Room and Auditorium Acoustics

Room Characteristics and Design

We can apply many concepts from this course to room acoustics. These include:
Frequency, sound intensity, Fourier spectra, reflection of waves, interference and diffraction, resonance.
Some important additional concepts in the following are:
Absorption of sound, reverberation time, room characteristics and design.

Topics and Key Words
Reverberation time
Sound reflection and absorption in enclosed spaces

Acoustical Design Criteria
Liveness
Intimacy
Fullness
Clarity
Warmth
Brilliance
Texture
Blend
Ensemble

Acoustical Design Problems
External noise
Double-valued reverberation time
Focusing of sound
Echoes and flutter echoes
Shadows
Diffraction of Sound
Resonances

Demonstrations
1. Play some music from CDs and judge the acoustical qualities of the lecture room for speech and different types of music.
2. Tap a big cylindrical cardboard packing tube on the floor. Listen as the resonance decays with time. This is only a simulation of the real reverberation time of a room.

Reverberation Time T_R

The reverberation time of a room, auditorium, or concert hall is one of the most important acoustical characteristics of an enclosed space. Sound does not immediately disappear when turned off. It reflects from walls, floor, and ceiling in multiple paths. With every reflection, the intensity decreases due to absorption by the material of the surfaces.

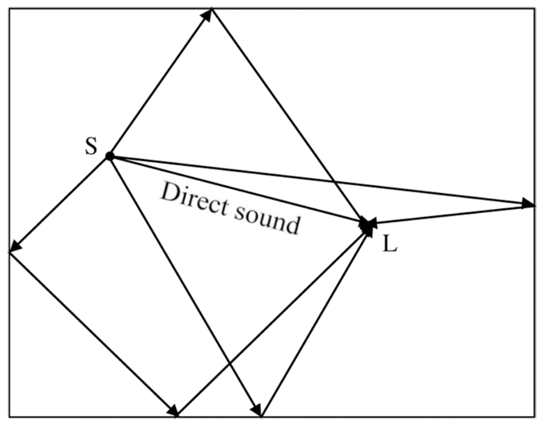
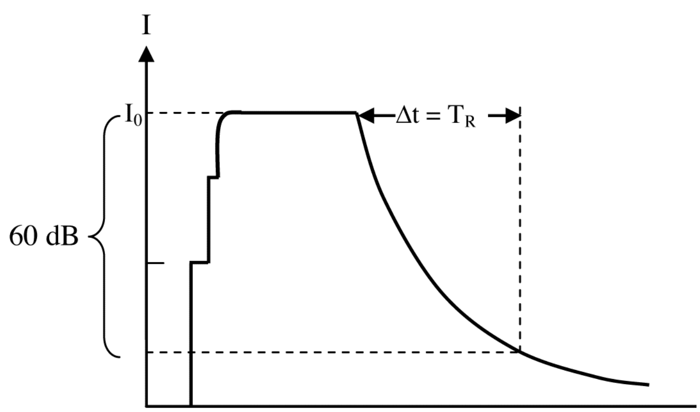


Figure. Sound paths in an enclosed room. Note the direct sound from the source “S” to the listener “L” and the reflected sound from the walls.

Definition of the Reverberation Time

The time it takes a sound to decay from an initial intensity I_0 to one-millionth of this value is called the reverberation time T_R, thus $I(T_R) = 10^{-6} \cdot I_0$, i.e. a decrease of 60 dB.



Change in sound intensity level:
$\Delta SIL = 10 \cdot \log(I/I_0)$ or
$\Delta SIL = 10 \cdot \log 10^{-6} = -60$ dB

Figure. Definition of the reverberation time T_R. The intensity in the room builds up to a plateau after the first few distinguishable reflections. After turning the sound off, the intensity decays exponentially by 60 db during the reverberation time T_R.

Questions

The sound intensity in a room is I_0 at time $t = 0$. At what times has the original sound intensity I_0 decreased by 10 dB, 20 dB, 30 dB, 40 dB, 50 dB, 60 dB?
Answer: $T = T_R/6$, $T_R/3$, $T_R/$,…, T_R. Can you figure out the missing two values?

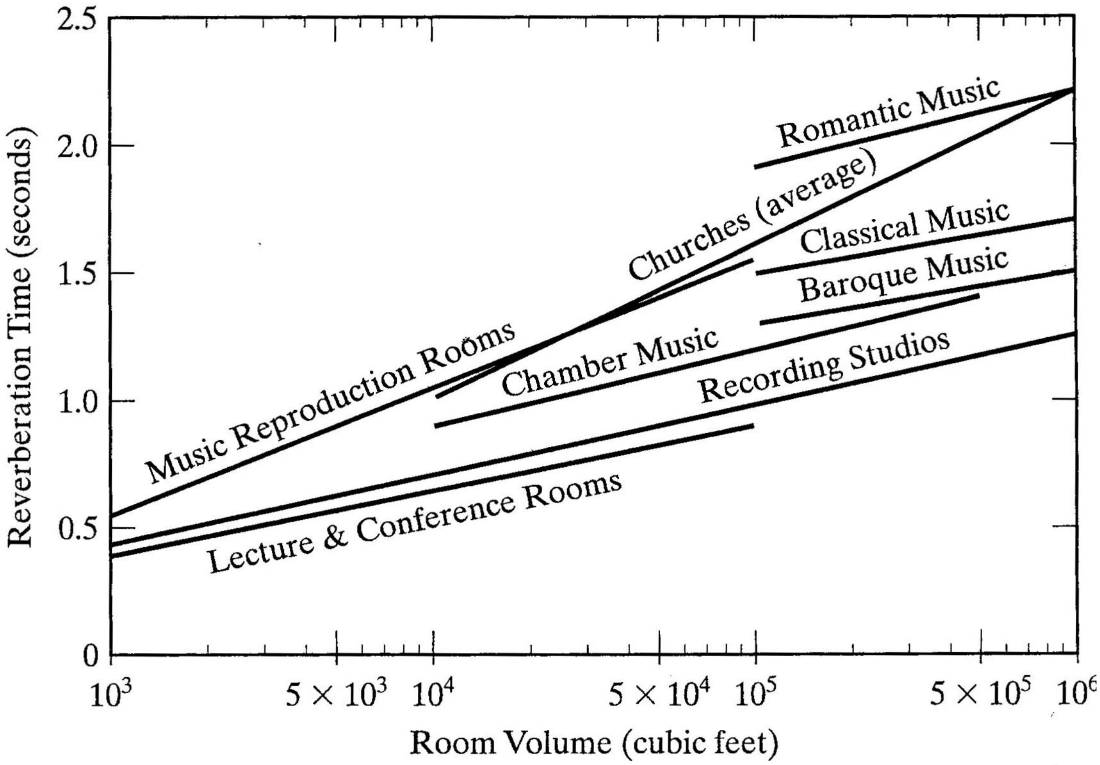


Figure. Ideal reverberation times for several room types and music styles. (From Berg & Stork, Fig. 8-4, p. 218.)

