Sound Propagation

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Speech And Audio Recognition
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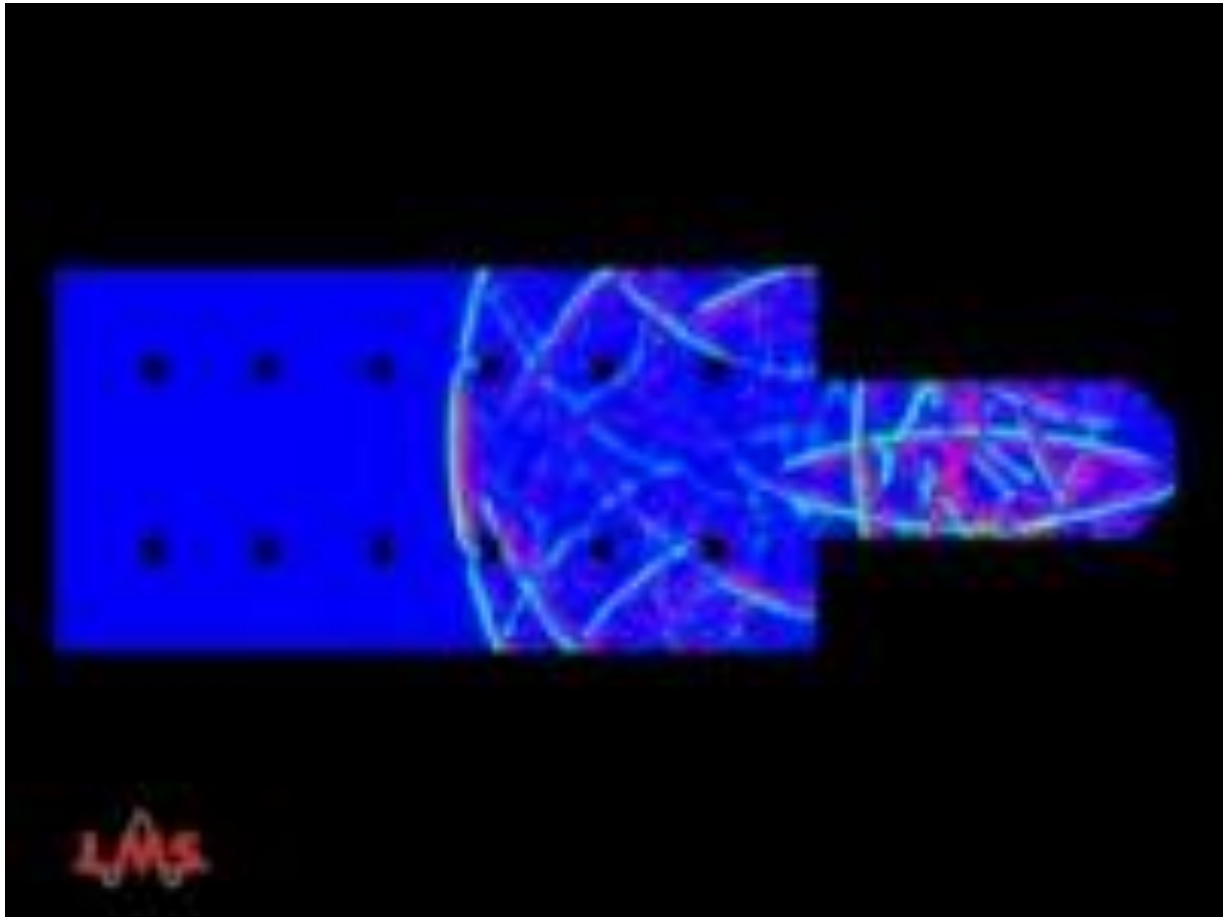
https://mairlab-km.github.io/

This lecture material is based on the Lecture Notes (EE837) of Prof. Jung-Woo Choi at KAIST
and the Ph.D. dissertation of Dr. Taeyoung Kim at Samsung Electronics

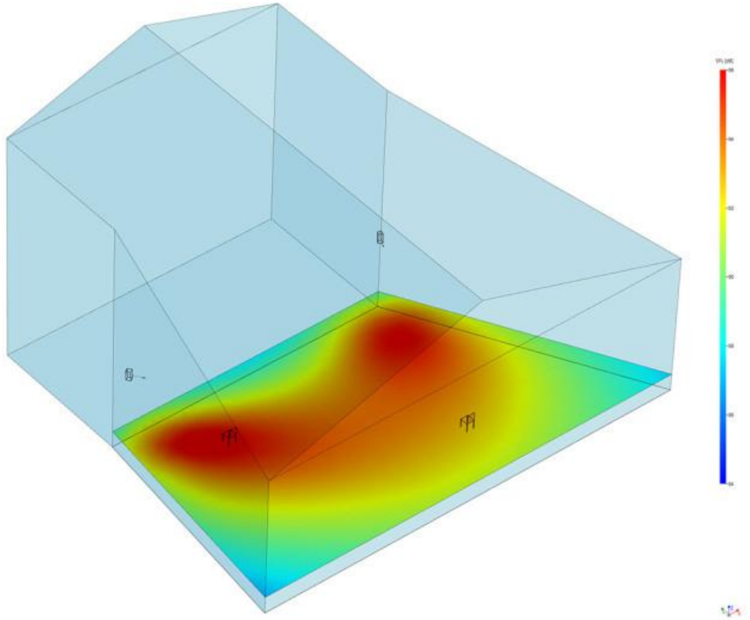
How does sound propagate?



https://www.youtube.com/watch?v=Xsx4VBEKciA

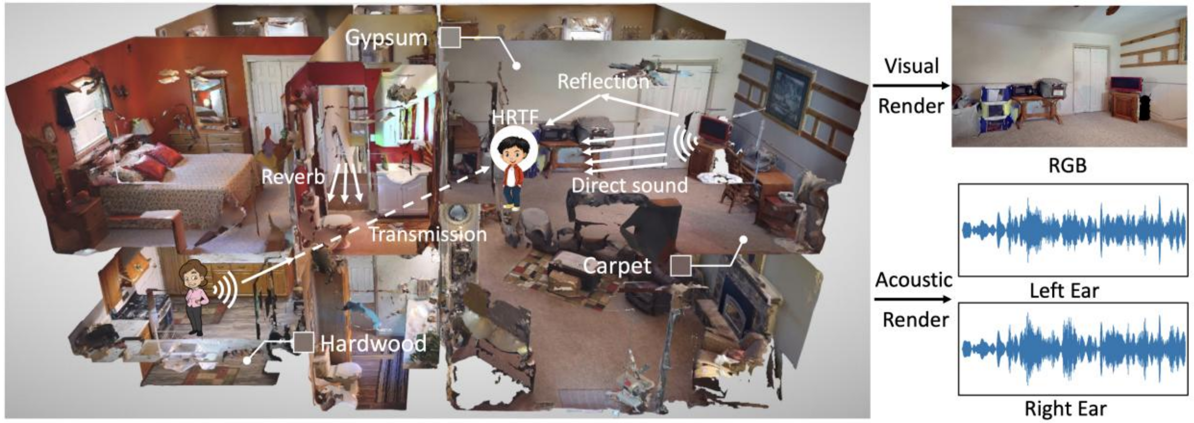
https://www.youtube.com/shorts/GnAvquGBmnY

To create realistic sound!



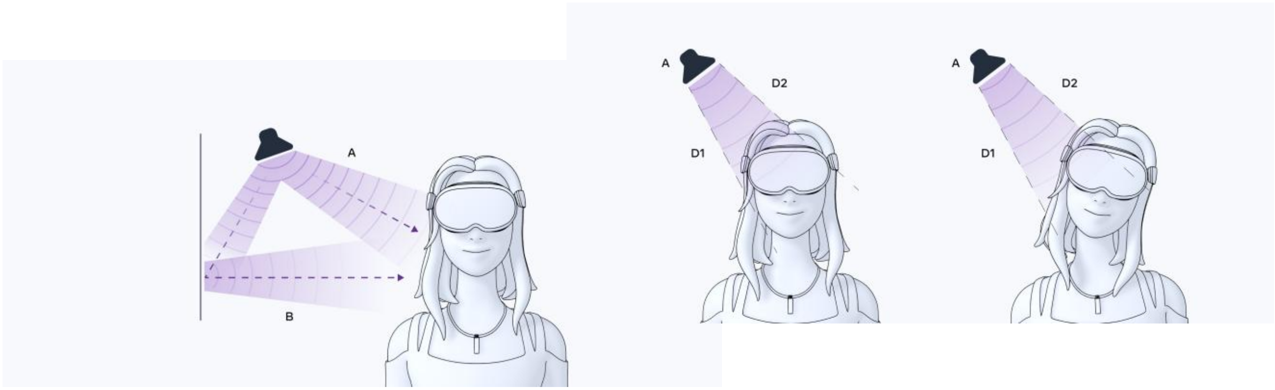
Acoustic simulation (designing Auditorium)

https://audioxpress.com/article/acoustic-simulation-ease-5-s-acousteer-engine-redefines-design-workflows



Sound simulation (generating synthetic data)

https://vision.cs.utexas.edu/projects/soundspaces2/



Sound simulation (Spatial audio in VR)

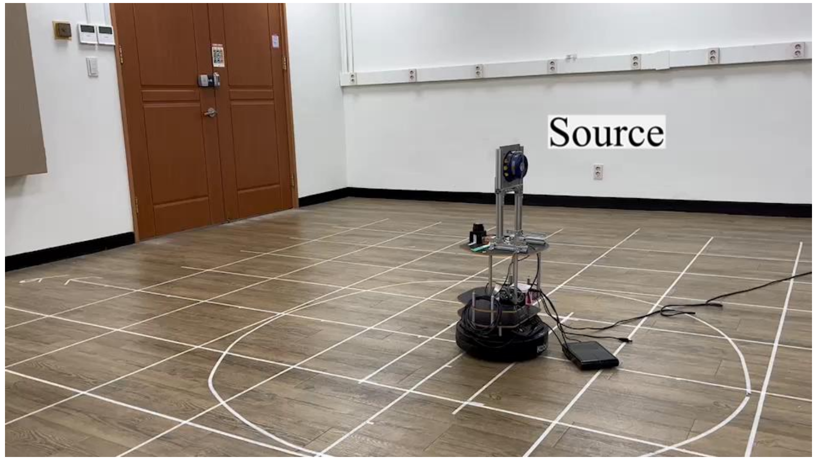
https://developers.meta.com/horizon/design/spatial_audio/

To create realistic sound!

