VERSION 2

An Acoustics Primer

FOR MUSIC SPACES

Wenger®

Introduction

Planning Guides for New Construction and Renovation

Used by thousands of music educators, architects and administrators, Wenger Corporation's original Planning Guides have helped set basic facility standards for effective music education and performance areas. Even if a new construction project isn't in your plans, these guides still provide a strong foundation for understanding issues of layout, acoustics, storage and equipment.

Wenger Corporation works with the American Institute of Architects Continuing Education System as a registered AIA/CES provider.

Call Wenger Corporation and make these guides part of your personal library. We have one for Elementary and one for Secondary school music areas.

Education and Performance Guides Based on Our Experience and Your Input

At Wenger Corporation we have over 60 years of experience studying music education and providing solutions to the needs you face. On staff, we have some of the industry's leading experts in the fields of music education and performance facilities, acoustics, storage and equipment. To create a series of resource guides, we pooled all of our experience and then consulted the real experts — music educators. After more than 6,000 surveys, hundreds of interviews and site visits, we focused our attention on topics and problems educators face every day.

The topics we cover in our Wenger Corporation guides are a joint effort — a combination of our knowledge, input and writings from leading acousticians, architects and facility planners, and of course, the creative solutions of individual music educators. There are as many variations on these topics as there are schools in North America. Although every facility and every situation is unique, Wenger Corporation guides will provide a starting point for addressing many of the questions you have and the problems you face in your facility. We are always working on updated versions and new topics — see page 15 for a current list of Wenger Corporation guides for music educators and the spaces in which they teach and perform.

Acoustics Primer

Music is learned by listening. To be effective, rehearsal rooms, practice rooms and performance areas must provide an environment designed to support musical sound. It's no surprise then that the most common questions we hear and the most frustrating problems we see have to do with acoustics.

That's why we've put this Acoustics Primer together. In simple terms we explain the fundamental acoustical concepts that affect music areas. Our hope is that music educators, musicians, school administrators and even architects and planners can use this information to better understand what they are, and are not, hearing in their music spaces. And, by better understanding the many variables that impact acoustical environments, we believe we can help you with accurate diagnosis and ultimately, better solutions.

For our purposes here, it is not our intention to provide an exhaustive, technical resource on the physics of sound and acoustical construction methods — that has already been done and many of the best works are listed in our bibliography and recommended readings on page 15. Rather, we want to help you establish a base-line knowledge of acoustical concepts that affect music education and performance spaces.

This Wenger Corporation Publication Was Reviewed By Professor M. David Egan

Hon. AIA, is a consultant in acoustics and Professor Emeritus at the College of Architecture, Clemson University. He has been principal consultant of Egan Acoustics in Anderson, South Carolina for more than 35 years. A graduate of Lafayette College (B.S.) and MIT (M.S.), Professor Eagan also has taught at Tulane University, Georgia Institute of Technology, University of North Carolina at Charlotte, and Washington University. He is the author of Concepts in Architectural Acoustics, Concepts in Thermal Comfort, Concepts in Building Firesafety, and Concepts in Architectural Lighting (two editions). In addition to consulting, teaching, and writing, Professor Egan is a fellow of the Acoustical Society of America, member of the National Council of Acoustical Consultants, and an Association of Collegiate Schools of Architecture (ACSA) Distinguished Professor.

This Acoustics Primer Also Serves as a Partner Guide to Other Wenger Corporation Education and Performance Guides

- Planning Guide for Secondary School Music Facilities
- Planning Guide for Music Facilities
- Elementary Planning Guide
- Acoustic Primer
- Acoustical Problems and Solutions for Rehearsal and Practice Spaces
- Planning Guide for Performance Spaces

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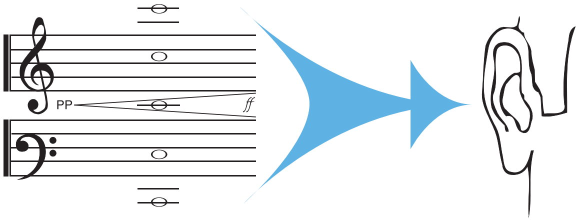
Critical Listening

Concept:

Musicians need to clearly and fully hear and critique musical sound, including subtle variations, across a wide range of dynamics (loud to soft) and frequencies (high to low pitches).

Relevance:

To support critical listening, a music space must provide a well-balanced acoustic environment which is also free from distracting noise. Unlike speech, musical sound contains complex elements of pitch, tone color, frequency, articulation and rhythm. A musician must be able to hear and distinguish between these subtle variations.



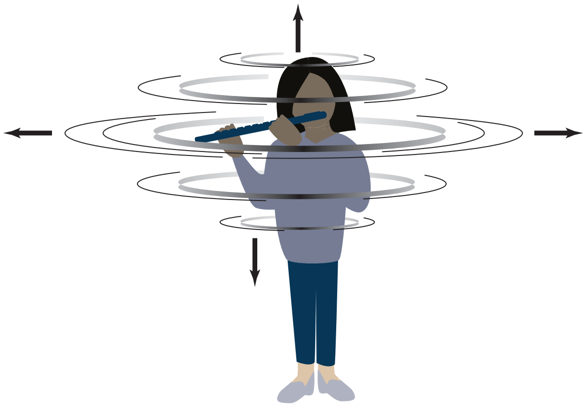
Sound Generation

Concept:

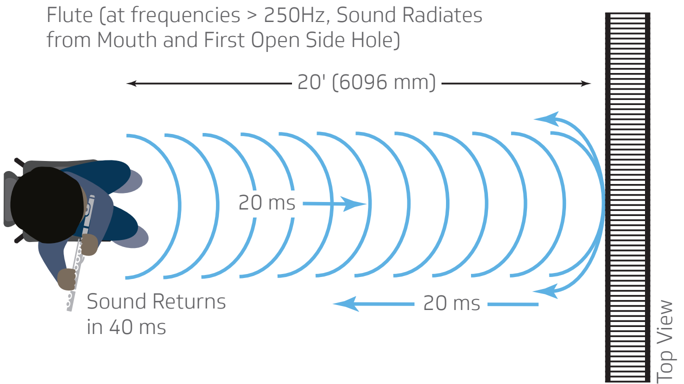
Sound radiates from its source in spherical waves by means of vibrations moving through the air. Sound travels through air at about 1 foot per millisecond (1000th of a second, abbreviated ms) or 1130 ft/sec until it strikes an obstacle that reflects, absorbs, or transmits it.

