BSc Degree in Physics

Room acoustics

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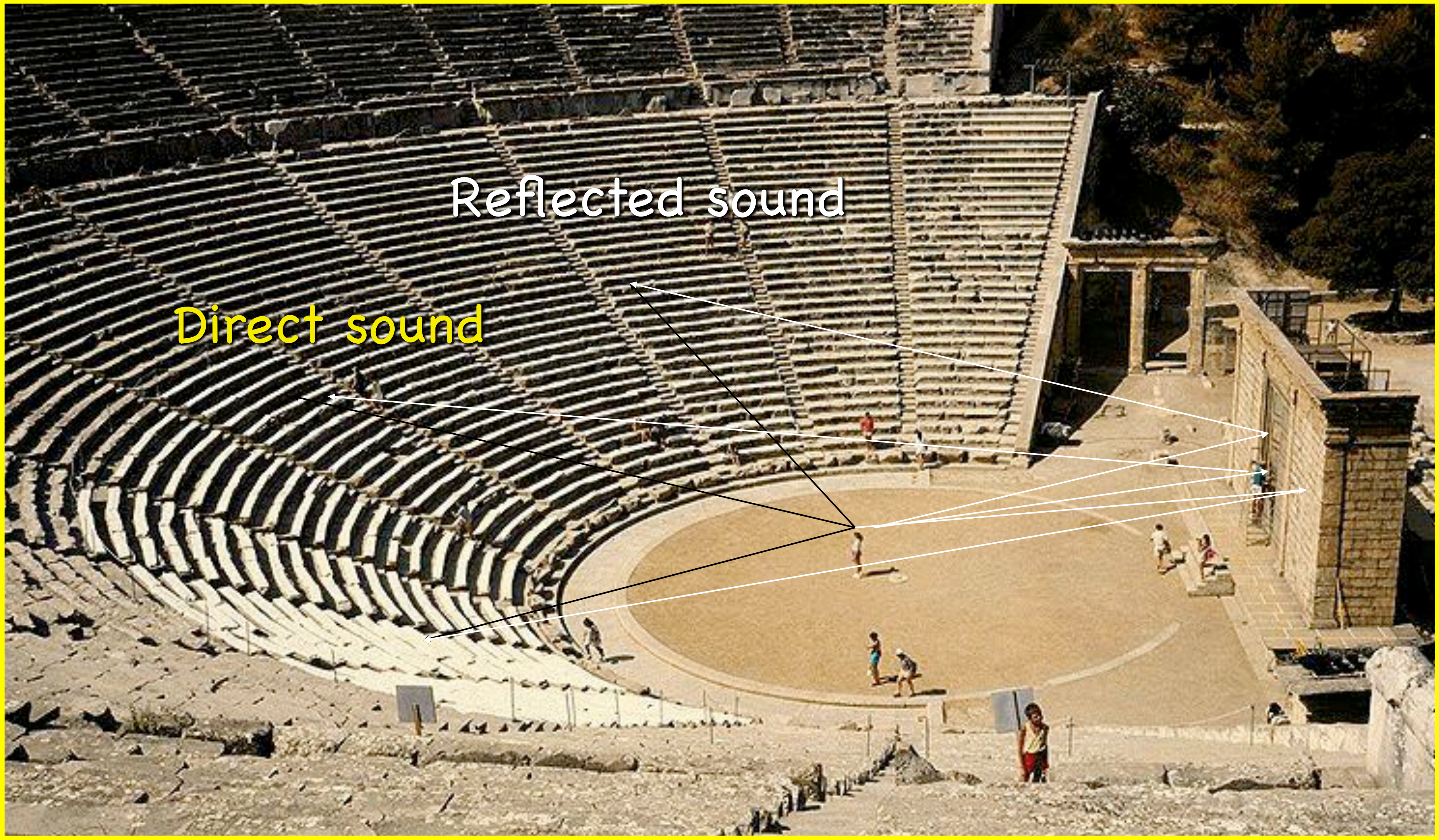
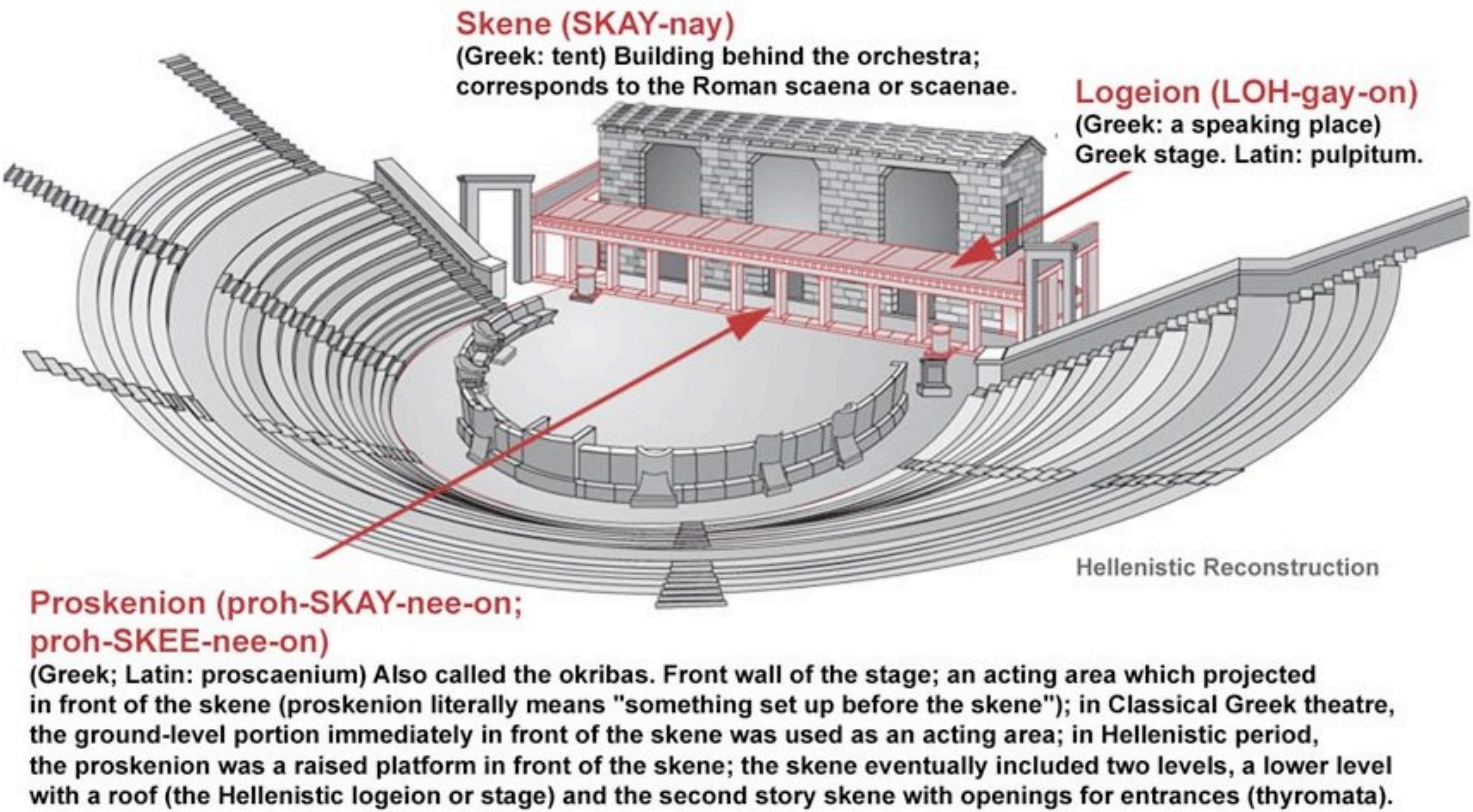
Greek amphitheater acoustics