READY OR NOT (Game)

https://www.youtube.com/watch?v=q267XIOBSr8&t=71s

To create realistic sound!



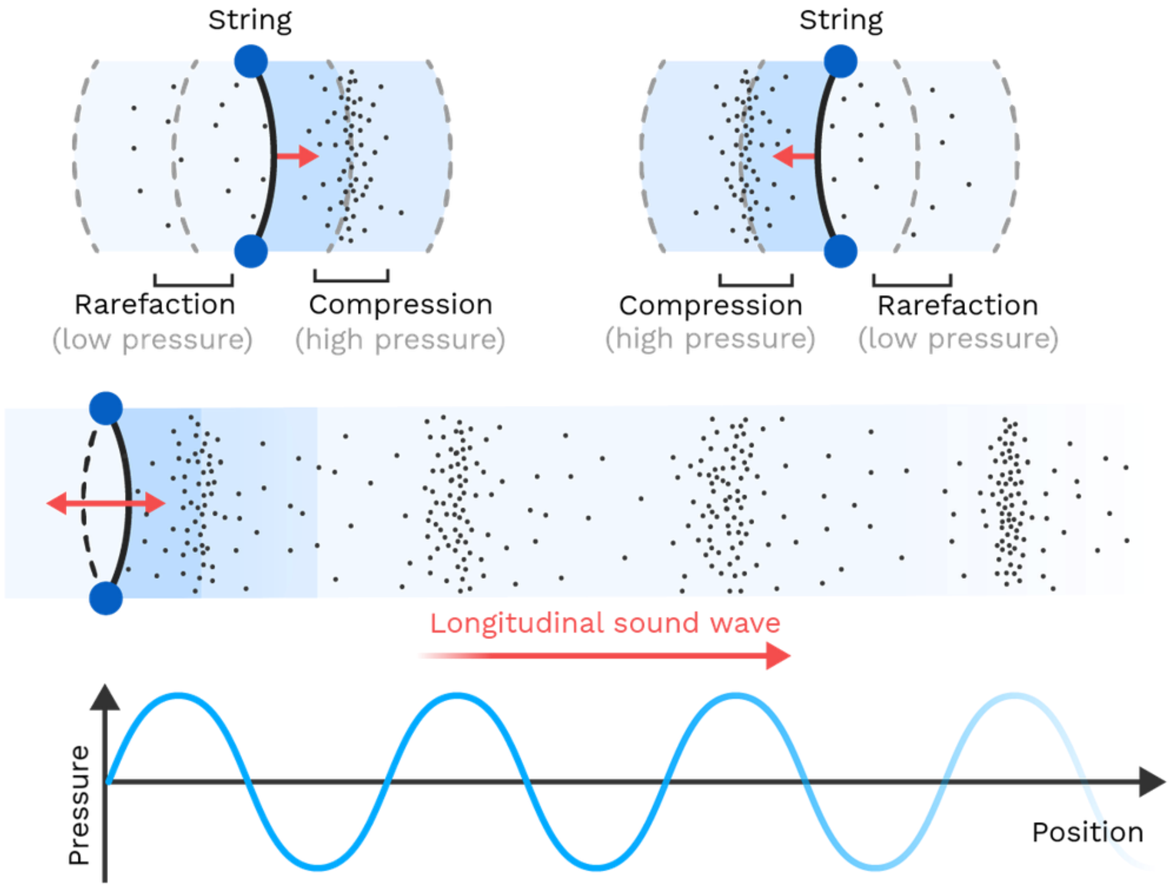
Recorded sound in the real environment

Generated sound in the virtual environment

Wave?

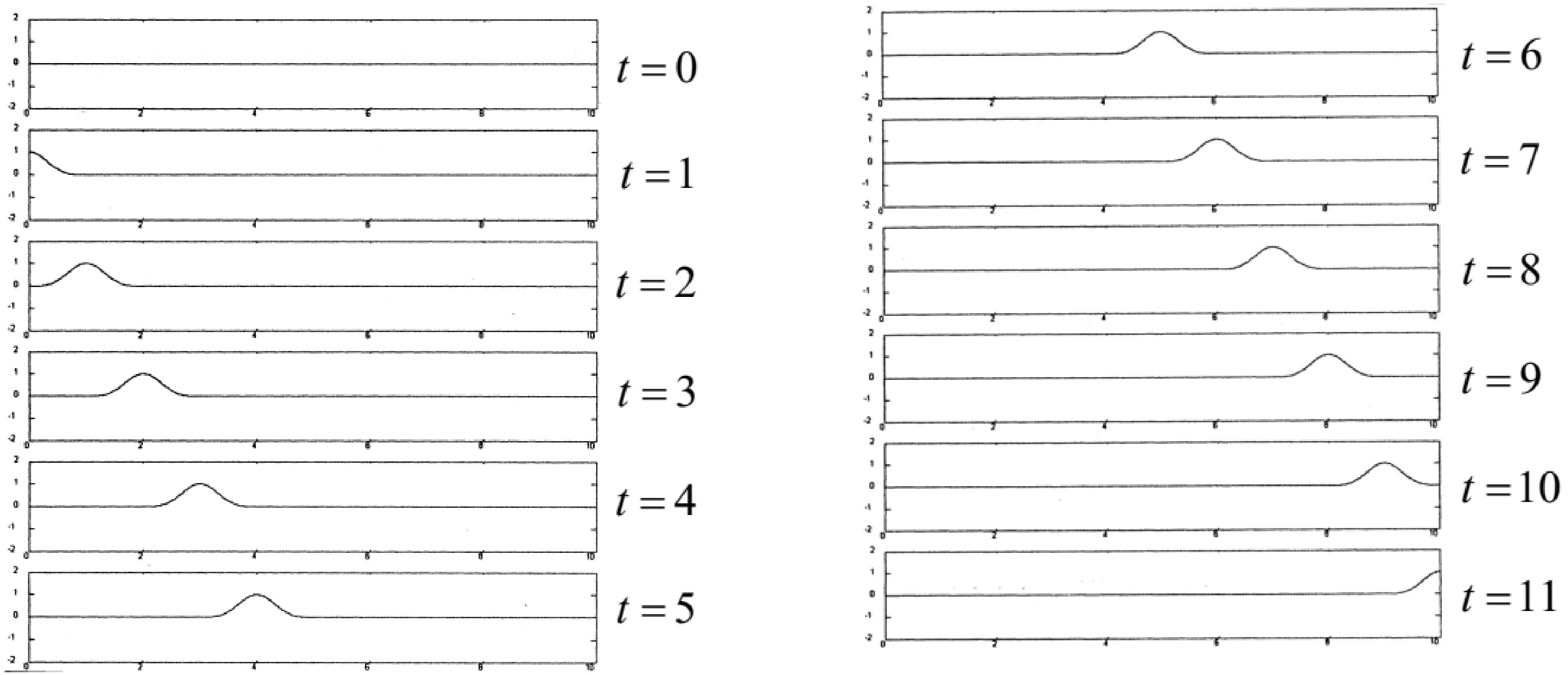
- What is wave?
  - Propagation of disturbances through medium in space and time
- Acoustic properties to consider
  - Acoustic pressure
  - Particle velocity
  - Acoustic density
  - Sound power and intensity
  - …

$f(r, t)$



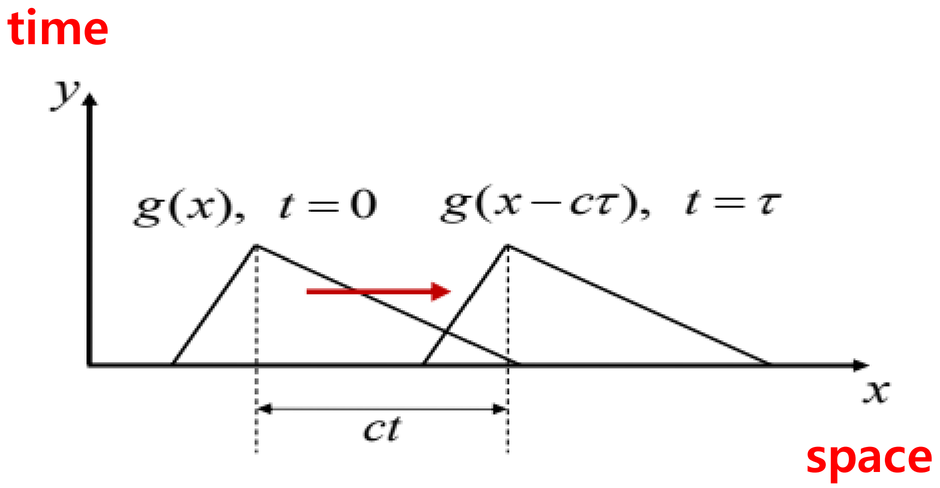
Simple Wave Propagation

- Wave propagation on a string
  - What propagating is an ‘event’, not a medium itself