Relevance:

The distances sound must travel before it is reflected and the surfaces or obstacles it strikes all affect the musical acoustics of a room. Because the human ear and brain have limits to their processing speed, a musician can hear better if sound reflected from walls and ceilings returns to the ear with a slight delay. This is one of the reasons rooms with adequate cubic volume create a better environment for music.



Sound Radiation of Flute at 250 Hz



Sound Reflected off Wall

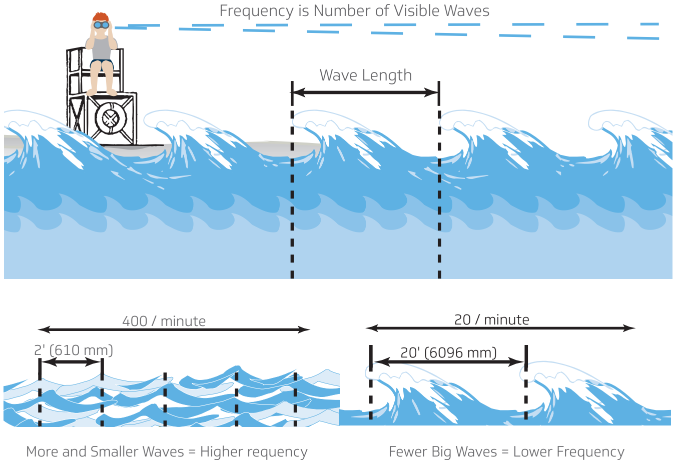
Frequency and Wavelength

Concept:

Frequency, the measurable attribute of the “pitch” we hear, is the cycles per second of a sound measured in Hertz (Hz). For example, the tuning pitch “A” generates sound waves at 440 cycles per second. You can think of this in terms of waves in the ocean — frequency would be the number of waves you can see at one time looking out over the ocean. And like ocean waves, sound waves can be measured by physical length from crest to crest. It is important to understand just how big are some of these wavelengths of sound — “C” below “middle C” generates a wavelength of about eight feet.

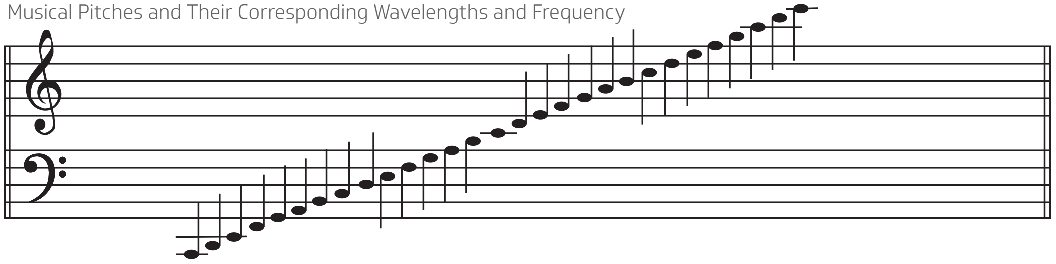
Relevance:

Large ocean waves move more water and have longer wavelengths than smaller waves. Because the large waves are unaffected by small obstacles, such as posts or protruding rocks, high solid breakwalls are needed to stop them. Similarly, low frequencies of sound move more air and have longer wavelengths than high frequencies. These longer wavelengths are also unaffected by small obstacles. As you think about your room, it is important to visualize the wavelength of the sound you are trying to affect. The size of reflectors and type of absorption used should be tailored to the wavelengths of sound in your room. To alter big, energetic sound waves, you will need equally large treatments.



Frequency and Wavelength.

Musical Pitches and Their Corresponding Wavelengths and Frequency

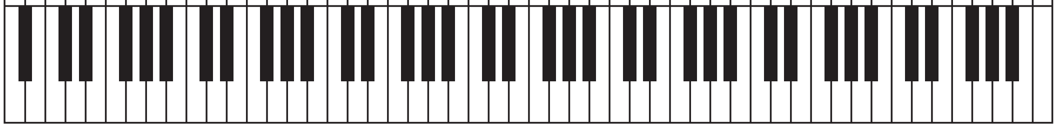


PHYSICAL WAVE LENGTH OF SOUND	40.4' (12314 mm)	36.5' (11125 mm)	34.2' (10424 mm)	30.5' (9296 mm)	27.5' (8382 mm)	25.7' (7833 mm)	23.1' (7041 mm)	20.5' (6248 mm)	18.2' (5547 mm)	17.4' (5304 mm)	15.5' (4724 mm)	13.8' (4206 mm)	13' (3962 mm)
FREQUENCY (Hz) TO NEAREST 1.0	28	31	33	37	41	44	49	55	62	65	73	82	87
MUSICAL NOTE	A	B	C	D	E	F	G	A	B	C	D	E	F

PHYSICAL WAVE LENGTH OF SOUND	11.8' (3597 mm)	10.3' (3139 mm)	9.2' (2804 mm)	8.6' (2621 mm)	7.7' (2347 mm)	6.8' (2073 mm)	6.5' (1981 mm)	5.8' (1768 mm)	5.1' (1554 mm)	4.6' (1402 mm)	4.3' (1311 mm)	3.8' (1158 mm)	3.4' (1036 mm)
FREQUENCY (Hz) TO NEAREST 1.0	98	110	123	131	147	165	175	196	220	247	262	294	330
MUSICAL NOTE	G	A	B	C	D	E	F	G	A	B	C	D	E

