Sound propagation and acoustic material estimation

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Contents

- Sound propagation
  - Reflection-path-based modeling
  - Sound intensity modeling

- Acoustic material
  - Automatic assignment
  - Optimization-based estimation

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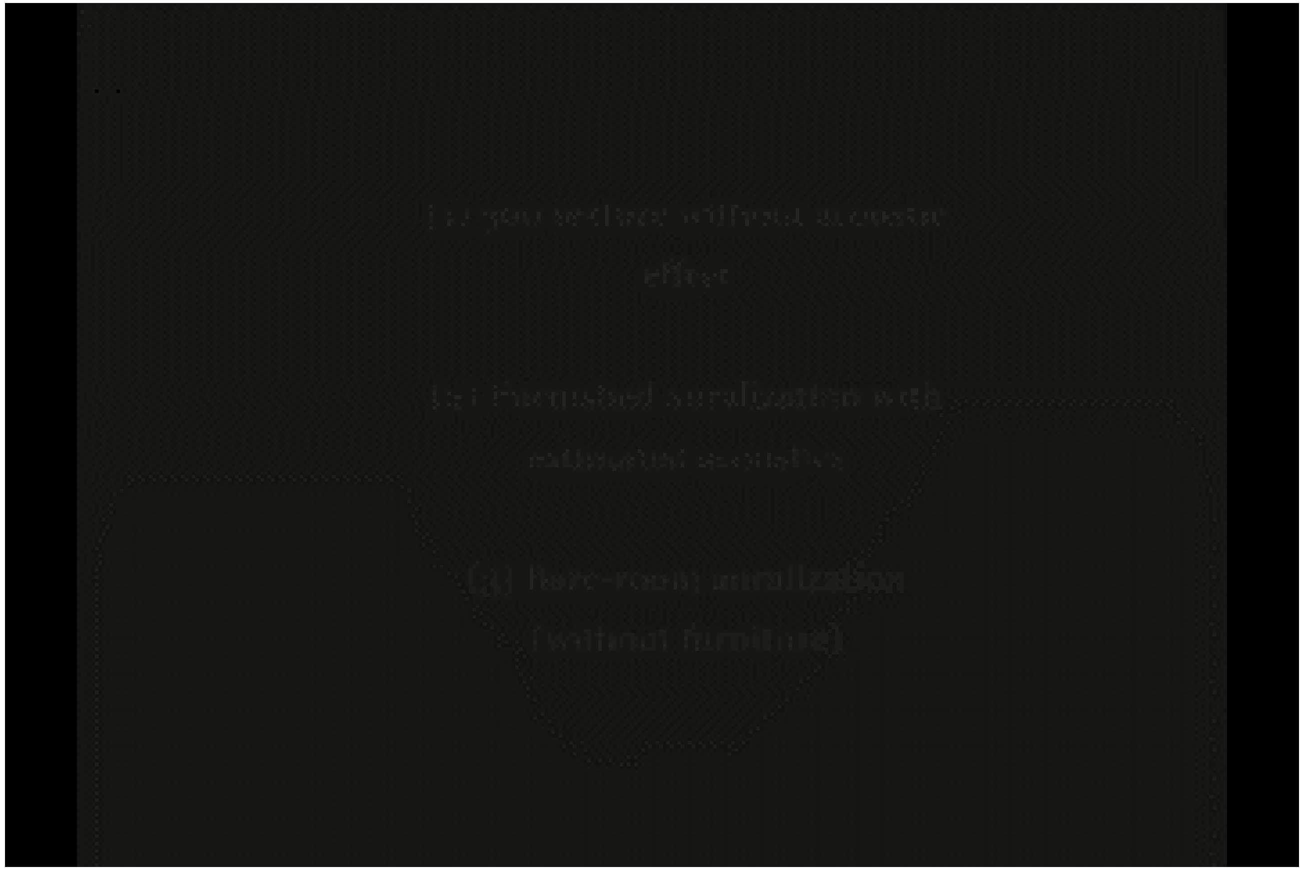
Sound simulation

- Generate a sound in VR/AR environment to maximize the immersiveness.



Video from “Immersive Spatial Audio Reproduction for VR/AR Using Room Acoustic Modelling from 360 Images”, VR 19

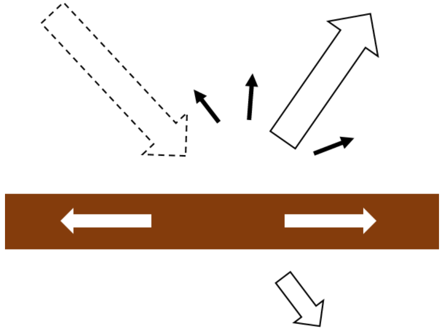
Sound simulation

- General sound simulation pipeline used in various applications. [1]

Modeling

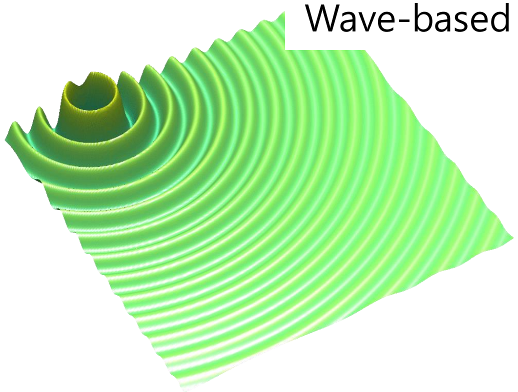
Acoustic Geometry

Acoustic Material

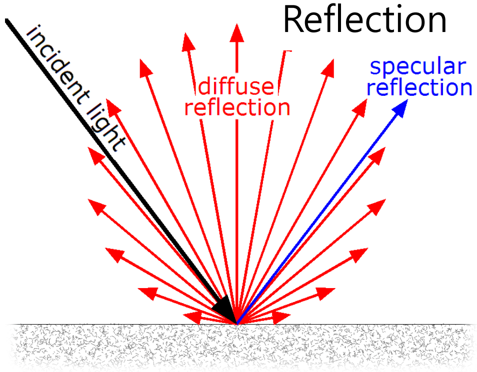


Propagation

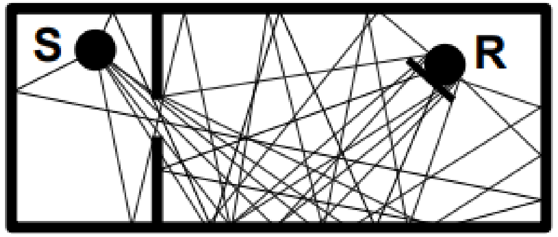
Wave-based



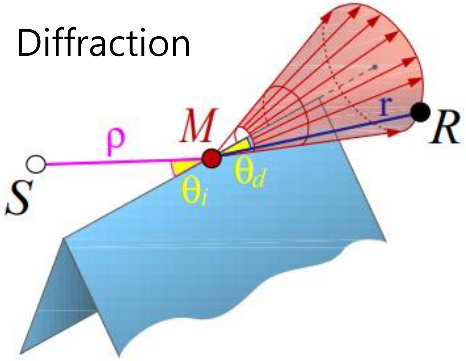
Reflection



Geometric-based



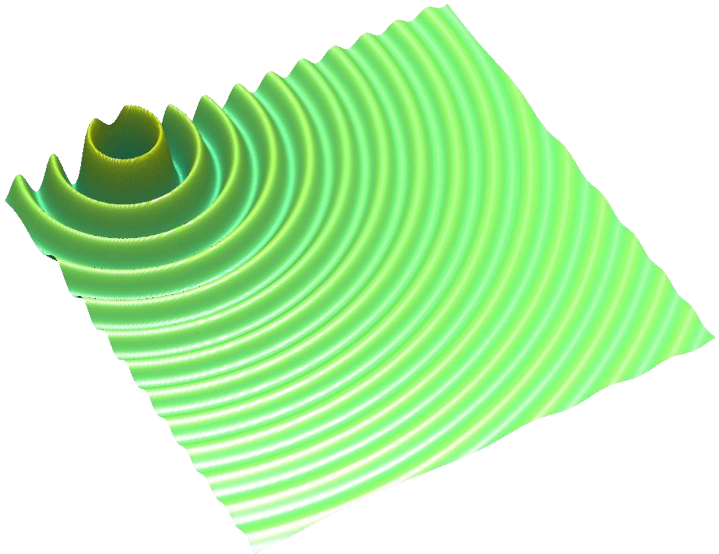
Diffraction



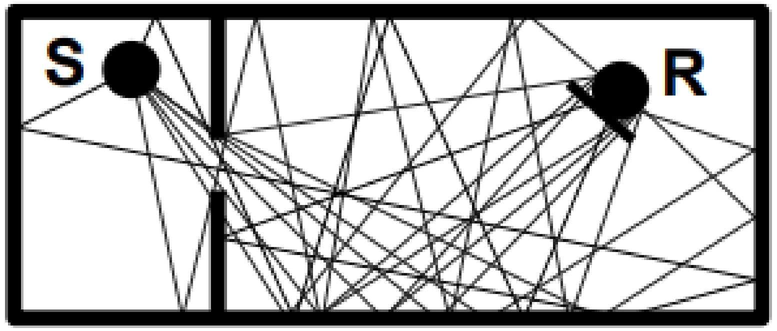
Sound propagation

- Two types of sound propagation approach. [2]

Wave-based



Geometric-based



Wave-based propagation

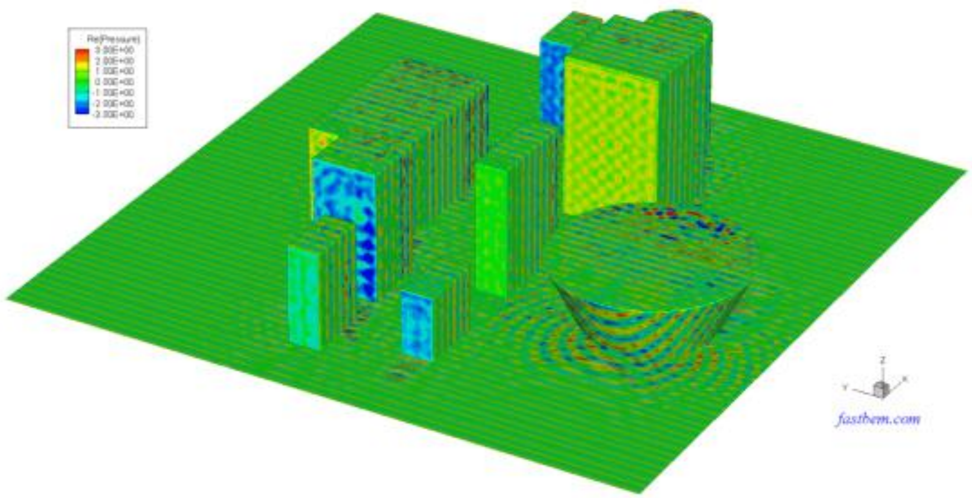
- Find a solution to an integral equation expressing the wave-field.