Simple Wave Propagation

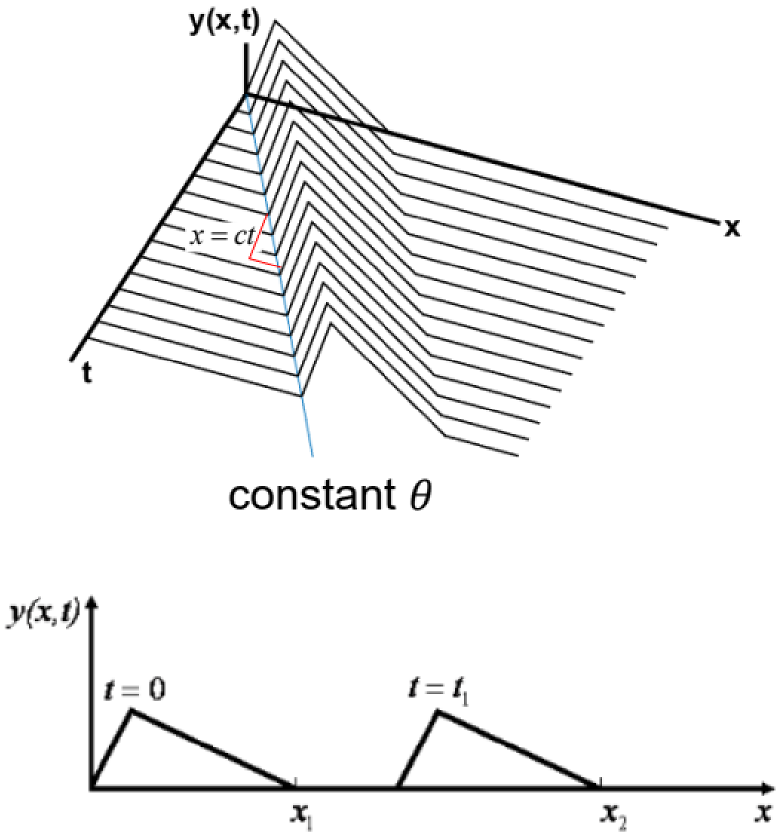
- Wave propagation on string
  - Non-dispersive wave: 파동의 속도가 주파수에 의존하지 않는 파동 (즉, 주파수 성분이 같은 속도로 이동)
  - Right-going wave (waveform)
    - $y(x,t) = g(x - ct) = g\left(-c\left(t - \frac{x}{c}\right)\right)$
  - Left-going wave (waveform)
    - $y(x,t) = h(x + ct)$
  - General form
    - $y(x,t) = g(x - ct) + h(x + ct)$



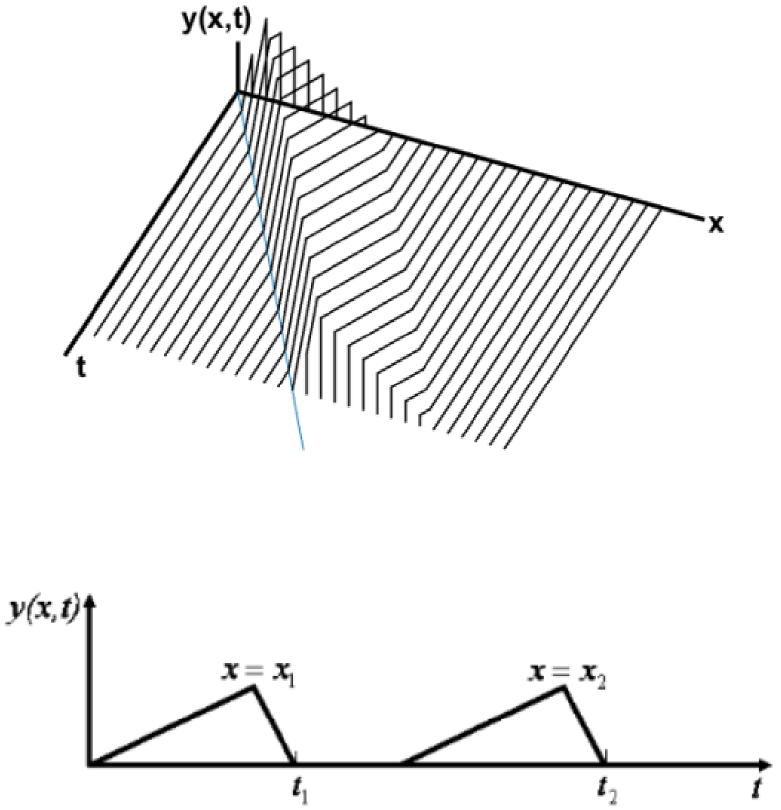
Simple Wave Propagation

- Wave observed in space-time domain

Snapshot at a fixed time

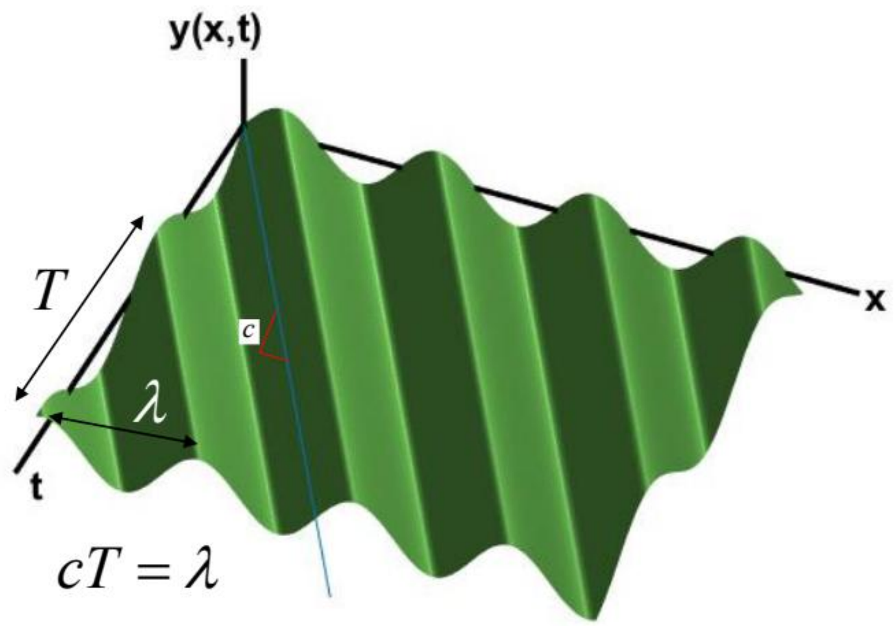


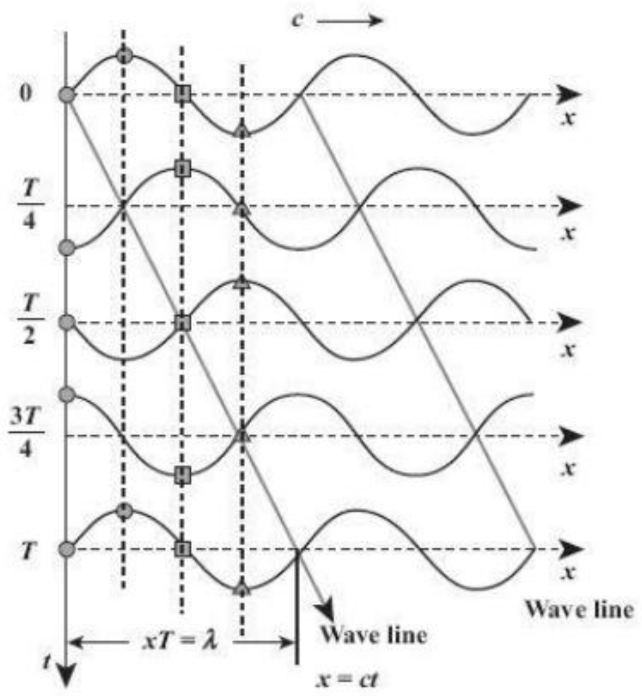
Recording at a fixed location



Simple Wave Propagation

- Harmonically propagating wave
  - Right-going wave (waveform)
    - $y(x,t) = y(x - ct) = Y\cos(k(x - ct) + \phi_0)$



