ROOM ACOUSTICS

Room acoustics

Room acoustics shapes every sound we hear and create. Understanding how spaces interact with sound enables:

- Microphone placement decisions
- Informed choice of performance venues
- Creative use of acoustic environments

Historical development of acoustics

Antiquity:

- Pythagoras & Hippasus: Mathematical basis of sound (monochord)
- Archytas: Physical vibrations as source of sound
- Vitruvius: Acoustic design in amphitheaters (echea/resonators)

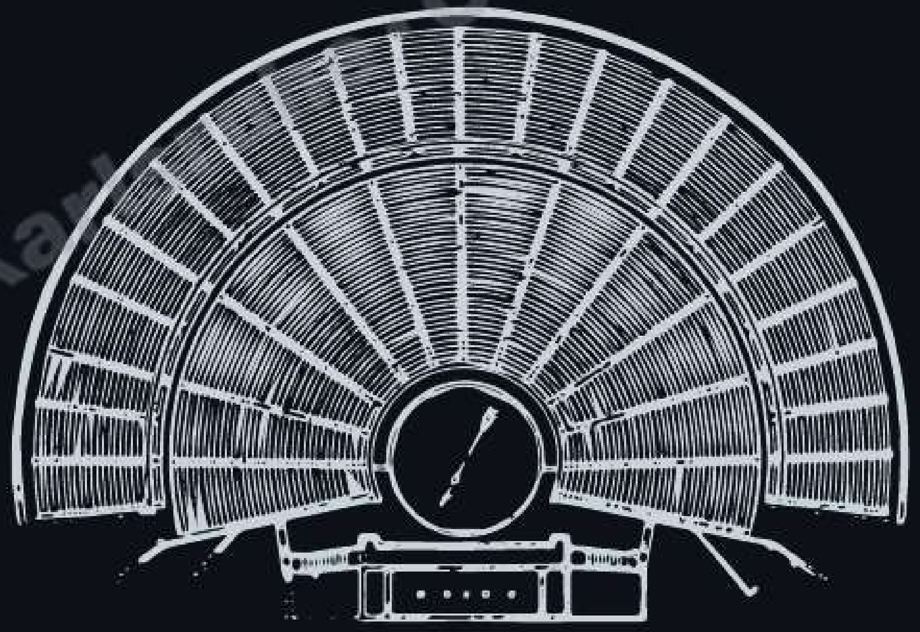
Modern era:

- Wallace Clement Sabine (1868–1919): Quantitative architectural acoustics
- Developed reverberation time measurement (RT_{60})
- First scientifically designed concert hall (Boston Symphony Hall)

Amphitheater

Amphitheaters exhibit remarkable acoustics, achieved through their architectural design, and are characterized by high speech intelligibility across the audience area:

- Amplification of relevant frequency bands
- Balanced reverberation time
- Uniform sound distribution
- Low background noise levels



Layout of the ancient theatre of Epidaurus

FIELDS · PROPAGATION · BOUNDARIES

Acoustic Fields

Understanding sound propagation requires considering:

- The **acoustic environment** (open or enclosed space)
- The **listening position** relative to the sound source

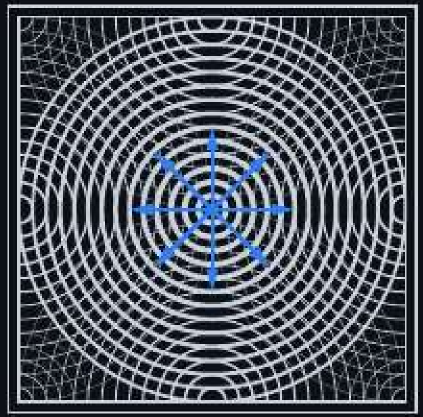
These factors determine how sound energy behaves and is perceived.

Free field vs. diffuse field

Free field (open space):
Sound propagates without reflections. Only direct sound is present; intensity decreases by inverse-square law.

Diffuse field (closed space):
Sound reflects off boundaries, creating a mix of direct and reflected sound.

▶ Free field (direct sound)



▶ Diffuse field (reflections)