Volume-based

- Finite element
- Time-domain finite difference

Surface-based

- Boundary element
- Equivalent source

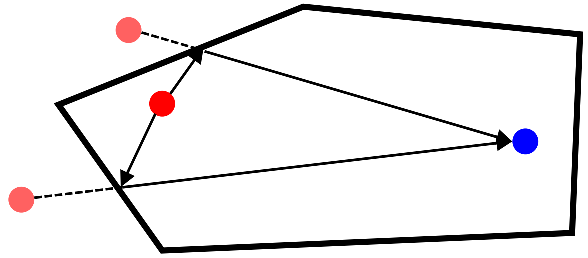


- The complexity of algorithms increase for the maximum frequency.
- Hard to handle at real-time.

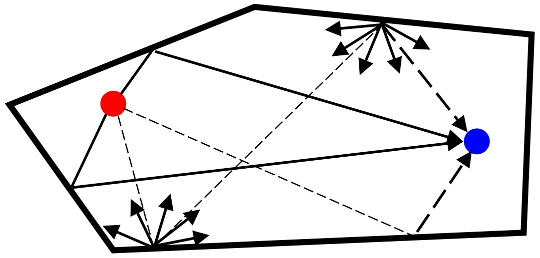
Geometric-based propagation

- Assume that sound waves travel like ray
- Calculate the sound path with reflection and diffraction
- All of the wave properties of sounds are neglected

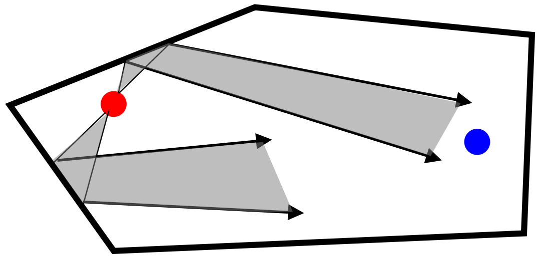
Image-source method



Ray tracing method



Beam tracing method



Room impulse response

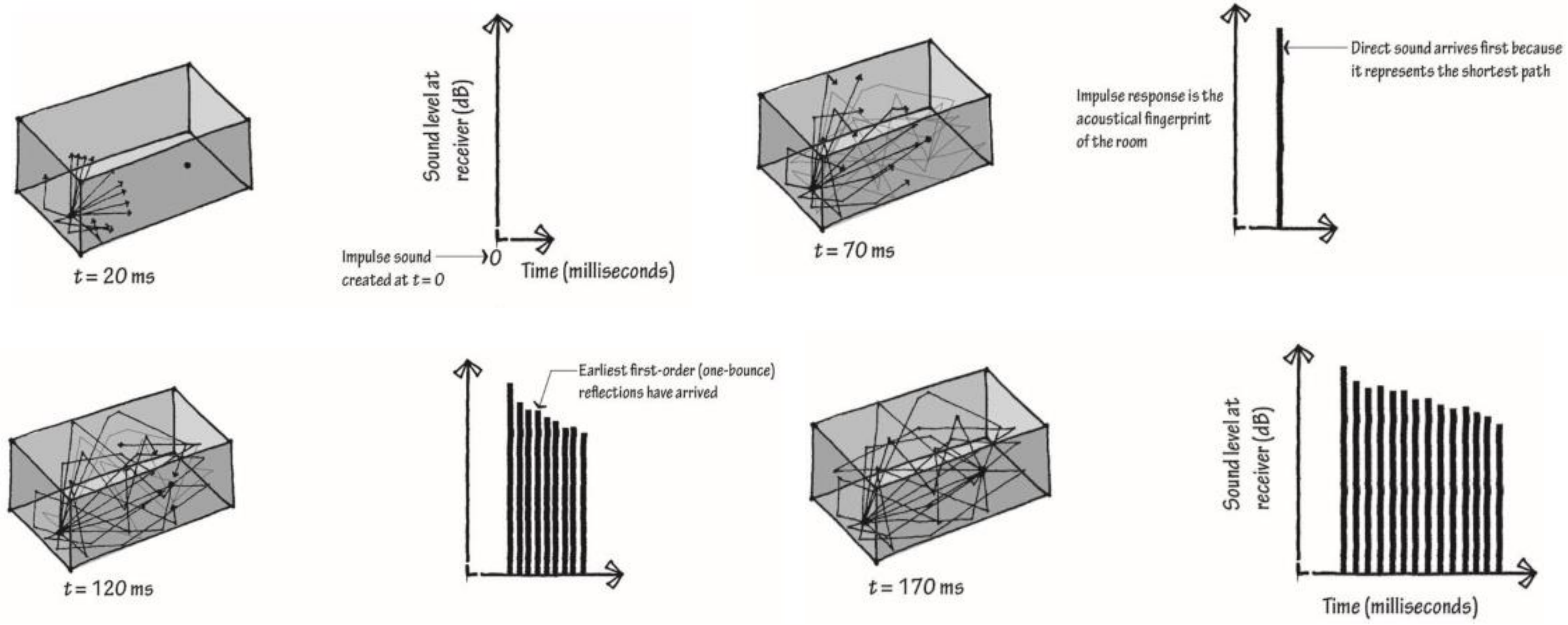
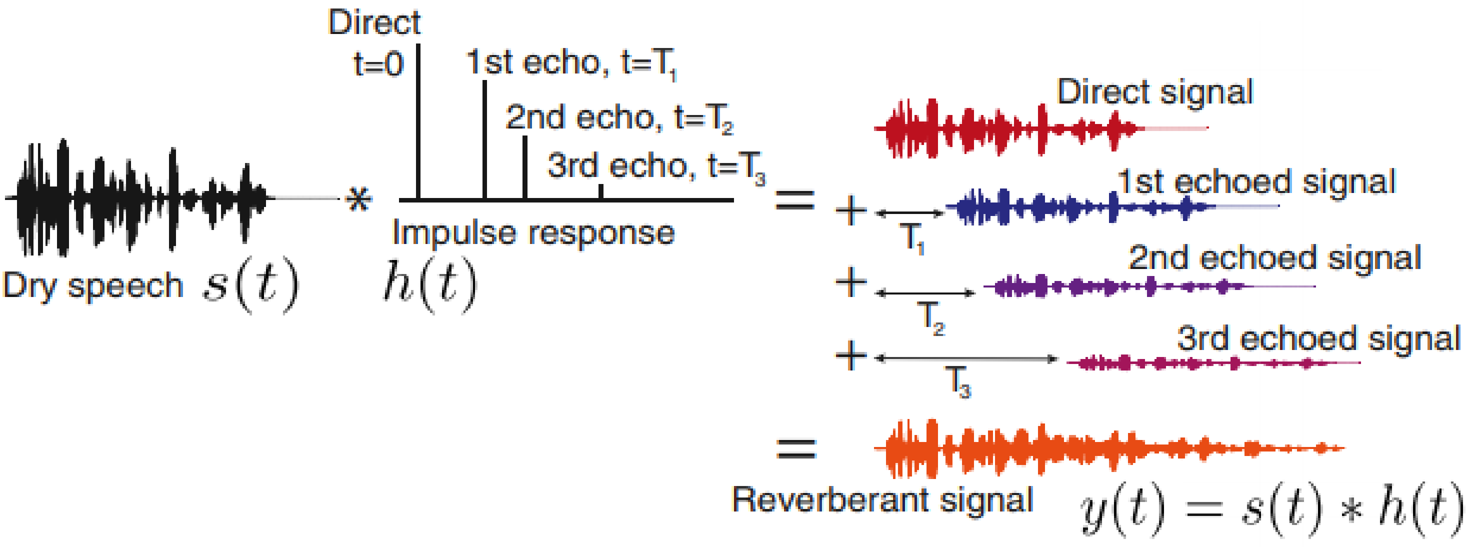


Image from "Architectural acoustics illustrated", Michael Ermann

Room impulse response

- Room impulse response
  - The transfer function between the sound source and listener in the room