PHYSICAL WAVE LENGTH OF SOUND	3.2' (975 mm)	2.9' (884 mm)	2.6' (792 mm)	2.3' (701 mm)	2.2' (671 mm)	1.9' (579 mm)	1.7' (518 mm)	1.6' (488 mm)	1.4' (427 mm)	1.3' (396 mm)	1.2' (366 mm)	1.1' (335 mm)	11.5" (292 mm)
FREQUENCY (Hz) TO NEAREST 1.0	349	392	440	494	523	587	659	698	784	880	987	1047	1175
MUSICAL NOTE	F	G	A	B	C	D	E	F	G	A	B	C	D

PHYSICAL WAVE LENGTH OF SOUND	10.3" (262 mm)	9.7" (246 mm)	8.6" (218 mm)	7.7" (196 mm)	6.9" (175 mm)	6.5" (165 mm)	5.8" (147 mm)	5.1" (130 mm)	4.9" (124 mm)	4.3" (109 mm)	3.9" (99 mm)	3.4" (86 mm)	3.2" (81 mm)
FREQUENCY (Hz) TO NEAREST 1.0	1318	1397	1568	1760	1974	2093	2350	2637	2794	3136	3520	3951	4186
MUSICAL NOTE	E	F	G	A	B	C	D	E	F	G	A	B	C



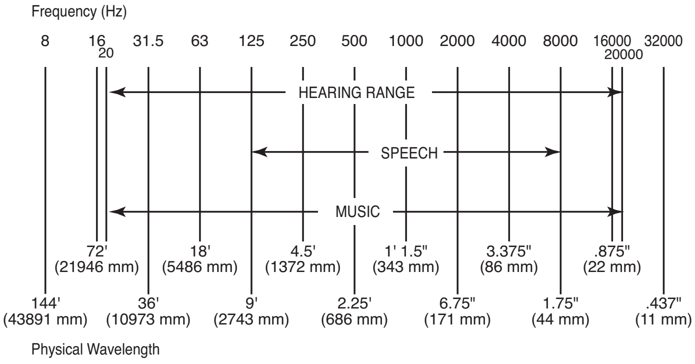
The Range of Musical Sound

Concept:

Throughout history, the art of music has explored the entire range of sounds audible to the human ear. Music utilizes frequencies as low as 20Hz to those as high as 20,000Hz across a dynamic range from below 25dB (decibels) to over 100dB.

Relevance:

Music areas must be designed and treated to support the broad dynamic range of musical sound. Unlike typical lecture rooms designed to support the relatively narrow range of speech, music rooms require special considerations and unique treatments.



Wavelength Chart

Absorption

Concept:

Absorption is the reduction of sound energy that occurs when sound comes into contact with surface materials. Hard, solid surfaces like concrete reflect most of the sound energy back into the room and provide little absorption. Sound energy hitting thick, fibrous surfaces will attempt to pass through the material and essentially lose energy by friction as sound energy flows along the pores. It is critical to understand that the physical nature of the absorption material, such as porosity and thickness, determines the level of absorption and the frequencies affected. Lower frequencies, for example, have a longer wavelength and more energy. As a result, they require thicker absorptive materials with large surface areas. Absorption of musical sound is more difficult than absorption of speech because music is generated across a much broader frequency range.

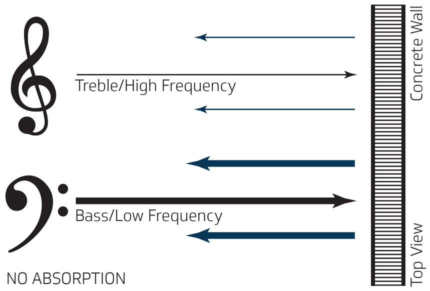
Relevance:

Rooms with little or no absorption can be excessively loud, making it difficult to hear. These rooms also do not provide a true balanced sound for critical listening.

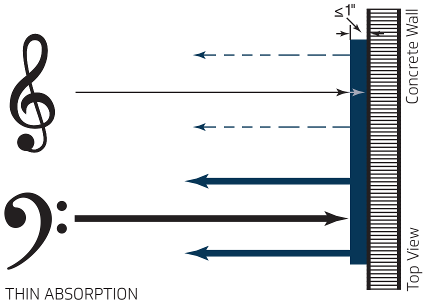
In many cases poor absorption causes acoustical anomalies such as flutter echo which is the prolonged buzz that occurs when sound energy is bounced between parallel, sound-reflecting surfaces.

Use of ineffective sound absorption leads to some of the most common mistakes we see in existing rooms. For example, to control loudness, thin, 1" absorbers or carpeting have been applied directly to the walls or floor. While they may be effective for speech absorption or give the first impression of a "quieter" space, these solutions strip out the high frequencies and harmonic overtones leaving middle and low musical frequencies unaffected. The result is a room that sounds boomy, distorts tone colors and is a poor environment for critical listening.

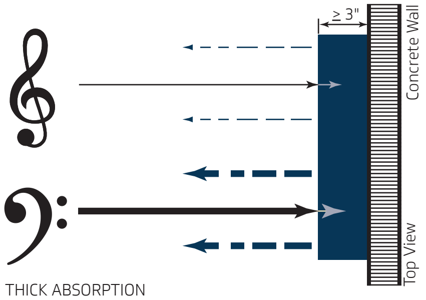
To create an effective critical listening environment, sound absorption must be used in conjunction with properly placed diffusion.