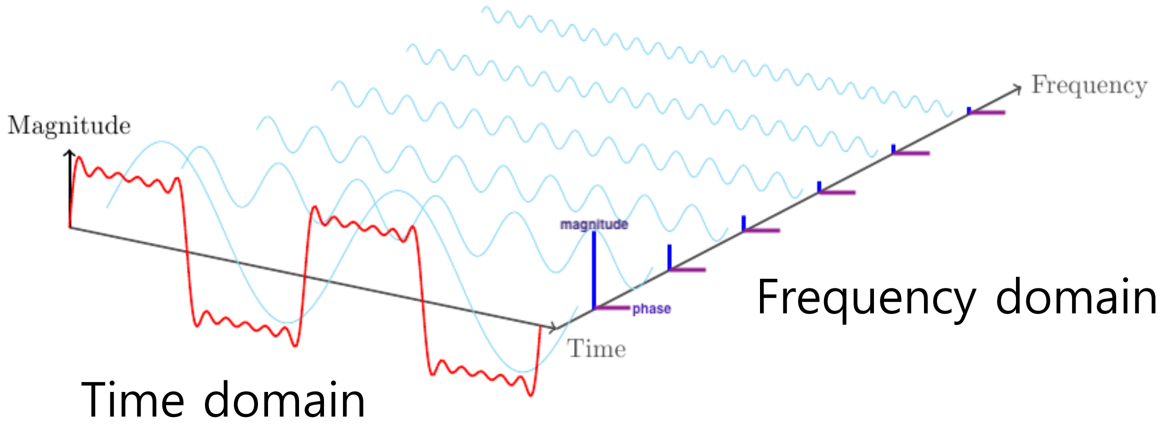


The distance across which a wave travels for a period T with a propagation speech c will be a wavelength λ

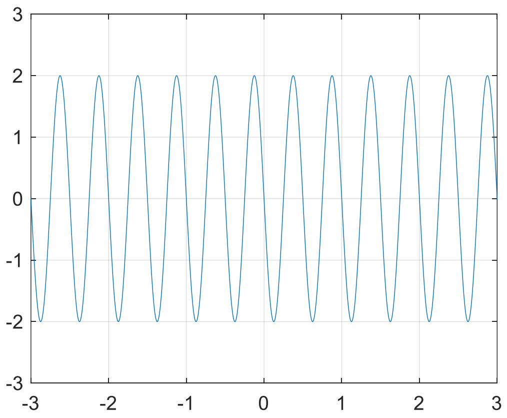
Fourier Series

- Any absolutely integrable periodic function $x(t)$ with period P can be represented as

$$x(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} \overbrace{A_n}^{\text{Amplitude}} \cos\left(2\pi \underbrace{\frac{n}{P}}_{\text{Frequency}} t - \overbrace{\phi_n}^{\text{Phase}}\right)$$



  - What is the amplitude and the phase?



- Amplitude?
- Phase?

https://angeloyeo.github.io/2019/06/23/Fourier_Series_en.html

Simple Wave Propagation

- Harmonically propagating wave
  - Right-going wave (waveform)
    - $\boldsymbol{y(x,t) = y(x-ct) = Y\cos(k(x-ct)+\phi_0)}$
  - Frequency: number of temporal oscillation per second
    - Cyclic frequency (Hz): f
    - Radian frequency (radian/s): $\omega = 2\pi f$
    - $\boldsymbol{y(x,t) = Y\cos(kx-\omega t)}$
  - Wavenumber: spatial oscillation per meter
    - Spatial frequency: radian/m
  - Period: time taken for single oscillation (T)
  - Wavelength: space taken for single oscillation (λ)

Simple Wave Propagation

- Harmonically propagating wave
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  - Wavenumber: spatial oscillation per meter
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  - Period: time taken for single oscillation (T)
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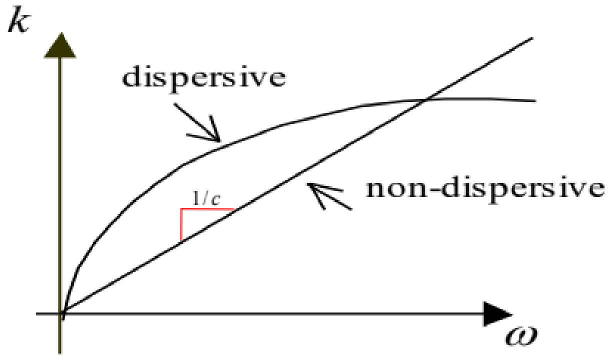
<Space-time relations>

- Frequency-time relation:
  - $f = \frac{1}{T}$
  - $\omega = 2\pi f = \frac{2\pi}{T}$
- Spatial frequency-space:
  - $k = \frac{2\pi}{\lambda}$
- Space-time:
  - $k = \frac{\omega}{c} = \frac{2\pi f}{c} = \frac{2\pi}{cT}$

Space-time variation is not independent in waves!

Simple Wave Propagation

- Space-time coupling
  - Dispersion relation
    - **Non-dispersive wave: sound speed is independent of frequency** ⟹ $\boldsymbol{\omega = ck}$
    - Dispersive wave: sound speed varies with frequency



    - Why the space-time coupling occurs?
      - Medium's behavior (dynamics): 파동이 지나가는 매질 (medium)의 물리적 특성이 $\omega - k$의 관계를 결정
      - **공기는 선형관계 (즉, non-dispersive)**

⟹ **Wave equation!**

Wave Equation

- Wave equation:
  - 파동 현상을 수학적으로 기술하는 편미분 방정식
  - One-dimensional wave equation (space가 1-D)

$$\underbrace{\frac{\partial^2 y}{\partial x^2}}_{\text{Spatial}} = \frac{1}{c^2}\underbrace{\frac{\partial^2 y}{\partial t^2}}_{\text{Time}}$$

- Wave equation describes the space-time coupling relation
- Second-order derivatives?
  - (Roughly) <u>spatial curvature</u> is related to <u>temporal curvature</u>

Wave Equation

- Wave equation:
  - 파동 현상을 수학적으로 기술하는 편미분 방정식
  - One-dimensional wave equation (space가 1-D)

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 y}{\partial t^2}$$

Spatial   Time

Sound pressure

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

1D → 2D

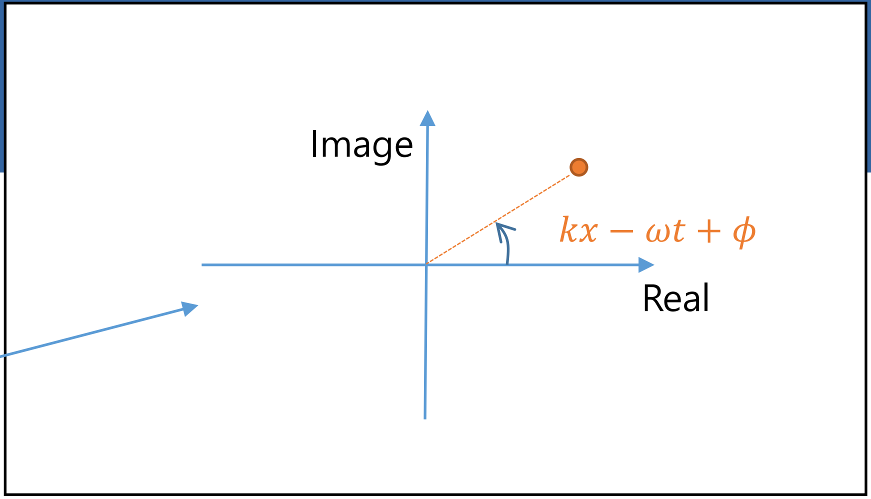
$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

- Wave equation describes the space-time coupling relation
- Second-order derivatives?
  - (Roughly) <u>spatial curvature</u> is related to <u>temporal curvature</u>

Solutions of Wave Equation

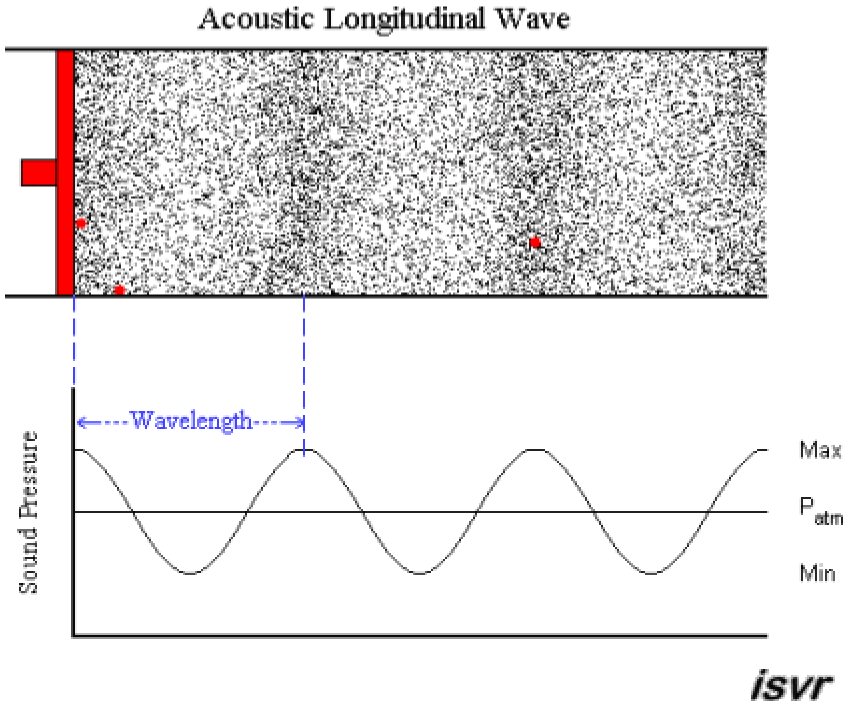
- Single frequency component of **a plane wave**
  - Complex pressure: $p(x,t) = Ae^{i(kx-\omega t)}$

$$\boxed{A = |A|e^{i\phi}}$$



  - What we observe in reality is only the real part!