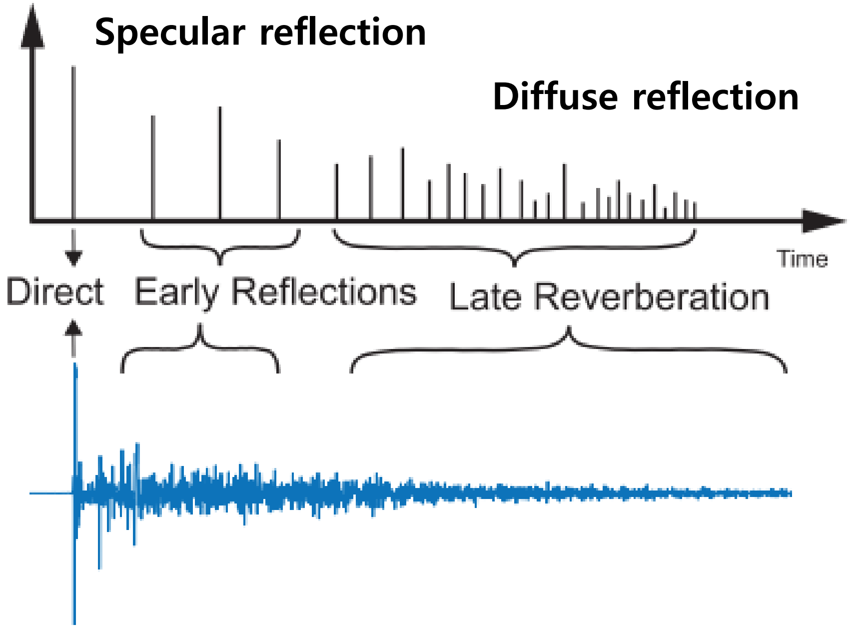
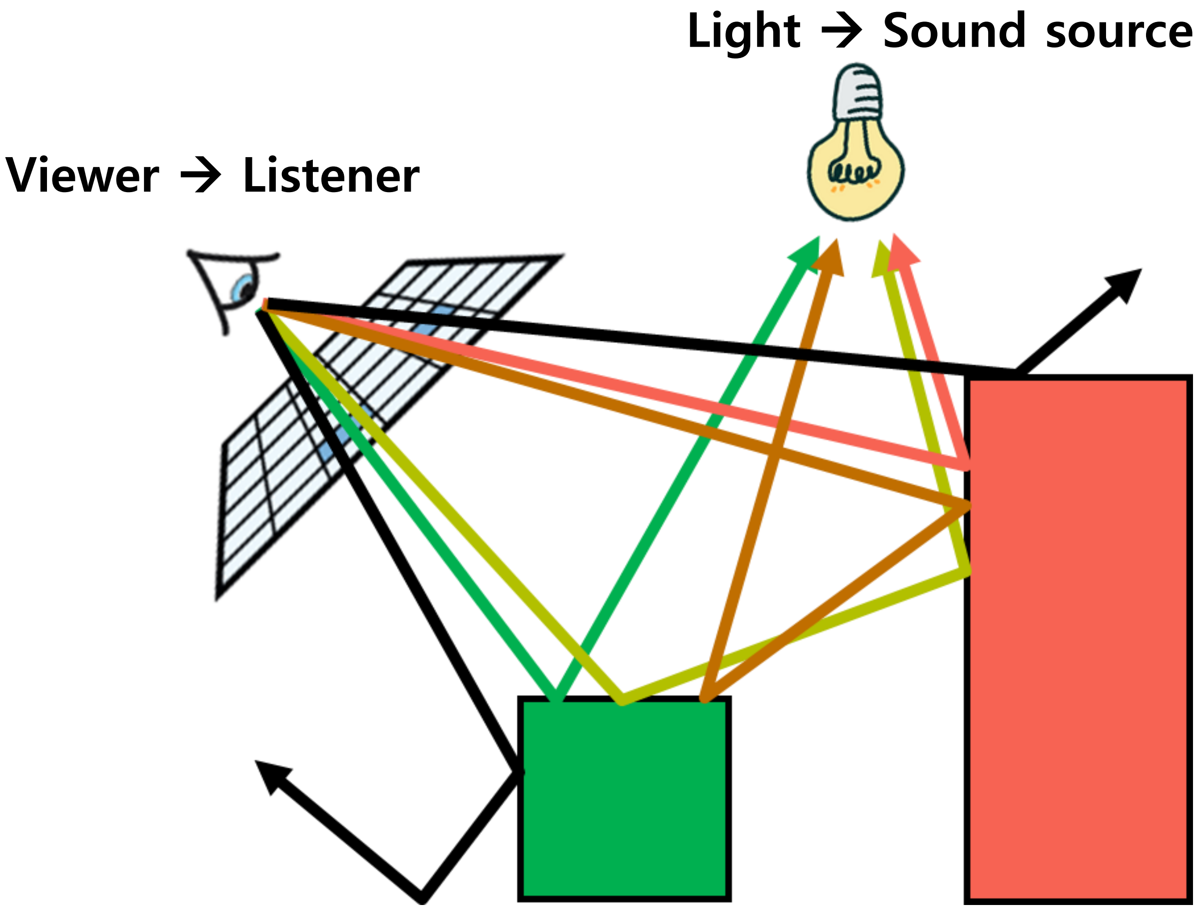


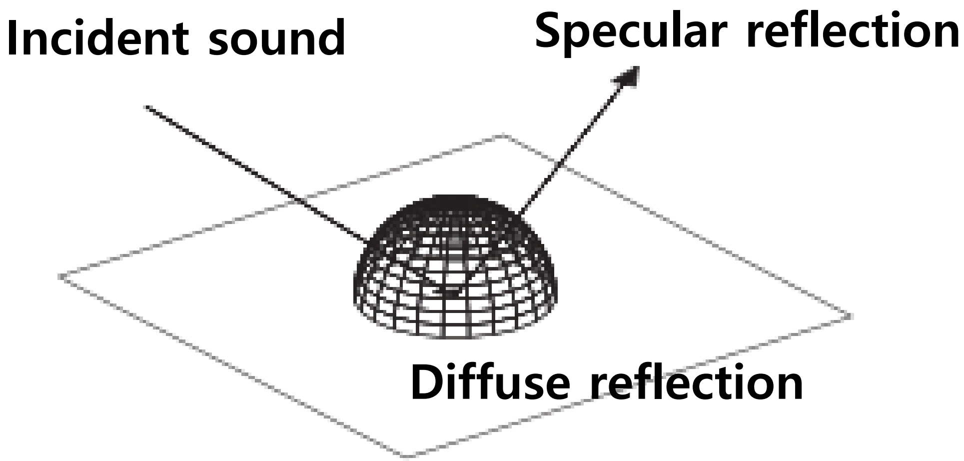
Image from "Estimated real world room impulse response, Statistics of natural reverberation enable perceptual separation of sound and space", BNAS 16, "Scene-aware audio for 360° videos», TOG 18

Ray tracing method

- Monte-Carlo path tracing from the image rendering field



Example of Monte-Carlo path tracing

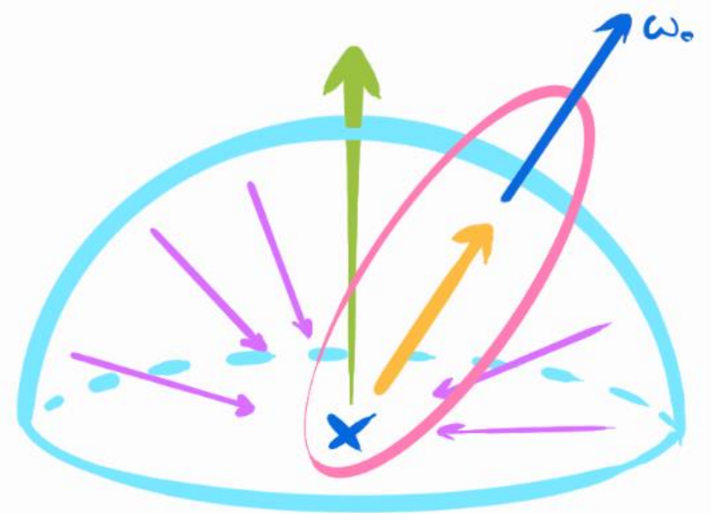


Acoustic BRDF of surface

Acoustic rendering equation

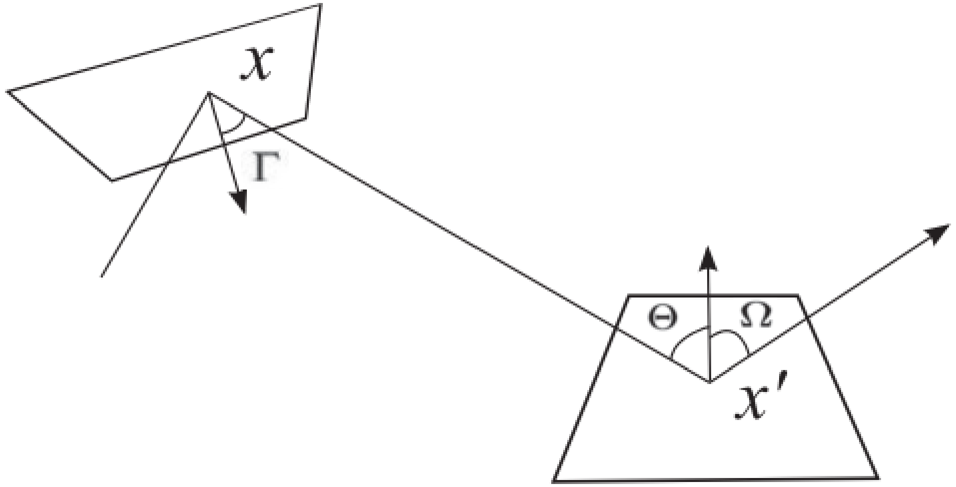
- Similar to rendering equation

Rendering equation



$$L_o(\mathbf{x}, \omega_o) = L_e(\mathbf{x}, \omega_o) + \int_{\Omega} f_r(\mathbf{x}, \omega_i, \omega_o) L_i(\mathbf{x}, \omega_i)(\omega_i \cdot \mathbf{n})\, d\omega_i$$

Acoustic rendering equation

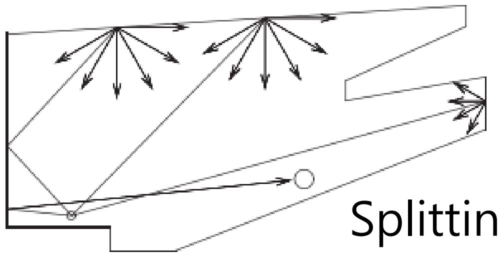


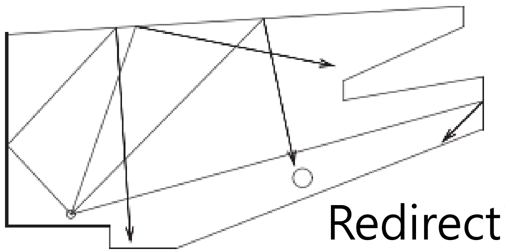
$$I(x', \Omega) = I_0(x', \Omega) + \int_G R(x, x', \Omega) I(x, \Gamma) dx$$