Demonstrations

1. Measure the SIL of the background noise in the lecture room with a sound level meter. Then clap your hands and note the SIL. Abruptly stop clapping. Guess the time it took for the sound to decay to the background level. Take the difference between the two dB readings. (This probably will be much less than the 60 dB decrease for one entire T_R.) Calculate the reverberation time T_R from this difference and compare with your guess.

Answer: T_R = _____________s for the lecture room.

2. Make sound pulses by clapping, gently striking the desk with a hammer, or repetitively pressing a key on the keyboard. Observe the pulses on a sonogram as a function of time. Note the rising attack and falling decay transients. You may be able to see a 30 dB decrease. Double this time to obtain the reverberation time.

Answer: T_R = _____________s for the lecture room.

Exercise

Estimate the volume of the lecture room in cubic feet. Read the reverberation time from the line in the above figure labeled “Lecture & Conference Rooms”.
Compare this with the values obtained in the demonstrations 1 and 2 above.

Answer: Read from the graph: T_R = ______s

Demonstration 1: T_R = _____s   Demonstration 2: T_R = _____s

3. Tap a large cylindrical cardboard packing tube on the floor and record the waveform of the pulses. Estimate the reverberation time T_R from the exponential decay of the waveform.

Reverberation Time Formula and Acoustical Materials

The reverberation time is the time for the sound intensity to decrease to one millionth of the original intensity, i.e. by a factor of 10^6 or 60 dB, after the sound is turned off.

The formula for calculating the reverberation time in seconds is

$$T_R = 55.2 \frac{V}{v \cdot A_{sabin}} \quad \text{(metric units)}$$

Here V is the room volume, v the sound velocity, and A_{sabin} the total effective absorbing area of all surfaces combined, expressed in units of *sabin*.

After substituting v = 346 m/s or 1136 ft/s (at 25^0C) in the above formula, we obtain two alternative expressions, one in SI-metric units, the other in British units:

$$T_R = 0.160 \frac{V}{A_{sabin}} \text{ (dimensions in meter) and } T_R = 0.0486 \frac{V}{A_{sabin}} \text{ (dimensions in feet)}$$

In the first formula, the effective area in *metric sabine*, in the second formula it is in *British sabine* or simply *sabin*.

We shall use British units of ft, ft^2, and ft^3 for calculating the reverberation time because of their greater familiarity when dealing with room dimensions.

The area A_{sabin} takes into account the degree of sound absorption by materials. If all sound were absorbed 100% by a surface, the effective area would be the actual area in ft^2, let's say 1 ft^2. If only 30% of the sound intensity is absorbed, then the effective area is only 0.3 ft^2. This effective area then is called 0.3 *sabin* to distinguish it from the actual area. (The unit *sabin* was chosen in honor of the American physicist William C. Sabine (1868-1919), a pioneer in acoustics.)

The total absorption by all room surfaces is given by the sum

$$A_{sabin} = a_1A_1 + a_2A_2 + a_3A_3 + a_4A_4 + \ldots,$$

where the coefficients a_1, a_2, a_3, etc. are the *absorption coefficients* of the various surfaces in the room. The areas A_1, A_2, A_3, etc. are the actual surface areas. For values of the absorption coefficients a_i, see the following Table.

Sound Absorption Data

Sound Absorption Coefficients of Building Materials at Octave Intervals

	Frequency (Hz)					
Material	125	250	500	1000	2000	4000
Concrete, bricks	0.01	0.01	0.02	0.02	0.02	0.03
Glass	0.19	0.08	0.06	0.04	0.03	0.02
Plasterboard	0.20	0.15	0.10	0.08	0.04	0.02
Plywood	0.45	0.25	0.13	0.11	0.10	0.09
Carpet	0.10	0.20	0.30	0.35	0.50	0.60
Curtains	0.05	0.12	0.25	0.35	0.40	0.45
Acoustical board	0.25	0.45	0.80	0.90	0.90	0.90

Note: These are dimensionless *absorption coefficients*. (They give the percentage absorption when multiplied by 100, e.g. 13% for plywood at 500 Hz.)

Sound Absorption by Persons and Seats in Sabin

	Frequency (Hz)				
	125	250	500	1000	2000
Unupholstered seat	0.15	0.22	0.25	0.28	0.50
Upholstered seat	3.0	3.1	3.1	3.2	3.4
Adult person	2.5	3.5	4.2	4.6	5.0
Adult in upholstered seat	3.0	3.8	4.5	5.0	5.2

Note: These are the *total absorption values* in sabin (effective areas). *Total absorption* is not to be confused with the dimensionless *absorption coefficients* in the upper table.

(Values in the two tables taken from Berg & Stork, Table 8-3 and Table 8-4, p. 227.)

Timbre and Reverberation

From the frequency dependence of the sound absorption coefficients we see that the timbre of a tone depends on the particular room in which it is played. For instance, in an enclosure made of glass or plasterboard, a given note will sound bright or brilliant, because the high frequencies are absorbed less than the low frequencies. Conversely, the same note will sound warmer in a room covered with carpet, curtains, and acoustical board.

Calculation of the Reverberation Time of a Lecture Room

As an exercise we calculate the reverberation time T_R of our lecture room.
Width of room: W = 24 ft
Length: L = 29 ft
Average height between ceiling and sloping floor: H = 9.5 ft

Verify that for the four walls the total area is $A_{walls} = (2W + 2L)H = 1007$ ft^2,
$A_{ceiling} = W \times L = 696$ ft^2, $A_{floor} \approx A_{ceiling} = 696$ ft^2.
Materials: Concrete walls $a_{concrete} = 0.02$, acoustical tile ceiling $a_{acoustical\ tile} = 0.90$,
wood floor $a_{floor} = 0.15$.
The numbers are approximate and are for frequencies in the middle range in the Table, around 500 Hz.

