# Perceptual Spatial Audio Recording, Simulation, and Rendering

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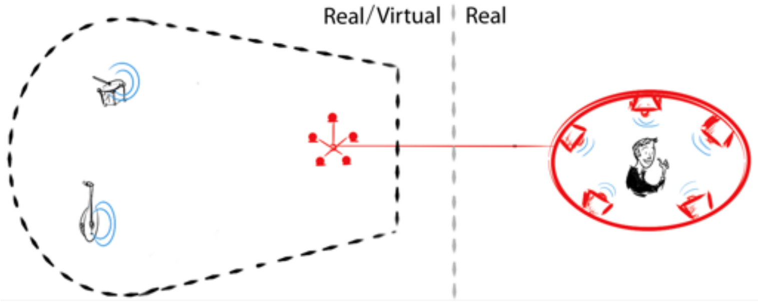
# Objective

- Making listener feel transported to a different auditory scene, which can be
  - a real recorded one (live music performance, sporting event..)
  - a virtual one (video games, VR/AR, architectural acoustics..)



# Outline

- Perceptual Soundfield Recording and Reproduction
  - Limitations of physical-based models
  - Localization uncertainty of phantom sources
  - Perceptual Soundfield Reconstruction
- Perceptual Simulation of Room Acoustics
  - Limitations of physical-based models
  - Scattering Delay Network
- Conclusions

# Acknowledgements

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# About this talk

- Interrupt me!
- Details and maths left to references (at the end)
- Demos after this talk

# Outline

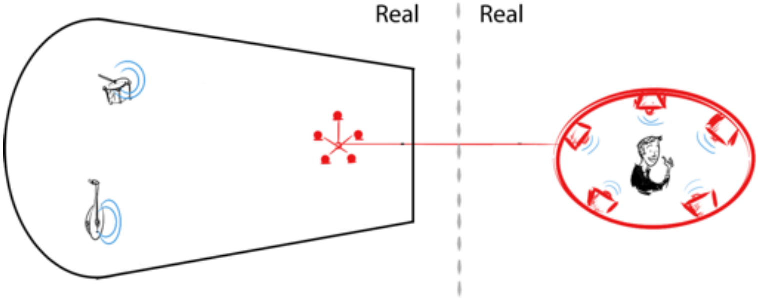
Perceptual Soundfield Recording and Reproduction
Limitations of physical-based models
Localization uncertainty of phantom sources
Perceptual Soundfield Reconstruction

Perceptual Simulation of Room Acoustics

Conclusions

# Perceptual Spatial Audio Recording

- Let's start from the case of a real sound scene to be recorded



# Physical and cross-talk cancellation methods

| | SFR | Multichannel | 2-Channel |
|---|---|---|---|
| **Channel count** | 50+ | $< 10$ | 2 |
| **Equipment Load** | High | Commercially viable | Low |
| **Psychoacoustics** | None | Required | Critical |
| **Sweet Spot** | Large | Medium, small group | Small, individual |

- Sound Field Reconstruction (SFR) provide mathematically elegant solution (e.g. HOA, WFS)...
  - but large number of loudspeakers: $r = \frac{c}{f} \frac{N}{2e\pi}$, e.g. $f = 10$ kHz, $r = 0.1$ m $\Rightarrow N = 56$
- 2-channel (cross-talk cancellation) methods, only two channels...
  - but small sweet spot (e.g. [Rose et al., 2002] report $\approx 3$ cm)
- We'll focus on multichannel systems with limited equipment load, which need to leverage somehow psychoacoustics effects

# Reproduction of plane waves

- Let's simplify: reproduction of a plane wave
- Assume for now that plane wave direction, $\theta_s$, is known
- Relevant case for spatial audio objects (MPEG-H)
- The plane wave could represent e.g. a single sound source or a wall reflection
- If we solve this, summation of plane waves trivial (linearity)