$$p(x,t) = Re\{Ae^{i(kx-\omega t)}\} = |A|\cos(kx - \omega t + \phi)$$



Solutions of Wave Equation

- Single frequency component of **a plane wave**
  - Does Complex pressure satisfy Wave equation?

$$p(x,t) = Ae^{i(kx-\omega t)}$$

$$\boxed{\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}}$$

$$\begin{aligned}\frac{\partial^2 p}{\partial x^2} &= \frac{\partial^2}{\partial x^2}\left(Ae^{i(kx-\omega t)}\right)\\ &= (jk)(jk)Ae^{i(kx-\omega t)}\\ &= -k^2Ae^{i(kx-\omega t)}\\ &= -k^2 p(x,t)\end{aligned}$$

$$\begin{aligned}\frac{\partial^2 p}{\partial t^2} &= \frac{\partial^2}{\partial t^2}\left(Ae^{i(kx-\omega t)}\right)\\ &= (-j\omega)(-j\omega)Ae^{i(kx-\omega t)}\\ &= -\omega^2Ae^{i(kx-\omega t)}\\ &= -\omega^2 p(x,t)\end{aligned}$$

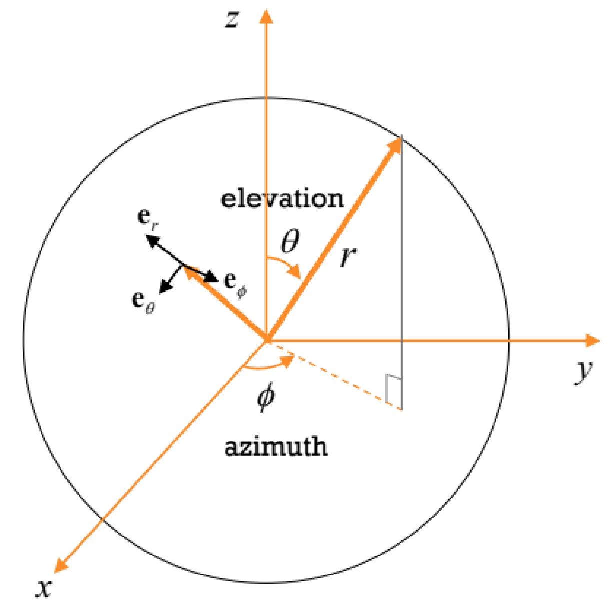
$$-k^2 = -\frac{\omega^2}{c^2}$$

$$\rightarrow k = \frac{\omega}{c}$$

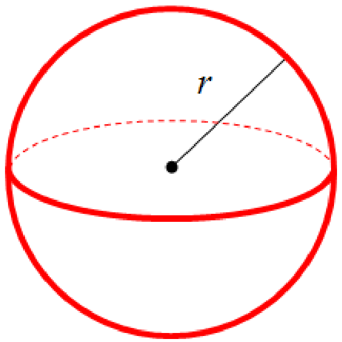
$$k = \frac{2\pi}{\lambda}$$

$$\omega = 2\pi f$$

Solutions of Wave Equation

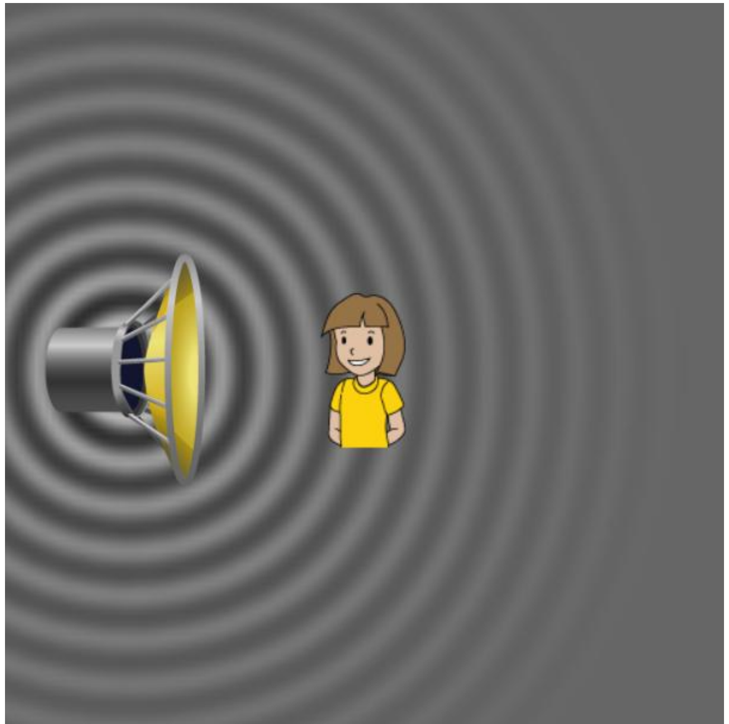


- Single frequency component of **a spherical wave**
  - Spherical coordinate, $p(\vec{r},t) = p(r,\theta,\phi,t)$
  - Complex pressure: $p(\vec{r},t) = \frac{A}{r}e^{i(kr-\omega t)}$



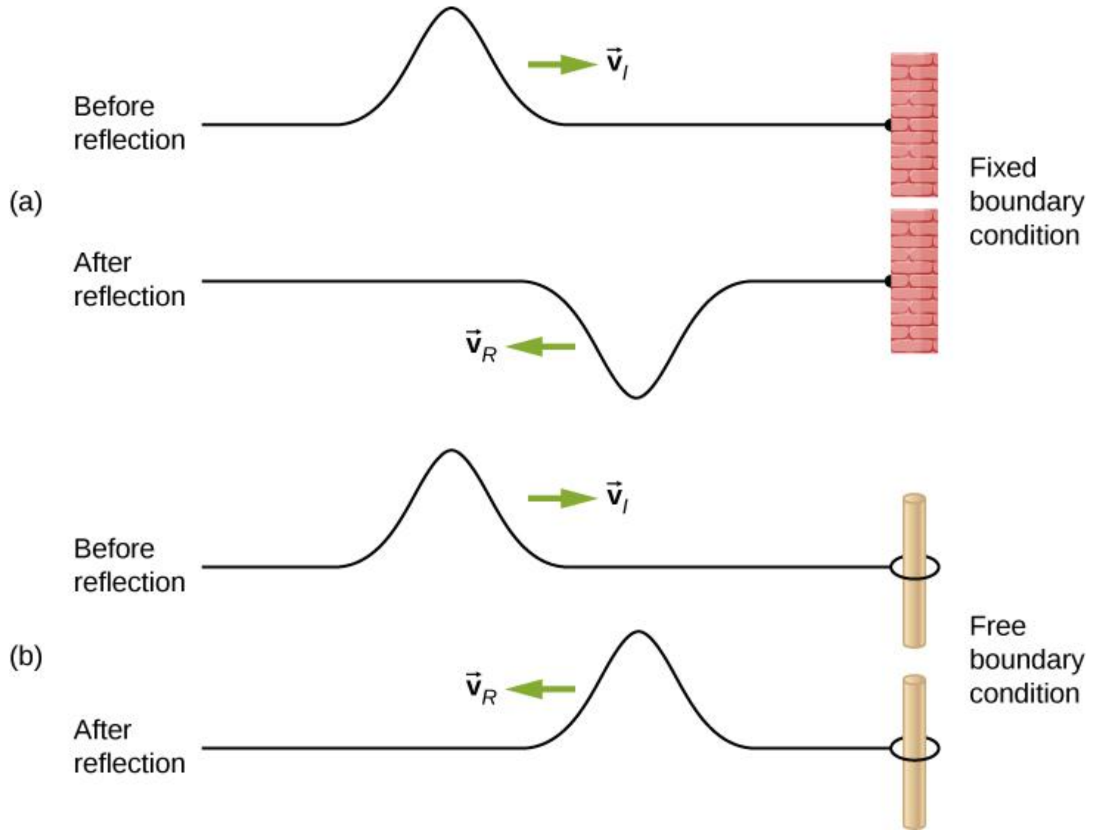
area of a sphere: $4\pi r^2$
→ Spherical wave의 r이 증가하여도,
→ 에너지보존 법칙에 의해 구 표면의 에너지가 항상 같아야 한다.
→ Sound intensity: $I = \frac{P}{A}$
→ Sound power P