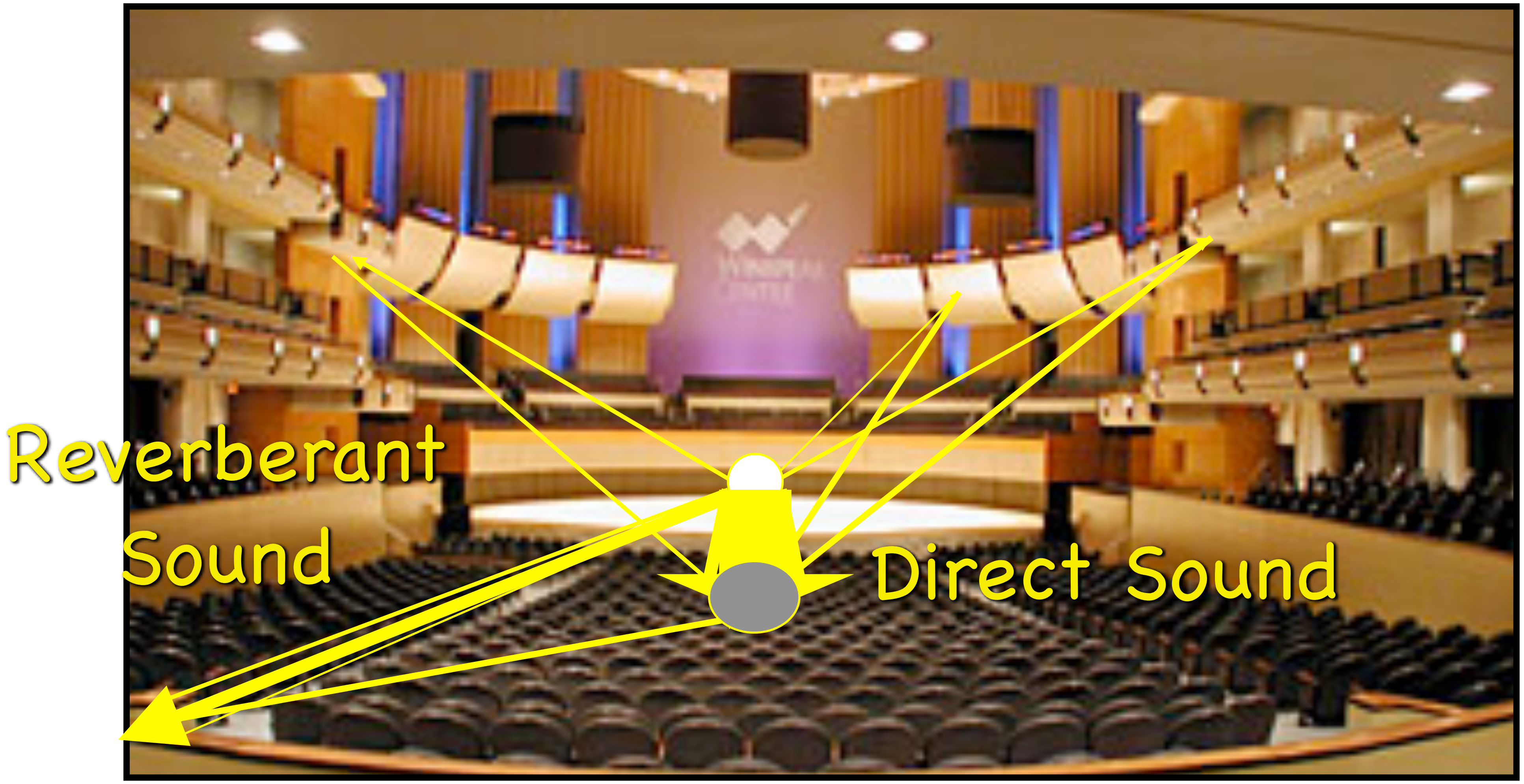


Greek amphitheater acoustics



Winspear Concert Centre

Edmonton, Canada



“Good” acoustics

Standards for “Good” Acoustics:

- Clarity ...little overlap of sounds
- Uniformity ...everywhere the same
- Envelopment ...sound from all directions
- Smoothness ...no echoes
- Reverberation ...appropriate length of time
- Performer satisfaction ...reflected to stage
- Freedom from noise ...no competition

Cardinal principle

Cardinal Principle of Room Acoustics

The temporal, spatial, intensity and phase relationships between the direct and reflected sound ultimately determine the quality of the acoustics in a room.

A room is an instrument that can dull the most illustrious performance by the most accomplished musician, or

it can increase the pleasure of listening.

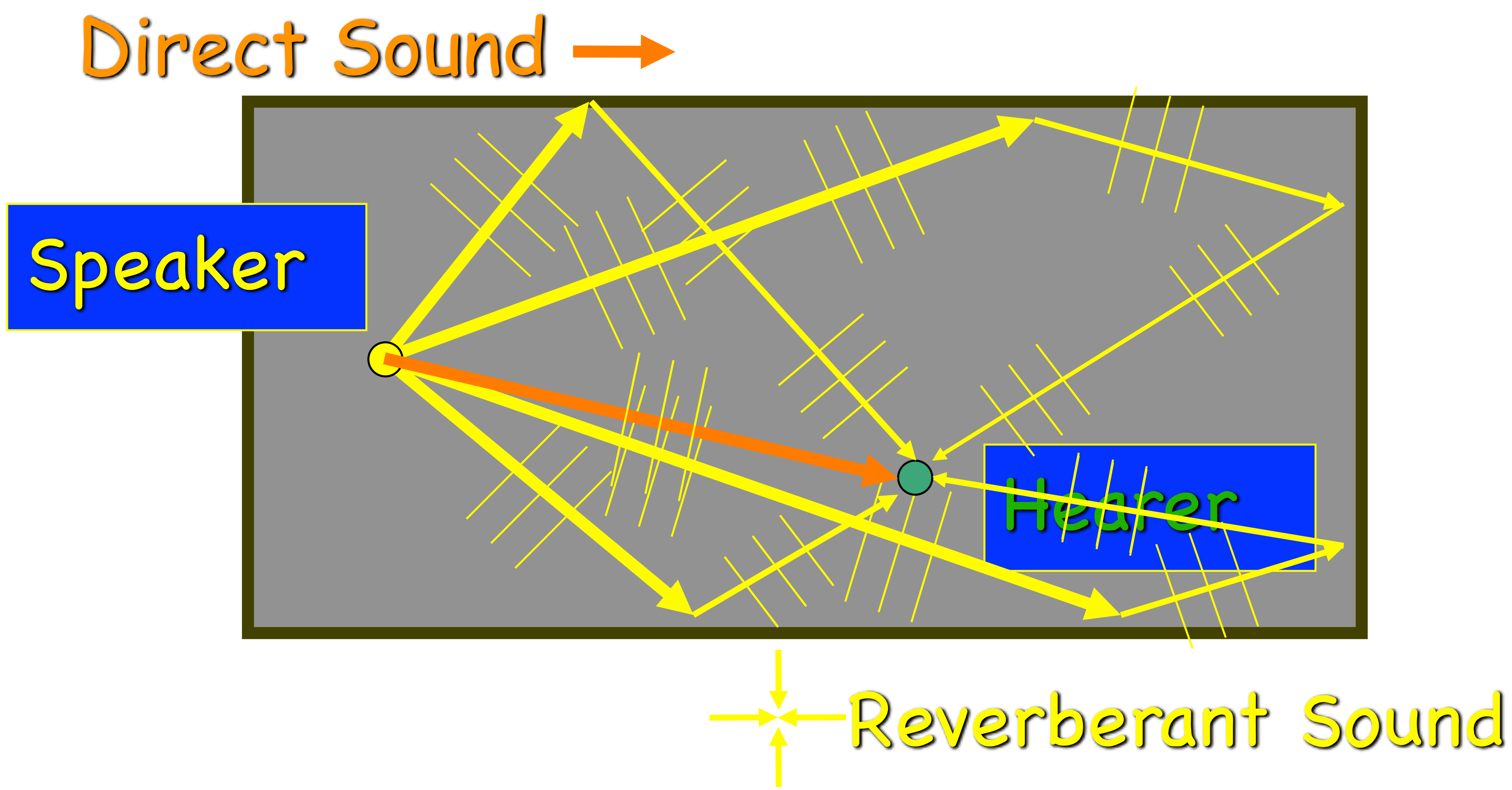
Haas effect

- (sometimes aka Precedence Effect)

- The earliest sound that arrives determines the sense of the origin of a sound, even if the later (<35 ms) reflections are louder.

- It is a psychoacoustic effect that refers to the way in which humans are able to perceive the direction of a sound source, even though the sound may reach one ear at a slightly different time to the other. The phenomena was first identified by Helmut Haas at the University of Göttingen around 1949.

Reverberation



Reflected sound

Energy Lost in Reflections:

- The sound reflects many times, each time losing energy to the reflecting surface.

- The quantity α is the absorptivity of the surface.

- The intensity of the sound that is lost in a reflection is $\Delta I_{lost} = \alpha\ I_{in}$.

Absorption coefficient

The intensity of the reflected wave is

$$I_{reflected} = (1-\alpha)\, I_{in}.$$

Values for α, the absorptivity, for many types of surfaces have been measured and appear in extensive tables.

Material	α (at 500 Hz)
Acoustic tile	0.6
Plaster wall	0.1
Concrete	0.02
Person	0.8 (x1 m^2)

Reverberation time

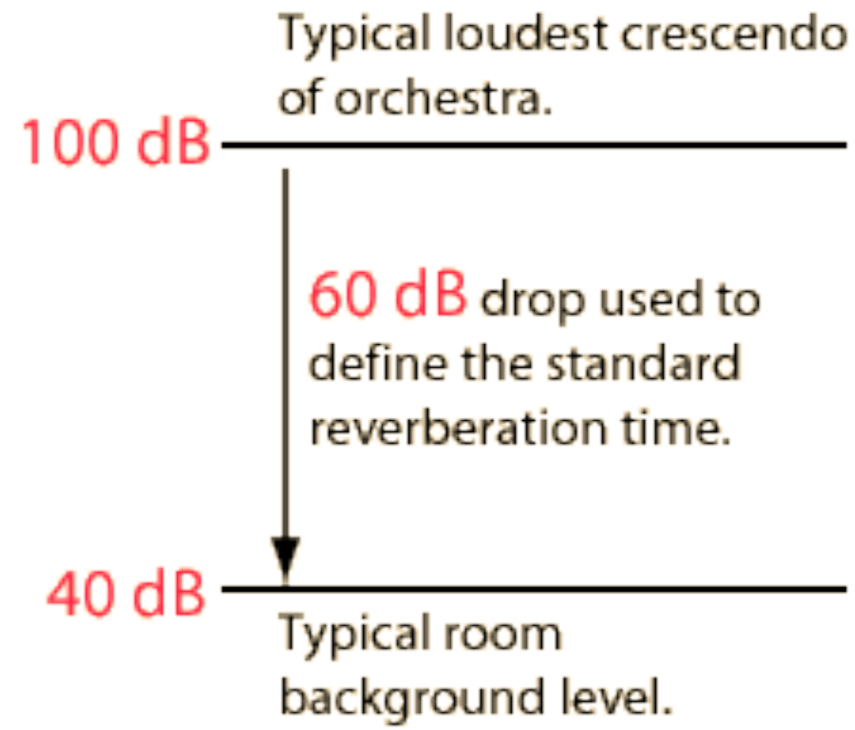
Wallace Sabine

(Harvard professor 1868-1919)