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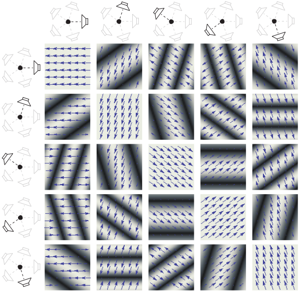
## Reproduced plane wave should be:

1. perceived in correct direction (low localization error)
2. easy to localize (low localization uncertainty)

- in the largest possible area (large sweet spot)

# How many loudspeakers to use to reproduce plane wave?

- **Question**: should we use $> 2$ loudspeakers for each source?
- Active intensity (AI) fields for plane waves



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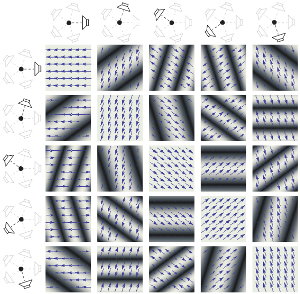
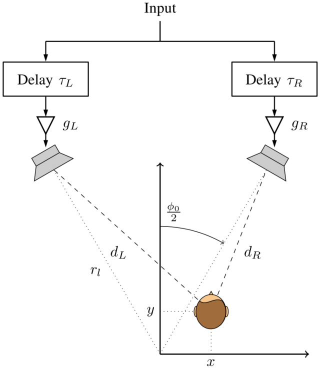


- Fluctuation speed depends on angle between loudspeaker pair
- **Answer**: use only the two loudspeakers closest to direction of plane wave [De Sena et al., 2013]
- This reduces problem to good ol' stereophonic reproduction

# Frequency-independent inter-channel differences

- What should we do with these two loudspeakers?

- Consider frequency independent inter-channel time differences (ICTD) and level differences (ICLD)
- ICTD/ICLDs lead to low coloration [Spors et al., 2013], which is most important attribute for sound quality [Rumsey et al., 2005]



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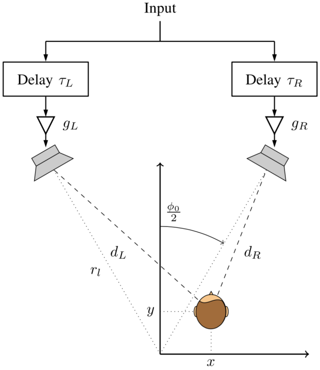
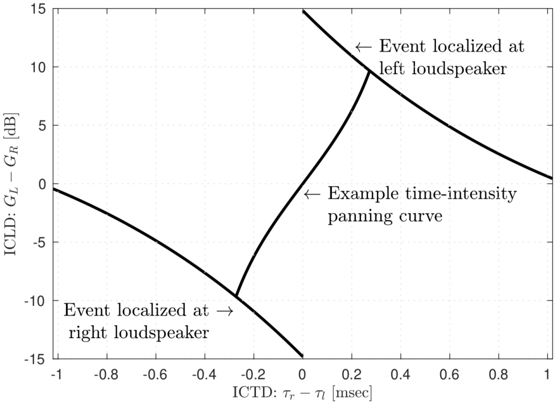



- As long as ICTD below echo threshold, listeners will perceive a fused “phantom source” (summing localization effect)

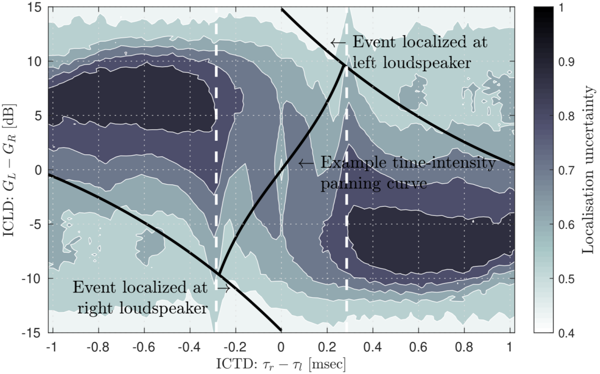
# Position of phantom source

- Position of phantom source depends on ICTD/ICLD pair
- Same position can be achieved with different ICTD/ICLD pair
- One can use e.g. intensity only (most commercial sound recordings), time only, or time-intensity



