University of California
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Department of Electrical Engineering
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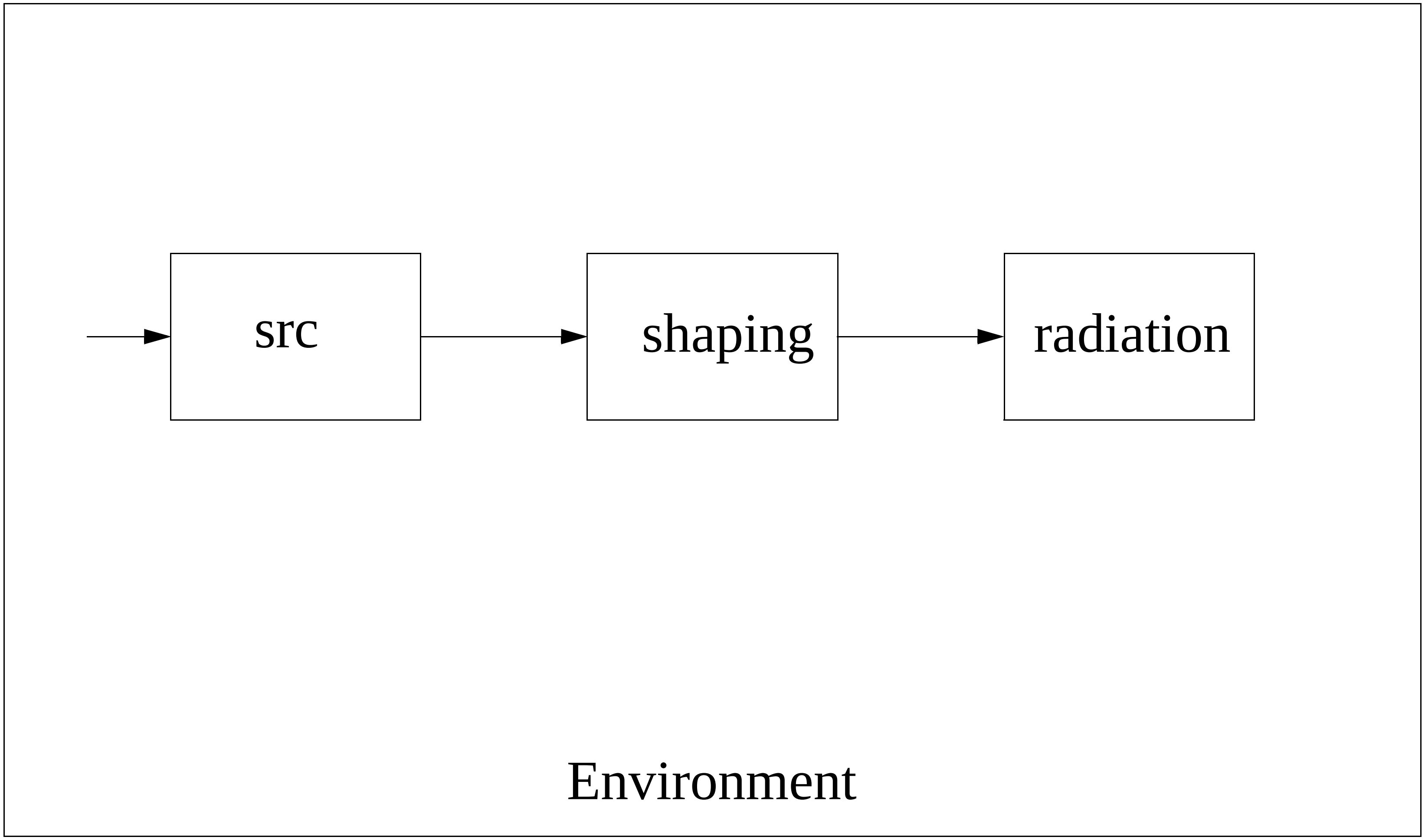
EE225D Spring,1999

Room Acoustics

Lecture 12



src

shaping

radiation

Environment

1-D Wave Equation

In *x*-direction :