Image from "https://computergraphics.stackexchange.com/questions/9241/difference-betwen-rendering-equation-lighting-model-ray-tracing-global-illumi"

Ray tracing method

- Diffuse reflection affects the late reverberation of sound

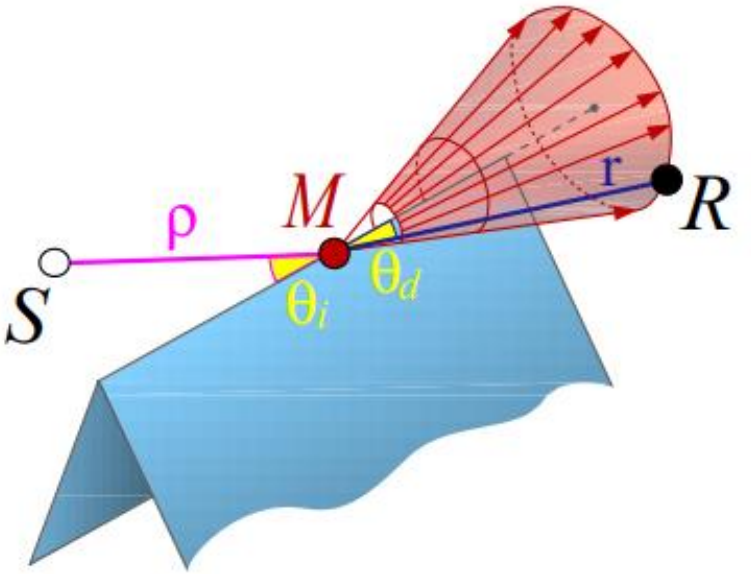

Splitting ray


Redirecting ray

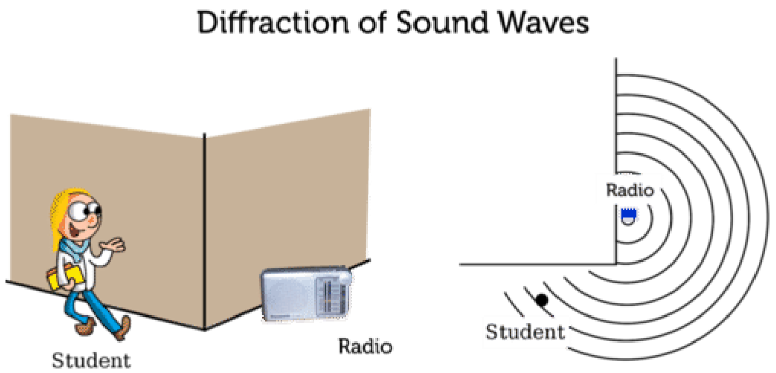
Video from “Interactive Sound Propagation and Rendering for Large Multi-Source Scenes”, TOG 16

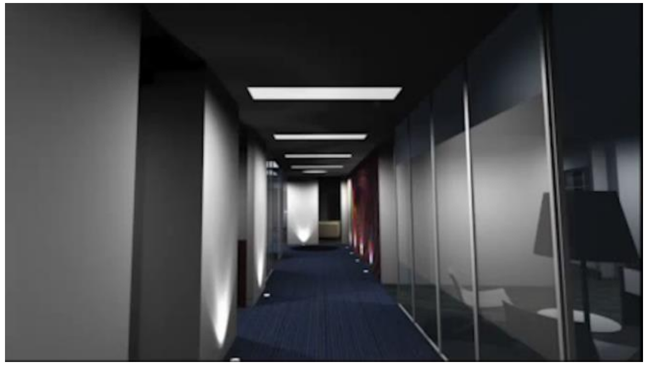
Handling wave property

- Diffraction occurs at the low frequency.



Uniform theory of diffraction (UTD)





No diffraction

3rd order diffraction

Video from "High-Order Diffraction and Diffuse Reflections for Interactive Sound Propagation in Large Environments", SIGGRAPH 14

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Sound intensity attenuation

- Factors affecting the sound intensity attenuation [3]
  - 1. Proportional to the square of the total distance traveled
  - 2. Damping with distance in the medium (air), $\alpha_{medium}(r)$
  - 3. **Absorption coefficient** of incident surface, $\alpha_{surface}$

- The intensity of sound is

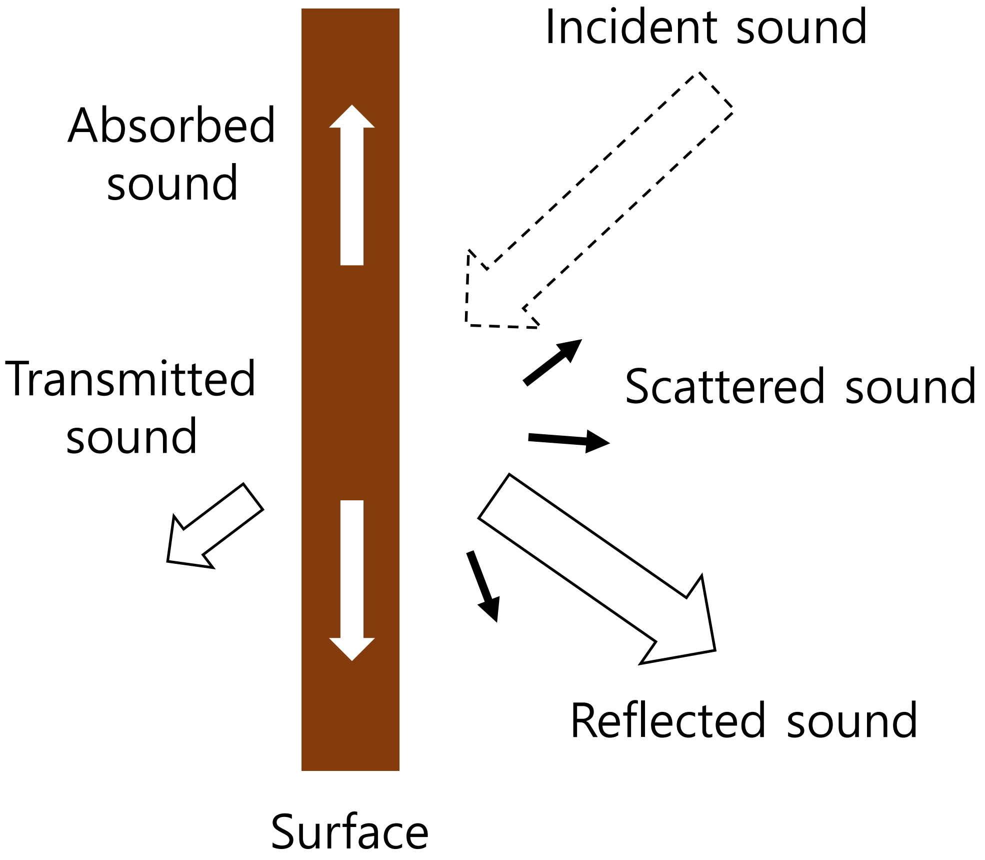
$$I(r) = S \times \frac{1}{r^2} \times \alpha_{medium}(r) \times \prod (1 - \alpha_{surface})$$

  - S is emitted power from the speaker.
  - r is total distance the sound travels to reach the speaker.

Acoustic material

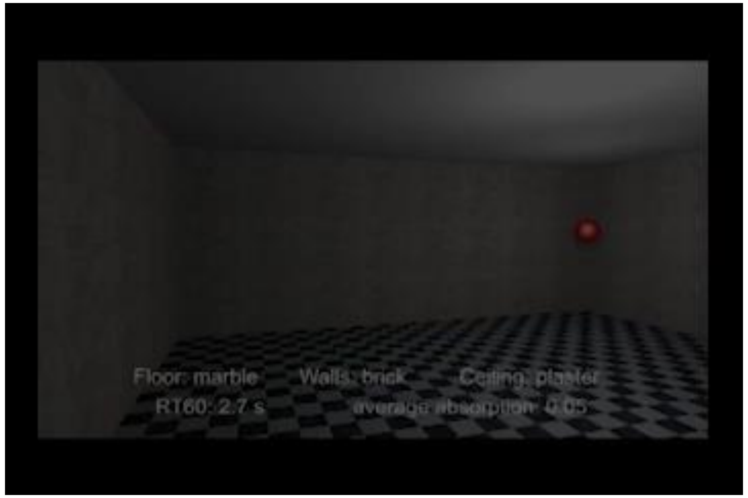
- The properties to determine how incident sound interacts with the surface.
  - Reflected
  - Scattered
  - Transmitted
  - Absorbed

- Frequency dependent



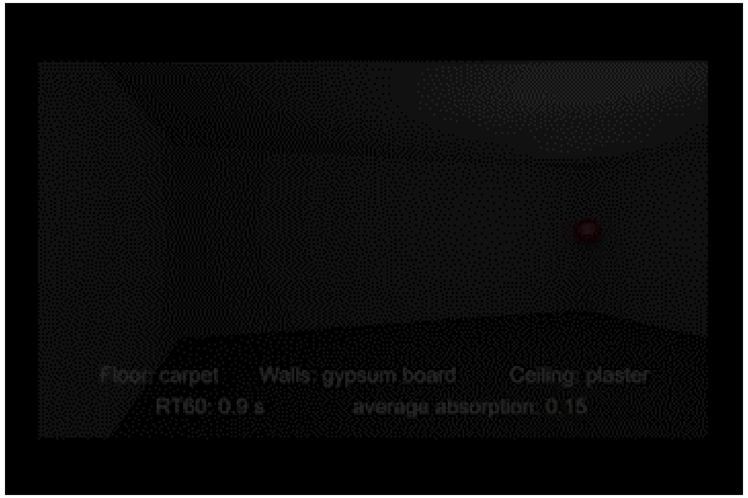
Why acoustic material?