Verify that the total absorption in sabin is
A_{sabin} = 20 sabin (walls) + 626 sabin (ceiling) + 104 sabin (floor) = 750 sabin

Add to this the absorption from occupied and unoccupied chairs:
Unoccupied unupholstered chair: A = 0.25 sabin around 500 Hz
Occupied unupholsered chair: A = 4.3 sabin around 500 Hz
Assume 30 chairs unoccupied: A = 30 x 0.25 = 7.5 sabin ≈ 8 sabin
Assume 20 chairs occupied: A = 20 x 4.3 = 86 sabin

The the total absorption in sabin is
A_{total} = 750 sabin (room) + 86 sabin (people in chairs) + 8 sabin (unoccupied chairs)
A_{total} = 844 sabin

The volume of the room is V = W x L x H = 24 x 29 x 9.5 ≈ 6600 ft^3
Final Answer
The reverberation time then is obtained by substituting the values in the formula

$$T_R = 0.050\frac{V}{A_{sabin}} \quad \text{or} \quad T_R = 0.050\frac{6600}{844} = 0.39 \text{ s or } \mathbf{T_R \approx 0.4\ s}$$

This is in very good agreement with a value of about 0.5 s in the Figure for the reverberation time labeled “Lecture & Conference Rooms”.

See the next page for the measurement of the reverberation time of our lecture room.

Question
If the reverberation time is 0.4 second for a 60 dB decrease in sound intensity, what is the time for the intensity to decrease by only 30 dB, as is more likely to be achieved in the lecture room because of background noise?
Answer: 0.2 second

Sonogram of the Reverberation Time of a Lecture Room

The reverberation time of our lecture room was measured by clapping and recording a sonogram of the pulses.

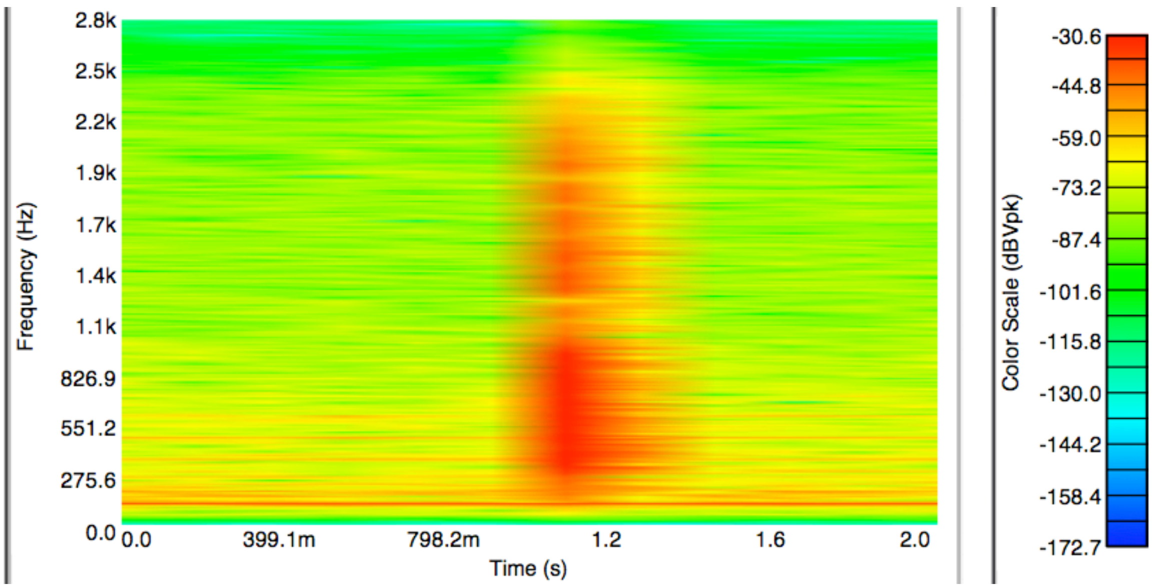


Figure. Sonogram of a rapid clap as recorded in the lecture room. Shown are the frequency on the ordinate and progressing time on the abscissa. Color indicates the sound intensity on the dB-scale (see also the color bar on the right of the figure).

We see that the signal from the clap is a noise spectrum ranging from below 200 Hz to about 2.5 kHz. The signal starts at the red area. The intensity builds up (attack transient) and reaches the deepest red in about 0.15 s. After an additional 0.1 s the intensity decreases again.

The reverberation time for a 60 dB decrease is reached when the color has changed from deep red to light green. This happens within about 0.25 s in the range 1 to 2 kHz and in 0.4 s in the range 300 Hz to 1 kHz . The longer reverberation at these lower frequencies means that our lecture room exhibits more “warmth” than “brilliance”.

Note that the reverberation time of 0.4 s agrees well with the time of $T_R \approx 0.4$ s calculated earlier for frequencies around 500 Hz.

Reverberation Time in the Southwest Collections Library at Texas Tech University

A sonogram of the reveration of sound was recorded in the entry hall to the Southwest Collections Library. The sound was produced with a clap of the hand.