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

With general solution :

$$p(x, t) = F(ct - x) + G(ct + x)$$

For sinusoidal functions, $\lambda = \frac{c}{f}$

Spherical Wave Equation

In polar coordinates :

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

Our solution is :

$$p(r, t) = P_0 \frac{\exp[j(\omega t - kr)]}{r}$$

Sound Waves

- c = 331.4m/sec + 0.60m/sec = 1133ft/sec

  at room temperature)
- This is about 1 msec/ft
- Real rooms, temp changes, movement

Intensity

Def: Sound energy flowing across a unit area surface in a second

$$I = \overline{pv} = \frac{\overline{p^2}}{\rho_0 c}$$

where ρ_0 is the medium density, c is the speed of sound as before, and $\rho_0 c$ is the characteristic impedance.

For a sinusoid,

$$I = \frac{P_0^2}{2\rho_0 c}$$

So I is proportional to p^2, and for a spherical wave I is proportional to $1/r^2$.

dB Sound Levels

$$L = 20\log_{10}\left|\frac{p_1}{p_2}\right| = 10\log_{10}\left|\frac{I_1}{I_2}\right|$$

Choosing reference values to correspond to typical threshold of hearing at 1kHz, namely

$$p_2 = 2 \times 10^{-5}\frac{N}{m^2}$$

$$I_2 = 10^{-12}\frac{W}{m^2}$$

The dB levels then become Sound Pressure Level (SPL) and Intensity Level (IL), respectively.

Typical Power Source

Source power (SPL at 16 in. for hemisphere,

1 meter surface)

- Whispered speech: 1nW (30 dB SPL)
- Average for speech: 10 uW (70 dB SPL)
- Loud speech: 200uW (83 db SPL)
- Shouting: 1mW (90 dB SPL)

Ignoring boundaries, SPL would be 6 dB lower for doubled distance

SPL is not loudness

- Cube root approximation (10 dB doubles loudness)
- Frequency dependencies
- Weighting curves for measurement