- In the indoor environment, the received the sound is interacted with the surface of various objects. [4]



Small absorption room

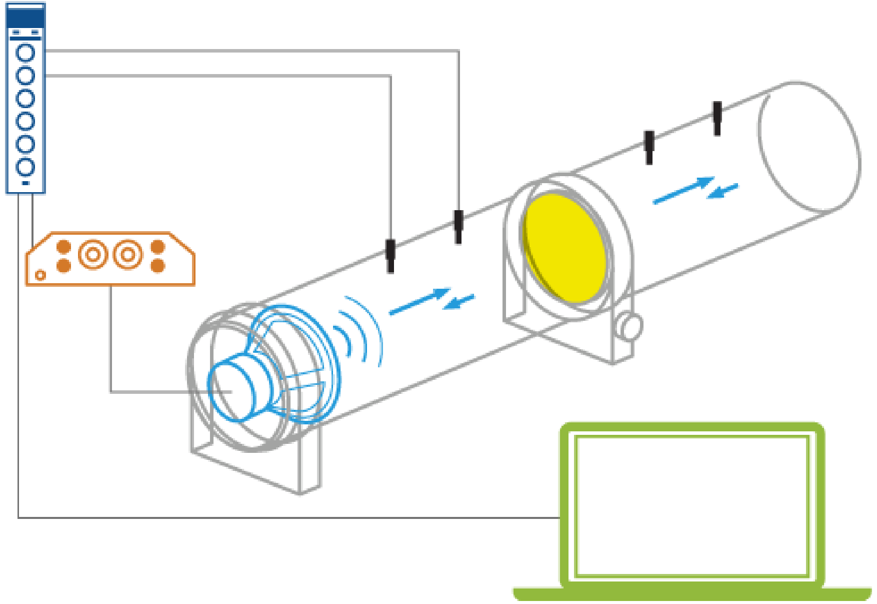
Middle absorption room

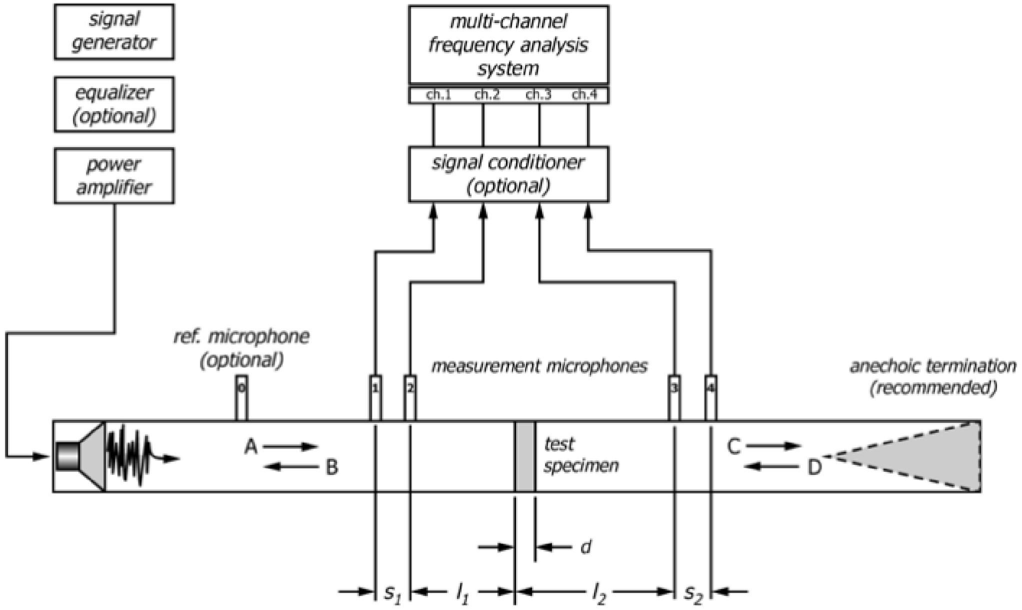


Large absorption room

Acoustic material estimation

- Acoustic material estimation in acoustics field
  - International standards ISO 10534-2, ASTM E1050-12 and ASTM E2611-09
  - Angular dependent absorption property is ignored (only measure the normal impedence)





Acoustic material estimation

- Various estimator kit

Microflown in-situ absorption

Alpha cabin

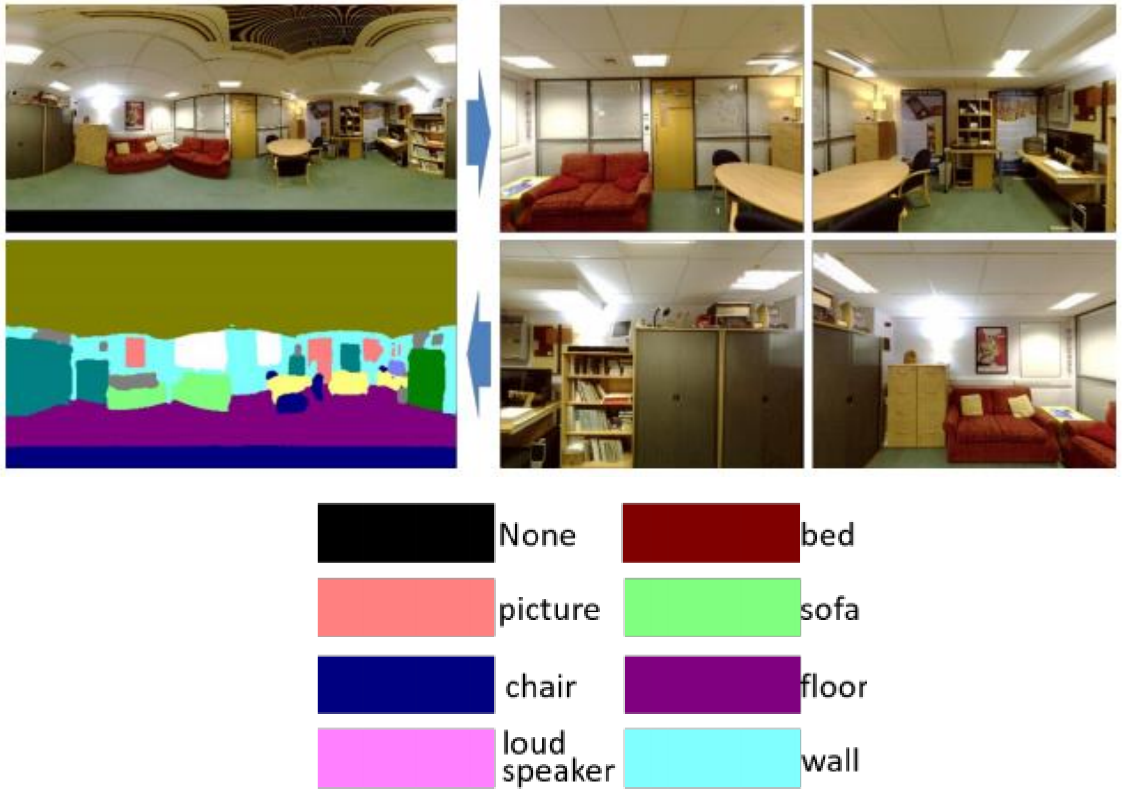
Material	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
%50 absorbent (voids)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Ceramic tiles with smooth surface	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Granite	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Gypsum board (under escalator, w:12.5 mm)	0.29	0.29	0.10	0.05	0.04	0.07	0.09	0.09
Steel trapeze profile (approximated)	0.40	0.30	0.25	0.20	0.10	0.10	0.15	0.15
Ballast, 3.2 cm aggregate, 45.7 cm depth	0.41	0.41	0.53	0.64	0.84	0.91	0.63	0.63
Concrete block, rough surface	0.36	0.36	0.44	0.31	0.29	0.39	0.25	0.82
Concrete block, painted	0.10	0.10	0.05	0.06	0.07	0.09	0.08	0.08
Large pane of glass	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02
Suspended ceiling	0.45	0.45	0.80	0.65	0.72	0.78	0.74	0.74
Escalator	0.05	0.05	005	0.05	0.06	0.04	0.02	0.02
Steel door	0.05	0.05	0.05	0.05	0.06	0.04	0.02	0.02

List of pre-estimated absorption coefficients

Table from "Material list and sound absorption coefficients", Christensen 02

Automatic acoustic material assignment

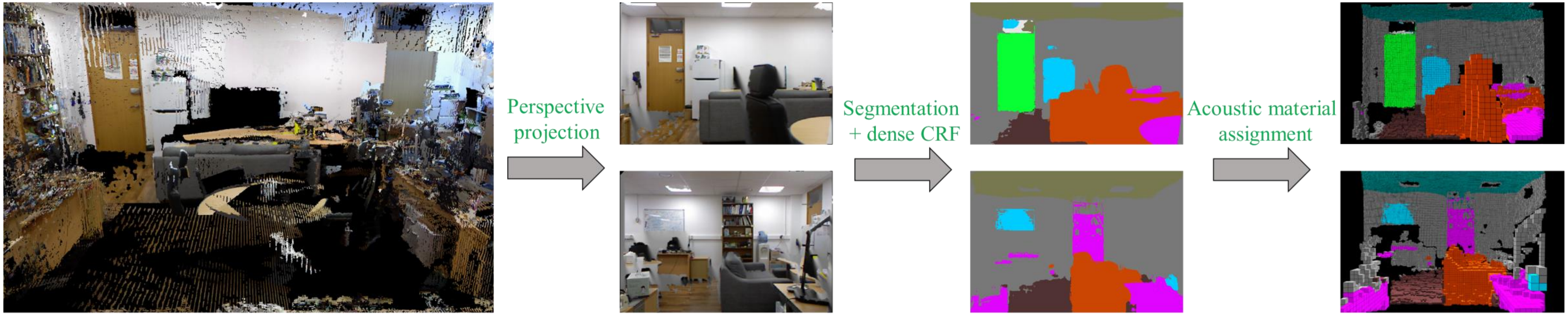
- Immersive Spatial Audio Reproduction for VR/AR Using Room Acoustic Modelling from 360° Images, VR 19



Object	Material	Object	Material
Ceiling	Wood panel	Furniture	Heavy curtain
Book	Sheetlock	Chair	Wood panel
Floor	Parquet	Object	Metal
Window	Thick Glass	Wall	Smooth Plaster
Sofa	Heavy curtain	Table	Wood panel
TV	Metal	Unknown	Transparent