$$\approx \frac{1}{T}\int_0^T [p(\vec{r},t)]^2 dt$$



Reflection

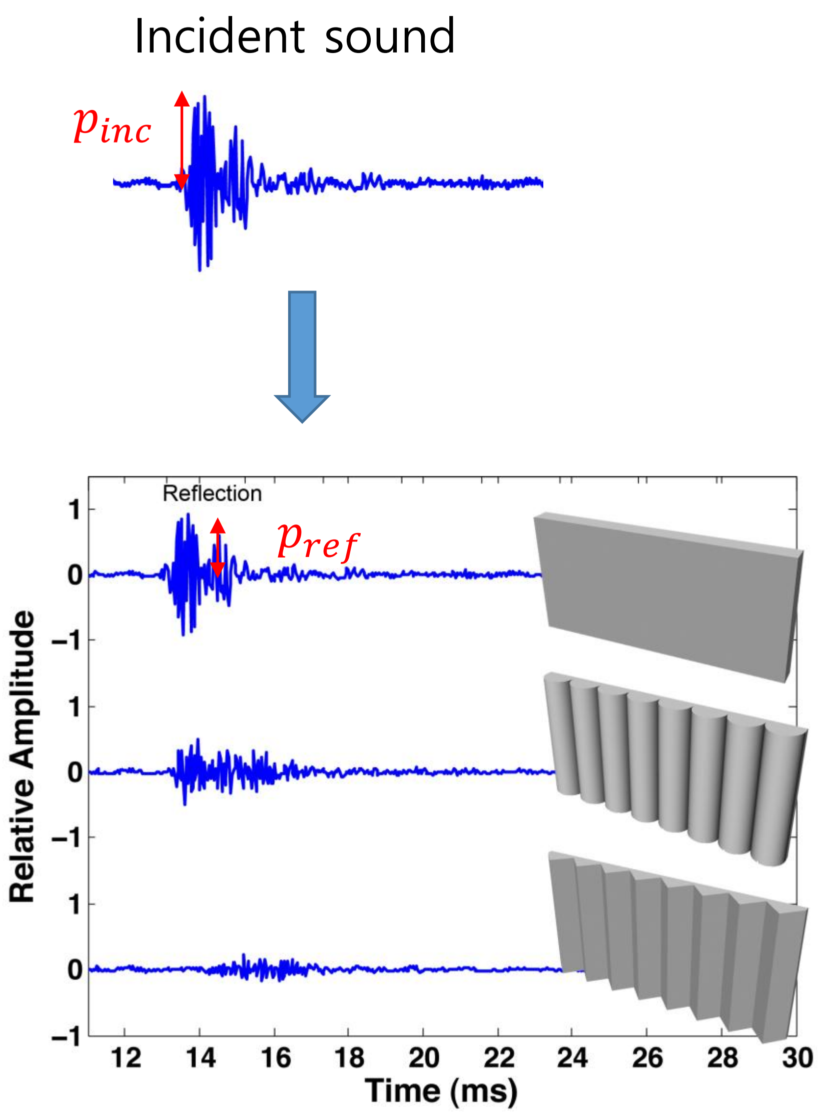
- If reflection occurs, what happens?
  - If the wall is a rigid body, It should be a fixed boundary condition



Reflection

- If reflection occurs, what happens?
  - If the wall is <u>a rigid body</u>, It should be a fixed boundary condition

  - How will the sound intensity change?
    - Reflection coefficient: $R_p = \frac{p_{ref}}{p_{inc}}$
    - Reflection coefficient는 material마다 다르다!

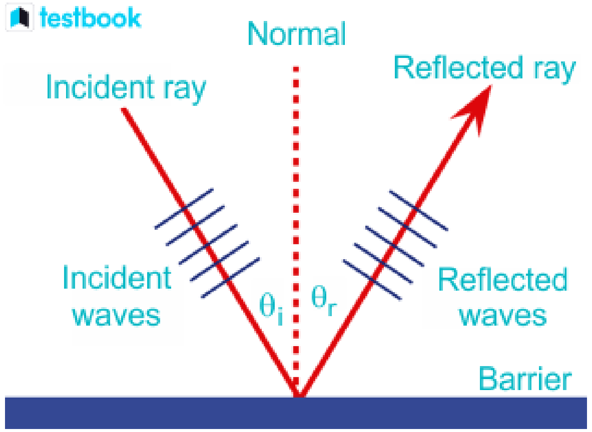


Reflection

- If reflection occurs, what happens?
  - If the wall is <u>a rigid body</u>, It should be a fixed boundary condition
  - How will the sound intensity change?
    - Reflection coefficient: $R_p = \frac{p_{ref}}{p_{inc}}$

입사각에 따라 Reflection coefficient가 달라진다.

  - What happens if the angle of incidence is not 90 degrees? → **Specular reflection**



Reflection law

Reflection

- If reflection occurs, what happens?
  - If the wall is <u>a rigid body</u>, It should be a fixed boundary condition
  - How will the sound intensity change?
    - Reflection coefficient: $R_p = \frac{p_{ref}}{p_{inc}}$

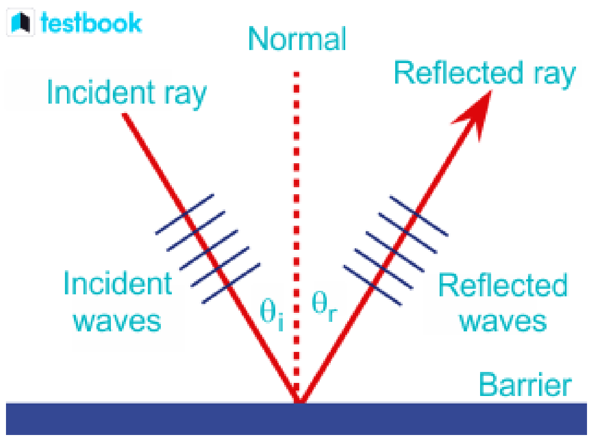
$$p_{inc}(x,t) = Ae^{i(kx-\omega t)}$$

$$\Downarrow$$

$$p_{ref}(x,t) = R_p \cdot p_{inc}(-x,t) \cdot e^{i\pi}$$

입사각에 따라 Reflection coefficient가 달라진다.

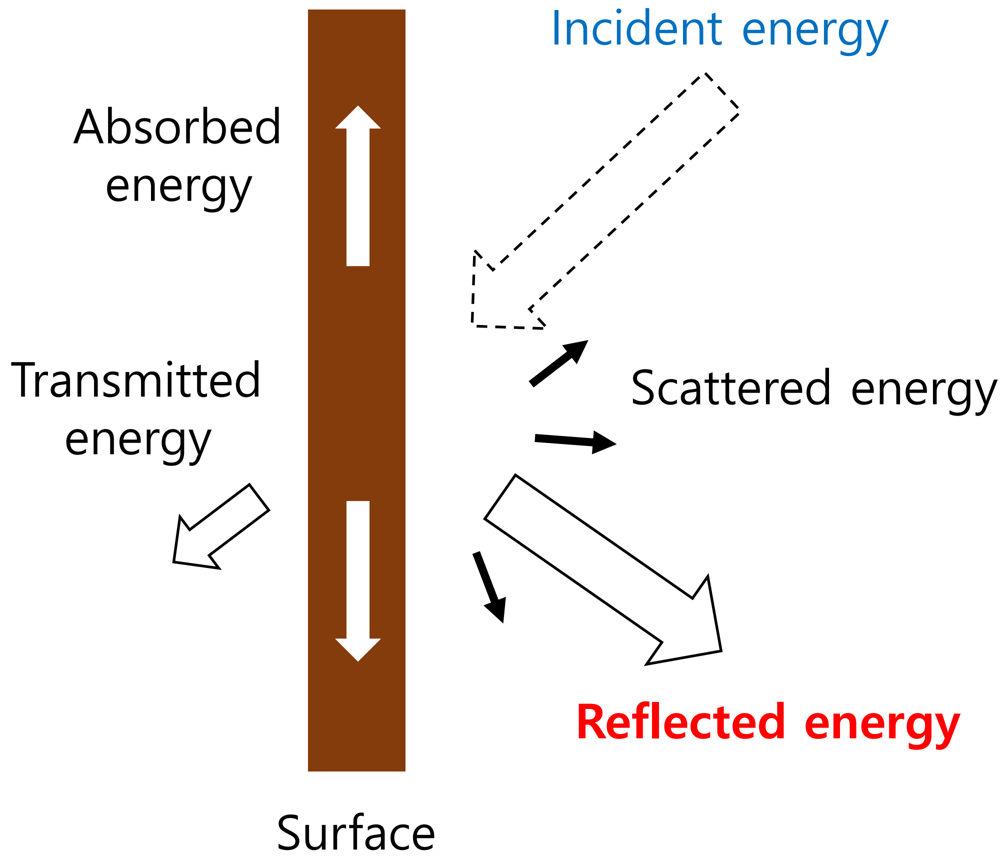
  - What happens if the angle of incidence is not 90 degrees? → **Specular reflection**



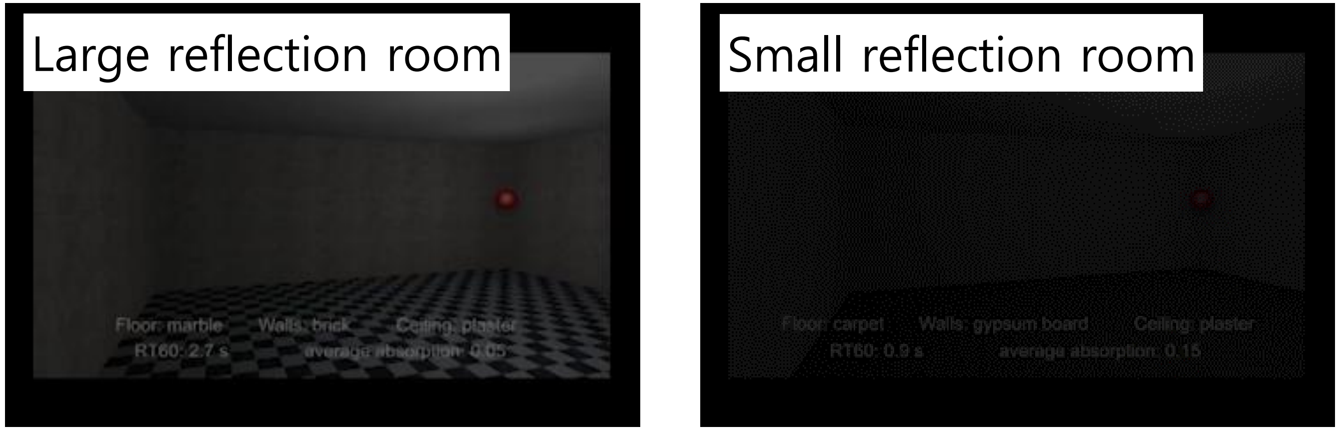
Reflection law

Acoustic Materials

- The properties to determine how incident sound interacts with the surface.
  - The acoustic material depends on the frequency of the sound.