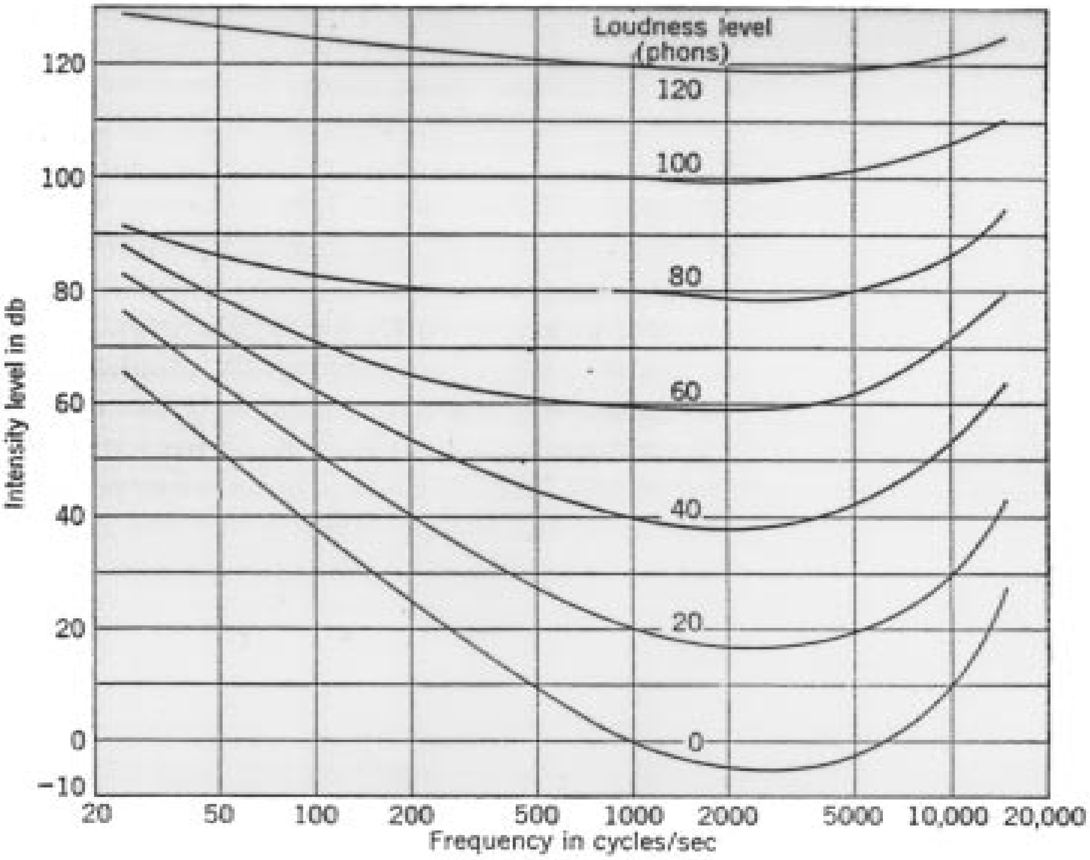


Fig. 13.10. Equal loudness level contours expressed in decibels relative to 10^{-12} watt/m^2.

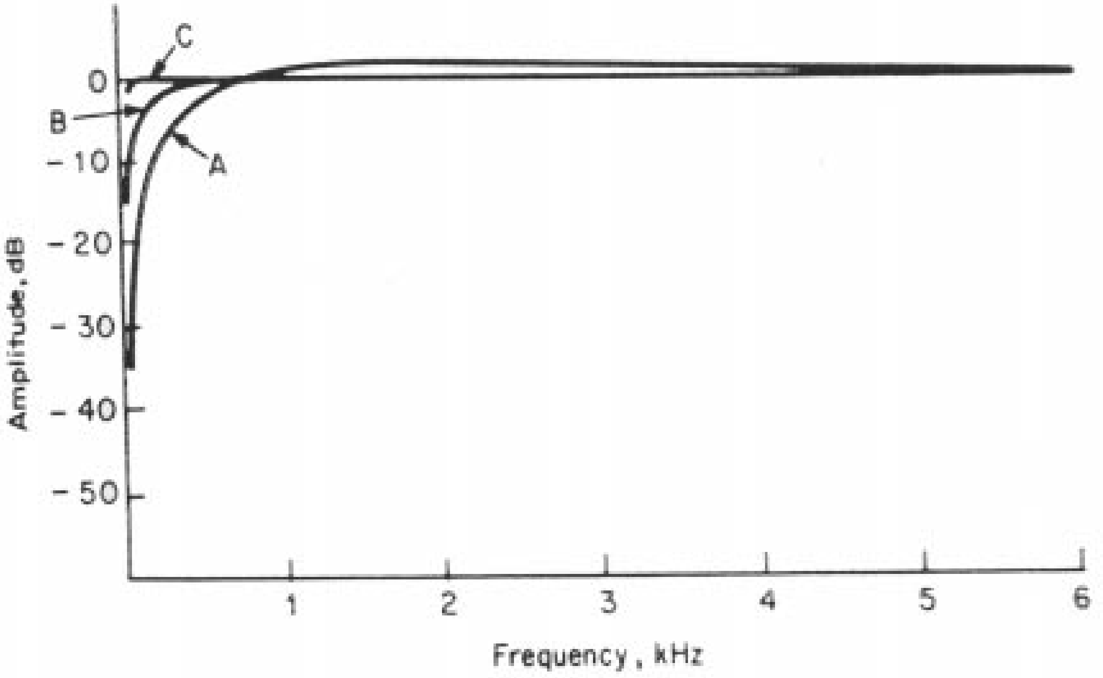


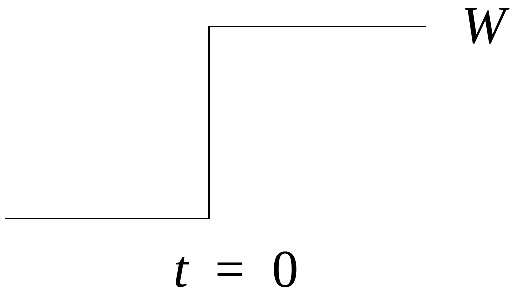
FIG. 6.2. A, B, C weighting curves.