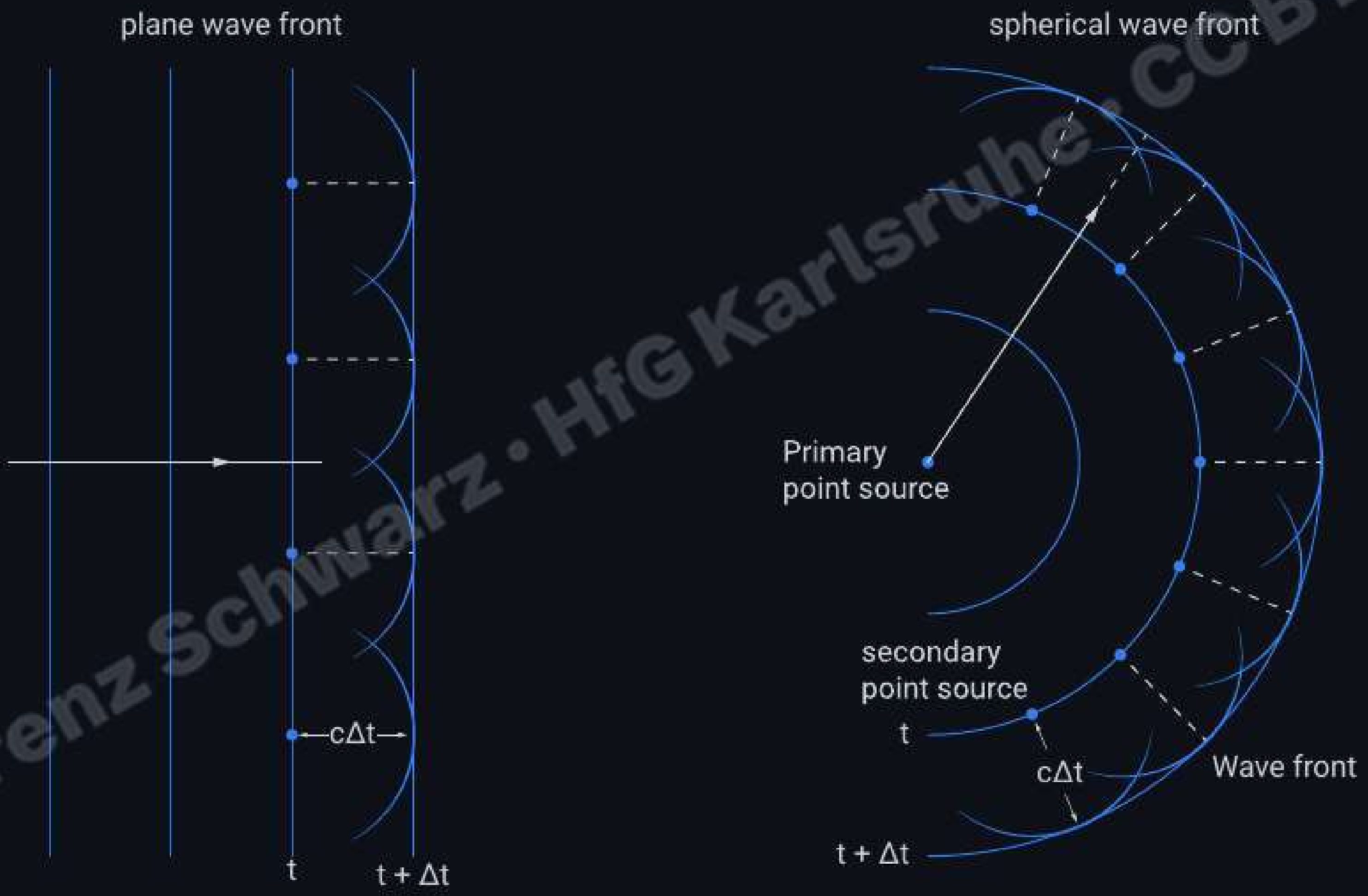
Wave propagation and Huygens' principle

Huygens' principle states that every point on a wavefront acts as a source of secondary spherical wavelets.
The superposition of these wavelets forms the new wavefront as the wave propagates.

This principle explains:

- **Diffraction:** bending and spreading of waves around obstacles or through openings
- **Refraction:** change in wave direction when passing between media

Wavefront construction from secondary wavelets

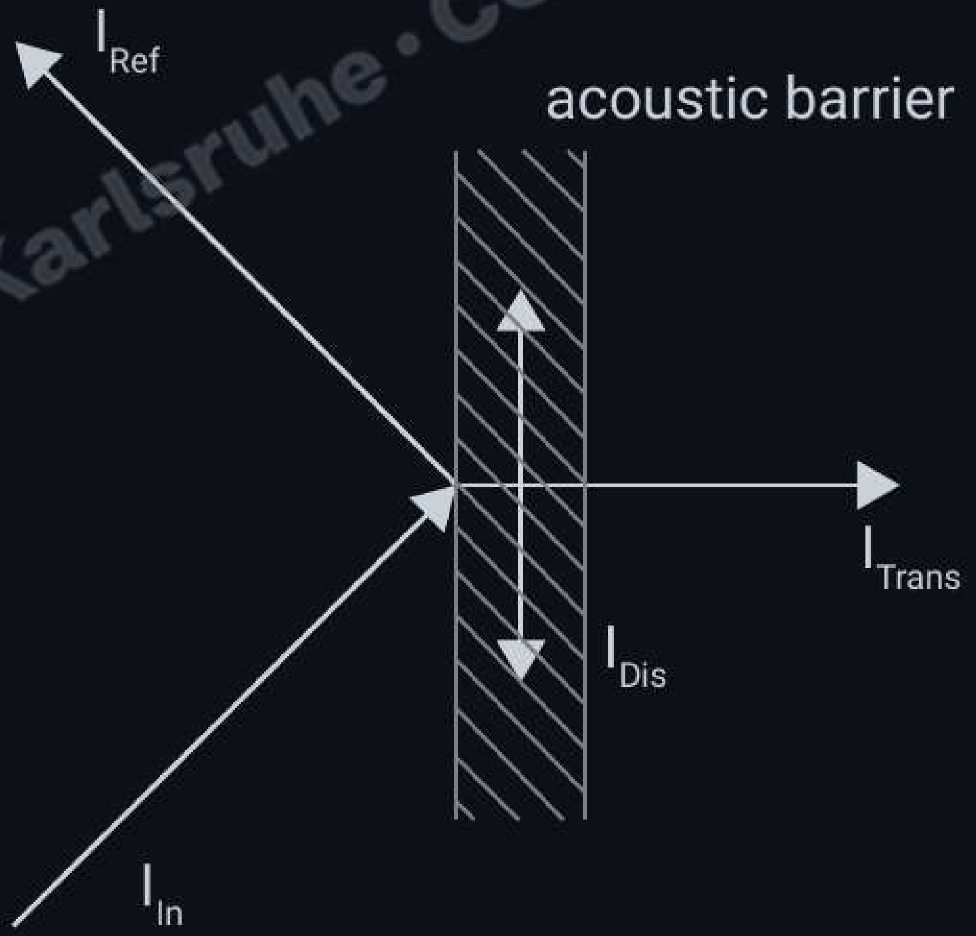


REFLECTION · DIFFUSION · ABSORPTION

Wave behaviour at acoustic barriers

Possible paths of sound waves when encountering an acoustic barrier:

- I_{In} Incoming sound wave.
- I_{Ref} Reflected sound wave.
- I_{Dis} Absorbed sound wave, dissipated as heat within the barrier.
- I_{Trans} Transmitted sound wave passing through the barrier.



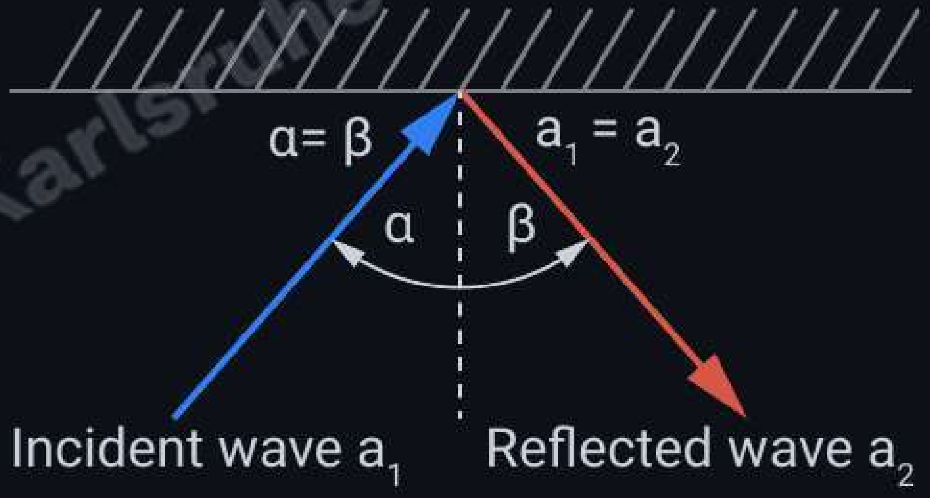
Acoustic barriers and boundaries

Surface shapes and materials have a profound effect on the behavior of sound waves:

- Reflection
- Diffusion
- Absorption
- Diffraction
- Refraction

Reflection

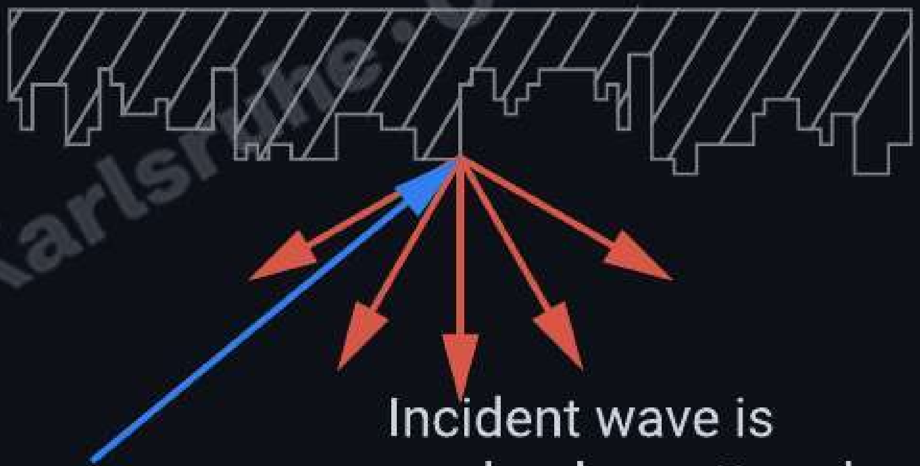
Sound waves interact with surfaces through reflection, where the angle of incidence equals the angle of reflection.