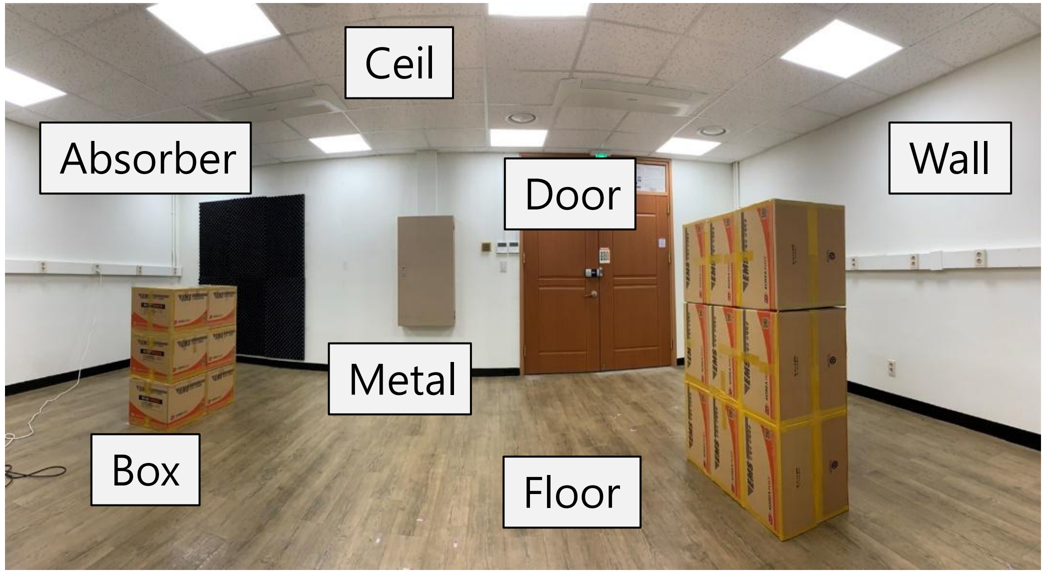


Sound comparison between different acoustic material (e.g. reflection)

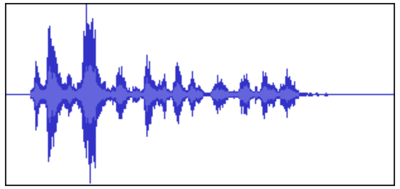


Videos from "Acoustic Classification and Optimization for Multi-Modal Rendering of Real-World Scenes, TVCG 18"

Acoustic Materials

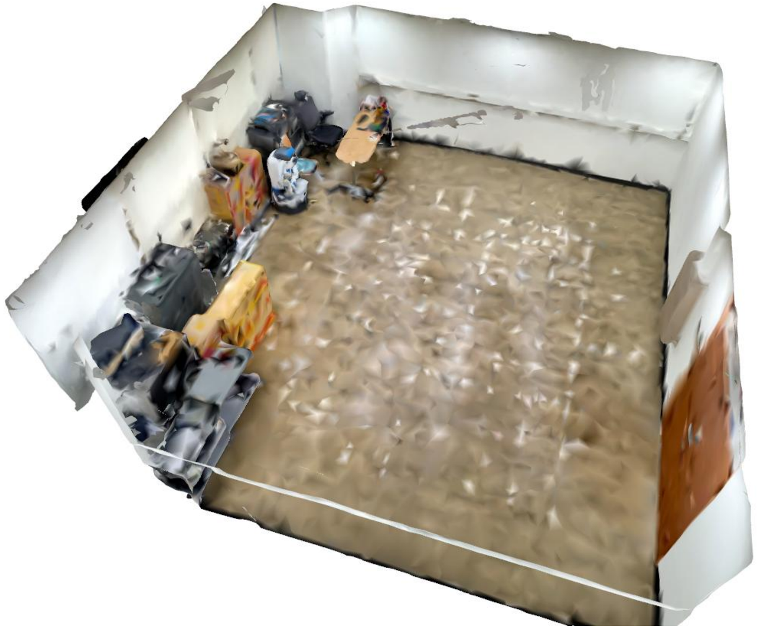


Real world indoor scene



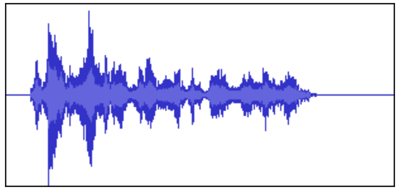
Recorded sound in real world

Estimating Acoustic Materials

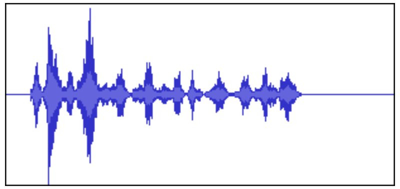


Virtual world indoor scene

Utilizing Sound Simulator (**Habitat2.0**)



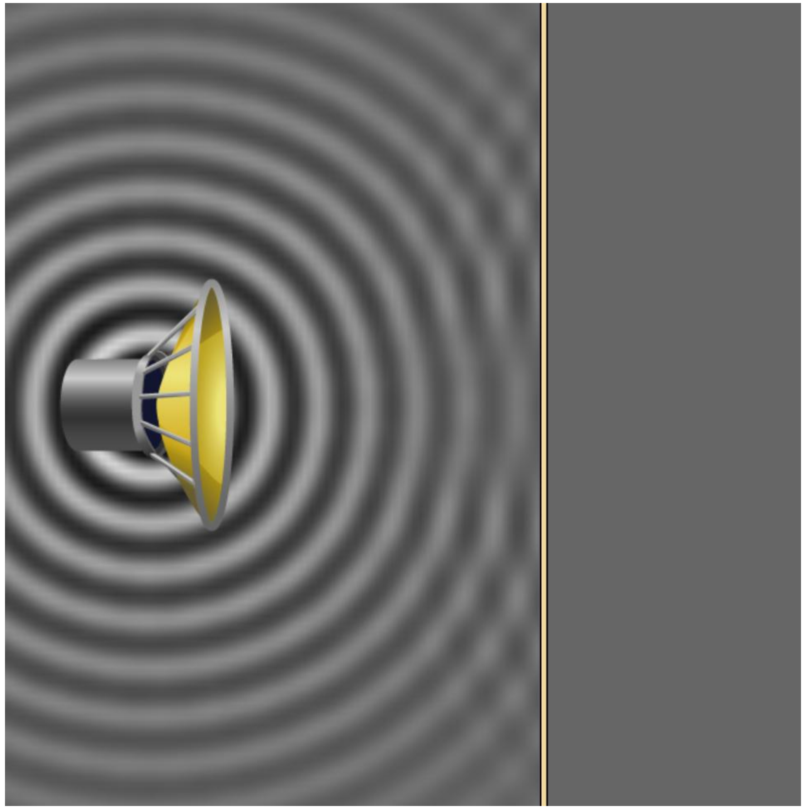
Generated sound without considering acoustic material