Room Modes

- Some math as for strings, horns
- Standing waves at characteristic frequencies
- Mostly significant at low frequencies
- At high frequencies essentially a continuum

  (number of modes below f is proportional to f^3)

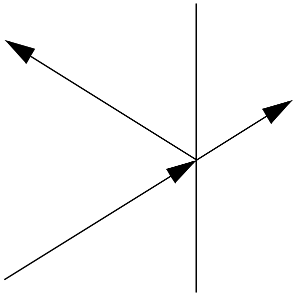
W = sound source energy



$$\tau = \frac{4V}{cS\bar{\alpha}}$$

$$I = \frac{W}{S\bar{\alpha}}\left(1 - \exp\left[-\frac{cS\bar{\alpha}}{2V}t\right]\right)$$

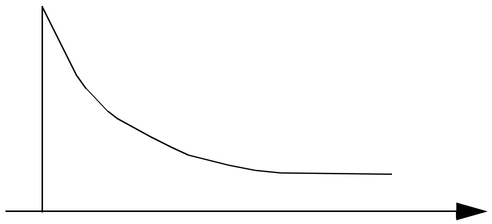
$\bar{\alpha}$ = average absorption

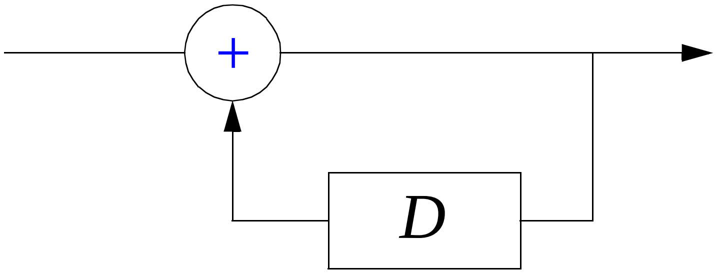


$$S\bar{\alpha} = (s_1\alpha_1 + s_2\alpha_2 + \ldots)$$

$$I = \frac{W}{S\bar{\alpha}}$$

$$I = \frac{W}{S\bar{\alpha}}\left(\exp\left[-\frac{cS\bar{\alpha}}{2V}t\right]\right)$$





$RT60 \qquad \mathrm{T}_{60}$

$$\tau = \frac{4V}{cS\bar{\alpha}}$$

$$\frac{I}{I_0} = \exp\left[-\frac{cS\bar{\alpha}}{4V}t\right]$$

$$\Delta IL = 10\log_{10}\exp\left[-\frac{cS\bar{\alpha}}{4V}t\right] = \frac{10}{2.3}\ln\exp\left[-\frac{cS\bar{\alpha}}{4V}t\right]$$

$$= -1.087\frac{cS\bar{\alpha}}{4V}t$$

$$\text{Decay Rate} = -\frac{\Delta IL}{t} = 1.087\frac{cS\bar{\alpha}}{4V}t$$

$$T_{60} = \frac{60}{\text{Decay Rate}} = 55.2\frac{V}{cS\bar{\alpha}} = 0.163\frac{V}{S\bar{\alpha}} \quad \text{(metric)}$$

$$\text{or} \quad 0.049\frac{V}{S\bar{\alpha}} \quad \text{(feet)}$$

Kinsler + Frey

Air Effects

$$RT60 = \frac{0.049V}{S\bar{\alpha} + 4mV} \quad \text{in feet}$$

The air term typcally dominates at very high frequencies, is irrelevant for low frequencies

Example: 237 Cory

- Dimensions: 20 x 24 x 16 (feet)
- Volume: 7680 cu. ft.
- Surface area: 2368 sq. ft.
- Mid-freq RT60: 1.2 sec (empty)
- We infer $\bar{\alpha}$ of about 0.13
- Air absorption less than 10% for 1kHz, about 50% for 4 kHz

Steady State, 237 Cory

For 10 uW source,

$$I = \frac{W}{S\bar{\alpha}} = 0.32\mu\frac{W}{ft^2} = 0.30\mu\frac{W}{m^2}$$

This is about 55 dB SPL, and 120 msec after cutoff this level will be about 49 dB. Will this interfere?