Automatic acoustic material assignment

- Real-time 3-D Mapping with Estimating Acoustic Materials, SII 20



<Raw point cloud from Kinect> <Reconstructed 2-D image> <Predicted semantic labels> <3-D map with estimated material>

Limitation of assignment

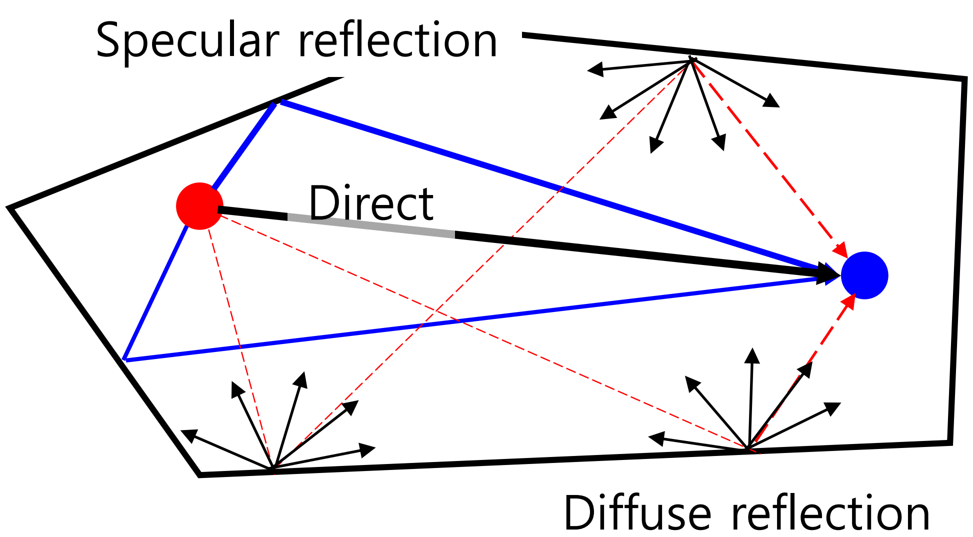
- May not match known acoustic characteristics of real-world scenes
  - Due to the inconsistencies between the measured data and actual scene materials.

Porous Absorbers
Shredded fiber board, flush mount & 1" (25 mm) thick
Painted on $\frac{3}{4}$" (19 mm) furring
Fabric covered
w/ furring & 1" (25 mm) glass fiber
$2\frac{1}{2}$" (64 mm) glass fiber
$1\frac{1}{2}$" (38 mm) thick
Painted on $\frac{3}{4}$" (19 mm) furring
2" (51 mm) thick
Painted on $\frac{3}{4}$" (19 mm) furring
w/ furring & $2\frac{1}{2}$" (64 mm) glass fiber
$2\frac{1}{2}$" (64 mm) thick
3" (76 mm) thick
Shredded fiber board, in drop ceiling & painted, 1" (25 mm) thick
w/ large airspace, 16" (406 mm)
w/ 1" (25 mm) glass fiber
w/ $3\frac{5}{8}$" (92 mm) glass fiber
w/ $6\frac{1}{4}$" (159 mm) glass fiber
2" (51 mm) thick
3" (76 mm) thick

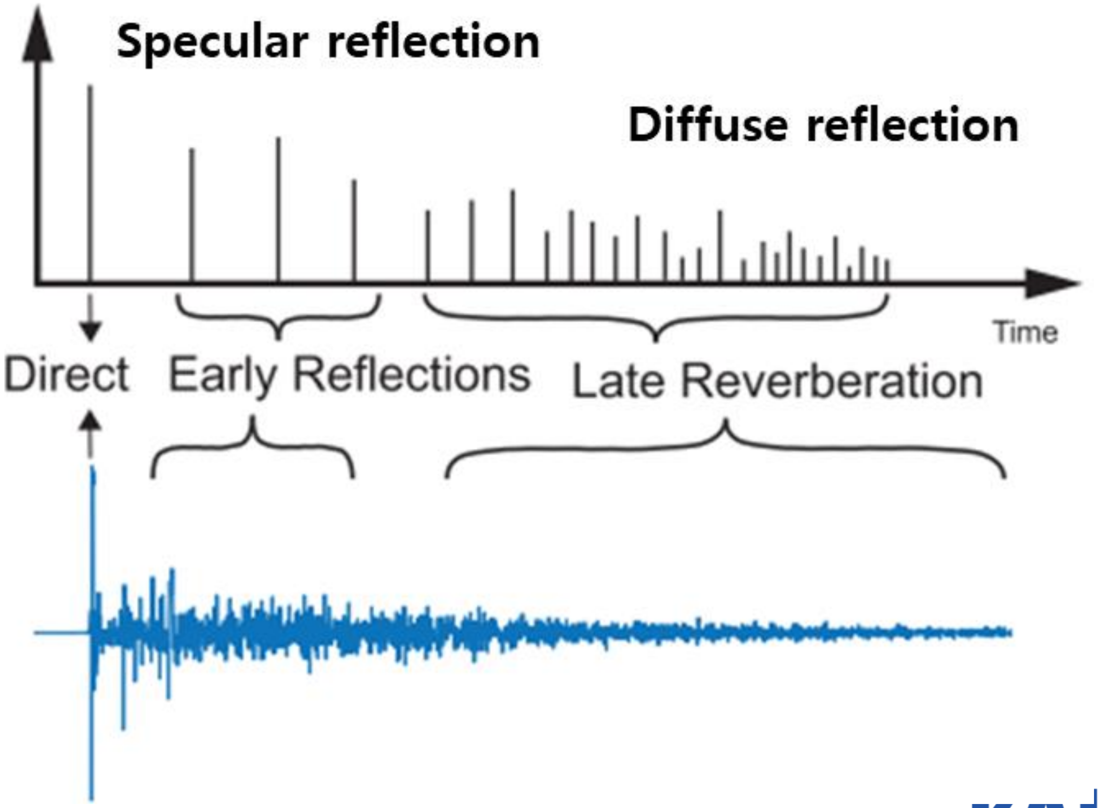
Sound Reflectors
Marble/glazed tile on concrete
Terrazzo
Poured concrete, smooth
Rough
Brick, unglazed & painted
Unglazed
Linoleum/rubber/vinyl/asphalt on concrete
Linoleum over plywood on 2 × 8 (38 mm × 184 mm) joists
Gypsum board, $\frac{1}{2}$" (13 mm) thick, on 2 × 4s (38 mm × 89 mm) 16" (406 mm) o.c.
On wood joists
On concrete
On steel joists
Plaster on lath, suspended on steel joists w/ airspace between structure and ceiling
Wood parquet on concrete
Plywood, $\frac{3}{8}$" (10 mm) thick, flush to ceiling

Optimization based estimation

- Optimization based acoustic material estimation
  - The acoustic material is calculated using a sound simulator to produce a simulated IR close to the target IR.

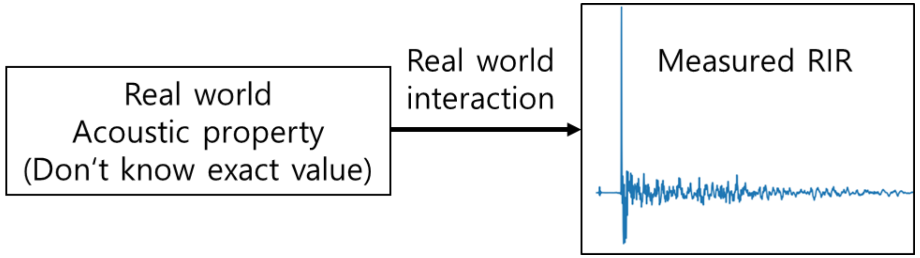


$$I(r) = S \times \frac{1}{r^2} \times \alpha_{medium}(r) \times \prod (1 - \alpha_{surface})$$



RIR estimation in real world

- Real world RIR estimation

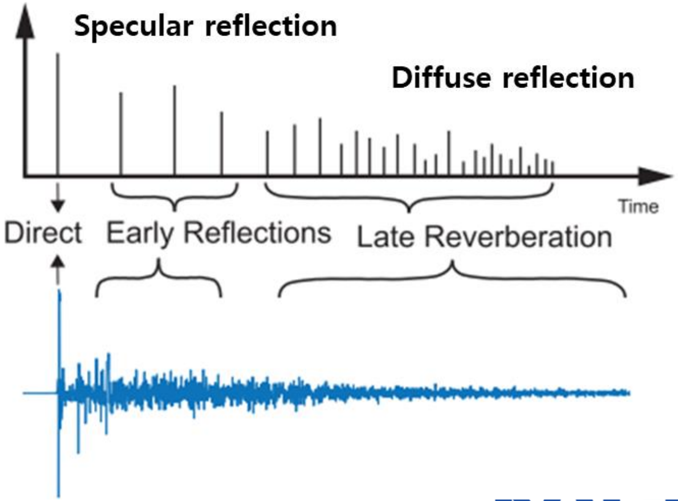


- Received sound $s_r(t)$ = Raw sound $s_e(t)$ * RIR $H(t)$ (convolution)
- If the autocorrelation of the raw sound $s_e(t)$ is a Dirac delta, $s_e(t) \star s_e(t) = \delta(t)$

