculations
Siltanen et al. (2010)	Geometrical complexity reduction
Raguvanshi et al. (2010)	Precomputing impulse responses
Antani et al. (2012)	Precomputing acoustic transfer operators

Hardware Acceleration

- GPU Implementation
- GPGPU



Representative Literature

Paper	Method
Jedrzejewski and Marasek (2006)	Room acoustics computation
Rober et al. (2007)	GPU for ray acoustics
Tsingos and Gascuel (1997)	GPU for sound visibility calculations
Cowan and Kapralos (2010)	GPU for fast acoustical occlusion modeling
Savioja (2010)	Accelerate FDTD algorithms

Non Graphics Techniques

- Due to the differences in sound and light, phenomena that are important for sound perception are not taken into account by graphics rendering techniques.

Representative Literature

Paper	Method
Lehmann and Johansson (2008) (2010)	Energy decay curve prediction
Chandak (2011)	Energy decay using Eyring's model

Conclusions

- Many similarities in graphics rendering and sound rendering.
- Common techniques can be used by both disciplines
- Research in each domain can enhance research in the other domain.

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