Boundary Losses

- Energy striking boundary
- Absorption coefficients for surfaces
- Absorption in air: intensity factor of e^{-mr}, where m is 0.013 m^{-1} at 1 kHz, 0.021 at 4 kHz (50% relative humidity)

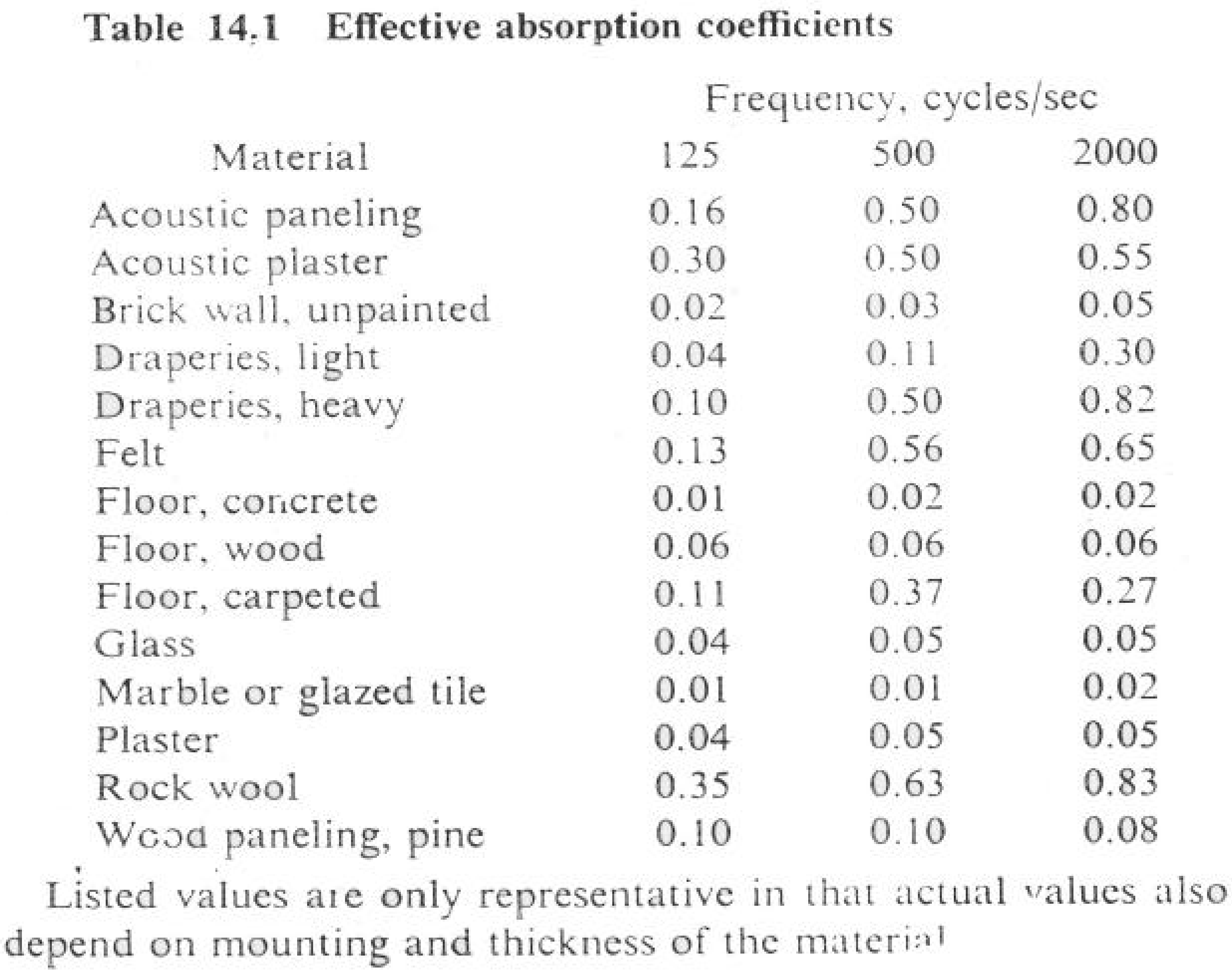


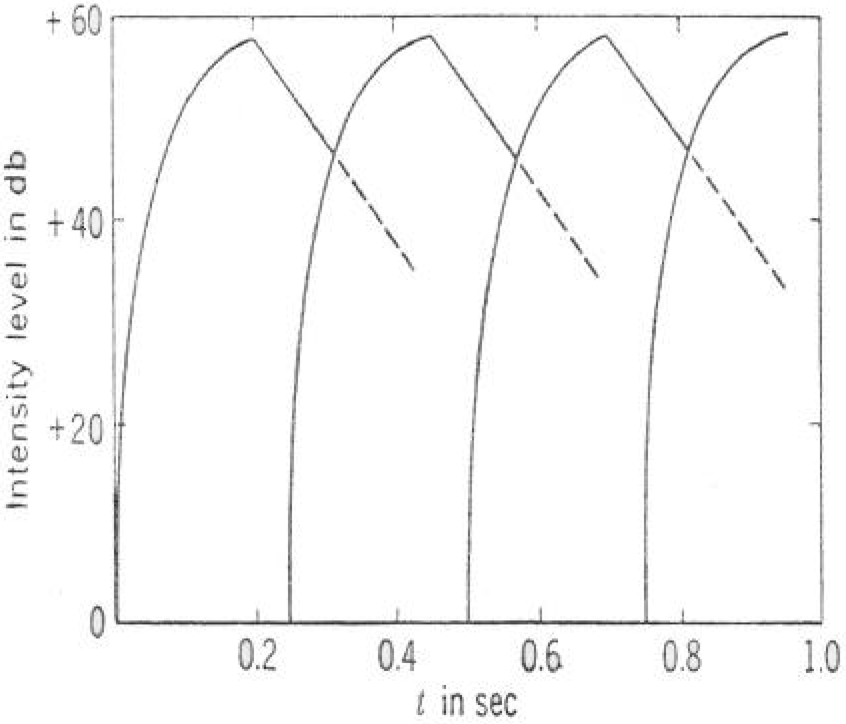
Table 14.1 Effective absorption coefficients

Material	Frequency, cycles/sec 125	500	2000
Acoustic paneling	0.16	0.50	0.80
Acoustic plaster	0.30	0.50	0.55
Brick wall, unpainted	0.02	0.03	0.05
Draperies, light	0.04	0.11	0.30
Draperies, heavy	0.10	0.50	0.82
Felt	0.13	0.56	0.65
Floor, concrete	0.01	0.02	0.02