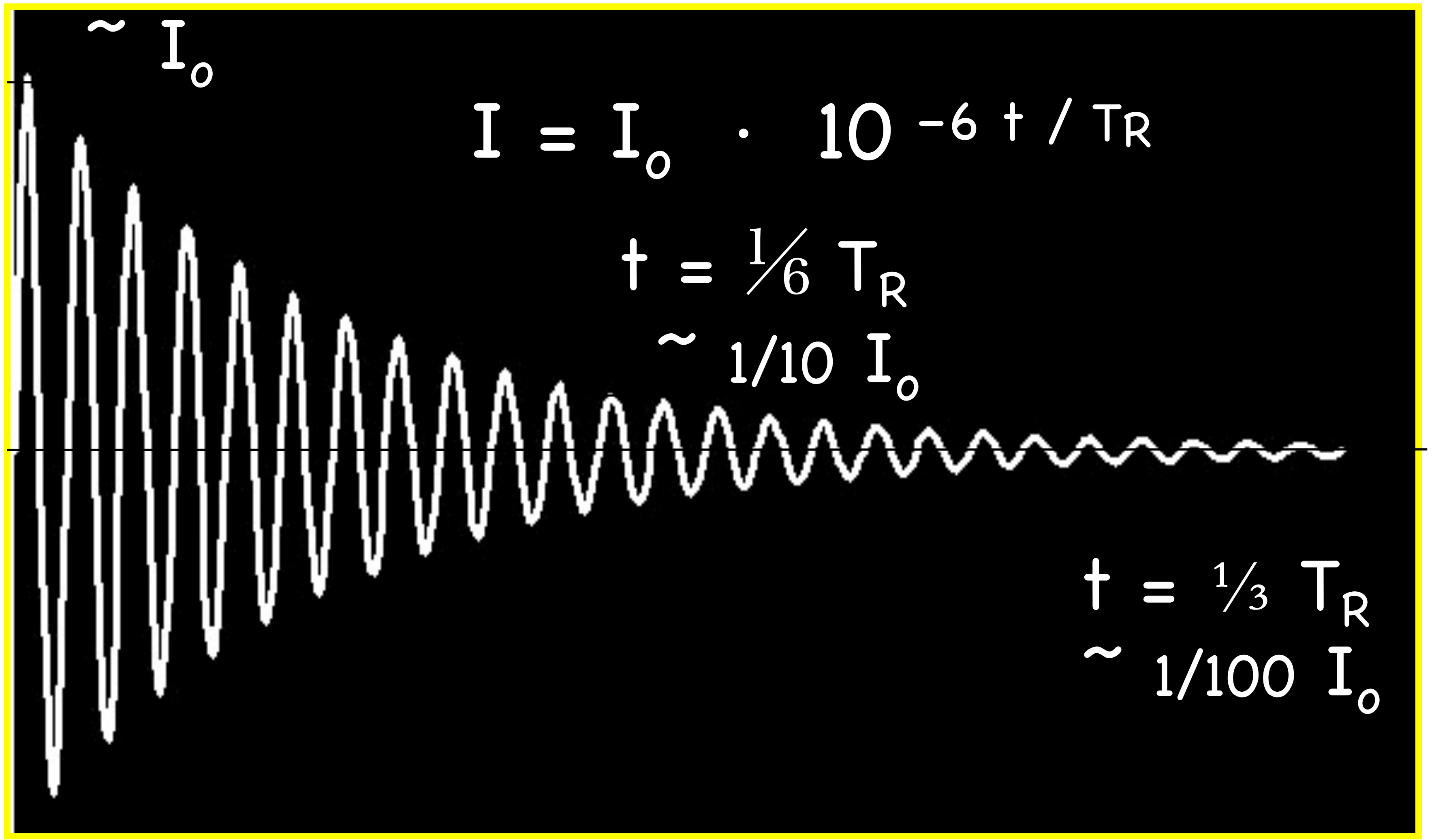
Asked: "How long will it take for the sound to die down to 1 millionth (-60 dB) of the initial value?"

Wallace Sabine

The reverberation time is the time for the intensity to decay by a factor of 10^{-6} (i.e. -60dB) of its initial value.



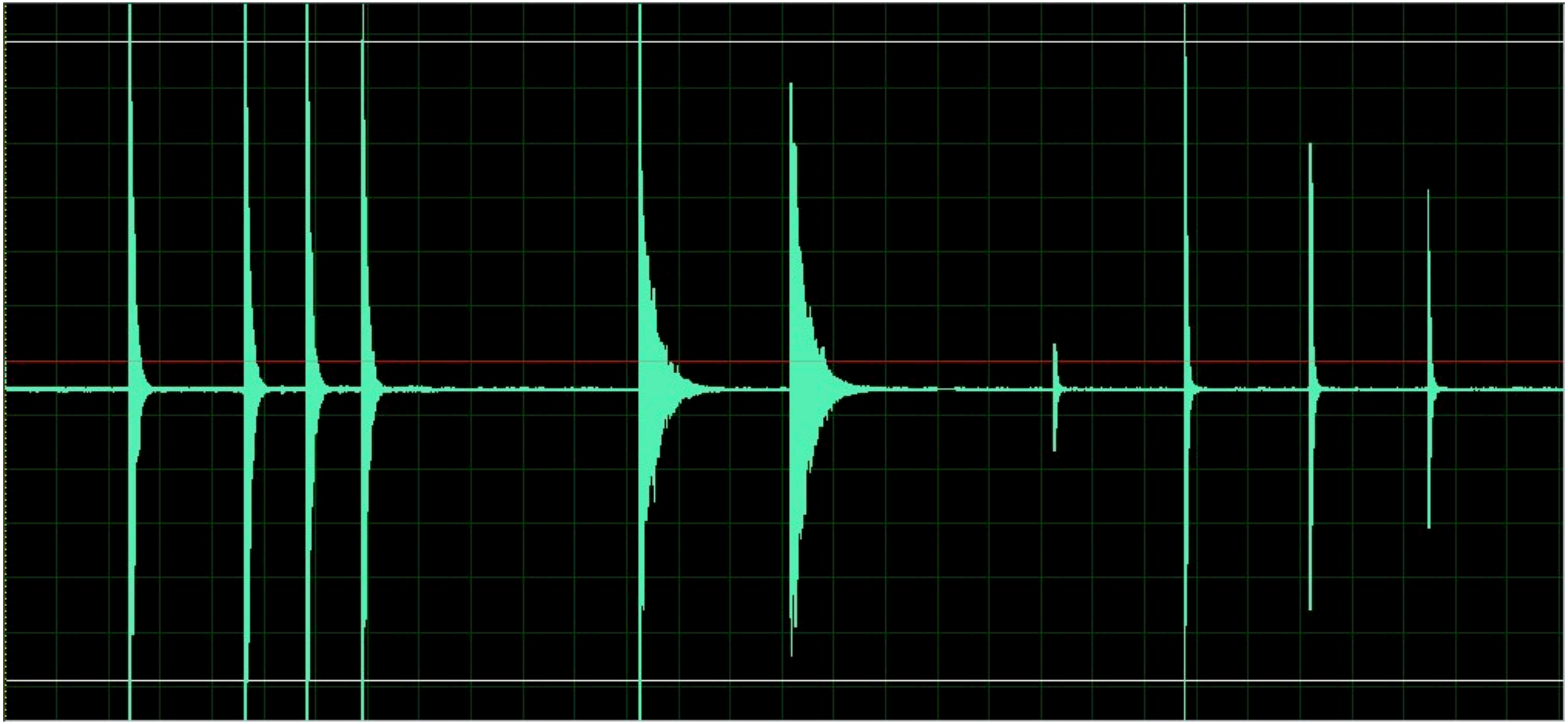
Intensity of Sound in a Room:



Pressure Amplitude

Time (ms)

3 rooms



time →

looking closer

Effect of Echoes

- ASA demo 35 Speech in 3 rooms and played backwards so echoes are more clearly heard

Sabine's equation

The Sabine Equation:

$$I = I_o \cdot 10^{-6(t/T_R)}$$

$$T_R = 0.16\ V/S_e$$

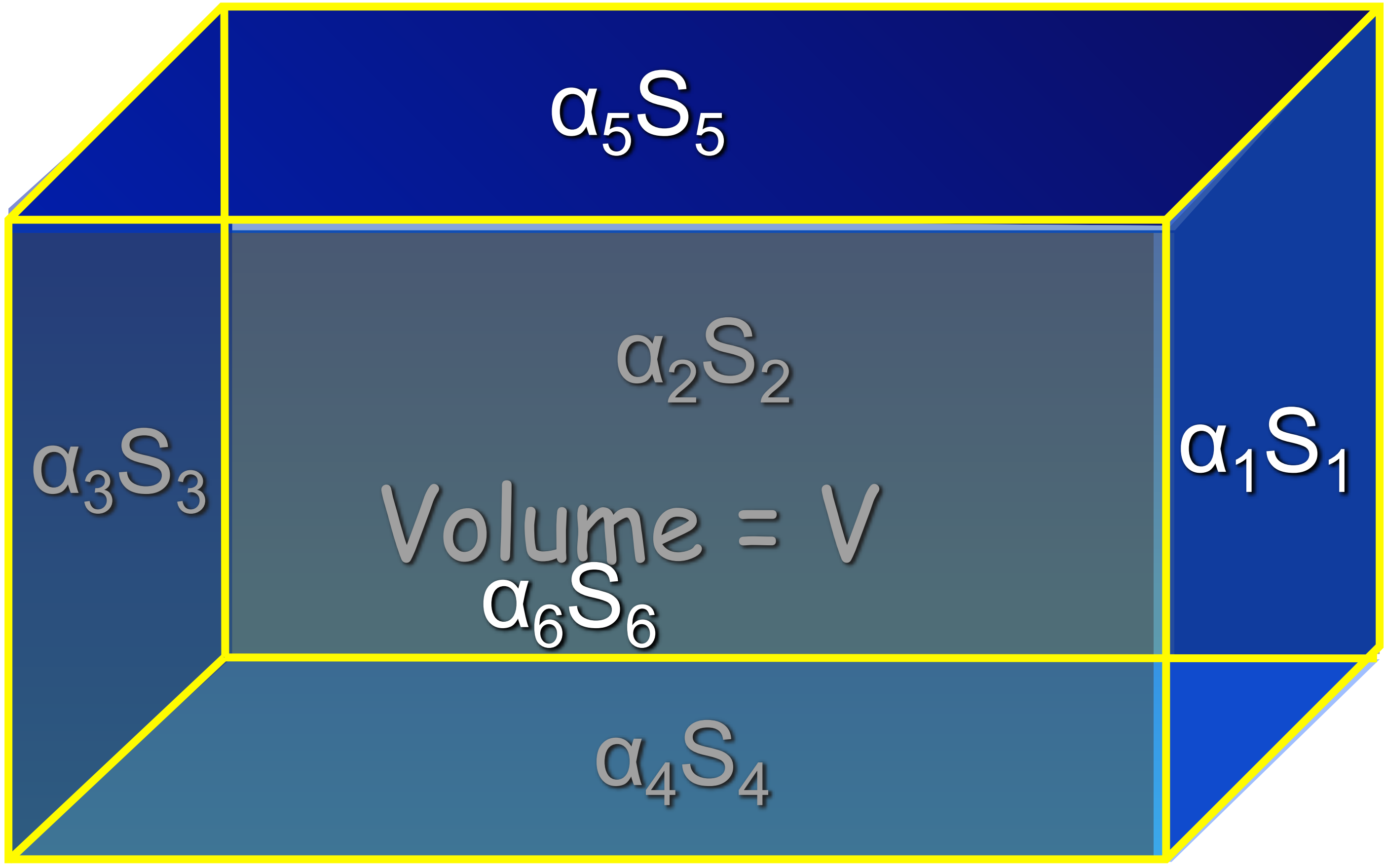
- V is the volume of the room.
- S_e is the "effective surface area" of the walls S_1, floor S_2 and ceiling S_3 (in sabin) etc.