# Not all ICTD/ICLD pairs are created equal

- ICTD/ICLD pairs lead to different localization uncertainty
- Computational model in [De Sena et al., 2019]:



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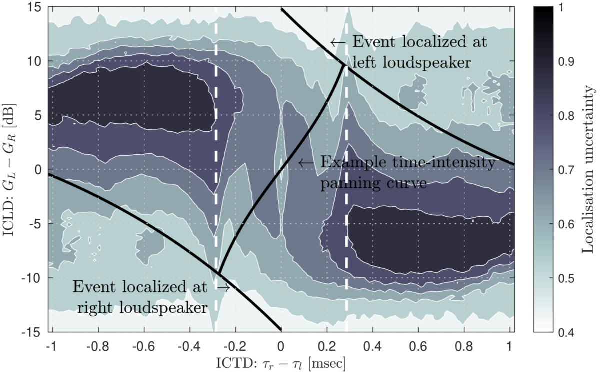
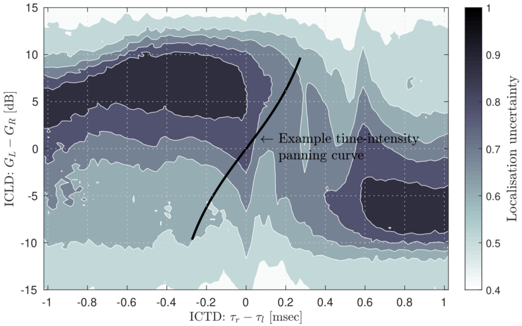



- Inconsistent ICTD/ICLD lead to high uncertainty
- The vertical bands correspond to cases where 2 replicates at one ear, but only 1 at the other

# Localization uncertainty in off-center positions




- Listener moves 10 cm to the right, then entire plot moves (approximately) to the right
- Now intensity methods lie in area with high uncertainty!
- Time-intensity largely avoids this area

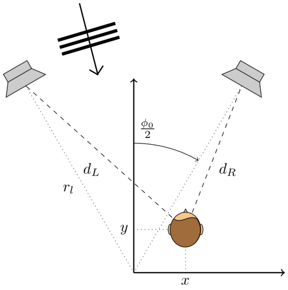
# What is happening?

- Useful to define "relative" ICTD/ICLD as observed by the listener:

$$\mathrm{RICLD} \approx \mathrm{ICLD} - \frac{x}{r_l}\frac{20\sin\left(\frac{\phi_0}{2}\right)}{\log_e(10)} ,$$

$$\mathrm{RICTD} \approx \mathrm{ICTD} - x\frac{2}{c}\sin\left(\frac{\phi_0}{2}\right) .$$

where $\phi_0$ base angle, $x$ lateral displacement and $c$ speed of sound



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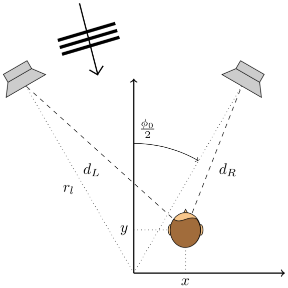


- E.g. consider ICTD = 0 ms and ICLD = 5 dB (left leading)
- RICTD = −0.29 and RICLD = 4.78, which are contradicting
- Adding a small ICTD will delay the onset of contradicting RICTD/RICLD pairs

# Parametrization of ICTD (time-delay microphone array)

- Convenient now to specify ICTD and ICLD functions of $\theta_s$, including a parameter taking into account how much we rely on ICLD compared to ICLD (time-intensity trade-off)

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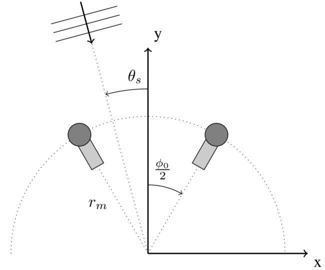
- Let the ICTD be defined according to the delay that would be observed on two spatially separated microphones as in figure:

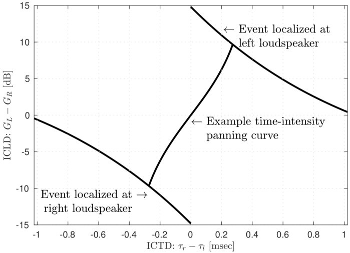
$$\text{ICTD}(\theta_s, r_m) = 2\frac{r_m}{c}\sin\left(\frac{\phi_0}{2}\right)\sin\theta_s$$




where $r_m$ is the array radius

- This parametrization is convenient since it allows to easily extend to the case of recording with circular arrays

# Parametrization of ICLDs

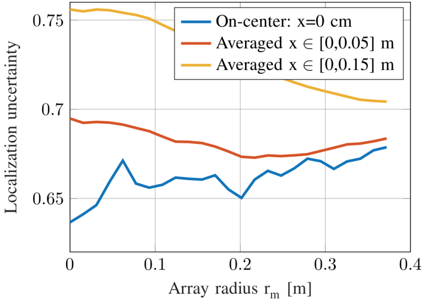



- Psychoacoustic curves give only extreme positions
- Could use different curves, for instance [De Sena et al., 2013]:

$$\mathrm{ICLD}(\theta_s, r_m) = 20 \log_{10} \frac{\sin\left(\frac{\phi_0}{2} + \beta(r_m) + \theta_s\right)}{\sin\left(\frac{\phi_0}{2} + \beta(r_m) - \theta_s\right)}$$

  where $\beta(r_m)$ is a parameter used to fit the extrema
- With this parametrization, a higher $r_m$ leads to more reliance on ICTDs and lower ICLDs

# Localization uncertainty as a function of array radius




- Larger radii lead to:
  - higher uncertainty for observer in the center
  - lower uncertainty for observer away from the center
- Help reconcile long-stanging debate between academia (preferring intensity methods) and sound engineering community (also using time-intensity methods)

# Choosing array radius parameter

- Trade-off between center and off-center
- If we don't know how far the listener will move, then avoid vertical bands mentioned before, which leads to

$$r_m = r_h \frac{\cos\left(\theta_e - \frac{\phi_0}{2}\right) + \frac{\phi_0}{2} + \theta_e - \frac{\pi}{2}}{2\sin^2\left(\frac{\phi_0}{2}\right)}$$

  where $\theta_e$ is angle of ear and $r_h$ is head radius
- Interestingly, larger head, means larger array!
- Examples:
  - $\phi_0 = 60^\circ$, $r_h = 9$ cm and $theta_e = 100^\circ$, then $r_m = 0.19$ cm
  - $\phi_0 = \frac{360^\circ}{5} = 72^\circ$, $r_h = 9$ cm and $theta_e = 100^\circ$, then $r_m = 0.16$ cm.

# More complex situations

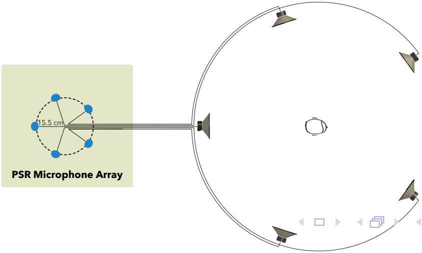
- So far we assumed we know the direction of the plane wave
- Possible approach is to estimate direction of arrival (DOA) and then artificially add ICTD/ICLD
- If multiple incoming waves, can estimated DOAs in time windows (see e.g. Dirac/SDM/SIRR)

# Perceptual Soundfield Reconstruction

- Another approach is to connect each microphone with loudspeaker
- Design the microphone directivity pattern to approximate ICLD($\theta_s, r_m$) [De Sena et al., 2013]
- This makes DOA estimation unnecessary!