Diffusion

Irregular surfaces diffuse sound waves by scattering them in multiple directions.

- Reduces echoes
- Enhances acoustic quality
- Creates a more balanced sound environment

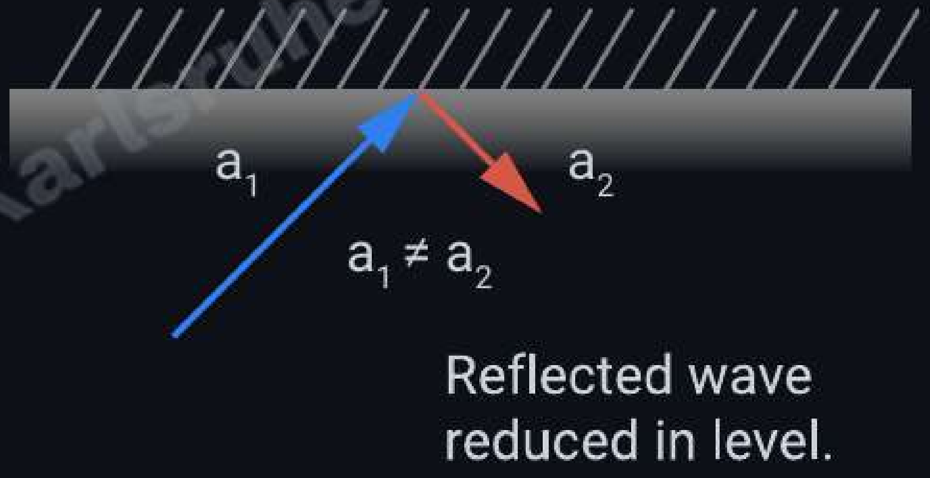


Incident wave is randomly scattered.

Absorption

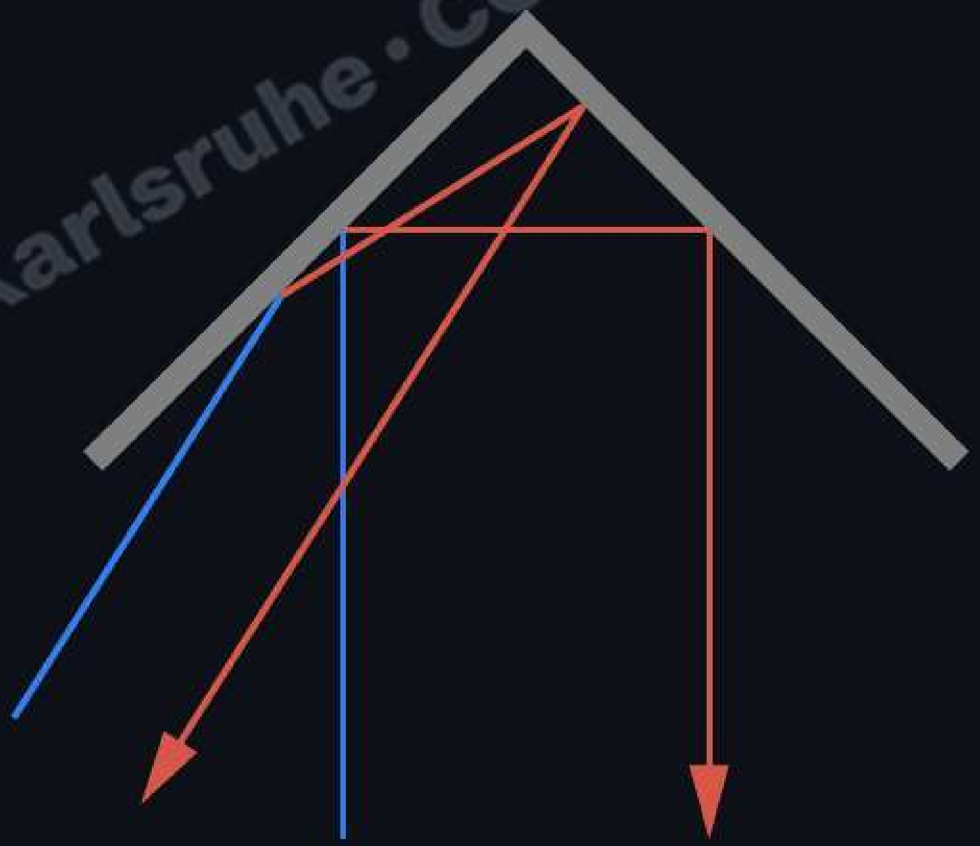
Porous or soft materials absorb sound energy, converting it into heat.

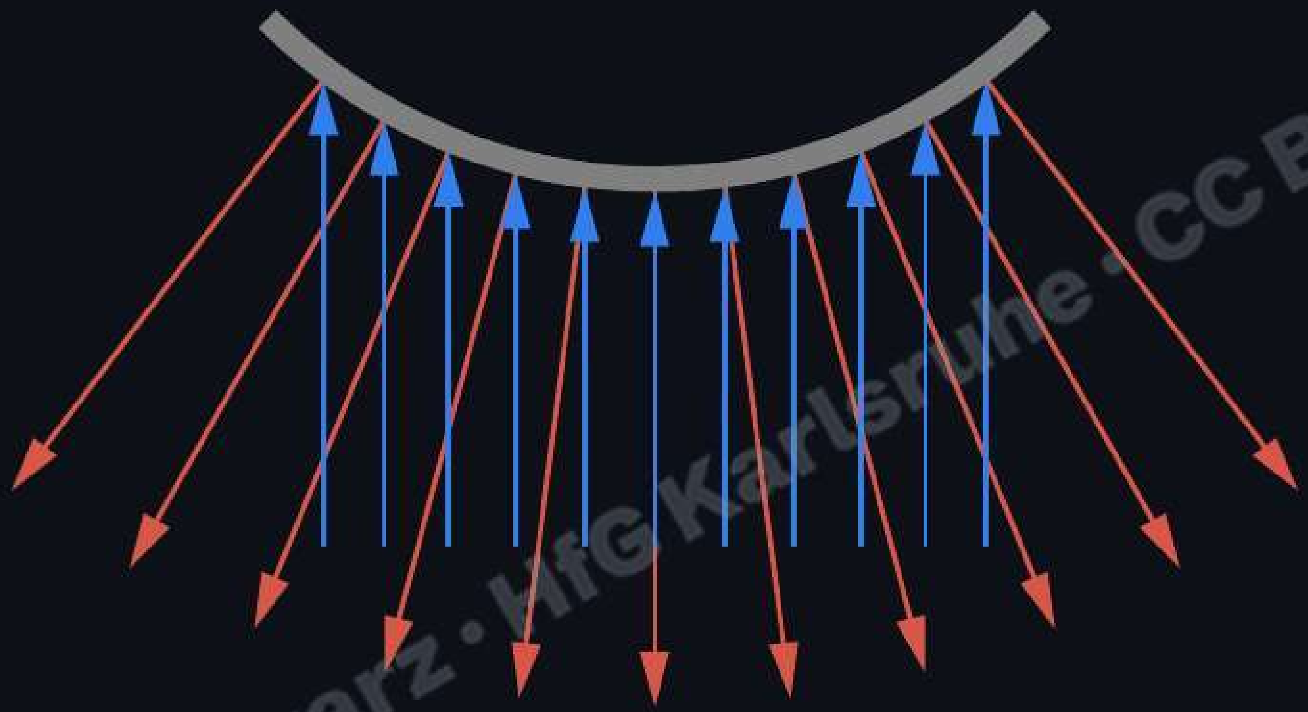
- Reduces reverberation and noise levels