α is the absorptivity of the surface (in table)

$$S_e = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \alpha_4 S_4 + \ldots$$

Reverberation in a room

$$S_e = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \alpha_4 S_4 + \alpha_5 S_5 + \alpha_6 S_6$$



$$T_R = 0.16\ V/S_e$$

Where did this (magic) equation come from?

The time required to reduce the SIL by 60 dB is equal to the number of times the sound reflects multiplied by the time it takes (on average) to make a trip across the room: $\mathbf{T_R = N_{reflections} \cdot \langle\tau\rangle}$

$$10^{-6} = (1-\alpha)^{N_{reflections}}$$

$$-6 = N_{reflections} \text{ Log } (1-\alpha)$$

$$N_{reflections} = -6 / \text{Log } (1-\alpha)$$

$$\mathbf{N_{reflections} \approx 13.8 / \alpha}$$

The average time is the average distance traveled between bounces divided by the velocity of sound: $\langle\tau\rangle = \langle d\rangle / v$, and the average distance traveled between reflections will scale as the size of the room, d. For a cube d x d x d:

$$6\ V/S = 6(d^3/6d^2).$$

$$T_R \approx (13.8 / \alpha) \cdot (2/3)\ (6\ V/S)/v = (55.2 / v)\ V / (\alpha S) = 0.16\ V/(\alpha S) \approx \mathbf{0.16\ V/ S_e}$$

What is the reverberation time for 500 Hz sound in a concrete room that is 3 x 3 x 3 meters?

$$T_R = 0.16\ V/S_e$$

- V is the volume of the room= 3x3x3 = 27.0 m^3.
- Walls $S_1 = 4\ (3x3\ m^2) = 36.\ m^2$),
- floor $S_2 = 9.0\ m^2$
- ceiling $S_3 = 9.0\ m^2$
- $a = 0.02$

$$S_e = (0.02)\ (36.) + (0.02)\ (9.0) + (0.02)\ (9.0) = 1.02 \text{ sabin}$$

$$T_R = 0.16\ V/S_e = 0.16\ (27)/(1.02) = 4.2 \text{ sec}$$

Why have reverberation (re-speaking)?

To even out the sound intensity throughout the audience.

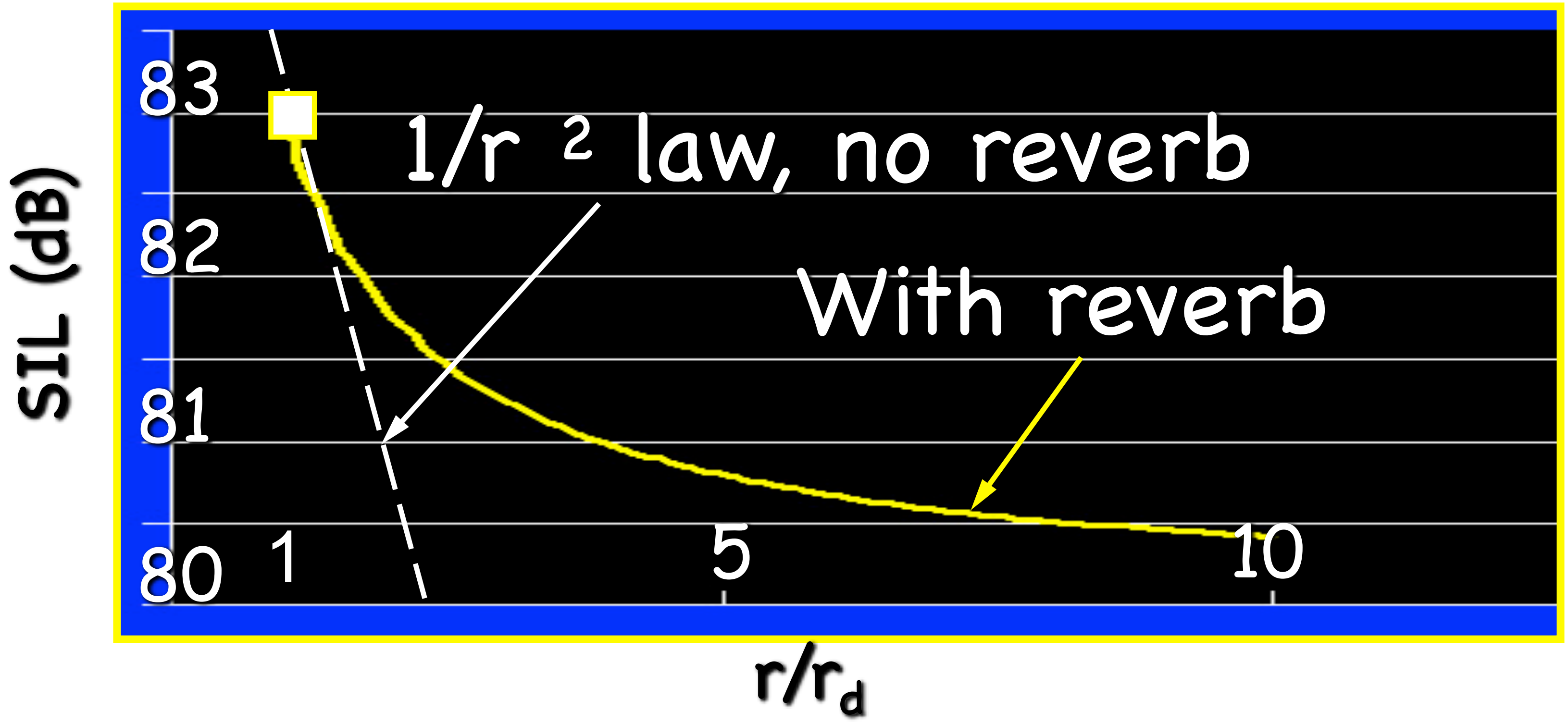
To permit the sound to reach greater intensity.

To give a "fullness" or "presence" to the sound.

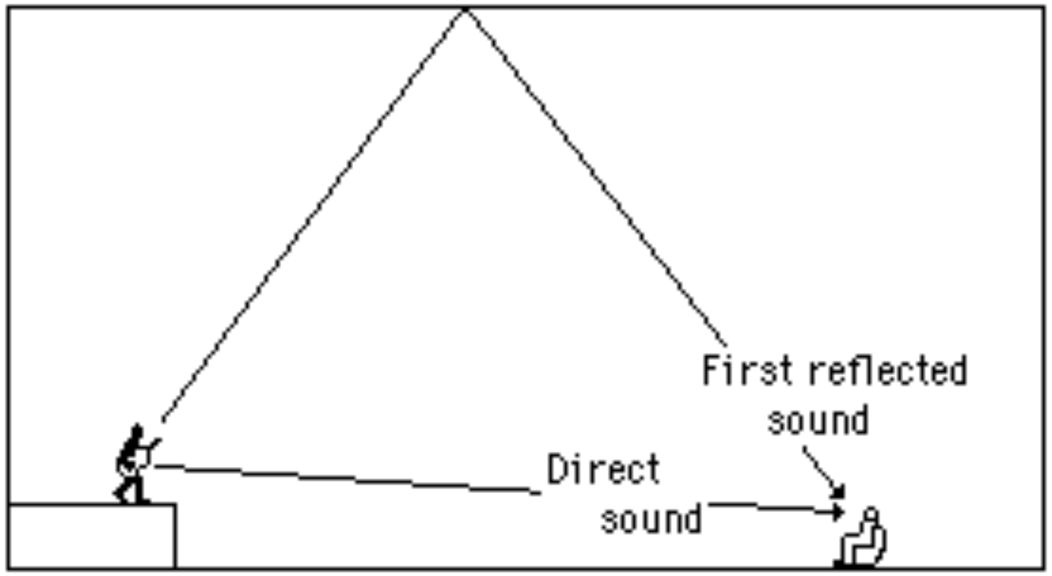
The downside? Clarity and precision.