NO ABSORPTION

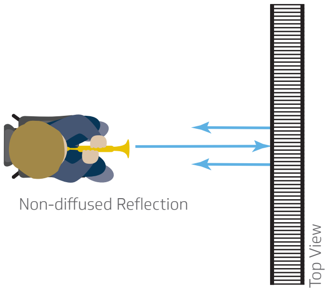


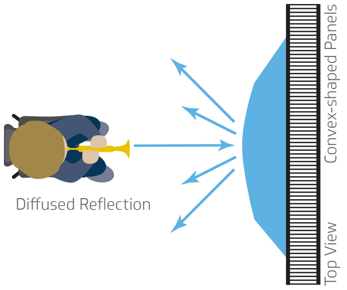
THIN ABSORPTION
(High Frequencies Absorbed, Low Frequencies Unaffected)



THICK ABSORPTION
(Broad Range of Even Absorption)

Reflecting and Diffusing Sound





Concept:

The concepts of reflection and diffusion go hand-in-hand with, and in some ways are opposite to, absorption. Reflection occurs when sound strikes a hard, dense surface and is reflected at the angle of incidence, just like shining a flashlight into a mirror. Diffusion occurs when the shape of a surface scatters and redirects the sound so that it is heard in other parts of the space, like shining that same light at a mirrored ball.

Relevance:

A good music listening environment should have ample diffusion so that all sound can be clearly heard throughout the room. This allows individual musicians within an ensemble to hear all of the parts from the entire group. It is equally important for audience members. For example, the extravagant plasterwork and ornamentation in historic theaters creates acoustically reflective surfaces with irregular angles and curves, which enhance diffusion.

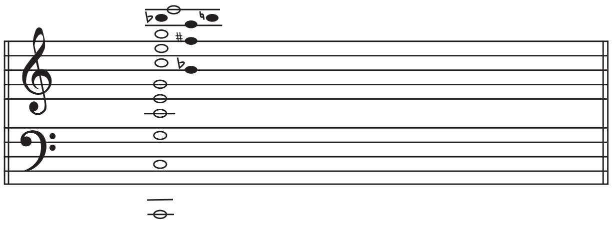
Tone Color and the Harmonic Series

Concept:

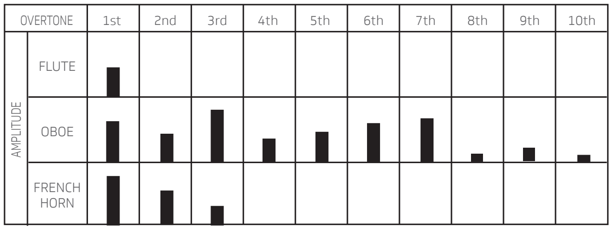
All musical instruments produce complex sounds made up of the main sound, or fundamental tone, plus a number of weaker, pure sounds or overtones. A fundamental tone and its overtones are referred to as the harmonic series. The number and greater or lesser prominence of harmonics sounding above a fundamental tone create an instrument's tone color. The more extensive the harmonic series of an instrument, the richer and brighter the tone. For example, an oboe has a complex harmonic series, compared to a flute.

Relevance:

When placed in a music space, absorption materials that are too thin to evenly absorb a wide range of frequencies, can "strip away" the upper harmonics of an instrument's tone leaving the sound altered, and less colorful.

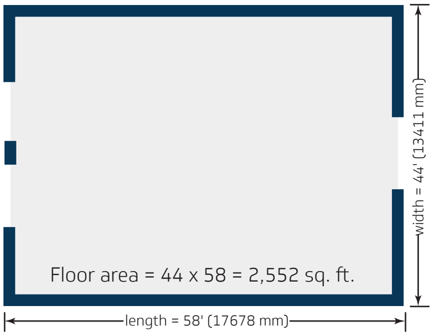


The harmonic series,
or potential overtones
generated from the
fundamental tone
c-65Hz.

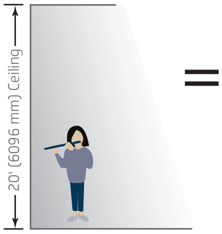


Number and prominence
of overtones for three
common instruments

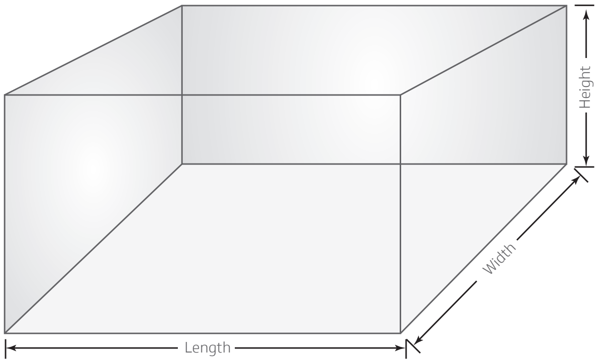
Cubic Volume



Plan View



Partial Section



Cubic Volume = Length x Width x Height

Concept:

Cubic volume is the floor area (square feet) of a space multiplied by the ceiling height (feet). For example, a 44' x 58' (13411 x 17678 mm) rehearsal space with a 20' (6096 mm) ceiling height would have a cubic volume of 51,040 cubic feet (44' x 58' x 20' = 51,040 cubic feet).

Relevance:

The cubic volume of a music space is the foundation of the acoustics you experience, good or bad. Adequate cubic volume helps dissipate loudness while providing an area large enough to slightly delay sound reflections off the walls, floor and ceiling. This delay allows the human ear and mind to process the sound. The result is an ability to accurately hear and critique the entire spectrum of musical sound.

How Much Cubic Volume Is Enough?
Rule of Thumb

Room	Class size	Ceiling Height	Typical Floor Space	Resulting Room Cubic Volume
Choral Rehearsal	60-80 Students	16-20 feet (4877-6096 mm)	1,800 ft^2 (167 m^2)	28,800 - 36,000 ft^3
Band/Orchestra Rehearsal	60-75 Students	18-22 feet (5486-6706 mm)	2,500 ft^2 (232 m^2)	45,000 - 55,000 ft^3

The ideal rehearsal room size is somewhat dependent on group type and size, but should provide musicians with enough room to move about and play instruments and sufficient cubic volume for the sound they produce.