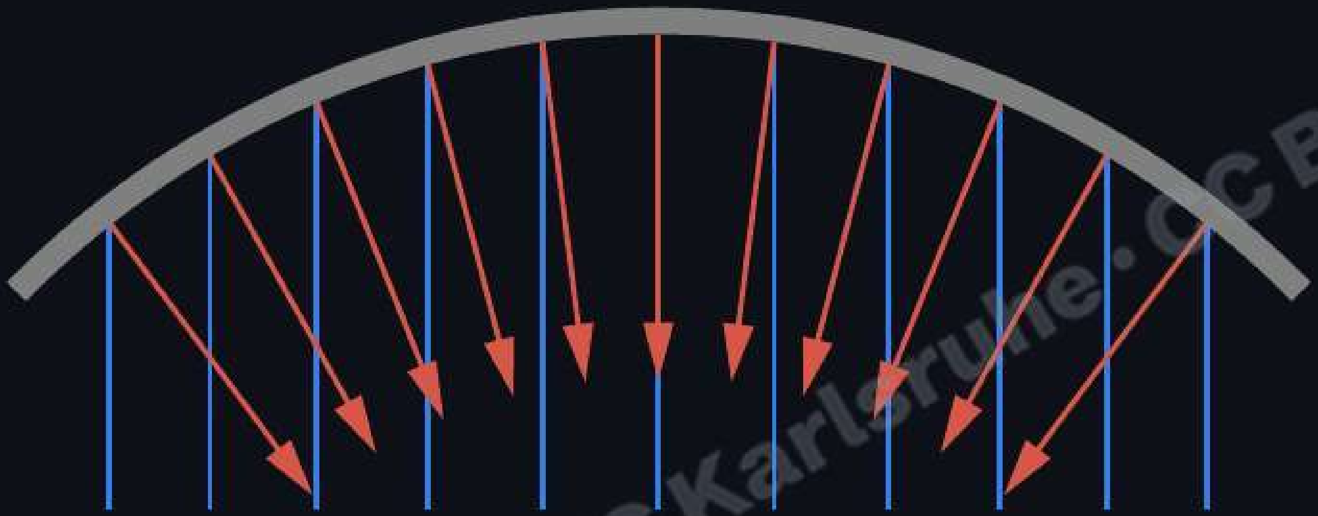
Room corners

- Corners return sound to its source.
- Directivity control at low frequencies.
- Problematic reflections at high frequencies.





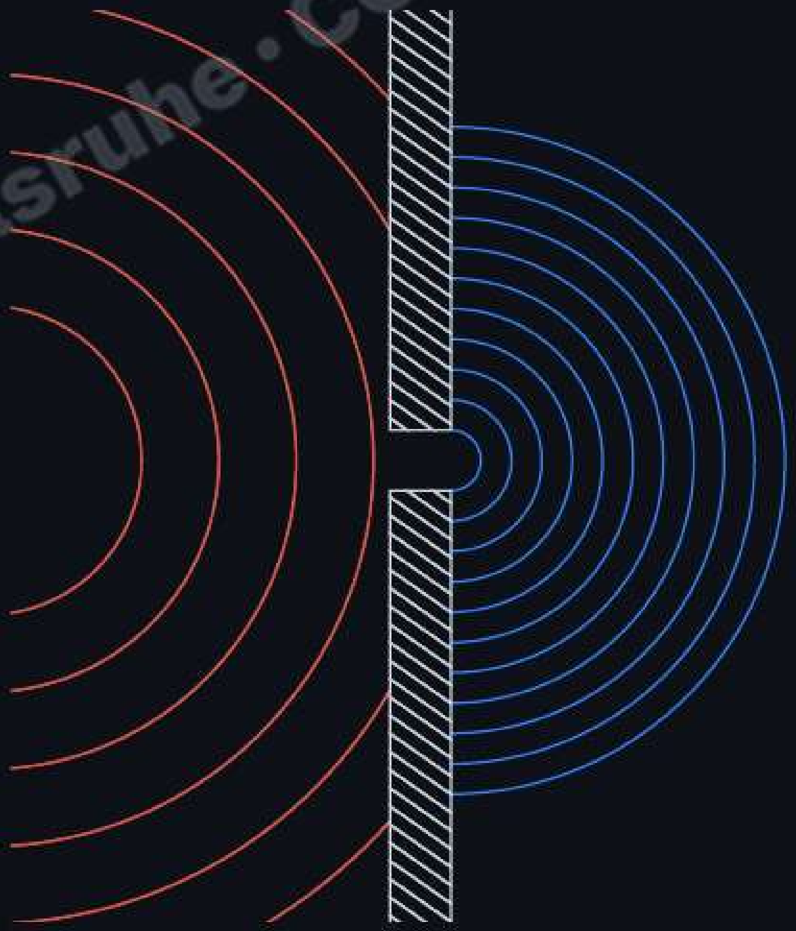
Convex surfaces scatter sound.



Concave surfaces focus sound.

Diffraction

Sound waves bend around obstacles and spread through small openings, allowing them to travel beyond direct lines of sight.