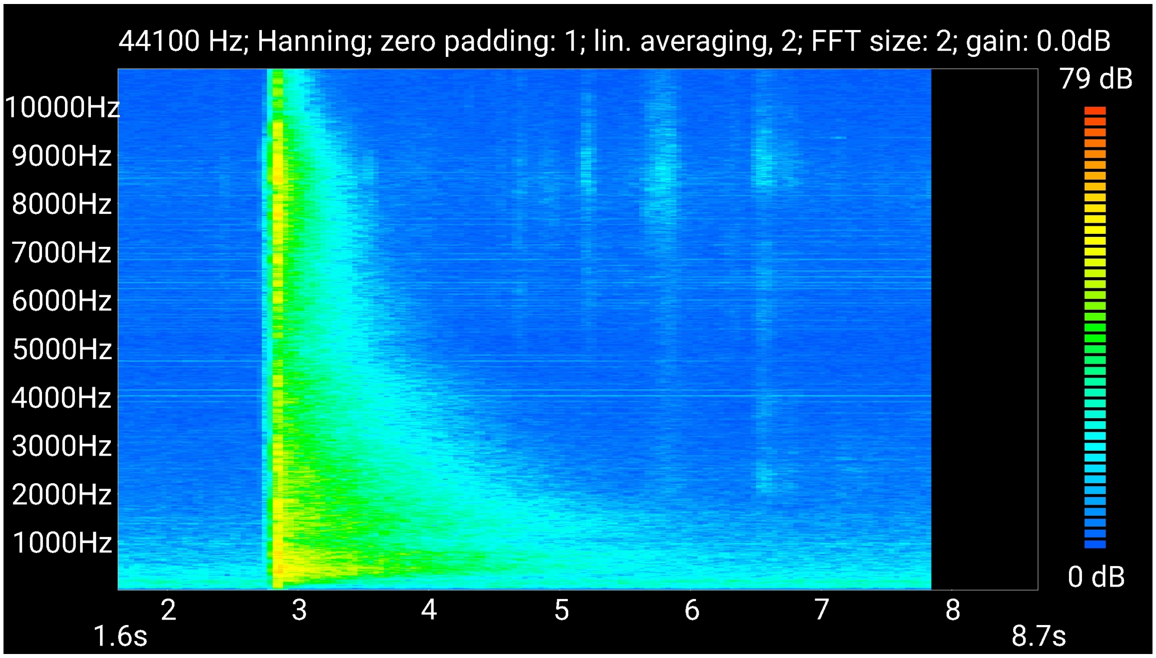


Figure. Sonogram from a single clap of the hand in the Southwest Collection Library at Texas Tech University. Its entry hall is big, the surfaces absorb little sound, and consequently the reverberation times are rather long. At the lowest frequencies the reverberation time is about 3 seconds, at the highest about 1 second. This means that the hall exhibits acoustical "warmth" rather than "brilliance". (Recording taken by Binod Rajbhandari.)

Project

Go to the Southwest Collections Library and clap your hand in the entry hall. Estimate the reverberation time. Note how the quality of the sound changes during the reverberation. Does the sound become warmer or more brilliant as it decays?

Acoustical Design Criteria

Liveness
Liveness is a qualitative term for the reverberation time T_R. A room is "live" if it has a long reverberation time. The desired "liveness" depends on the type of music played (see figure of reverberation times).

Intimacy
A room is said to have *intimacy* when the first reflected sound from surfaces reaches the listener within 20 ms after the original direct sound. This generally is the case for smaller lecture halls. For large auditoriums or halls one can use canopies above the speaker or the performers to reduce the time to the desired 20 ms. The canopies may be inclined to reflect the sound to the listeners.

Exercise
How far does sound travel in 20 ms? What, therefore, is a "small" or "large" hall?
Answer: Travel distance $\approx$ 7 m $\rightarrow$ "small hall" = 5 to 10 m, "large hall" > 10 m.

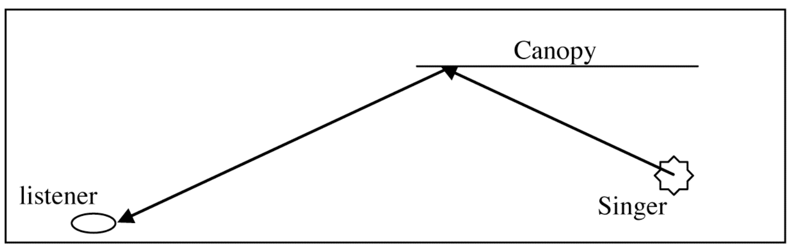


Figure. A canopy above a singer in a large hall to reflect the sound to the listener and reduce the travel time for better room intimacy.

Fullness
An auditorium has *fullness* if the intensity of the reflected sound is higher than the direct sound. Greater fullness means a longer reverberation time. Fullness is desired for romantic music played by a large orchestra and less so for chamber and baroque music.

Clarity
Clarity is the opposite of fullness. The intensity of the direct sound is higher than the reflected sound. Acoustical clarity is needed for speech and early orchestral music. The reverberation time is short (see figure of reverberation times).

Warmth
For a room having *warmth,* the reverberation time should be about 1.5-times longer at low frequencies up to about 500 Hz than for higher frequencies. Above 500 Hz the reverberation time should be approximately constant. Such a frequency-dependent reverberation time can be obtained by the suitable choice of materials for walls, ceilings, and floor. The room will lack clarity if the reverberation time becomes too long at the lowest frequencies.

Brilliance
Brilliance is the opposite of warmth. The reverberation time is longer for high frequencies than for low frequencies. If it becomes too long at high frequencies the room may be "ringing" at a high pitch.

Texture

Texture addresses the time pattern of how the reflections reach the listener. For good texture the first reflection should arrive within 20 ms after the direct sound in order to have intimacy. The next four or five reflections should arrive within 60 ms after the direct sound. The overall intensity from the reflections should decrease monotonously with time. Echoes and focusing of sound result in poor texture and produce intensity spikes during the overall decrease of the sound intensity with time.

Blend

Blend means a proper mixing of sound from all instruments at the location of the listener. It is best to mix the sound first at its origin. This can be accomplished with reflecting surfaces surrounding the stage. Individual instrument sections should not be singled out and the sound should be diffused before it reaches the audience.

Ensemble

A stage has good *ensemble* if the performers can hear each other, enabling them to play well together. For this it is necessary that fast notes in the music should not be delayed too much by reflections. This limits the size of the stage to less than 20 m.

Exercise

Suppose that the temporal separation between the fastest notes is 50 ms in a piece of music. Estimate the maximum distance between the sides of the stage.

Answer: Size of stage $x = v \cdot t = (346\ \text{m/s}) \cdot (0.050\ \text{s}) = \underline{17.3\ \text{m}}$.

Ensemble and Opera

The *ensemble* between opera singers on the stage and the musicians in the orchestra pit may be poor. Reflectors directing sound from the pit to the singers may help, but then the audience does not get much direct sound. As an alternative, small loudspeakers may be used to aim the sound from the orchestra to the singers.

Ensemble and Marching Band

A lack of ensemble is likely to exist in a marching band on a football field. The band is spread out and the time delays between the various band sections can be large compared to the time between successive notes in the music. Watching a band director signaling the rhythm may minimize the problem, but then the players from the far ends of the band should not listen to each other! People in the stands listening to the music still will not hear the instruments quite synchronized because of different time delays from the band.

Exercise

1. Take a typical size of a marching band and estimate the differences in the arrival times of the music from the different band sections at a listener in the stands.