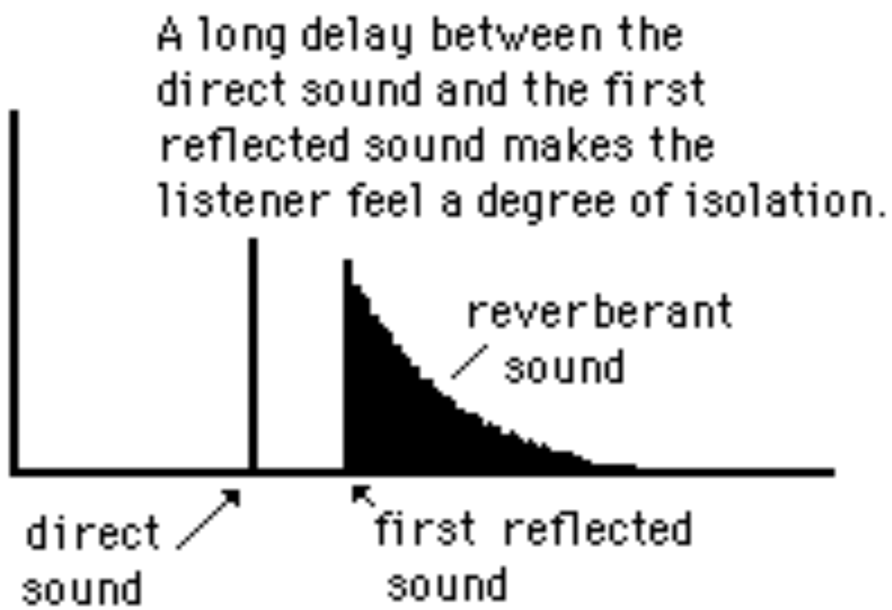
Reverberation evens out the sound:

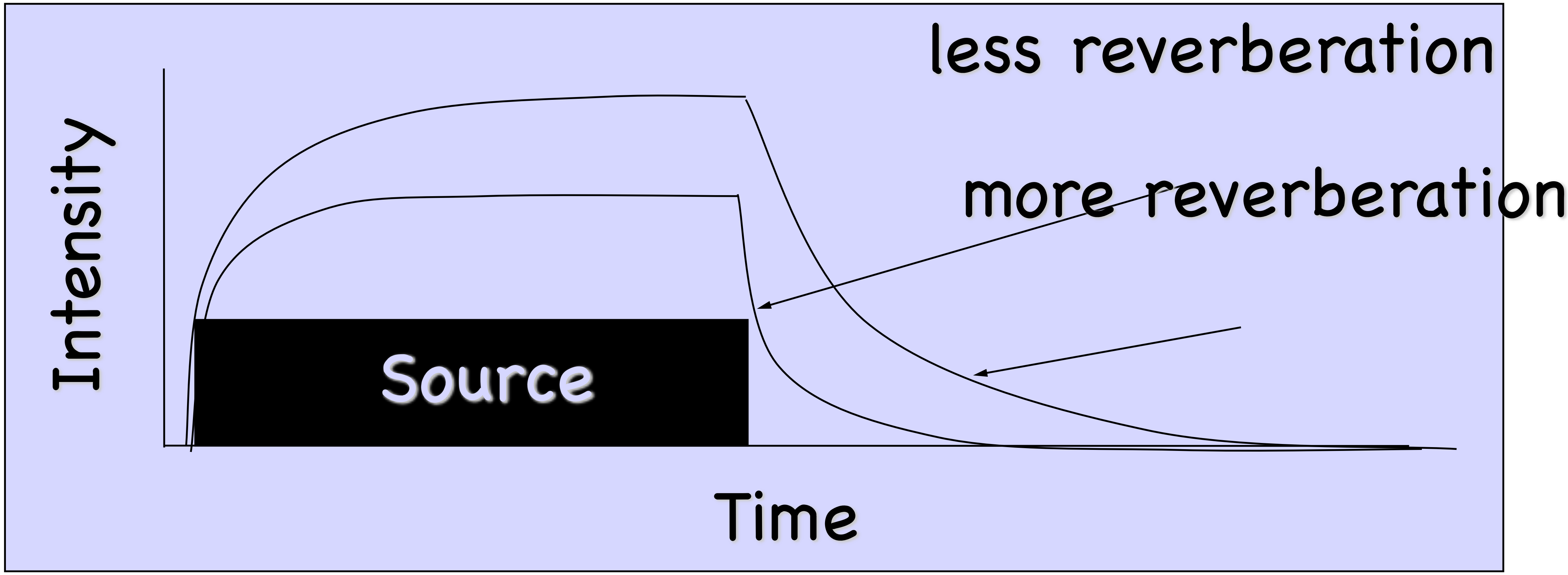
- Beyond r_d (aka "critical distance" or "room radius")the sound intensity is much more uniform than it would be if there were no reverberation.
- r_d is the distance beyond which the reverberant sound intensity is greater than the direct sound intensity.



Intensity vs. time

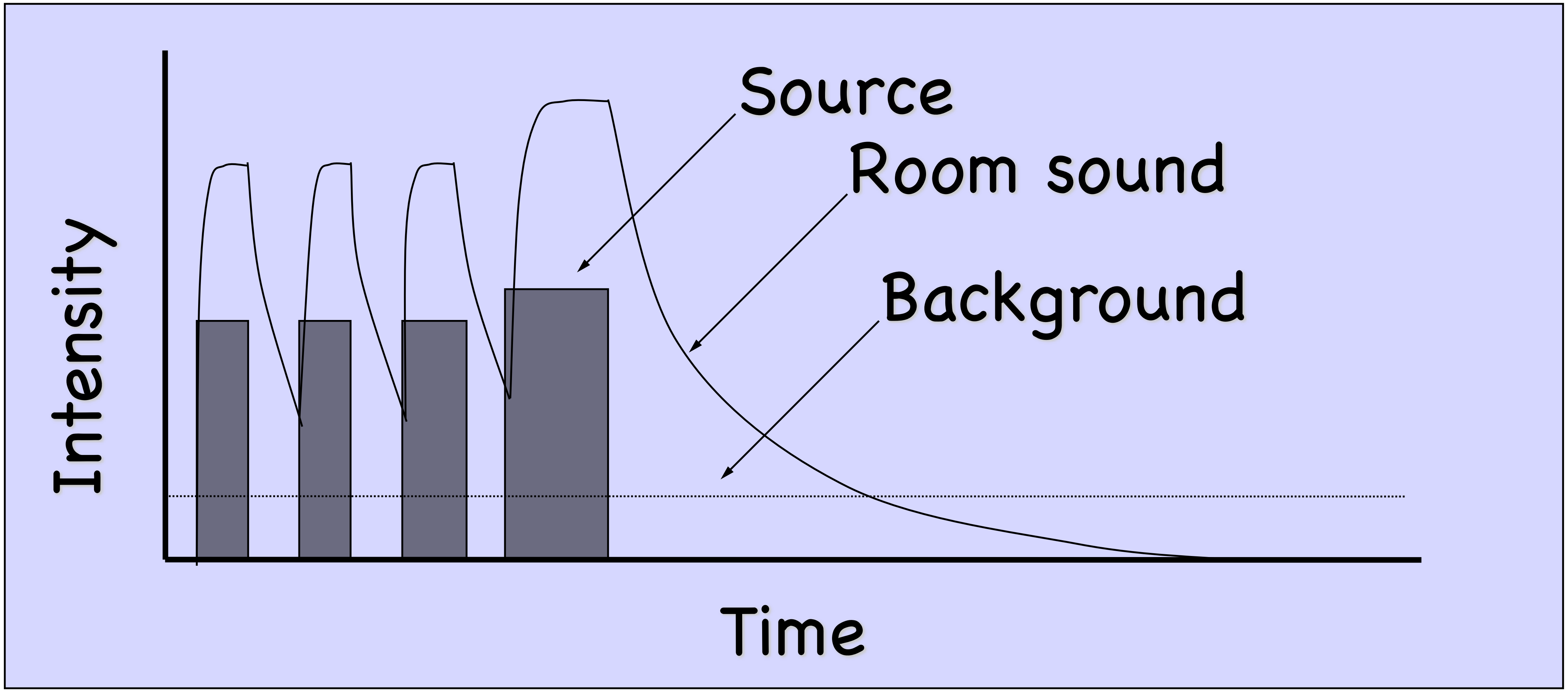






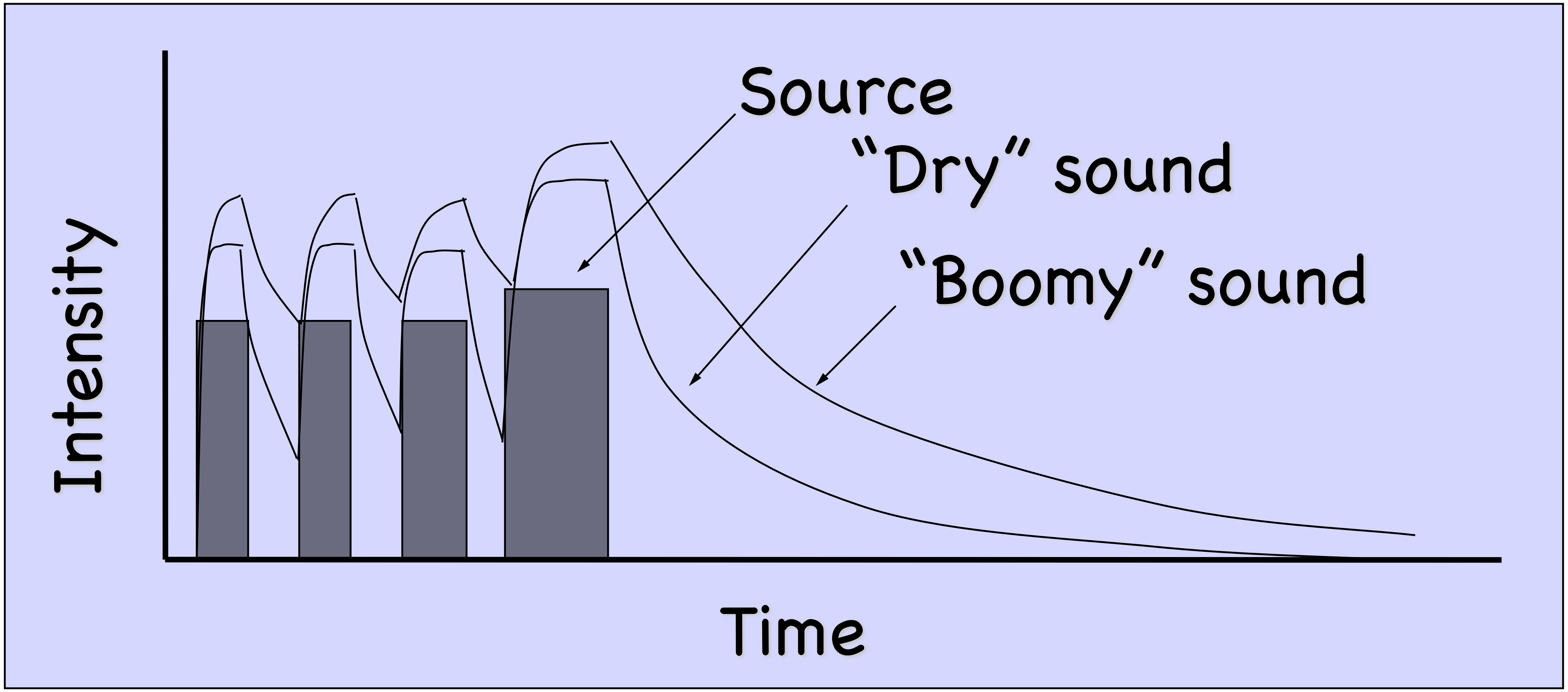
Presence

- Reverberation gives to sound "**presence**".
- The tail of every note is overlapping to the next one creating an harmonic chain…



Clarity

- Too much reverberation reduces the **clarity** of the sound



What happens to the sound after many reflections?