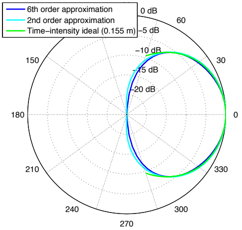
## Perceptual Soundfield Reconstruction (PSR) Array

- 5 channels, uniformly distributed, 15.5 cm radius (optimal according to



# Microphone directivity that approximates ICLD($\theta_s$, $r_m$)

- First-order microphones (e.g. cardioid, hypercardioid) not sufficiently directive for this purpose
- Second-order already sufficient (e.g. differential microphone array [De Sena et al., 2011])




## Results of PSR formal listening experiments:

- Comparable performance in the center of the array...
- but larger sweet-spot

# PSR Extensions

- PSR recently extended to third dimension using extrapolation from Eigenmike [Erdem et al., 2019]
- Time-intensity in the vertical dimension leads to a perceived improvement in stability of sweet spot [Andrew-Jones, 2019]

# Outline

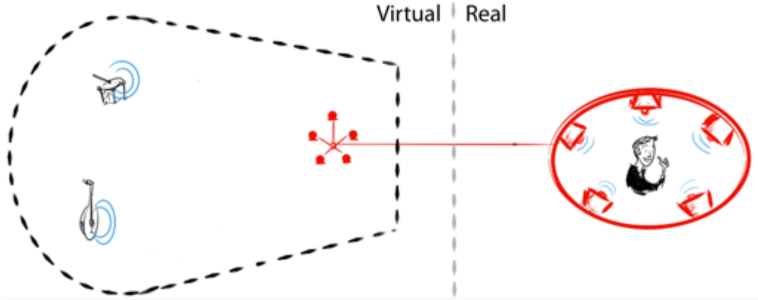

Perceptual Soundfield Recording and Reproduction

Perceptual Simulation of Room Acoustics
- Limitations of physical-based models
- Scattering Delay Network

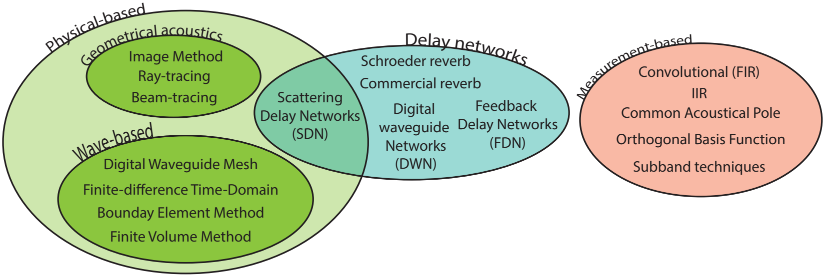
Conclusions

# Perceptual Simulation of Room Acoustics

1. Simulate virtual room acoustics
2. *Virtual* recording and *real* reproduction (simulate microphone array as described in first part of talk)



# Overview




- Overview of more than 50 years of room acoustic simulation in [Välimäki *et al.*, 2012], [Välimäki *et al.*, 2016] and [Hacıhabiboğlu *et al.*, 2017]
- Wave-based models are the most accurate ones

# Rendering of dynamic scenes with wave models

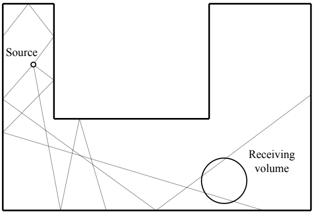
- In a complete wave model of a room:
  - sources and listeners can be moved
  - *spatialized* using microphone arrays or "virtual dummy head"

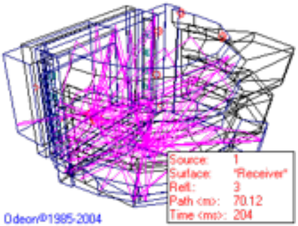
## Example: How expensive is a wave-based model?