$$s_e(t) \star s_r(t) = s_e(t) \star s_e(t) * H(t) = \delta(t) * H(t) = H(t)$$

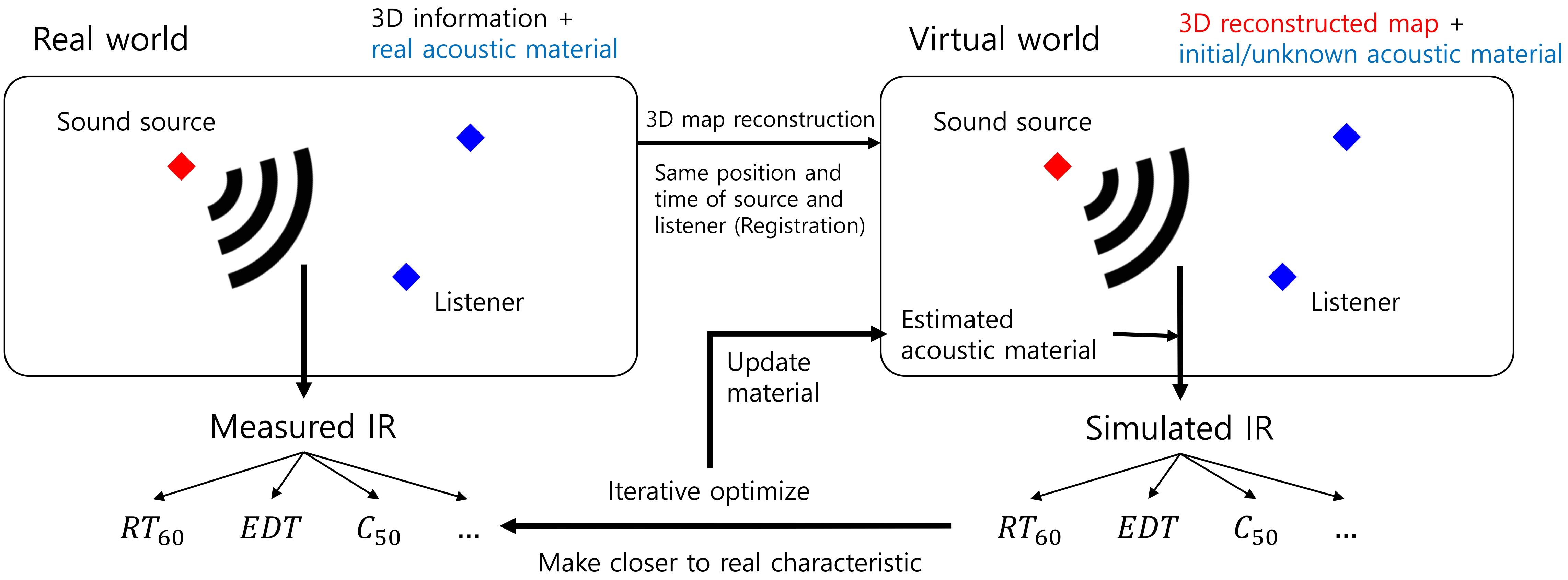
- Sine sweep function

$$x(t) = \sin(2\pi\left(f_0 t + \frac{f_1 - f_0}{2T} t^2\right))$$



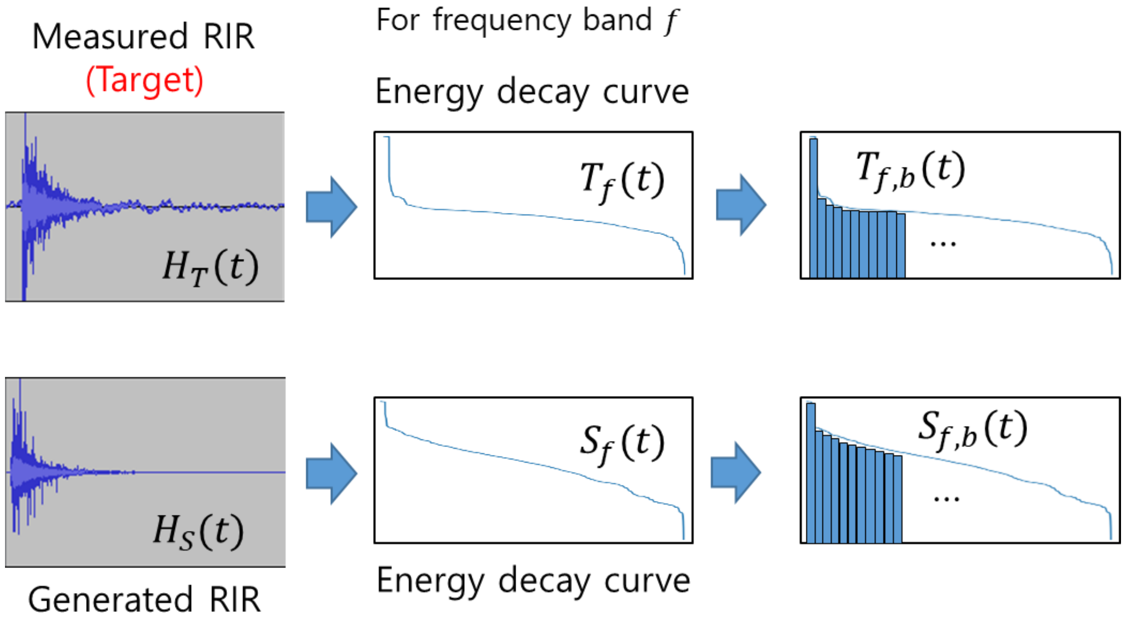
Optimization pipeline

- Optimization approach



Optimization based method

- Acoustic Classification and Optimization for Multi-Modal Rendering of Real-World Scenes, TVCG 18
- Minimize the error between simulated IR's histogram $S_f(t)$ and recorded IR's histogram $T_f(t)$



Optimization based method

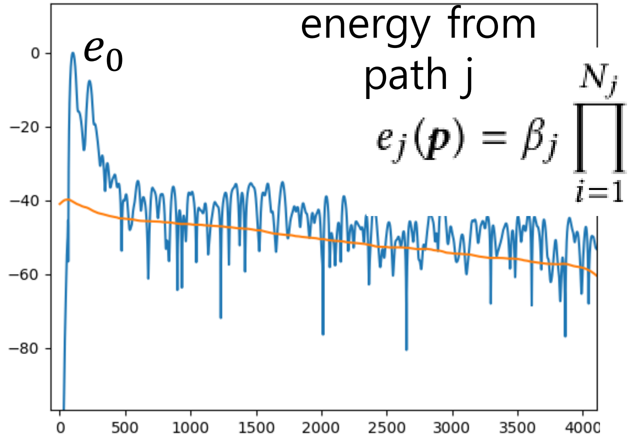
- Scene-Aware Audio for 360° Videos, TOG 18

- Find $\boldsymbol{p} = [p_0, \ldots, p_n]$, reflection coefficient of each material

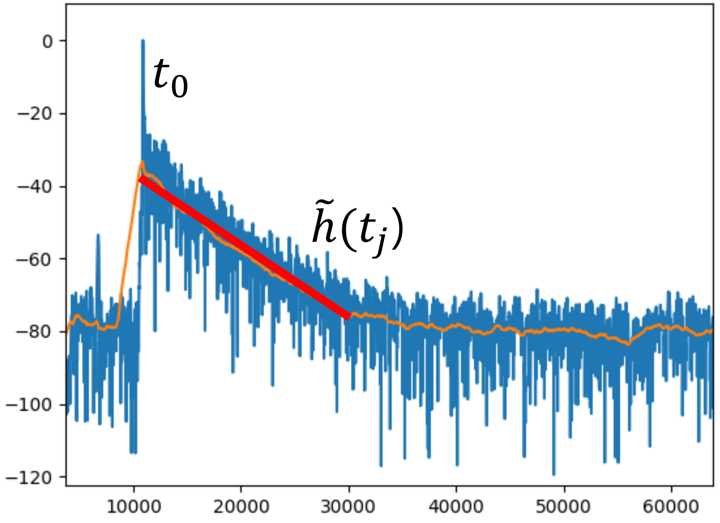
$$J(\boldsymbol{p}) = \sum_{j=1}^{M} \left[\log_{10} \boxed{\left(\frac{e_j(\boldsymbol{p})}{e_0} \right)} - \log_{10} \boxed{\left(\frac{\tilde{h}(t_j)}{\tilde{h}(\bar{t}_0)} \right)} \right]^2$$

Calculated energy from path j

$$e_j(\boldsymbol{p}) = \beta_j \prod_{i=1}^{N_j} \boldsymbol{p}_{m(i)}$$



Intensity of simulated IR



Intensity of target IR

Optimization based method

- Scene-Aware Audio Rendering via Deep Acoustic Analysis, TVCG 20
- Find $\boldsymbol{p} = [p_0, \dots, p_n]$, reflection coefficient of each material

$$\boxed{J(\rho) = (m - m')^2}$$

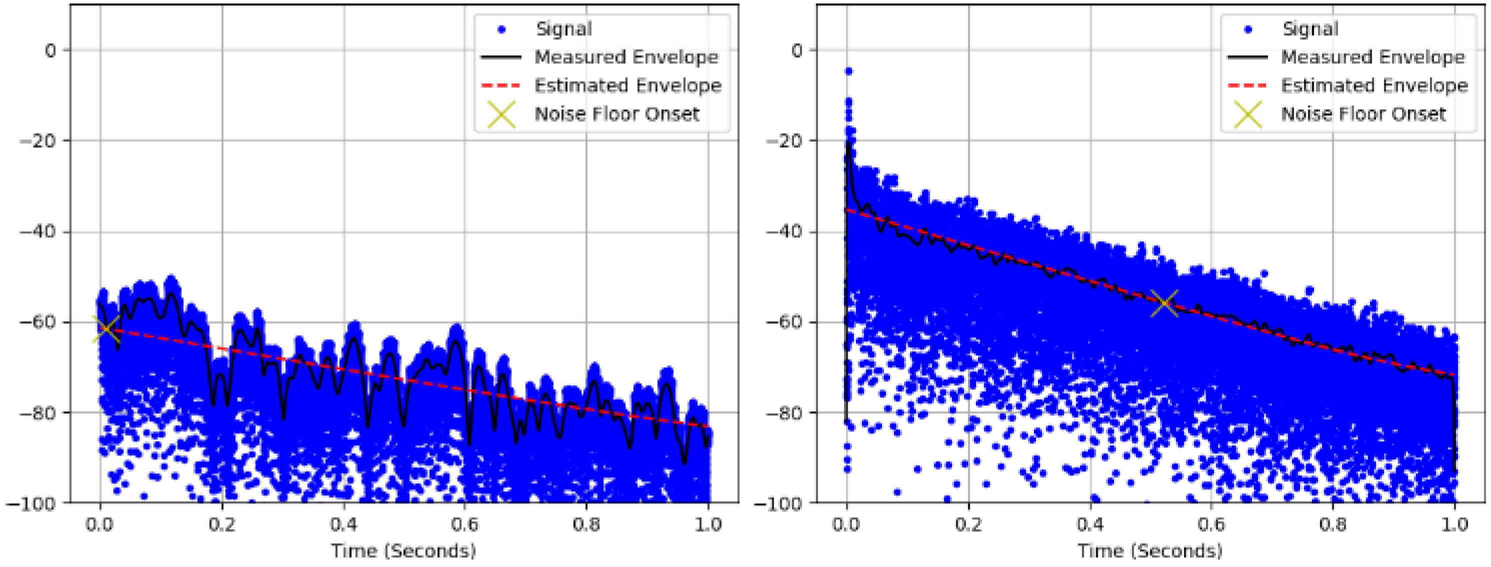
$$y_i = 10\log_{10}(e_i)$$

$$m = \frac{n\sum_{i=0}^{n} t_i y_i - \sum_{i=0}^{n} t_i \sum_{i=0}^{n} y_i}{n\sum_{i=0}^{n} t_i^2 - \left(\sum_{i=0}^{n} t_i\right)^2}$$