Floor, wood	0.06	0.06	0.06
Floor, carpeted	0.11	0.37	0.27
Glass	0.04	0.05	0.05
Marble or glazed tile	0.01	0.01	0.02
Plaster	0.04	0.05	0.05
Rock wool	0.35	0.63	0.83
Wood paneling, pine	0.10	0.10	0.08

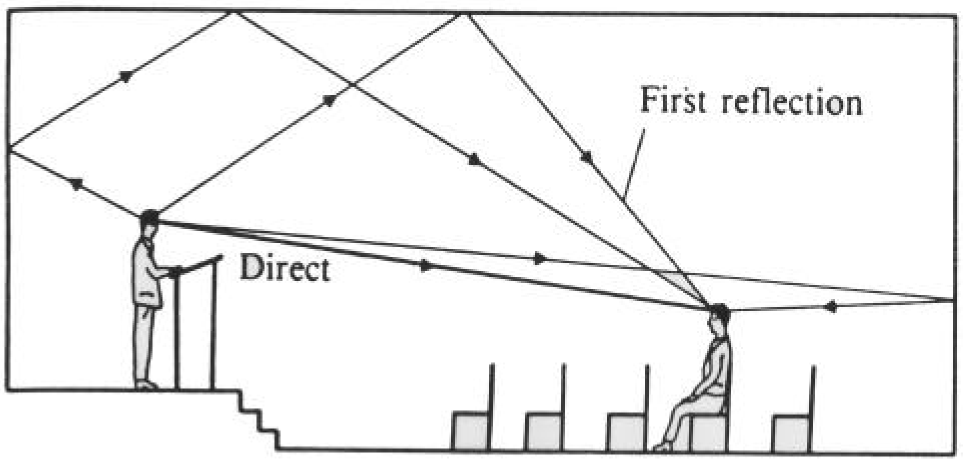
Listed values are only representative in that actual values also depend on mounting and thickness of the material

Effect on Intelligibility

- Energy is larger than without reverb
- Decay stretches it out in time
- Masks following sounds
- Colorations change the spectrum



Intensity level in a live room as produced by successively spoken syllables.