Answer: Take $d = 70$ m for the size of the band. Then the maximum time difference is given by $\Delta t = d/v = 70/346 = 0.2\ \text{s} = \underline{200\ \text{ms}}$.

2. Guess what time delay might still be tolerable for most people. Or how much could the sound from different band sections be out of sync and still be agreeable?

Answer: A guess for tolerable time delays: _______s.

Acoustical Design Problems

External Noise
An auditorium may have background noise from traffic, air blowers, air conditioners, etc. Noise has a wide frequency spectrum. Its low frequencies can mask the higher frequencies in music and speech. Means to address the problem include better sound insulation and constructing the room as a "box in a box". This was done at the John F. Kennedy Center for the Performing Arts in Washington, D.C. Environmental noise levels should not exceed the values in the following table. Actual noise levels often are much higher.

Table. Acceptable background Noise Levels. (Add 5 to 10 dB for more typical values.)

Recording studios	25 dB
Auditoriums and theaters	30 dB
Lecture halls	30 dB
Hospitals	30 dB
Homes	40 dB
Offices	45 dB
Restaurants	50 dB

Demonstrations: Does our classroom meet these requirements? Measure the sound intensity level (SIL) and compare with the table.
Answer: Measured SIL in classroom: SIL = ________ dB
From table: SIL = ________ dB

Conclusion: ____

Double-Valued Reverberation Time
For recorded speech or music, the reverberation times of the recording and listening rooms most likely are different. When the listening room has a long reverberation time, the recording may sound unpleasant and speech may become unintelligible. Smaller listening rooms or wearing headphones can partly address the problem.

Focusing of Sound

Sound may be focused in a room by reflection from curved surfaces such as spherical surfaces, ellipsoids, paraboloids, or flat panels improperly arranged. If some musicians in an orchestra are at one focal point of a curved surface, the listeners at the other focal point will hear these players louder than others.

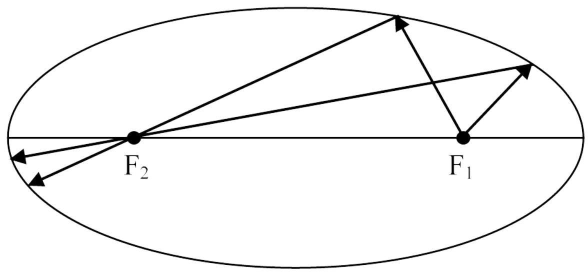


Figure. Sound from one focal point of an ellipsoid is focused into the other focal point. You may find this effect in "whispering chambers" in science museums. It is to be avoided in concert halls and auditoriums.

Echoes and Flutter Echoes

Echoes generally are undesirable and adversely affect the sound texture of a room. They originate from concave curved surfaces. This happens when musicians are at the focus of a curved surface behind them. The direct sound to the audience is then followed by the echo waves from the curved surface, giving the illusion of being in a cave.
Sound reflecting back and forth between two parallel walls is called a flutter echo.

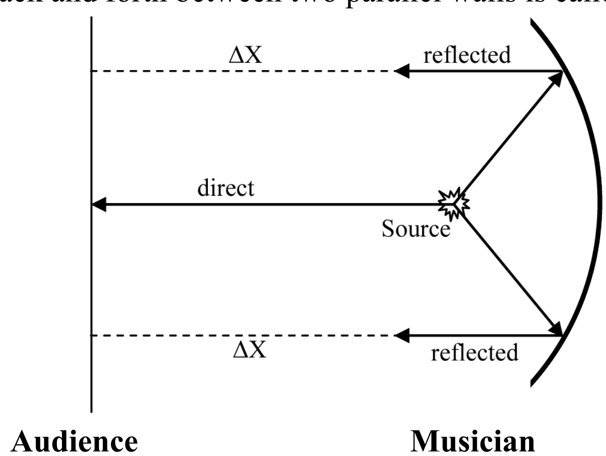


Figure. Parabolic reflecting surface with a sound source at its focus. The direct sound arrives earlier at the audience than the reflected sound. The path difference Δx causes an echo-like sound.

A Project

Clap your hands at the center of the Memorial Circle at Texas Tech University. Do you hear echoes, reverberation, or resonances? Step off the center and note the changes.

Shadows

Acoustical shadow regions may exist in parts of an auditorium that protrude into the space near the listener. In order to minimize the effect, an open space in front of the listener should exist with a sufficiently large angle between the obstruction and the stage.

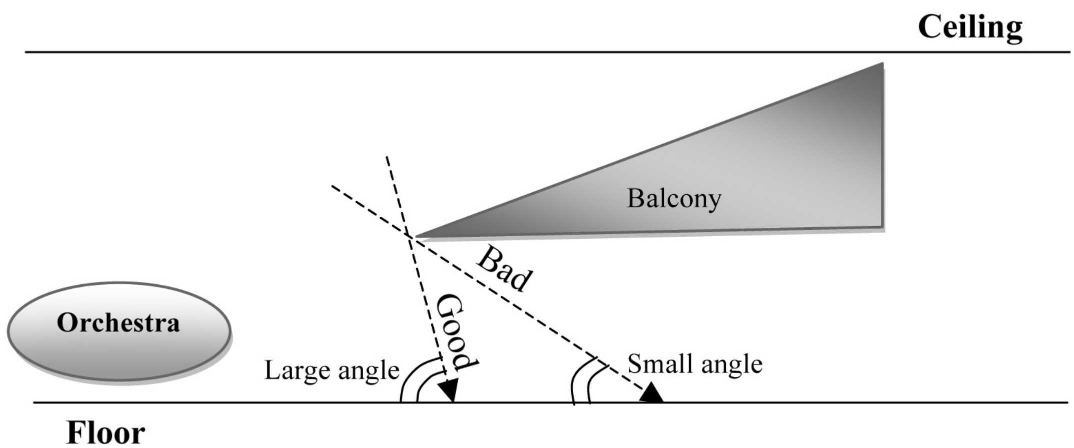


Figure. A listener (arrow tips) below a balcony in a concert hall. The balcony casts a sound shadow impairing the sound quality. A large subtended angle with respect to the front of the balcony is good, a small angle is bad.

Diffraction of Sound

Diffraction of sound occurs when the wavelength approaches the size of an obstacle. The resulting intensity variations behind the obstacle depend on the location of the observer and the wavelength of the sound. Therefore, the timbre of the direct sound from an orchestra may change behind the obstacle. However, reflections from other surfaces will diminish this effect.