- Audio bandwidth = 20 kHz ≈ 1.27 cm wavelength
- Spatial samples every 0.63 cm or less
- 3.65 × 5.8 × 2.4 m room requires > 200 million grid points
- 3D finite difference model requires one multiply and 6 additions per grid point ⇒ 70 billion FLOPS at $F_s = 50$ kHz
- 30 × 15 × 6 m concert hall requires > *3 quadrillion FLOPS*

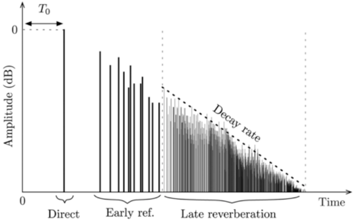
# Geometric Models

- Geometric acoustics models have lower complexity
- Source emits rays in all directions
- Specular reflections (diffraction also possible)
- Build impulse response by recording time and amplitude at receiver
- Choice of receiver size and number of rays is critical



# Room Impulse Response (RIR)




## RIR components:

- Direct line-of-sight
- Early reflections: relatively sparse first echoes
- Late reverberation: so densely populated with echoes that it is best to characterise the response *statistically*.

# Rendering of dynamic scenes with geometric models

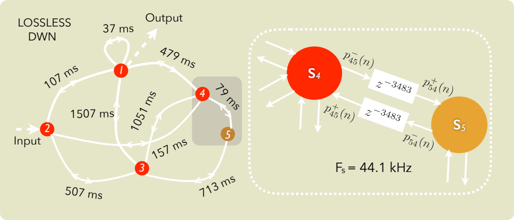
- When source moves recalculate RIR
- Still need to run a convolution with anechoic sound sample

Example:

- $T_{60} = 2$ s, $F_s = 50$ kHz: convolution requires 5 *billion* FLOPS
- Three sources and two listening points (ears) $\Rightarrow$ 60 billion FLOPS
- 20 dedicated CPUs clocked at 3 Gigahertz
- FFT convolution is faster, if throughput delay is tolerable (and there are low-latency algorithms)

- If physical accuracy not needed, perceptual methods provide better option

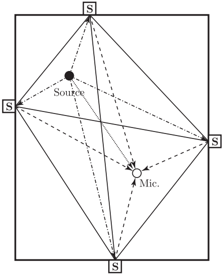
# Digital waveguide networks (DWN)




- Network of bi-directional delay lines connected at scattering junctions [Smith, 1985]
- Can be interpreted as network of acoustic tubes
- **Question:** How to set parameters (delay line lengths, network connections, scattering matrix..)?

# Scattering delay network (SDN) [De Sena et al., 2015]

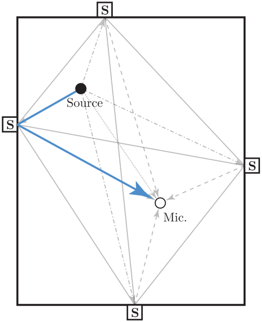
- Design DWN based on characteristics of a physical room



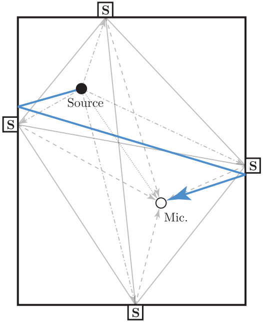

- Position nodes at first-order reflection points
- Fully connected DWN network
- Mono-directional lines for source-junction and junction-mic

# SDN: approximation of geometric acoustics

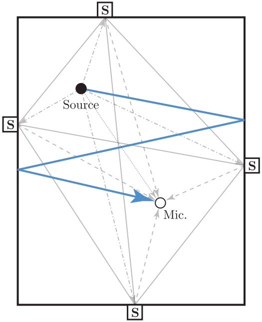
- Correct rendering of LOS and first-order reflections in time, amplitude and direction
- Approximation of second and higher-order reflections, less important perceptually