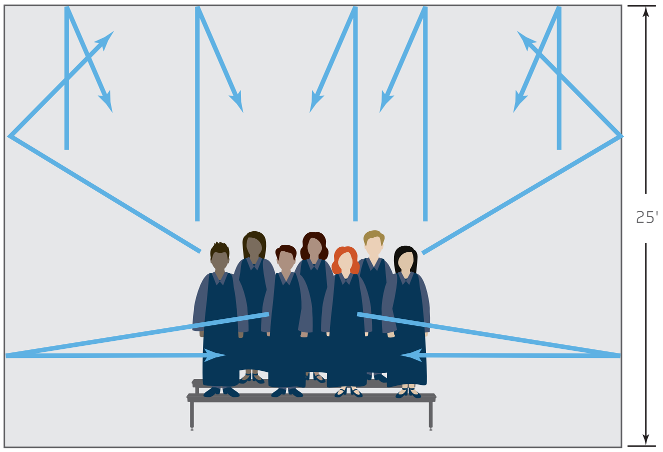
Musical Presence and Envelopment

Concept:

Presence is a general term musicians use to describe the positive acoustic attributes of a space. When a room, has “good presence”, early reflections of sound from walls and ceilings are returned to the musicians’ ears in approximately 30 milliseconds time interval. Envelopment is a similar term used to define the characteristics of larger auditoriums and performance spaces where the lateral reflections from side and back walls return to the ear approximately 80 milliseconds after the direct sound. For performers and audience members alike, envelopment is the sense of being immersed in, or surrounded by, the music. Presence and envelopment cannot be achieved without significant room size and cubic volume.

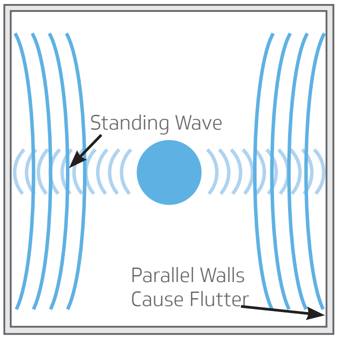
Relevance:

When musicians can hear their sound “out in the room” it allows them to better focus on phrasing, intonation and communication with other musicians in an ensemble. Rooms with presence and envelopment simply feel more supportive and can be more musical.

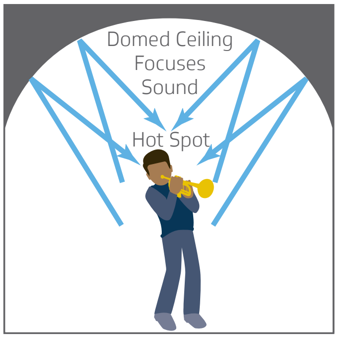


Choral performers immersed in sound. Reflections supporting mutual hearing should arrive after short delay of 30 - 80 milliseconds.

Room Shape



Plan View



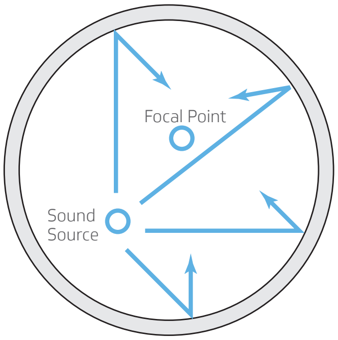
Section View

Concept:

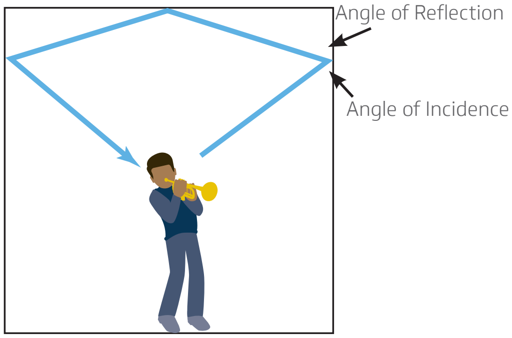
When sound reflects off hard surfaces, the angle or shape of these surfaces affect the pattern of the reflections and ultimately what is heard. As a result certain geometric room shapes will result in undesirable acoustic phenomena.

Relevance:

The shape of your room has a profound effect on the way sound behaves in the room. Untreated parallel walls can cause flutter echoes. Designs that may look “acoustical” often create problems. Concave curved ceilings and walls, for example, will focus sound to acoustic “hot-spots” while leaving musicians in other areas unable to hear much at all. Cube-shaped rooms (length, width, and ceiling height are equal) can result in a phenomenon called a standing wave where lower frequencies are exaggerated due to the mathematical correlation between the room’s dimensions and the wavelength of the frequency. (see chart on page 5)



Plan View (Circular Shape)



Section View (Cube-shaped Room)

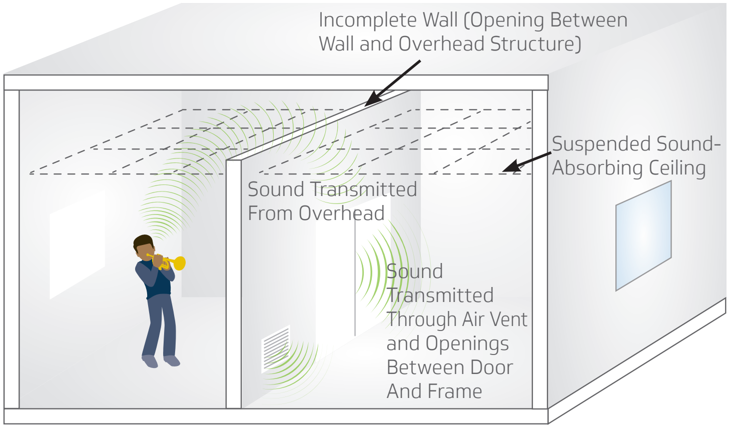
Sound Isolation

Concept:

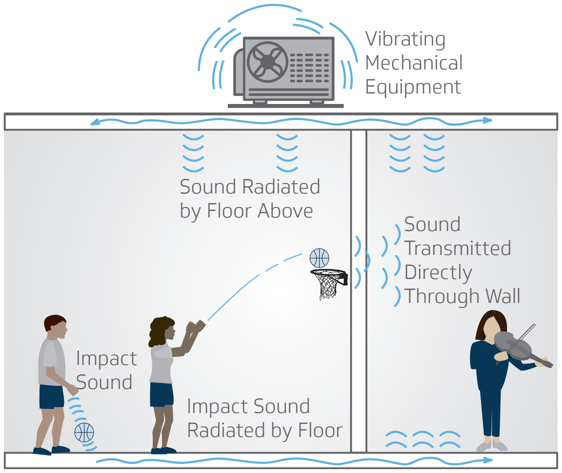
Sound isolation depends on how well the construction elements of a room (floor, walls, ceiling) keep sound created in the room contained and keep sound generated outside from penetrating into the room. Sound isolation is compromised by airborne sound leaking through any openings in your structure — doorways, windows, electrical conduits, ventilation openings and gaps in building construction elements. Sound isolation is also compromised by sound vibrations traveling along or passing through a physical structure such as the floor or a wall.

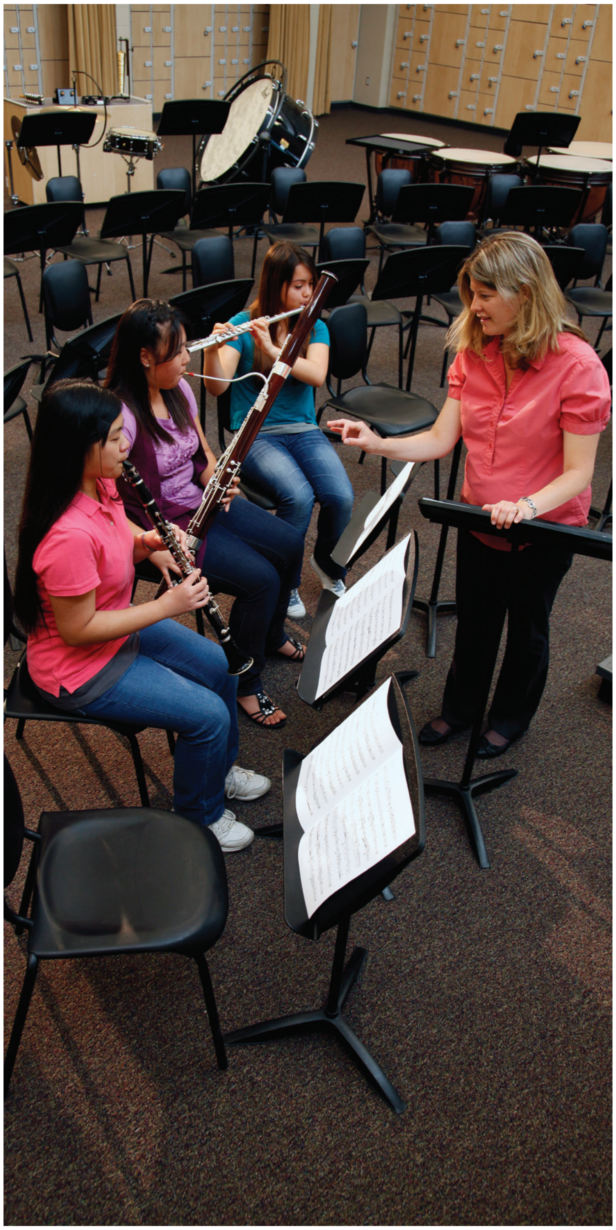
Relevance:

Simply put, poor sound isolation makes critical listening difficult or impossible. For example, practice rooms are often unusable because they leak sound both in and out. Noise from a nearby gymnasium may disrupt music rehearsal, or music rehearsals may disrupt nearby classrooms or offices. Use high performance, sound-isolating construction elements to contain noise from gymnasiums, mechanical equipment rooms, and the like.



Airborne Sound Leaking From One Space To Another.



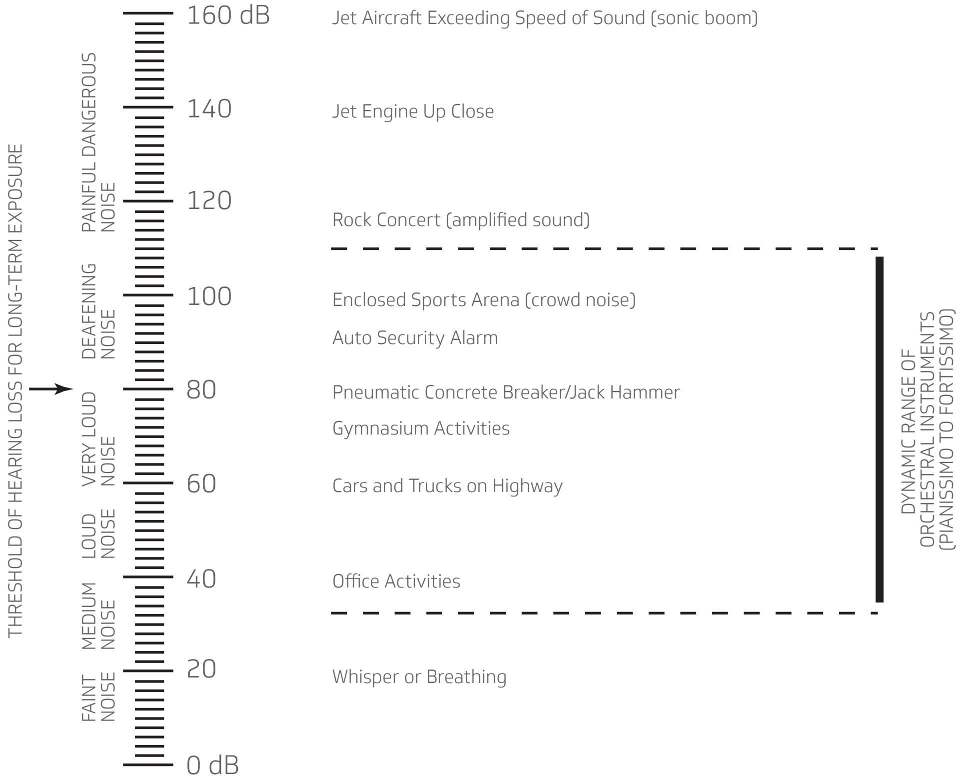
Structure-Borne Sound Not Only Transmits Through Walls But Also Travels Horizontally Through Floors and Ceilings

Loudness

Concept:

Sound pressure level in decibels (dB) is a measure of loudness. In auditoriums for music performance, louder passages should be comfortable and weaker passages sufficiently audible. Loudness is affected by room height-to-width ratio (H/W), absorption of seating and occupants, and cubic volume of room.