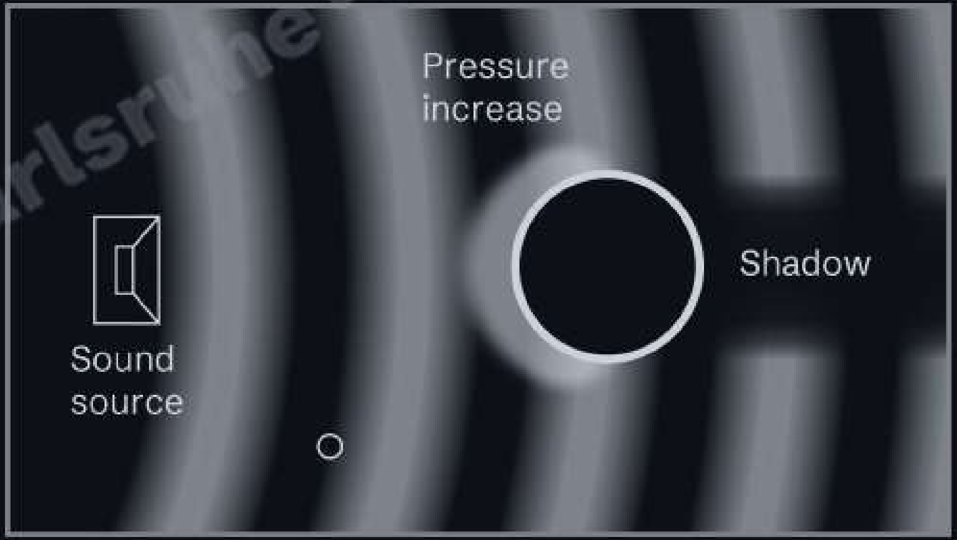


Acoustic shadow

Acoustic shadow and diffraction depend on wavelength and obstacle size.

$$d = 5 \cdot \lambda = 5 \cdot \frac{c}{f}$$

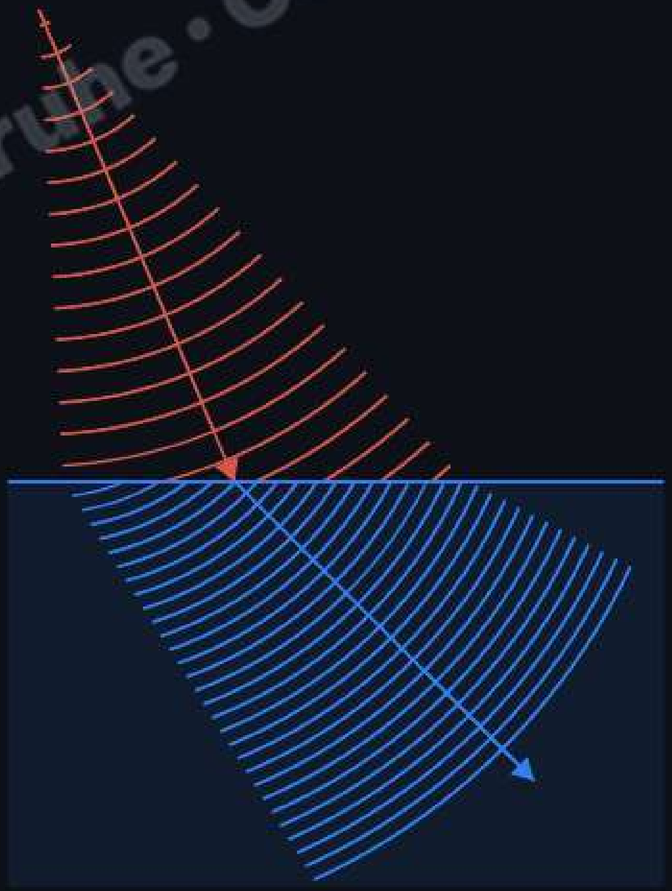
where d is the obstacle size, λ is wavelength, c is speed of sound, and f is frequency.



Acoustic shadow behind an obstacle

Refraction

Changes in the medium (e.g., temperature, air density) or variations in surface curvature cause sound waves to bend, altering their direction and intensity.



REVERBERATION · MODES · RESONANCE

Sound in enclosed spaces

When sound propagates within an enclosed space, it interacts repeatedly with multiple surfaces.
These interactions give rise to characteristic acoustic effects that shape how a room sounds.

Typical phenomena include:

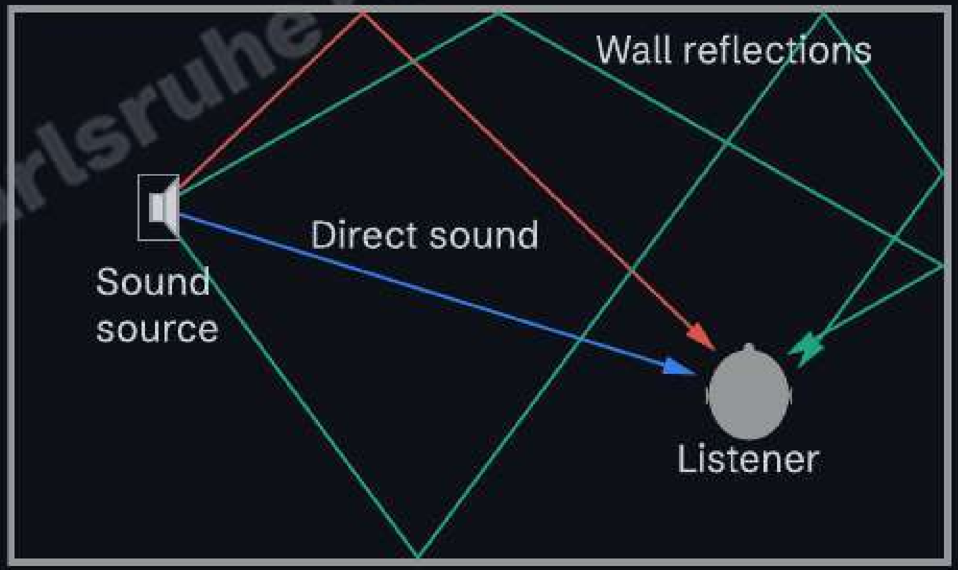
- **Reverberation** – persistence of sound due to repeated reflections
- **Standing waves** – resonances caused by boundary conditions

Together, these effects determine the acoustic character of a space.

Reverberation

Reverberation is the persistence of sound in a space, caused by multiple reflections of sound waves off surfaces. It is the sum of sound reflections in an enclosed space that arrive after the direct sound.

▶ Impulse responses of various spaces



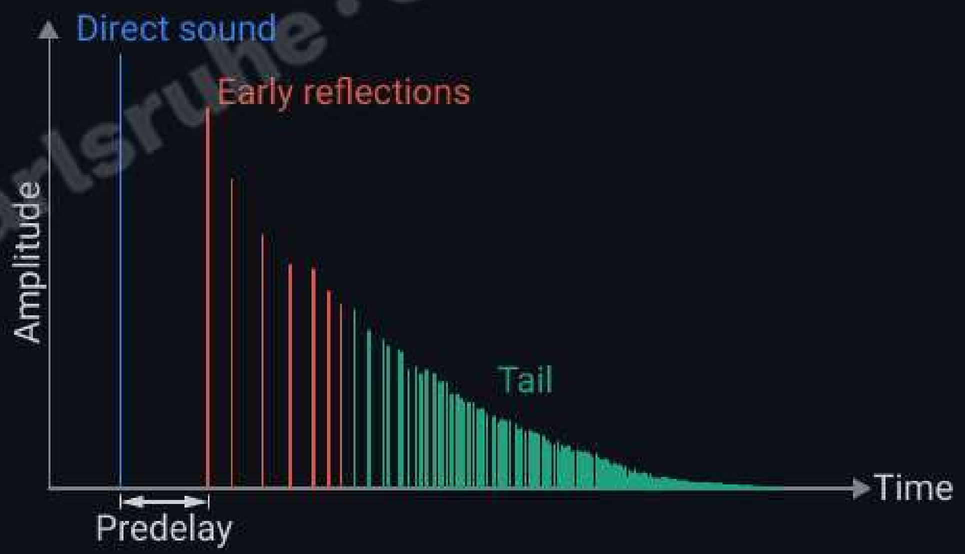
Reverberation in an enclosed space

Reverberation

- No reverberation (e.g., in an anechoic chamber) sounds unnatural and artificial.
- Excessive reverberation reduces speech intelligibility (e.g., measured by Alcons).
- Can make certain sound structures muddy and unclear.
- Can mask imprecise playing by a musician.
- Enhances and amplifies sound, making it richer and more resonant.