I-order reflection



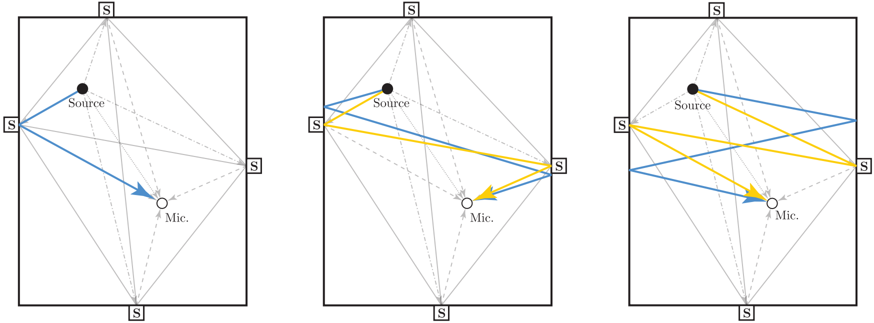

II-order reflection




Another II-order reflection

# SDN: approximation of geometric acoustics

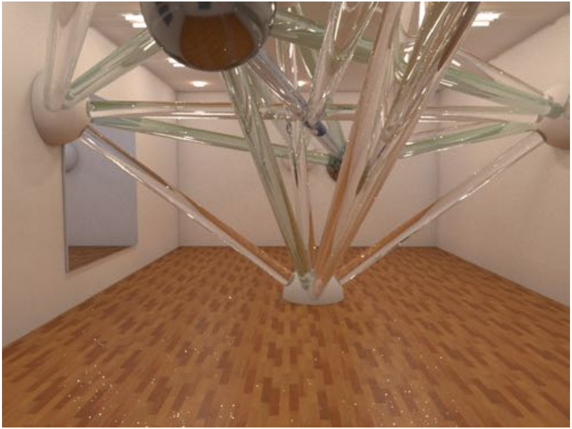
- Correct rendering of LOS and first-order reflections in time, amplitude and direction
- Approximation of second and higher-order reflections, less important perceptually




I-order reflection II-order reflection Another II-order reflection

# SDN: alternative interpretation

- Can also be interpreted as model of network of acoustic tubes



# Advantages

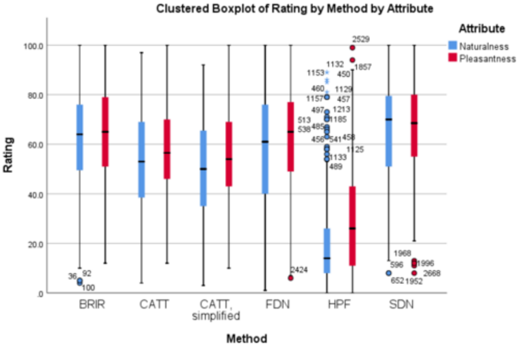
- Less resources spent for less important part of room impulse response (late reverberant tail)
- Also, not shown here:
  - similar frequency-dependent RT60 to full-scale models
  - similar echo density to full-scale models
  - sufficient modal density
  - axial resonant modes of room well approximated
- Orders of magnitude faster than convolution (alone!)
- All parameters of model derived from physical properties

## Advantages w.r.t. other delay networks:

- No need for hands-on parameters tuning
- Physical interpretation $\Rightarrow$ spatialisation possible, e.g. using microphone array as defined in the first part of the talk

# Perceptual evaluation [Djordjevic, 2019]

- Headphone-based (binaural) comparison (28 subjects)
- Higher pleasantness ($p < 0.001$) and naturalness ($p < 0.001$) than comparable delay-network based method



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# Conclusions

- Physical methods for spatial audio require significant resources
  - Recording and reproduction: many loudspeakers
  - Room Acoustics Simulation: high computational complexity
- Known perceptual effects allow to reduce requirements
  - Recording and reproduction: exploit summing localization effect and small ICTDs to achieve larger sweet spot
  - Room Acoustics Simulation: spend more resources for important perceptual features

Thanks for your attention!
(demos to come)

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(demos to come)

Questions?

# Further Reading

**Spatial Sound Overview**

H. Hacihabiboglu, E. De Sena, Z. Cvetkovic, J. Johnston, J. O. Smith III, "Perceptual Spatial Audio Recording, Simulation, and Rendering: An overview of spatial-audio techniques based on psychoacoustics," IEEE Signal Processing Magazine, 34(3), 36-54, 2017. F. Rumsey, *Spatial audio,* Focal Press, 2012.

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# Further Reading

**Perceptual Sound Field Reconstruction**


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