Relevance:

Musical ensembles can be extremely loud, often in excess of 100dB. Sustained exposure to sound pressure levels this high can result in discomfort, short-term hearing loss or permanent damage to hearing. A ringing in your ears after a day of teaching or playing music is a sign that your ears are strained. If the ringing is persistent day after day, you likely are in an environment that is too loud.



A Note on Hearing Health:

All too often we are called in to help with rehearsal rooms that are too loud. Topping the list of concerns in a loud room is the effect on the hearing health of educators and students. According to OSHA standards, 90dB is the maximum acceptable level of noise in a workplace without hearing protection. An independent study* reported noise levels in band rehearsal rooms were often 7 -12dB over the limit. The study went on to examine the affect of this on music educators. The findings showed a correlation between years on the job and the rate of noise-induced hearing loss. The message is clear — band rooms can become dangerously loud places to work and measures must be taken to address overly loud rooms.

*Research by Robert A. Cutietta, Coordinator of music education in the School of Music at the University of Arizona, and colleagues. From the Journal of Research in Music Education 1994. Volume 42, Number 4, Pages 318-330.

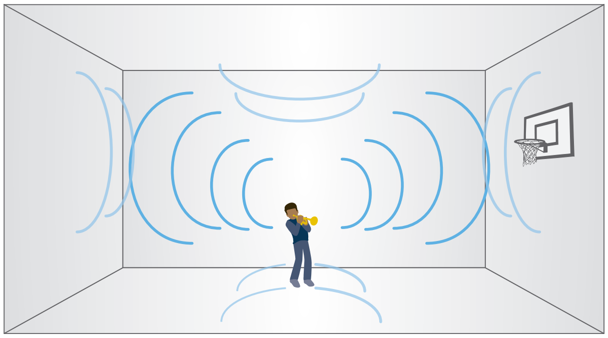
Reverberation

Concept:

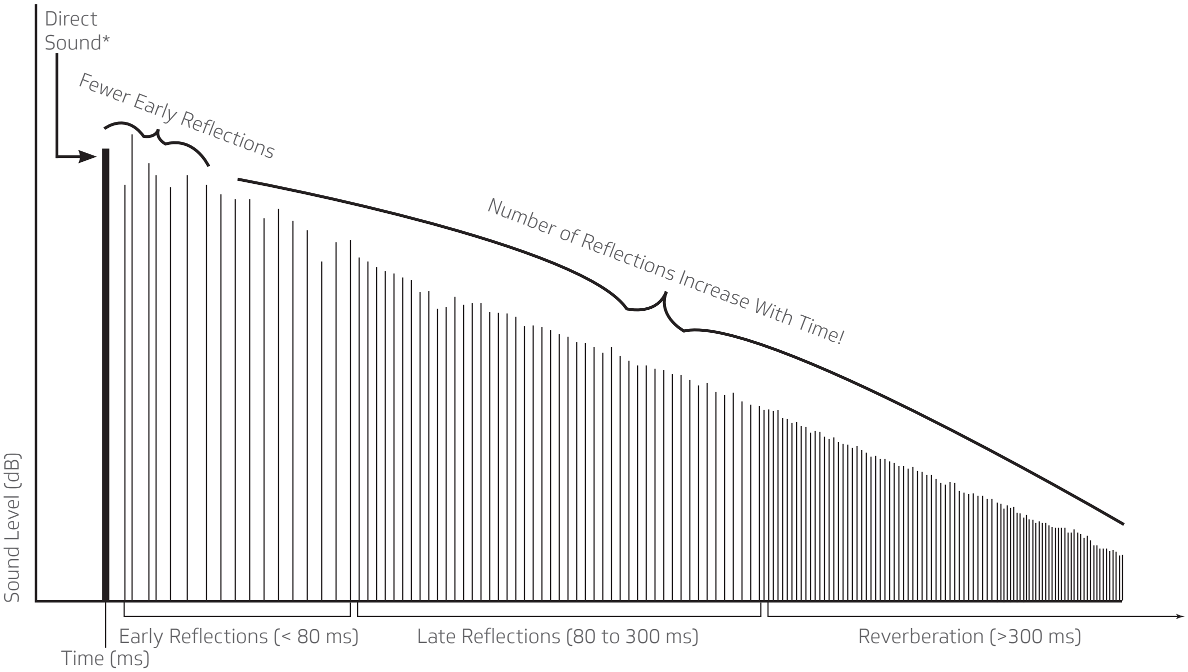
Reverberation is the persistence of sound in an enclosed space. Reverberation affects the character and quality of music. It is measured in seconds, from when the sound is generated to when it decays to the point of inaudibility. Reverberation is affected by the interior surfaces and size of a room, and absorption of people and seats and other furnishings. For example, cafeterias and gymnasiums often are overly reverberant because the hard surfaces allow sound to build up and reflect many times before losing its energy.

Relevance:

Excessive reverberance can prevent an ensemble from accurately hearing definition and detail. Articulation and timing become muddy and clarity is lost.