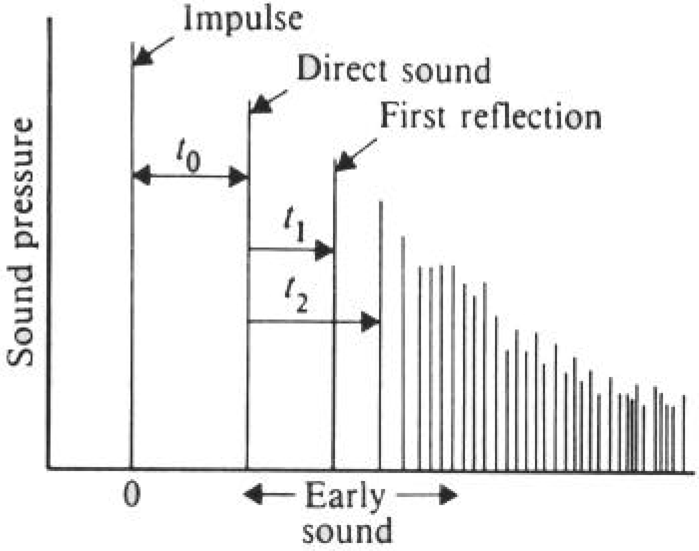


FIG. 23.3
Paths of direct and reflected sound from source to listener with corresponding time delays for a sound impulse. (From *Music, Acoustics, and Architecture.* © 1988 Leo Beranek. Used with author's permission.)