Temporal structure of reverberation

- **Direct sound:** The initial sound wave that travels straight from the source to the listener without any reflections.
- **Predelay:** The time gap between the arrival of the direct sound and the first early reflection.
- **Early reflections:** First set of reflected sound waves that arrive shortly after the direct sound.
- **Reverberation tail:** Overlapping reflections that decay gradually over time.

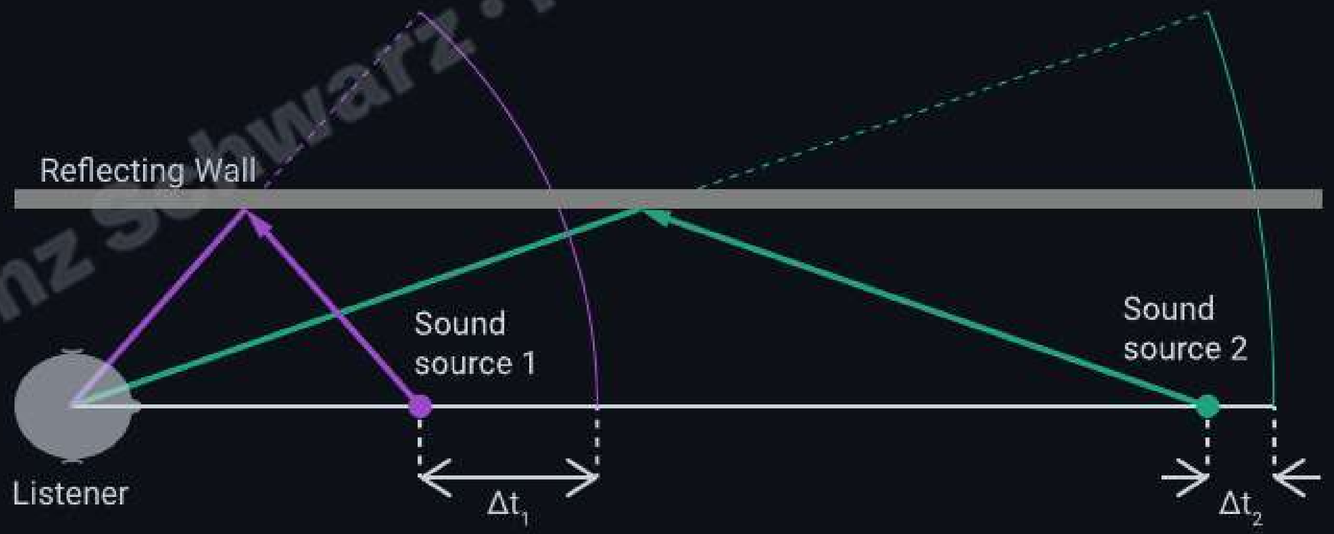


Temporal structure of reverberation

Initial time delay gap (ITDG)

The Initial Time Delay Gap (ITDG) is the time interval between the direct sound and the first early reflection at the listener's position.

→ *Close sound sources result in a longer ITDG, while distant sound sources result in a shorter ITDG.*



Echo

An echo is a distinct, repeated sound reflection heard after the original direct sound.

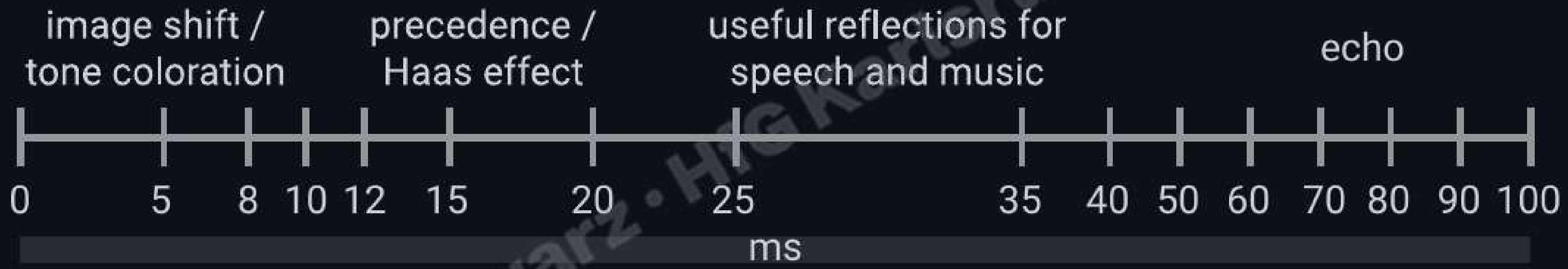
→ Whether a sound is perceived as an echo depends on the nature of the sound and the number of reflecting surfaces.

Precedence effect (Haas effect)

The precedence effect describes how spatial localization of a sound is dominated by the "first wavefront", even if subsequent copies of the sound (reflections) arrive within a short delay window (a few ms to ~30 ms).

- Law of the first wavefront

Audible effects of delayed signals of equal level

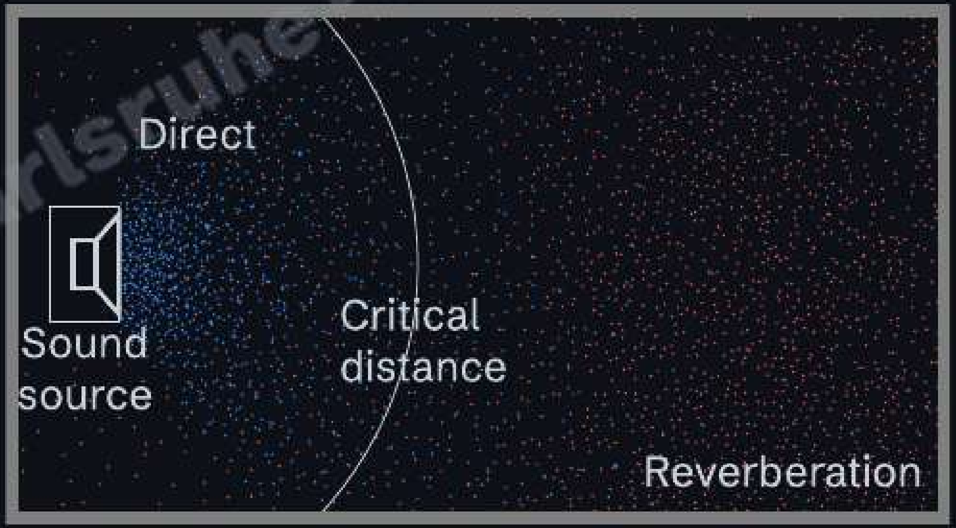


▶ Effects of different delays 0, 1, 20, 45, 100 ms

Critical distance

The critical distance is the point in space where the combined amplitude of all reflected sound (R) equals the amplitude of the direct sound (D) from the source (D = R).