Does sound go on forever?

Where does the sound energy go?

Heat is "disorganized" motion of the air molecules.

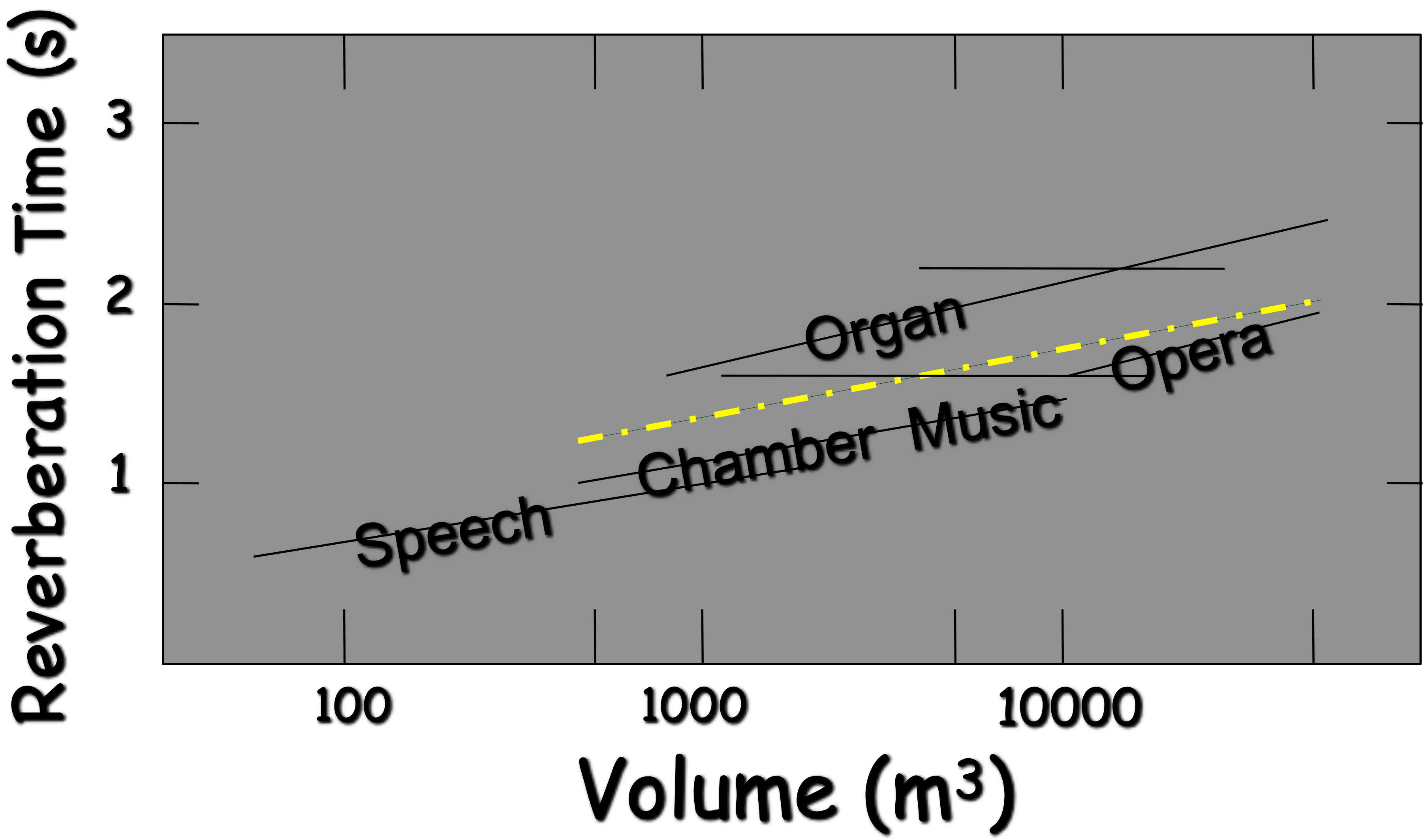
When the sound intensity drops below the ambient it is masked and lost for ever.

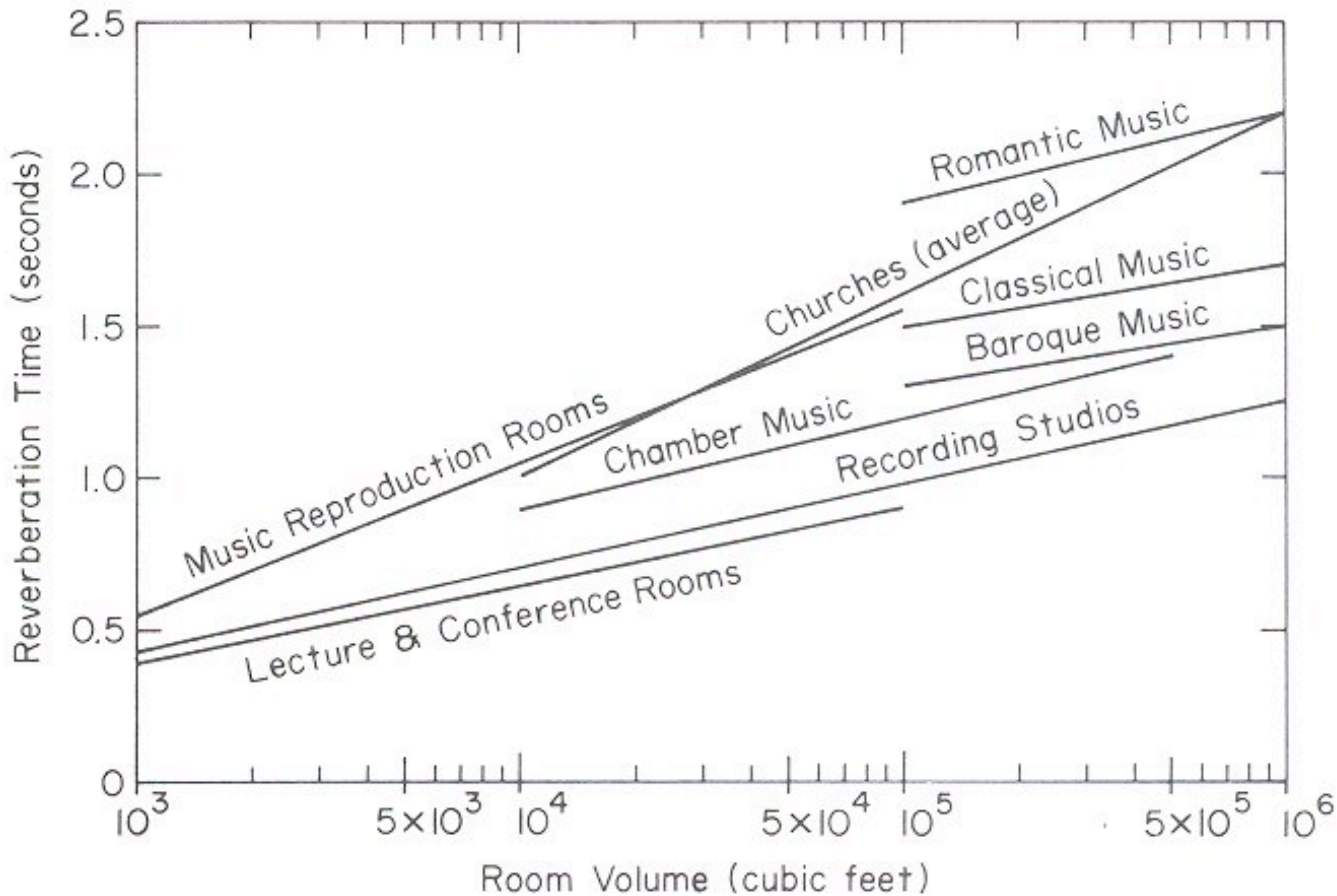
Recommended reverberation

Depends on the use and on the size! Design Equations:

$$T_{recommended} \approx R \sqrt[3]{V};$$

- R = 0.06 s/m for lecture, 0.07 s/m for music
- For Lecture Hall Room, V =1600 m³, $T_{rec} \approx R\sqrt[3]{V}$ = 0.7 s ☏ or 0.9 s ♬