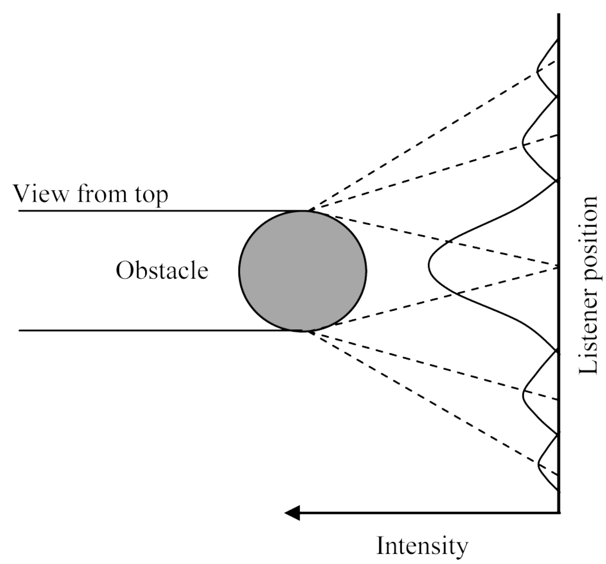


Figure. Sound diffraction by a column (as viewed from above). Intensity minima and maxima occur behind the column and the sound color or timbre may change.

Room Resonances

Sound resonances in rooms generally are undesirable. They adversely affect the sound texture, but are an interesting phenomenon and so we treat them in some detail here. A close analogy exists between the air resonances in a room and the resonances of vibrating strings. Strings are fastened tightly at two "closed ends". Similarly, resonating air columns encounter "closed ends" at opposing rigid walls. We can make good use of what we know from vibrating strings, because the vibration patterns look the same.

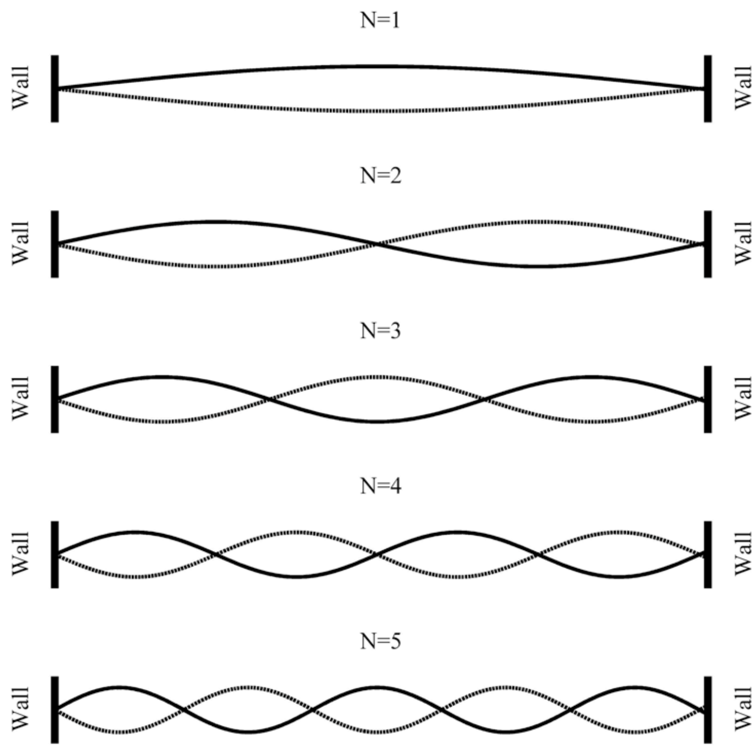


Figure. The first five air resonances between the parallel walls of a room. The ordinate shows the longitudinal displacement of the air molecules between the walls, but plotted here in the vertical direction for clarity.

For the fundamental mode we have $x = \lambda/2$ or $\lambda = 2x$.
The fundamental frequency is $f_1 = v/\lambda_1 = v/2x$, where $v = 346$ m/s is the speed of sound.
For the higher vibrational modes, we have the integer multiples $f_N = Nf_1 = N(v/2x)$, where N = 1, 2, 3, 4, …… are the harmonic numbers.

Exercise
You are singing in a shower stall of length x = 1.2 m. What are the lowest three resonance frequencies between two parallel walls separated by the distance x?
Answer: Verify that $f_1 = 144$ Hz, $f_2 = 288$ Hz, $f_3 = 432$ Hz.

For a room we actually have the three dimensions length *x*, width *y*, and height *z.* All three contribute to room resonances, and so we must include them. We consider only the simplest case of an empty box-like room. For the vibrational modes in the individual x-, y-, and z-directions we have, respectively,

$$f_x = N_x(v/2x) \qquad f_y = N_y(v/2y) \qquad f_z = N_z(v/2z)$$

where N_x, N_y, N_z are the integers 1, 2, 3, 4, ….

The question arises how these three sets of frequencies are to be combined for vibrations in all directions. What are the resultant frequencies?
The answer is

$$f_{xyz} = \sqrt{f_x^2 + f_y^2 + f_z^2} = \frac{v}{2}\sqrt{\left(\frac{N_x}{x}\right)^2 + \left(\frac{N_y}{y}\right)^2 + \left(\frac{N_z}{z}\right)^2}$$

Example
A tornado shelter has the dimensions x = 3.46 m, y = 2.77 m, z = 1.73 m. Assume for the speed of sound v = 346 m/s. Calculate the frequencies of some of the lowest resonance modes (N_x, N_y, N_z) in the shelter.
Verify the following values for the first few resonance frequencies:

Modes		Mode Frequency
(1, 0, 0)	$\rightarrow$	f_{100} = 50.0 Hz
(0, 1, 0)	$\rightarrow$	f_{010} = 62.5 Hz
(0, 0, 1)	$\rightarrow$	f_{001} = 100.0 Hz
(1, 1, 0)	$\rightarrow$	f_{110} = 80.0 Hz
(1, 0, 1)	$\rightarrow$	f_{101} = 111.8 Hz
(0, 1, 1)	$\rightarrow$	f_{011} = 117.9 Hz
(1, 1, 1)	$\rightarrow$	f_{111} = 128.1 Hz
(2, 0, 0)	$\rightarrow$	f_{200} = 100.0 Hz
(0, 2, 0)	$\rightarrow$	f_{020} = 125.0 Hz
(0, 0, 2)	$\rightarrow$	f_{002} = 200.0 Hz etc.