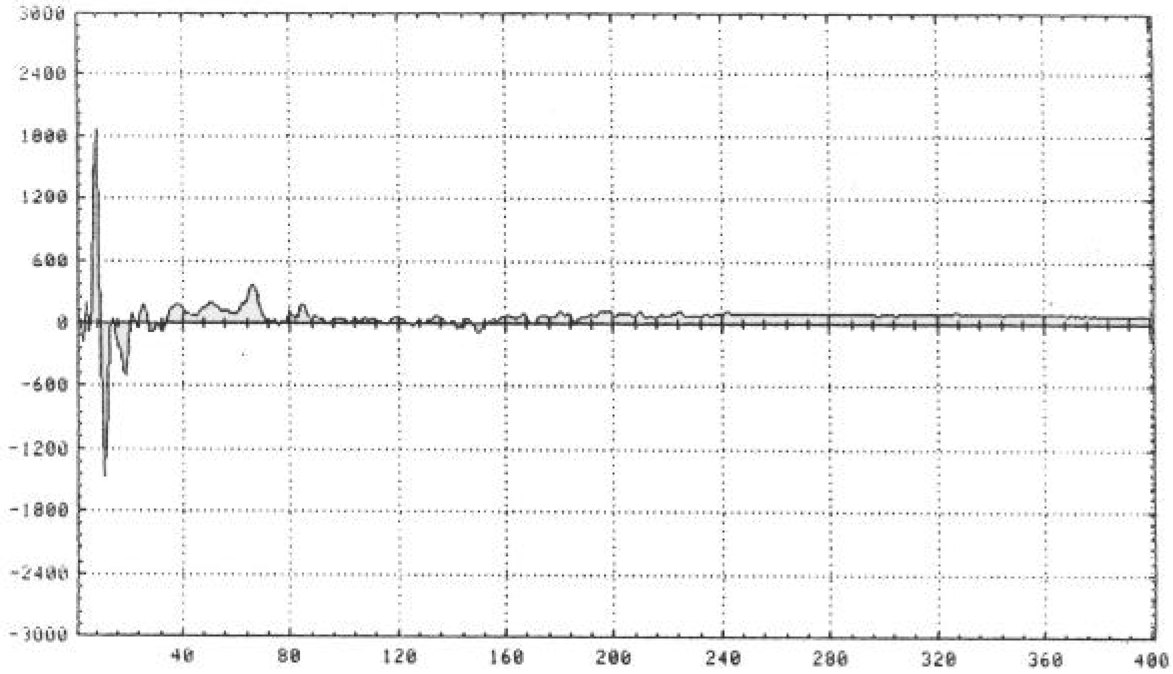


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Figure 13: Anechoic direct impulse response, Rogers speaker

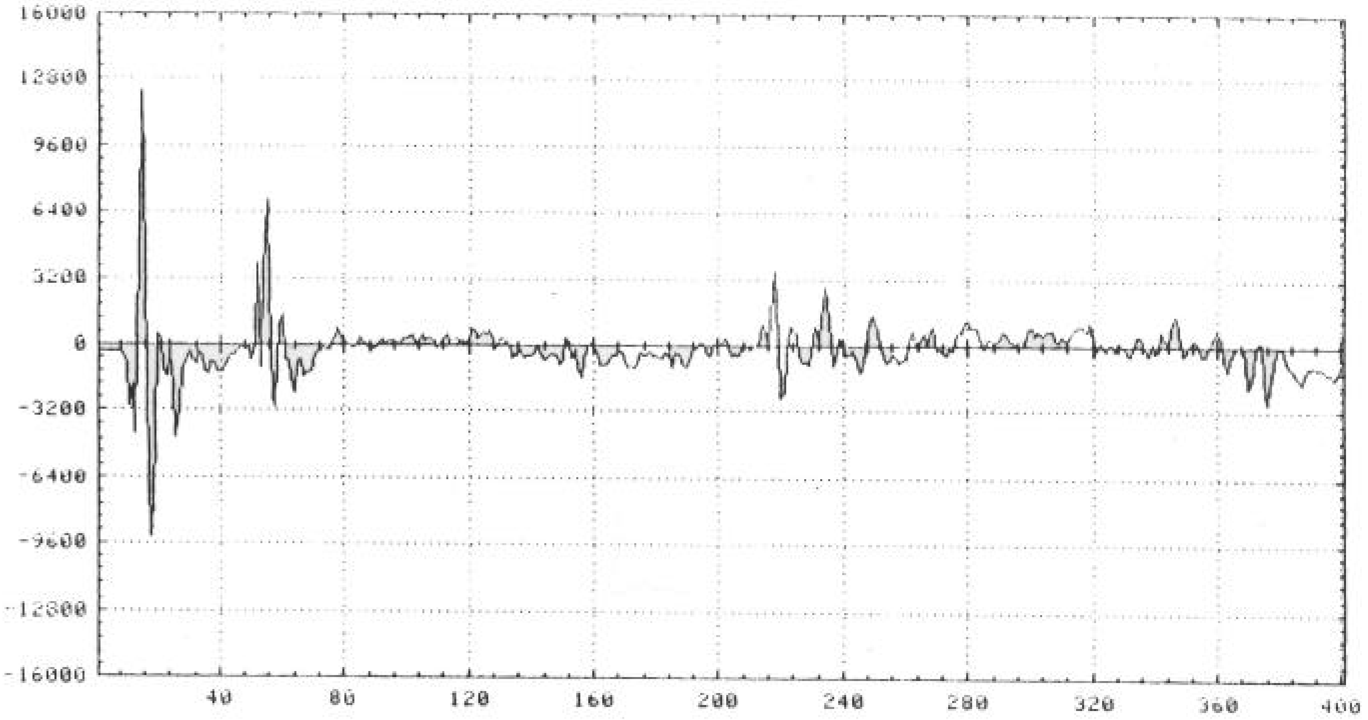

Figure 14: Room 237 direct impulse response, Rogers speaker

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Reverberation : Effect on Word Error Rate

	Close-mike	RT60 = 0.55
Human	0.3%	0.3%
ASR	5.9%	22.2%
ASR w/ treatment	4.7%	13.0%