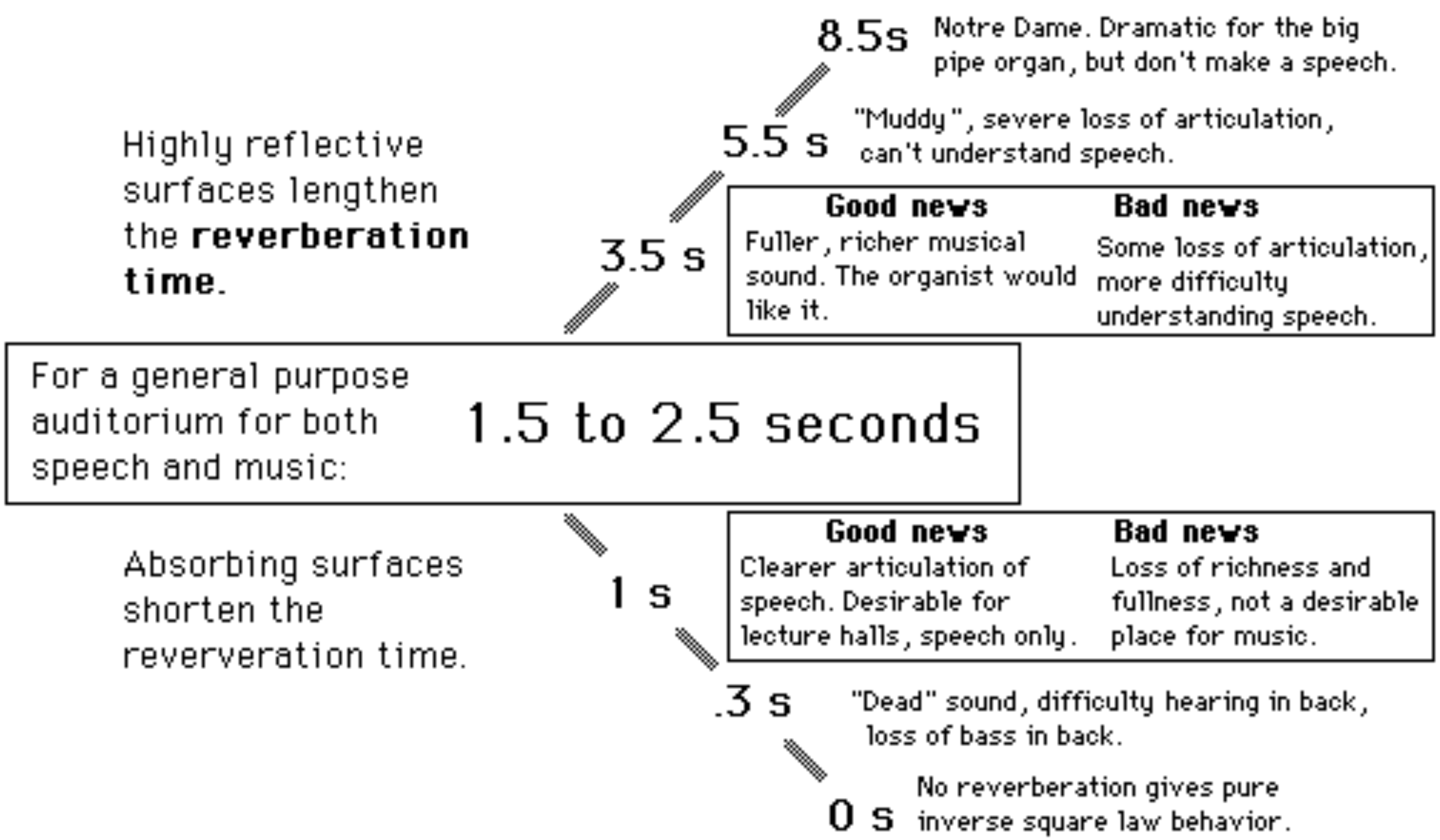




Reverberation Time (seconds)
2.5
2.0
1.5
1.0
0.5
0
Romantic Music
Churches (average)
Classical Music
Baroque Music
Music Reproduction Rooms
Chamber Music
Recording Studios
Lecture & Conference Rooms
10^3
5×10^3
10^4
5×10^4
10^5
5×10^5
10^6
Room Volume (cubic feet)

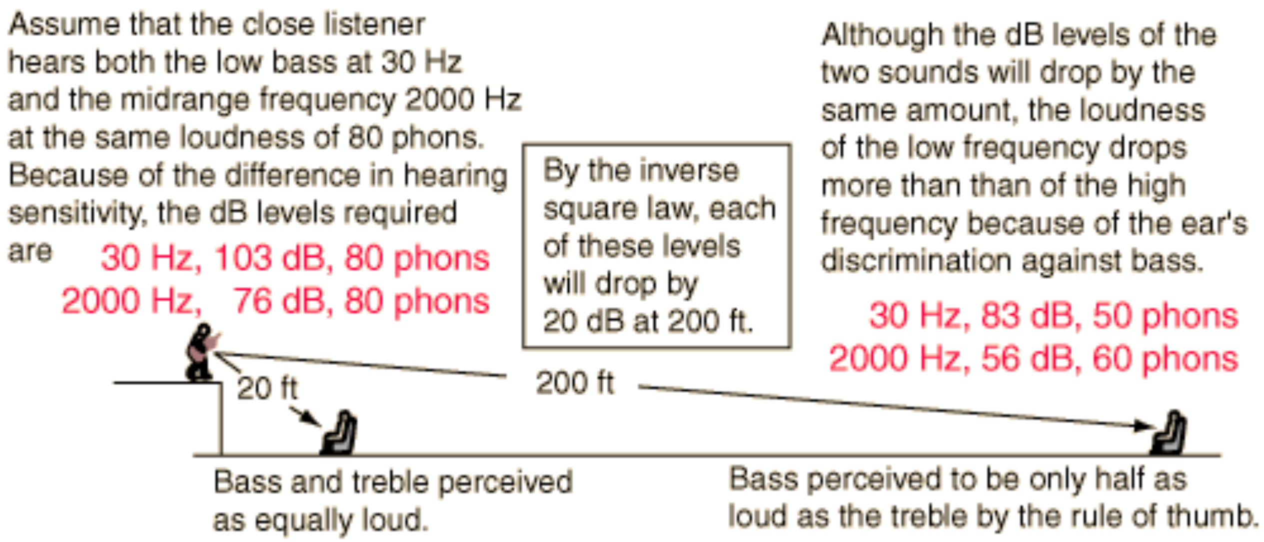
Quality factors

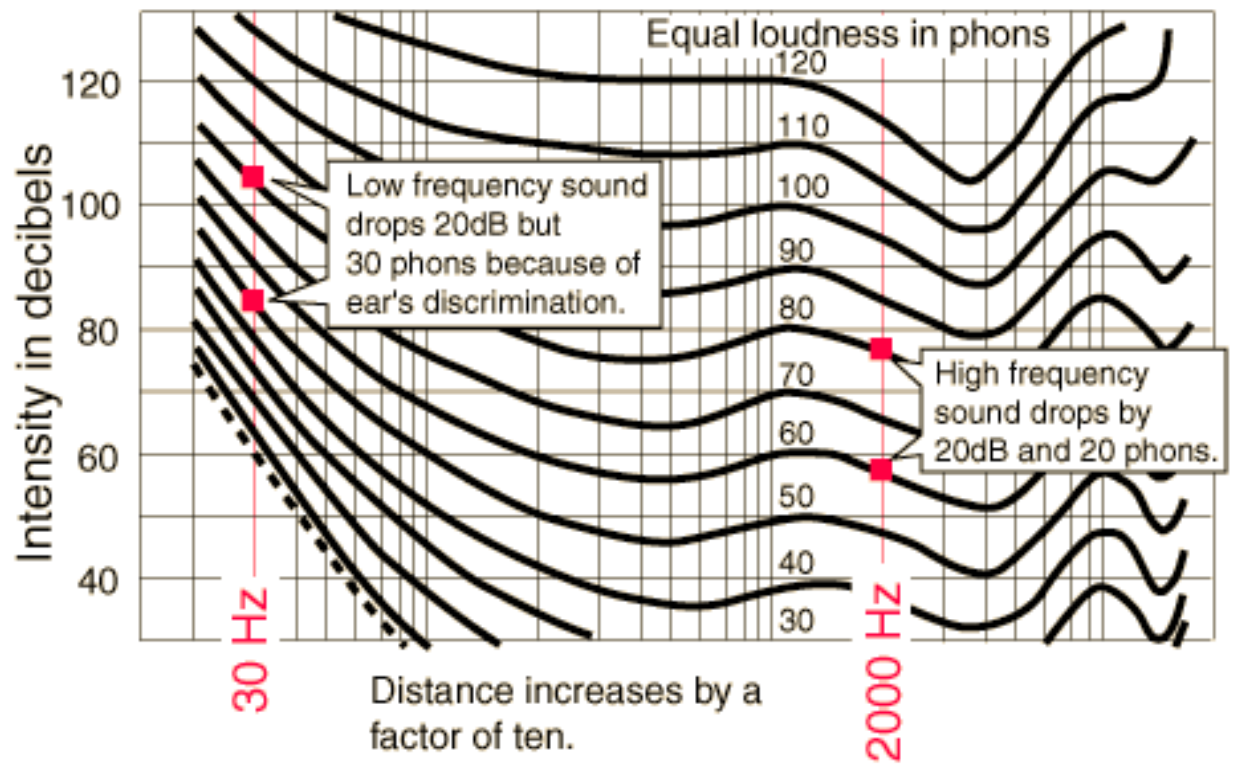
- **Liveness**: rich sound for the various frequencies
- **Fullness**: high ratio between reflected and direct sound
- **Clarity**: good comprehension of the sound message