We can arrange these frequencies in order of ascending values:
50, 62.5, 80.0, 100, 100, 111.8, 117.9, 125.0, 128.1, 200.0 Hz.
Some of these frequencies are closely spaced. Generally, the frequency spectrum becomes more crowded for the higher resonances.

Question: What measures can you take to minimize undesirable room resonances?
Answer: ____

Resonances in a Cubical Model "Room"

In the laboratory of this course we use a wooden box as a "model room" and observe some of its "room resonances". (They will have higher values than for the tornado shelter because of the smaller size of the box.) The simplest box is a cube. Resonances for such a cube are shown in the following two figures:

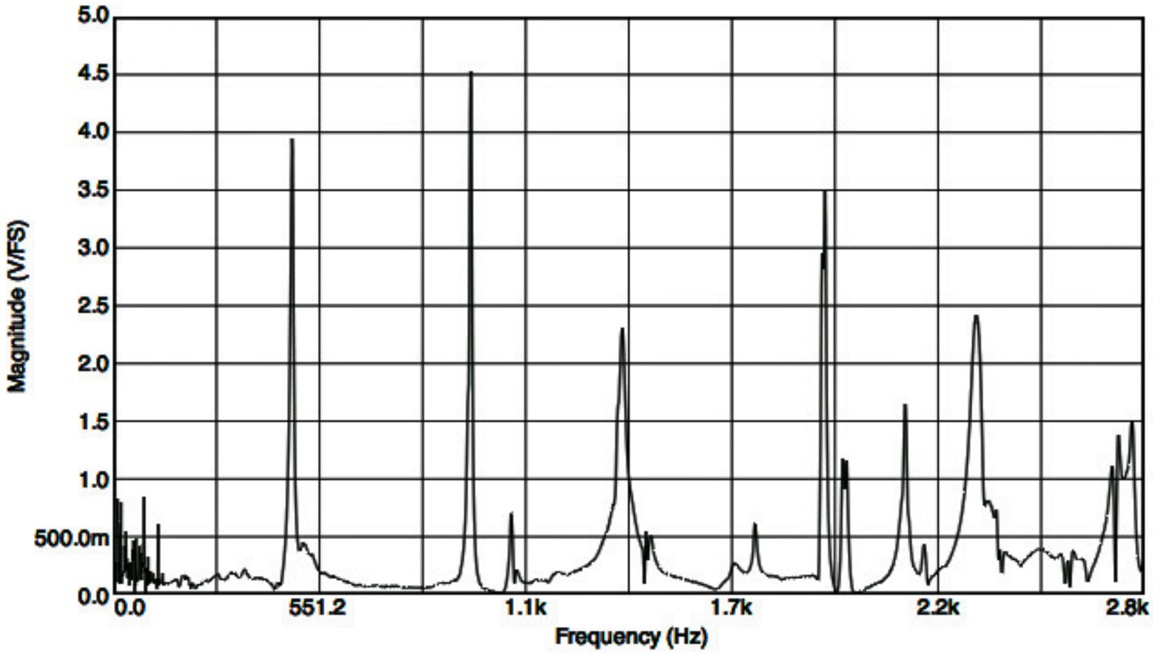


Figure. Frequency spectrum of a cubical plywood box with interior dimensions $x = y = z = 361.5$ mm (25.5 ^{0}C, sound velocity $v = 346.3$ m/s). The lowest resonance is the (1, 0, 0) mode with a frequency of $f_{100} = 479$ Hz.

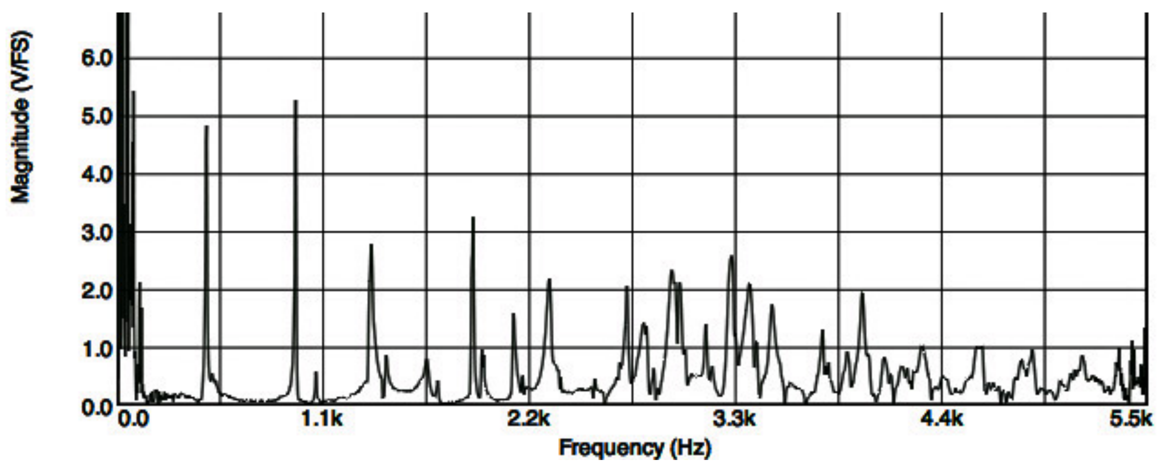


Figure. Compressed frequency scale for the same cubical box showing the ever more densely packed resonances at higher frequencies.

One sees that the lowest room resonances are well separated. They become more densely packed at higher frequencies. Some "formant regions" of the room may be seen, especially beween 2.4 to 3.7 kHz. The amplitudes of the resonances depend on microphone and speaker placement inside the "room". Some possible frequencies may not be seen at all.