Hard, Sound-Reflecting Surfaces and Large Cubic Volume Create Excessive Reverberation



Decay of sound in an auditorium. Reverberation is time it takes sound to decay by 60 dB.

*Time it takes for the sound from the stage to reach the listener.

Brightness

Concept:

Brightness describes the perceived loudness of higher musical frequencies (> 2000 Hz). When a room is bright, these frequencies are in balance with, and not overpowered by, lower frequencies. To achieve brightness in auditoriums, it is important that interior surfaces be heavy and massive.

Relevance:

A bright acoustic environment enables a musician to clearly hear attacks and releases, helping the entire ensemble to accurately execute complex rhythmic passages. A "bright" environment that supports higher frequencies also allows the full tone color of the instrument or voice to be heard. Maintaining brightness while acoustically treating a space for loudness requires specific acoustic materials precisely placed throughout the room.

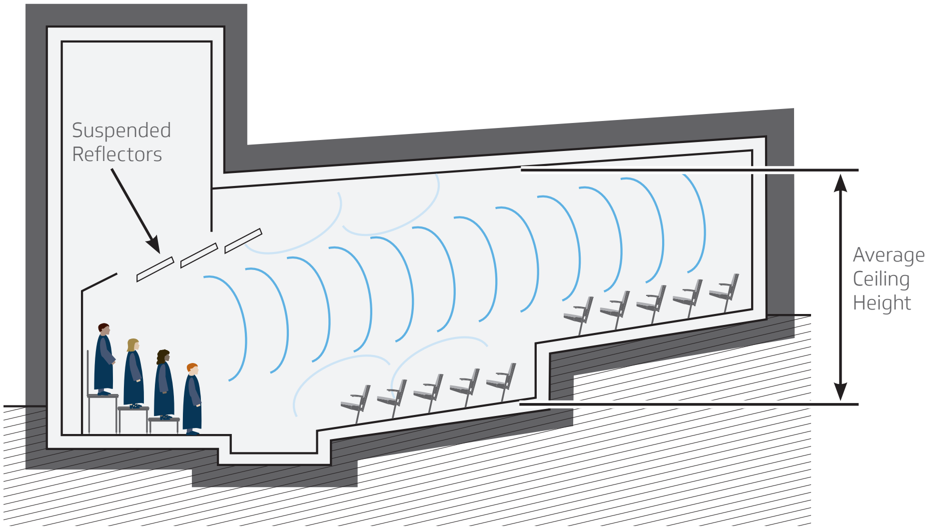
Warmth

Concept:

In large auditoriums warmth describes the relative loudness of bass frequencies (< 250 Hz) to loudness of mid-range frequencies. Researchers have long used bass ratio (BR) as a measure of warmth. The BR is the reverberation at low-frequencies divided by reverberation at mid-frequencies. BR should be greater than 1.0. Recent research by the Concert Hall Research Group (CHRG) indicates ceiling height is a critical element of strength of bass in auditoriums.

Relevance:

To Reflect and diffuse long sound waves require large surfaces with substantial mass and rigidity. Large acoustic shells on stage, for example, aid in enhancing a sense of warmth. In general, auditoriums with diffusing ceilings tend to have weaker bass, but auditoriums with over-stage reflectors have stronger bass.



Solid massive construction and suspended sound reflectors reflect low frequencies, creating a sense of warmth.

Additional Acoustic Terms

Active Acoustics:
Also referred to as electronic architecture or "virtual acoustics." Electronic devices (such as microphones, loud speakers, digital signal processors) are used to enhance the natural acoustics of a space. Effective active acoustics are also dependent on the correct room treatment with passive acoustics.

Echoes:
Echoes are produced when surfaces reflect sound to the listener after the direct sound from the source has been heard. For example, horn sections on stage may create a distracting echo off the back wall of an auditorium. Although both absorbers and diffusers can help correct this type of echo, diffusers are generally preferred because more sound energy will be conserved.

Flutter:
Flutter echoes occur when a sound source is situated between parallel, sound-reflecting surfaces. The effect is a prolonged buzzing sound. For example, a rim shot off a snare drum in an untreated room will produce a distinct flutter echo.

Masking:
Masking occurs when an unwanted noise conflicts with or masks a musician's ability to hear musical sounds of a similar or higher pitch. For example, the whooshing noise of air coming out of an air supply duct can mask musical sound.

NC:
Noise Criteria is: A single number rating to quantify the level of background noise. The lower the NC, the quieter the space.

Passive Acoustics:
This term refers to the use of architectural (non-electronic) design and acoustical surface treatments to create a musical space. Primarily broken down into absorptive and diffusive properties, elements such as geometric wall and ceiling shape and acoustic panels on walls and ceilings are examples of passive acoustics.

Reflection:
Sound reflection off a hard surface can be compared to the reflection of light off a mirror. Without reflective surfaces such as acoustical shells and overheads on a proscenium stage, for example, sound energy may be dissipated or absorbed without ever reaching the audience.

Sound Transmission Path:
Air borne: Sound that is transmitted through the air than strikes a barrier and is retransmitted on the other side.

STC:
Sound Transmission Class is: Single number rating system for describing the amount of sound isolation provided by a construction element (i.e. wall, door, window). Typically the STC rating best represents a construction ability to isolate speech. The higher the STC number, measured in the lab, the greater the sound isolation by the construction element.

Structure/Flanking:
Sound that is transmitted by direct contact with the sound source, such as an air compressor attached to a room duck or the legs of a ground piano in contact with the floor.

NIC:
Noise Isolation Class is: Similar to STC, but takes into account all parts of a structure enclosing a room.
The higher the NIC, the greater the sound isolation between rooms.

NRC:
Noise Reduction Coefficient is: Single number describing the average amount of absorption (measured in percent of perfect absorption) at octave band frequencies at 250Hz, 500Hz, 1kHz and 2kHz. It provides a good estimate of absorption when used for the speech range, but has limited value when used for music applications since it ignores frequencies below 176Hz and above 2825Hz.

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