→ Sound reflections = direct sound

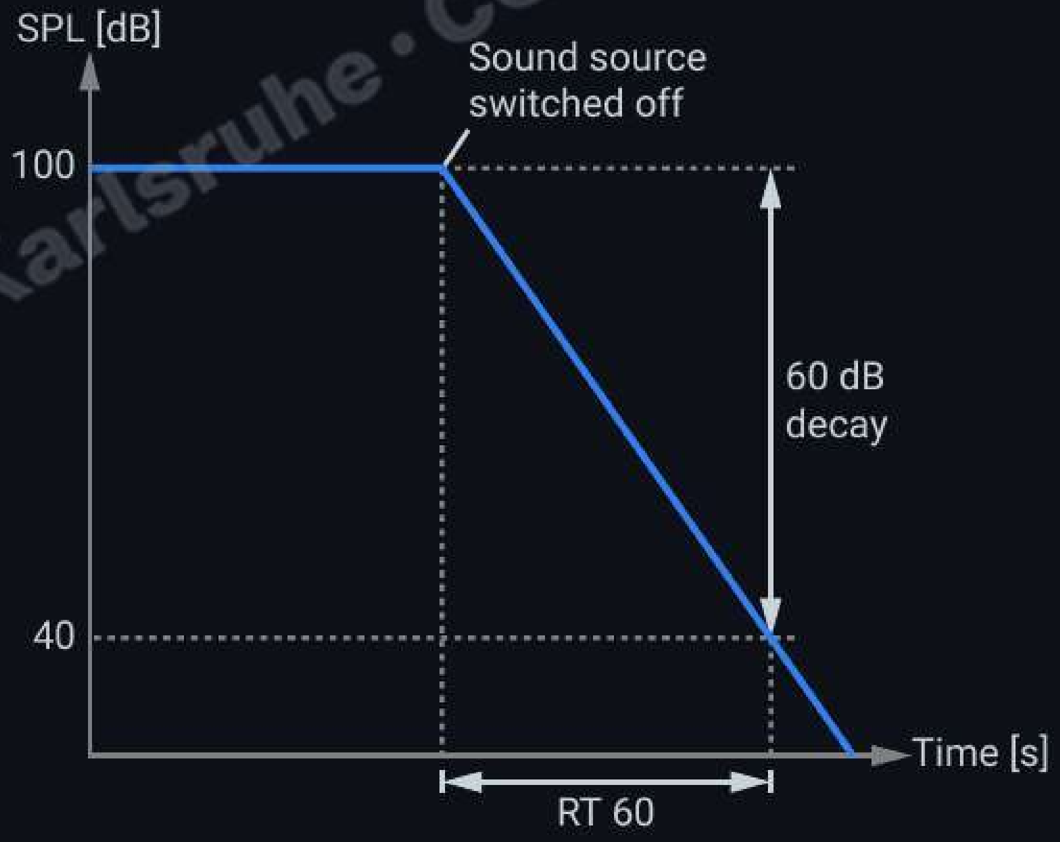


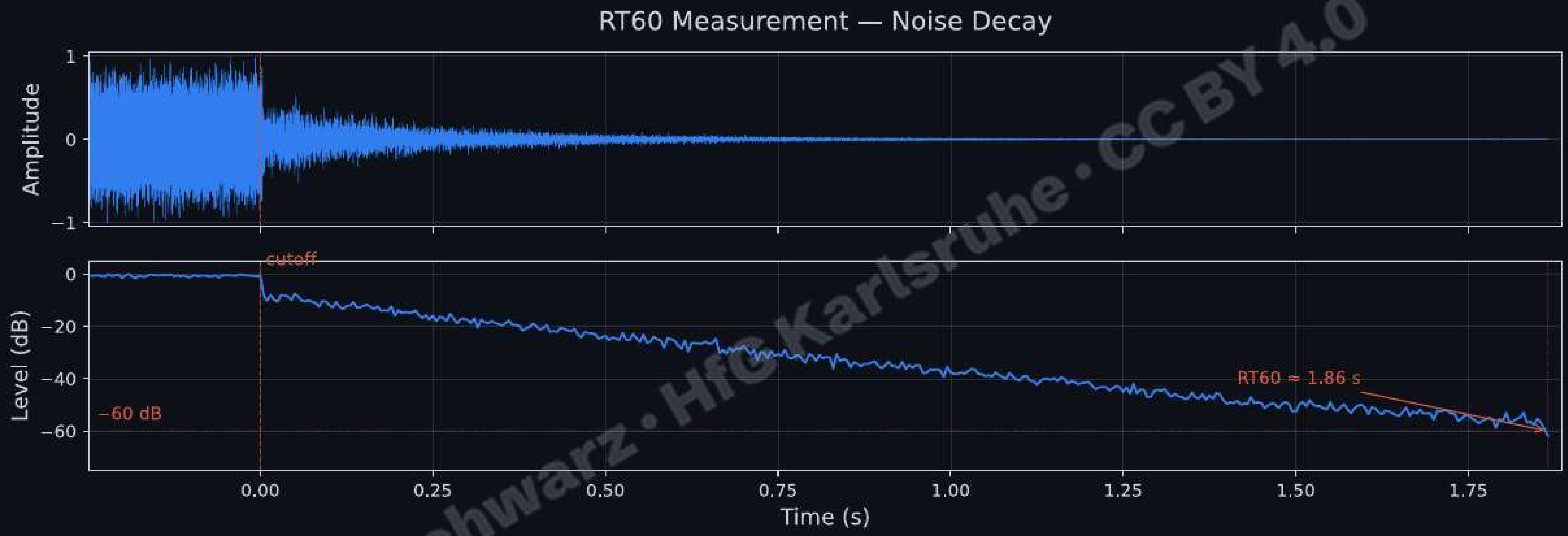
Critical distance: D = R

Reverberation time (RT_{60}) measurement

T_{60} measurement:

- The time required for the sound pressure level to decrease by 60 dB after a test signal is abruptly stopped.