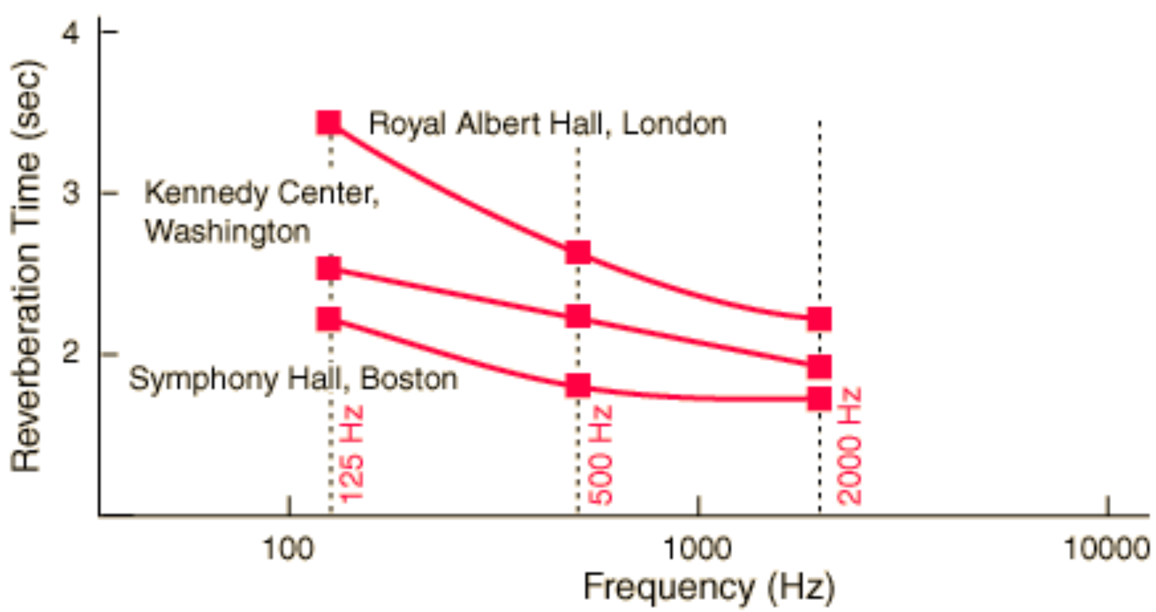


Quality factors

- **Warmth**: solve the loss of basses (different T_r)

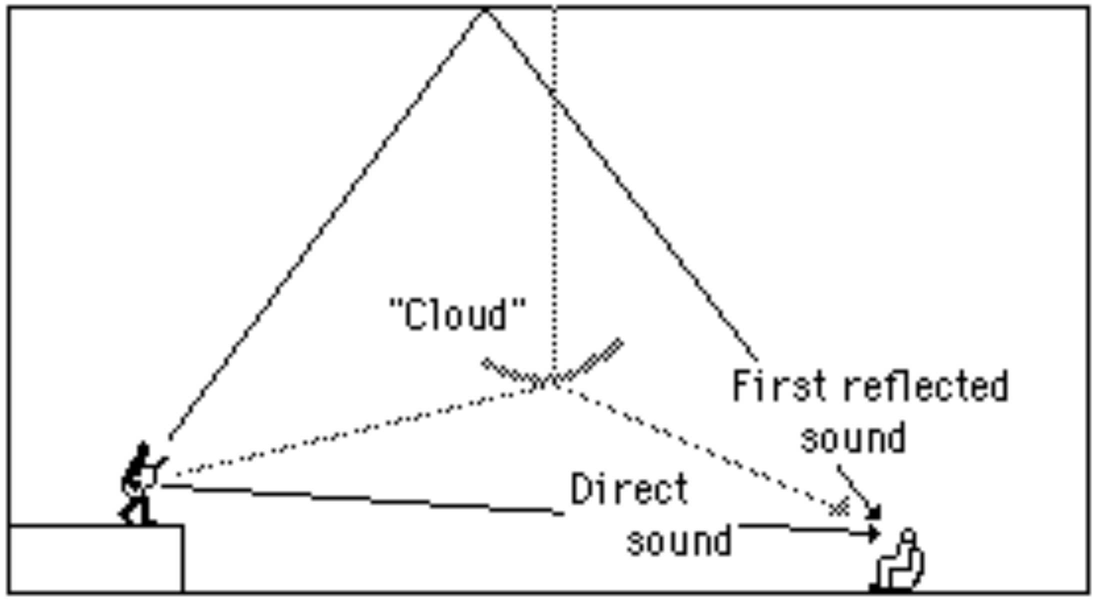


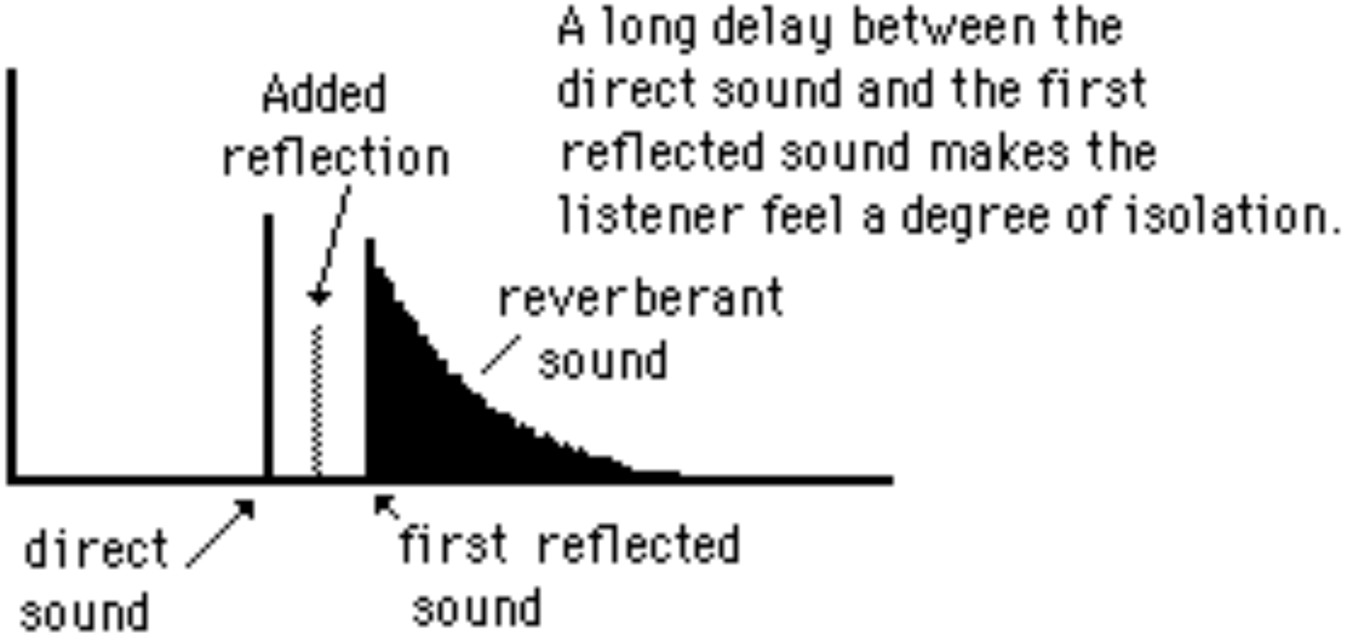




Quality factors

- **Intimacy**: feeling "near" to orchestra. Room is said to be "intimate" when the first reverberation arrives within 20 ms of the direct sound

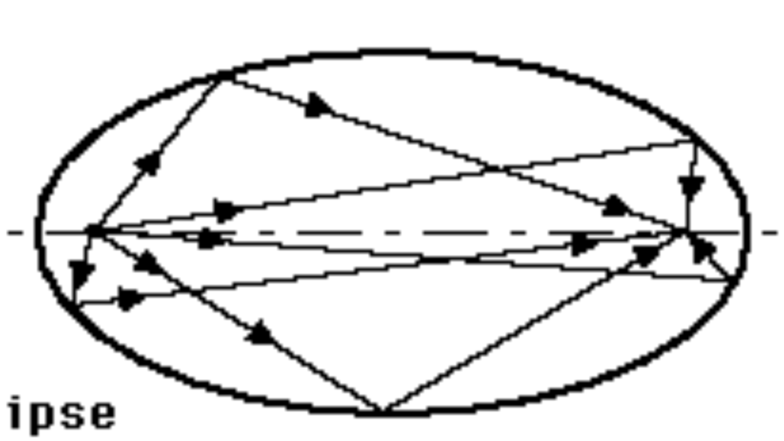


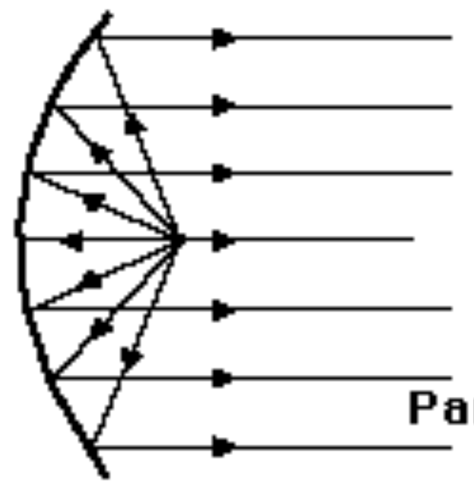


Quality factors

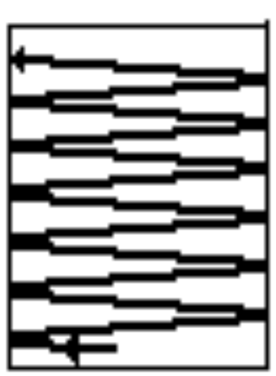
Homogeneity: avoid echoes, acoustic shadows, focalizations

Echo can be defined as a reflected sound whose intensity is louder than normal reverberations, and can be caused by focusing surfaces or too reflecting ones. One can then use anti-focusing elements.



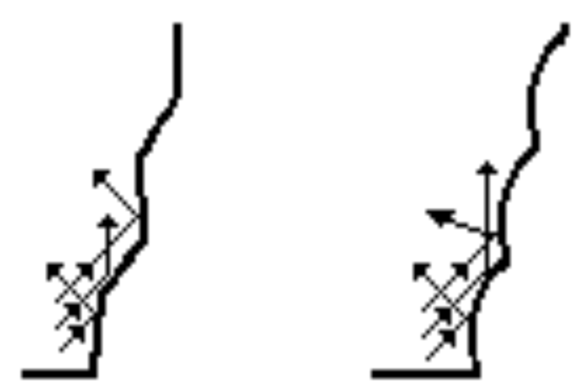


Highly reflective flat parallel walls are to be avoided since they produce a "flutter echo"



Angled side walls spread the sound and contribute to even dispersion

Sometimes the side walls are broken into angled segments or anti-focusing surfaces are used for dispersion.



Echoes & Resonances

Highly reflective flat or parabolic wall shapes

Flutter echos from parallel walls

Standing waves between parallel walls