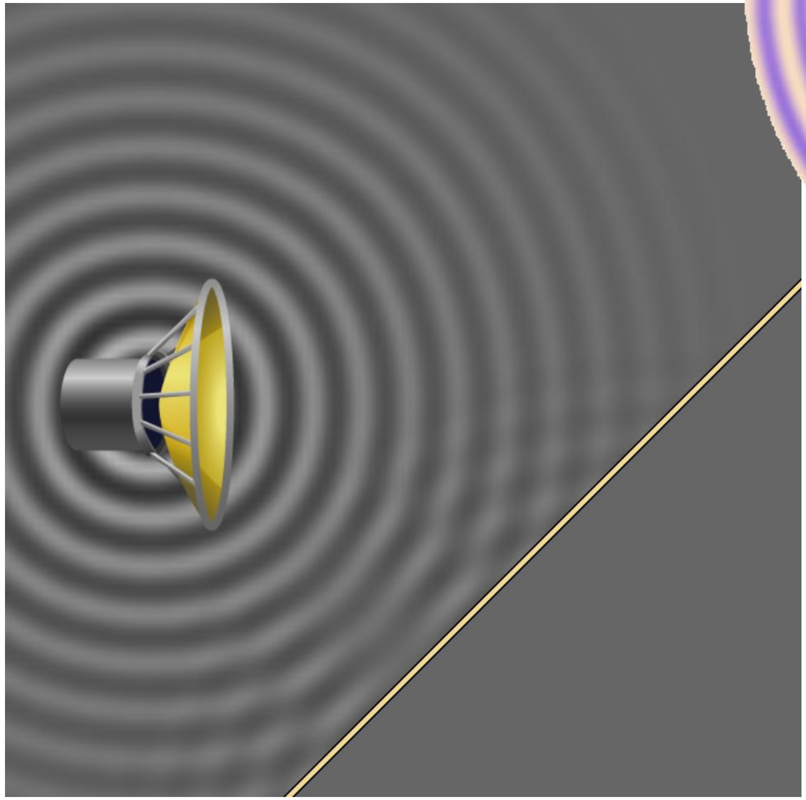


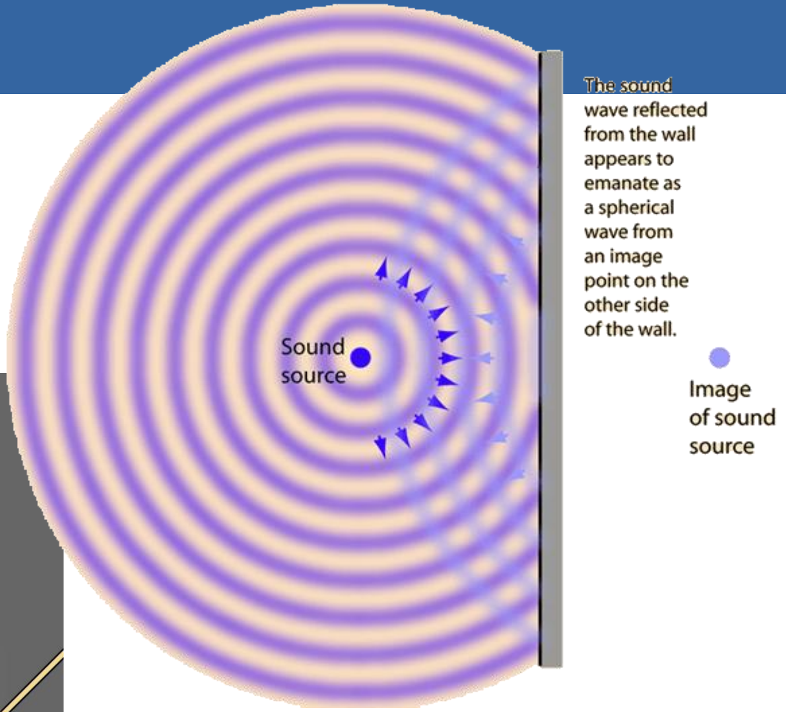
Generated sound using appropriate acoustic material

Reflection

- If reflection occurs, what happens?
  - Spherical wave → **Imaginary source (<u>Specular reflection only</u>)**



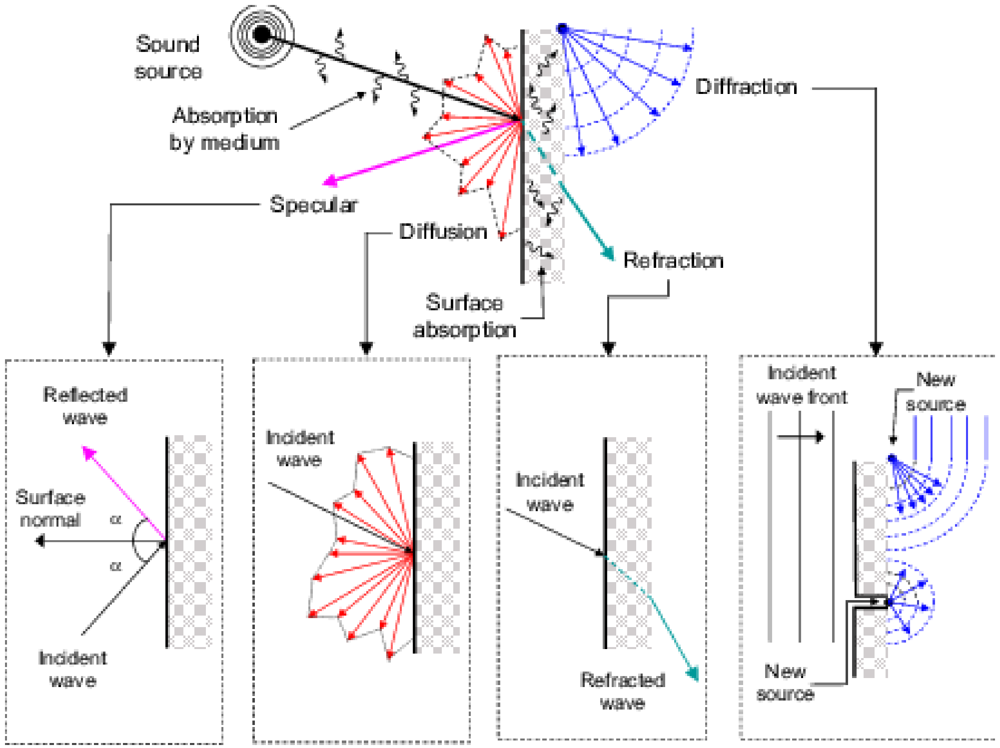


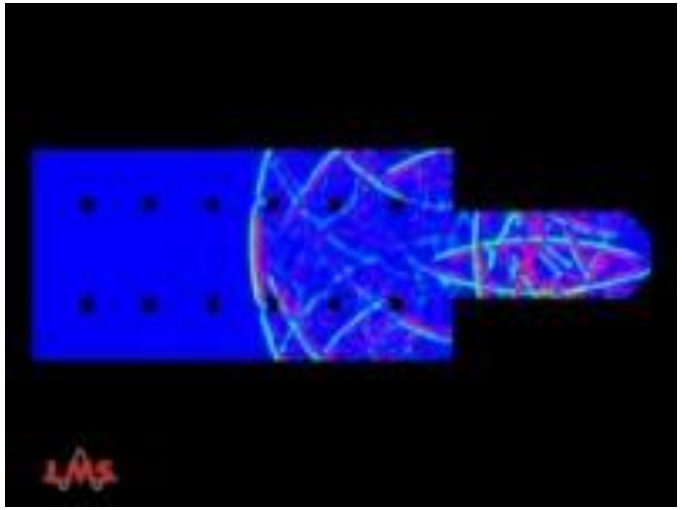


Reflection

- If reflection occurs, what happens?
  - If the wall is a rigid body, It should be a fixed boundary condition

소리가 물체에 충돌할 때, specular reflection (정반사) 뿐만 아니라, **Diffuse, refraction, diffraction** 등이 함께 발생한다.

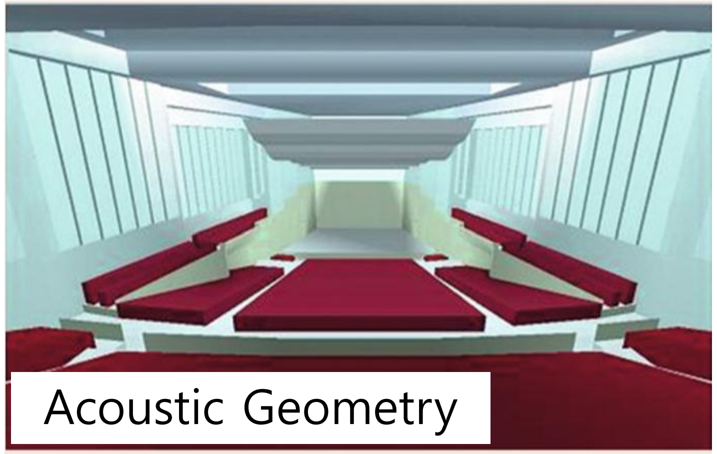




이를 정확하게 Simulation하는 것은 매우 시간이 많이 걸린다.

Geometrical Acoustics

- The easiest way to model a realistic sound is by recording.
  - Difficult to simulate the various sound effects.
- Recently, a method using "**Sound propagation**" has been used.
  - Sound simulator needs **3-D geometry information** and **acoustic material properties** for realistic sound generation.



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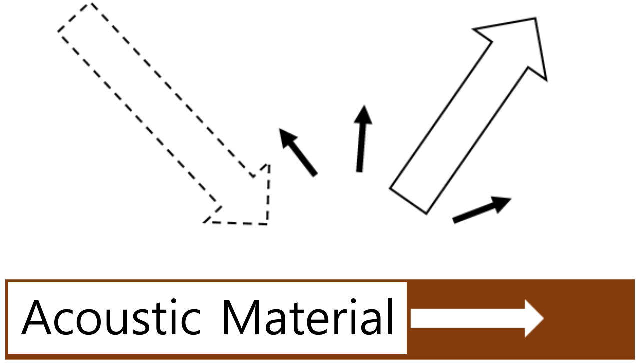

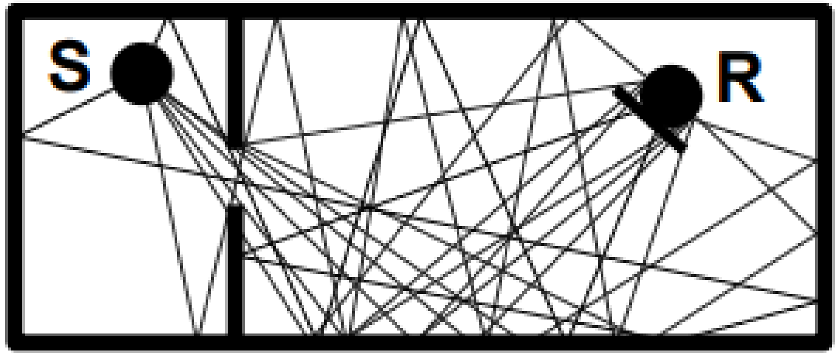

Sound propagation paths