Simulated decay slope

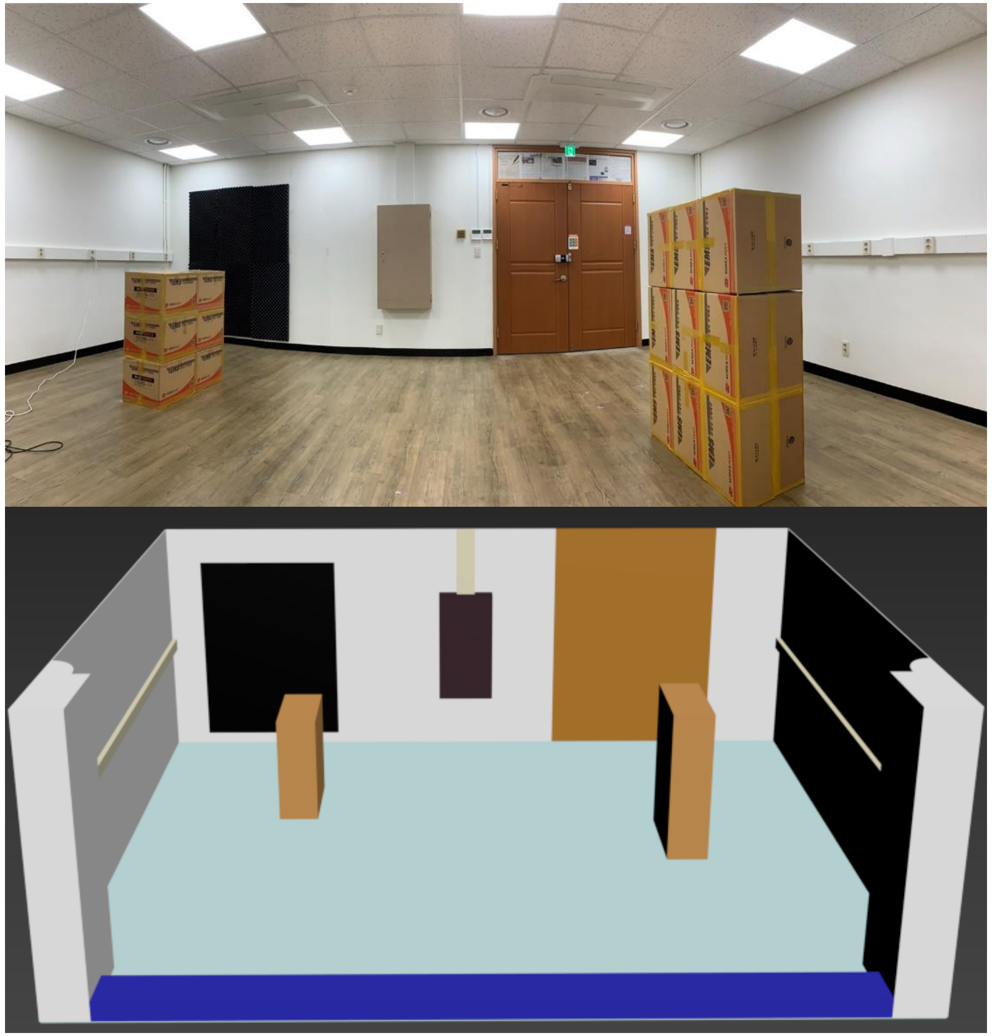
$$m' = -60/T_{60}$$

Target decay slope



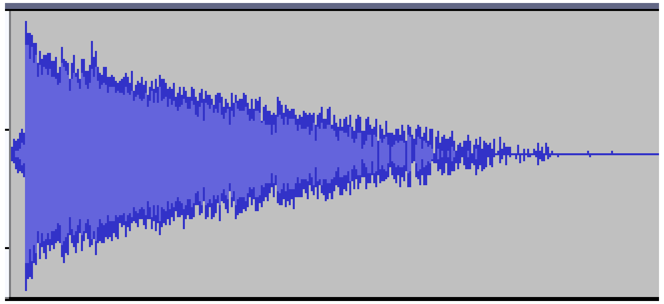
(a) 125Hz sub-band. (b) 8000Hz sub-band.

Sound simulation result

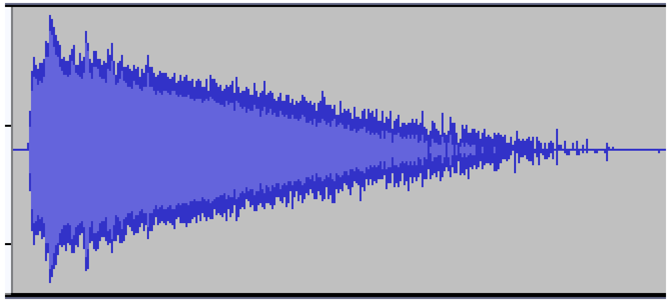


Amplitude (db scale of IR)

Real recorded (GT)



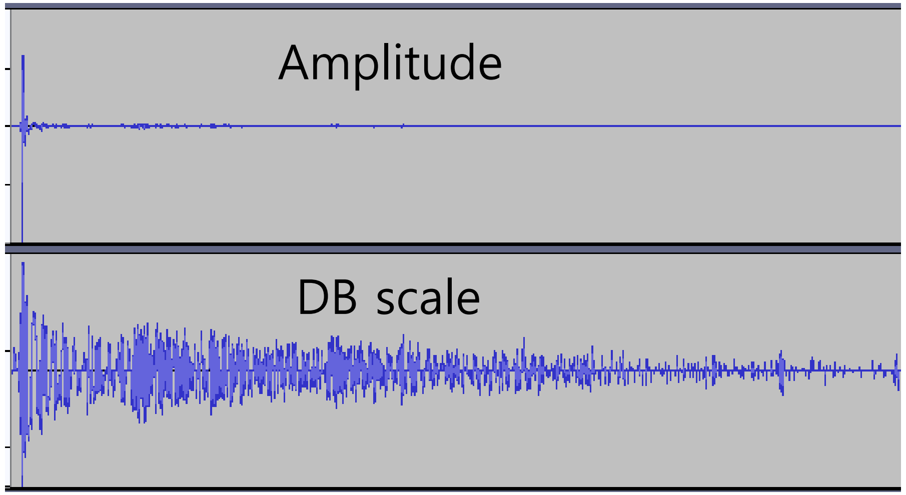
Simulated



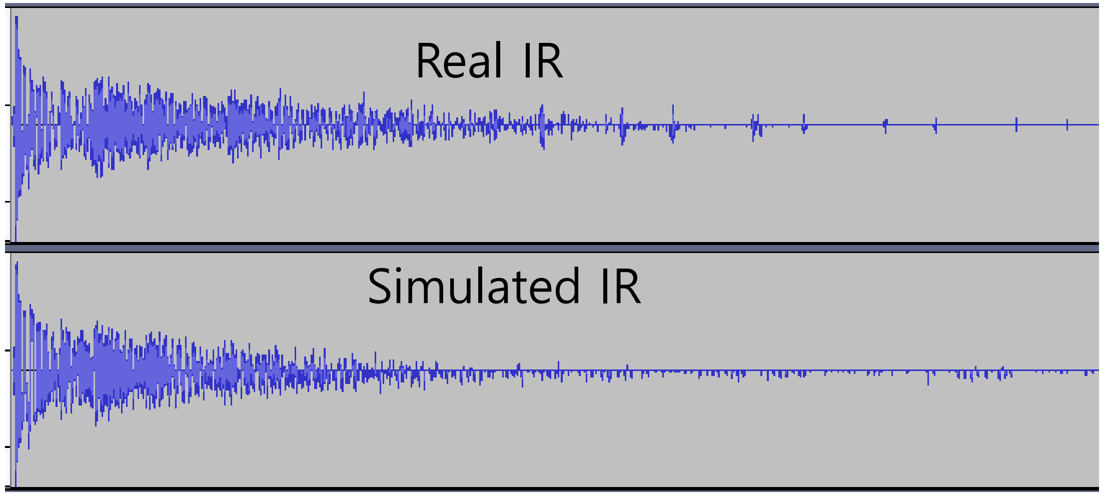
Sound comparison

Real recorded

From simulated IR



Recorded IR from real world



IR comparison (dB scale)

References

- [1] Liu, Shiguang, and Dinesh Manocha. "Sound Synthesis, Propagation, and Rendering: A Survey." *arXiv preprint arXiv:2011.05538* (2020).
- [2] Savioja, Lauri, and U. Peter Svensson. "Overview of geometrical room acoustic modeling techniques." *The Journal of the Acoustical Society of America* 138.2 (2015): 708-730.
- [3] Kuttruff, Heinrich. *Room acoustics*. Crc Press, 2016.
- [4] Schissler, Carl, Christian Loftin, and Dinesh Manocha. "Acoustic classification and optimization for multi-modal rendering of real-world scenes." *IEEE transactions on visualization and computer graphics* 24.3 (2017): 1246-1259.

Q & A