- RT60 measurement of noise decay

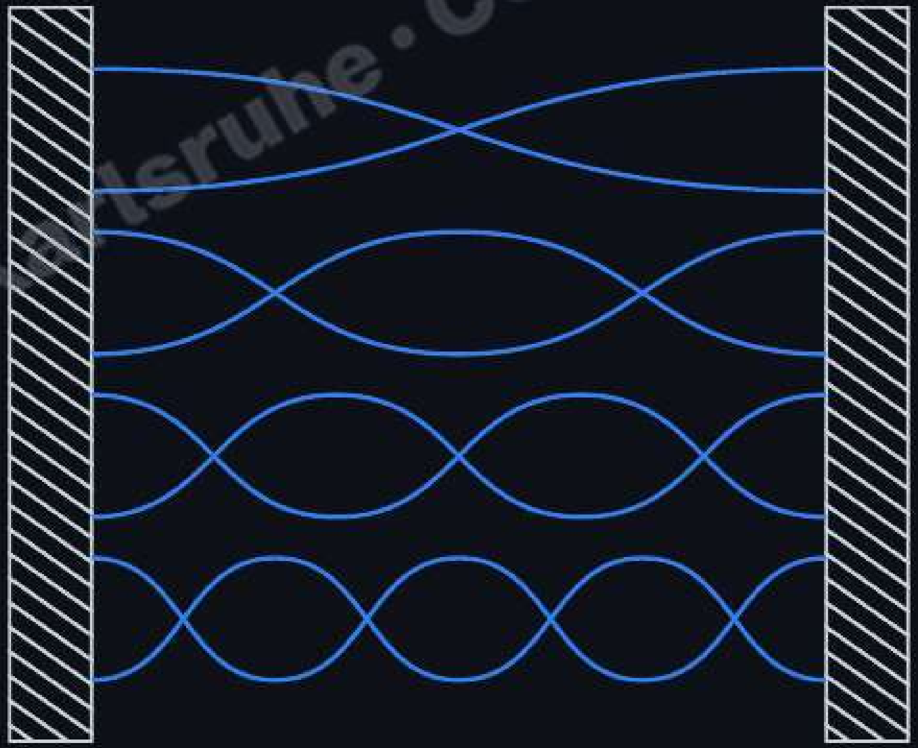
Room modes

Resonant frequencies in a room create standing waves with zones of high and low sound pressure, shaping the room's frequency response.

- **Node:** Point where sound waves cancel each other out (minimum pressure)
- **Antinode:** Point where sound waves reinforce each other (maximum pressure)

$$f_{res} = \frac{c}{2L}$$

L — longest distance in meters between boundary surfaces.



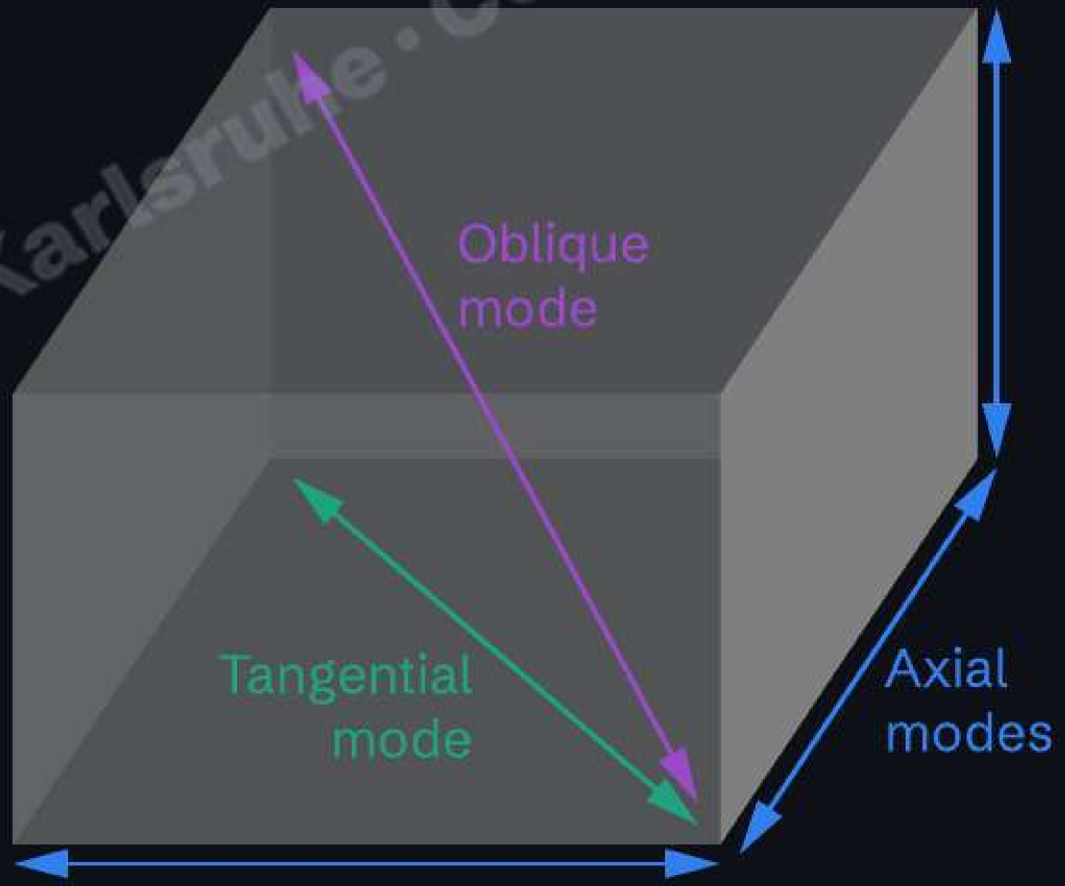
Room modes refer to standing waves that occur in an enclosed space.

Room modes

- **Axial:** along one dimension (strongest)
- **Tangential:** between two surfaces (≈3 dB weaker)
- **Oblique:** across three surfaces (≈6 dB weaker)

→ *Room modes can lead to uneven bass response, with certain frequencies being amplified or diminished at specific locations.*

▶ Sine sweep and room modes



Anechoic chamber

A controlled environment for acoustic measurements under free-field conditions.

- Insulated against structure-borne sound.
- Constructed using sound-absorbing materials.
- Provides an approximation of free-field conditions.

Reverberation time guidelines

A general guideline for roughly evaluating the quality of auditory conditions in a typical multi-purpose auditorium:

- **Below 1 second (lecture hall):** Good for speech, too dry for most music
- **1 to 1.5 seconds (concert hall):** Good for speech and chamber music
- **1.5 to 2 seconds:** Fair for speech, good for orchestral, choral, church music
- **Over 2 seconds (church):** Poor for speech, good for large organ, liturgical choir

Artificial reverberation

Artificial reverberation simulates the natural persistence of sound in a space, adding richness and spatial depth.

- **Physical approaches:**
  - **Echo chambers:** Utilizing physical spaces to record natural reverberation
  - **Convolution reverb:** Recreating real acoustics by applying impulse response recordings
  - **Acoustic raytracing / finite element method:** Computational modeling of sound propagation and reflections
- **Synthetic approaches:**
  - **Plate and spring reverb:** Vibrating metal plates or coiled springs to emulate reflection patterns
  - **Digital delay lines:** Creating reverb through digital signal processing algorithms

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