We had for the frequencies of a box-like room with dimensions x, y, z the formula

$$f_{xyz} = \sqrt{f_x^2 + f_y^2 + f_z^2} = \frac{v}{2}\sqrt{\left(\frac{N_x}{x}\right)^2 + \left(\frac{N_y}{y}\right)^2 + \left(\frac{N_z}{z}\right)^2}$$

where N_x, N_y, N_z are the harmonic mode numbers 1, 2, 3, 4, ….that correspond to the directions *x*, *y*, *z*, respectively. For our cubical box this formula simplifies considerably, as all three sides are the same: x = y = z = 361.5 mm. This simplifies considerably the above formula:

$$f_{xyz} = \frac{v}{2x}\sqrt{(N_x)^2 + (N_y)^2 + (N_z)^2}$$

Exercise
Read the frequencies of the strongest 5 resonances from the upper of the two preceding figures. For good accuracy, use a ruler on the frequency scale and a calculator.
Answer: The strongest 5 measured frequencies are

f = _____Hz, f = ______Hz, f = ______Hz, f = ______Hz, f = ______Hz

Exercise
Calculate the five lowest resonance frequencies for the cubical box. Take v = 346.3 m/s and x = y = z = 361.5 mm = 0.3615 m. Label the vibrating modes, for instance (2, 1, 0). Compare your calculated frequencies with those from the preceding exercise.
Answer: Write down the measured frequencies and mode labels, for instance (1, 0, 1). Write the vibrational mode numbers (N_x, N_y, N_z) below each frequency this way:

f = ______Hz, f = ______Hz, f = ______Hz, f = ______Hz, f = ______Hz
(, ,) (, ,) (, ,) (, ,) (, ,)

Home Rooms

Usually we cannot build our own studio for home listening. But a few design features are under our control:
1. Materials of the room surfaces (walls, ceiling, floor).
2. Placement of reflecting panels or furniture.
3. Carpets, rugs, flooring material.
4. Audio systems with equalizers.
5. Loudspeaker placement.

Audio Systems

Perform some experiments in your room by placing the speakers strategically for best sound, especially for multi-speaker systems. For example, a 5.1 audio system has one subwoofer and 4 speakers. Place two speakers in front and two in back. The subwoofer can be anywhere. An optimal place for speakers is above ground and away from walls or corners. The listening area should be between the speakers and not far from them.

Great amplifier power such as 500 Watt of *electrical* output generally is not needed in a living room. However, a relatively high electric power is needed because of the very low efficiency of less than 1% for converting electric to acoustic power. Short sound bursts also require a higher electrical power from the amplifier. Normally less than 1 Watt of *acoustical* power is quite sufficient. Taking all this into account, a 100 or 200 Watt amplifier should be adequate for most home audio systems.

Room Resonances, Pink Noise, and Room Tuning

Acoustic resonances in small rooms are undesirable. The problem can be addressed by “tuning” the room with *equalizers* in the audio system. Strong resonances that are “booming” at certain frequencies can be minimized this way. Conversely, frequencies that are absorbed strongly can be boosted with an equalizer.

Room resonances also can be minimized by design elements positioned under an angle with respect to the walls. Absorbent wall hangings are an example.

The acoustical power in typical music, per unit frequency interval, drops off with about 3 dB/octave. A steady decrease like this is called *pink noise.* In order to achieve such a 1/f response in a room, try the following:
Play pink noise from a test CD through your audio system. Use a sound-level meter at different locations in the room. Ideally the sound intensity level (SIL) should be fairly constant throughout the room. If it is higher at some locations, you are having room resonances or speaker resonances. Adjust the equalizer of the audio system, change the room decor, or change the speaker placement to cut down these intensity maxima. This may take some experimentation, but the room probably will sound better.

Auditorium Design

Open Air Auditoriums
On a flat unobstructed field the sound intensity *I* drops off with distance *r* from the source according the *inverse square law* $I \propto 1/r^2$. For every doubling of the distance, the intensity decreases by a factor of four, where 4 = 2x2 or 3 dB + 3 dB = 6 dB. But the actual attenuation can be higher than this if the source is close to the ground and there are sound absorbing obstacles in the path to the listener such as other people, grass, etc.. This may result in a nearly 12 dB decrease in intensity for each doubling of the distance. In order to minimize the absorption by the ground the stage can be raised. On the other hand, the stage was lowest in ancient Greek and Roman amphitheaters where the spectators sat on an upward sloping surface. This contained the sound well within the theater. Small valleys also are suitable as natural amphitheaters.

Steps in Constructing an Indoor Auditorium
We can start with an "open-air auditorium" and cover the sides and top to build an indoor auditorium or concert hall.
1. Add a shell above the performers for reflecting the sound and achieving fullness.
2. Add side panels for more fullness and texture.
3. Keep these additions close enough for intimacy.
4. Diffuse the sound with side panels that should be flat to avoid focusing.
5. Provide better ensemble for the performers with panels on the sides.
6. Enclose the audience with a ceiling and walls.
7. Let the sides of the hall fan out from the stage.
8. Cover the sides and rear wall with absorbers to avoid standing waves and flutter echo.

Additional Auditorium Components
1. Balconies
Balconies should be steeply sloped. They should not protrude far into the hall so that diffraction of waves and shadows in the opening under the balcony are minimized. Pillars and columns under a balcony should be avoided.
2. Movable Elements and Reverberation Time
The reverberation time can be adjusted with retractable absorbers and choice of materials.
For speech, use sound absorbing panels for shorter reverberation times.
For small groups of performers, use small shells.
For chamber music, use movable ceiling sections and lower them.
3. Electronic Enhancements
Loudspeakers and amplifiers can be part of the reverberation system. The amplified sound should not arrive before the direct sound. Otherwise the listeners may get the impression that the orchestra is playing from the ceiling! This happens in the so-called *precedence effect*, where a listener places the sound source from where he hears the sound first.

Exercise: Identify some auditoriums on campus with good sound characteristics.
Answer: ____

Sound Concentration with Curved Surfaces Outdoors

Figure. Acoustic mirror at Denge, Great Britain, built in 1928 to listen to approaching airplanes from continental Europe in the 1930s. A microphone was attached to the metal rod at the focus of the parabolic mirror to collect the sound. (Reference: Thomas Cogley.)

Figure. Open-air stage at Oberstdorf (Allgäu), Germany. The curved surface behind the stage reflects the sound towards the listeners thus increasing the loudness.

Acoustics at the Campus Circle of Texas Tech University

Figure. The Center of the Campus Circle at Tech Tech University (Pfluger Fountain). If you clap your hands once at the center, you will hear an echo due to focusing of sound from the surrounding circular low brick walls. If you step away from the center, the echo becomes much weaker because of de-focusing of the sound.

Question

Besides an echo, do you also hear sound reverberation and resonances?
Whether or not you hear all three phenomena, describe the differences between them.

Project

Do this experiment at the Campus Circle and write a brief report.