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.

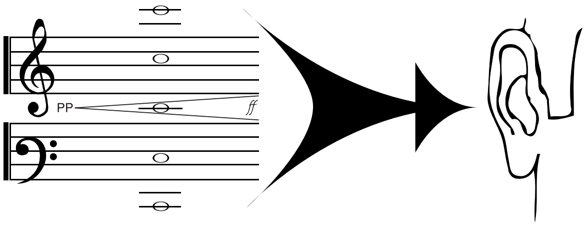
For our purposes here, it is not our intention to provide an exhaustive, technical resource on the physics of sound and acoustical construction methods — that has already been done and many of the best works are listed in our bibliography and recommended readings on page 10. Rather, we want to help you establish a base-line knowledge of acoustical concepts that affect music education and performance spaces.

This publication contains information reviewed by Professor M. David Egan. Egan 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.

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).

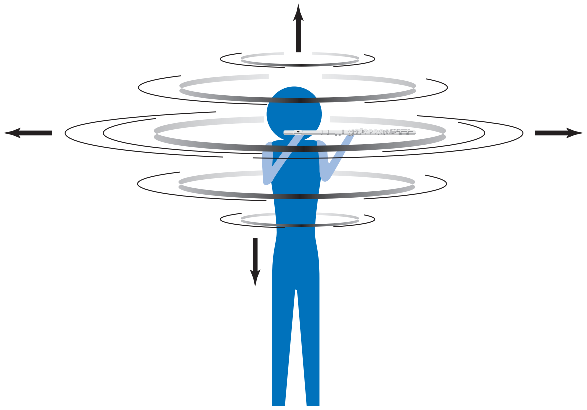
Relevance:
To support critical listening, a music space must provide a well-balanced acoustic environment which is also free from distracting noise. Unlike speech, musical sound contains complex elements of pitch, tone color, frequency, articulation and rhythm. A musician must be able to hear and distinguish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



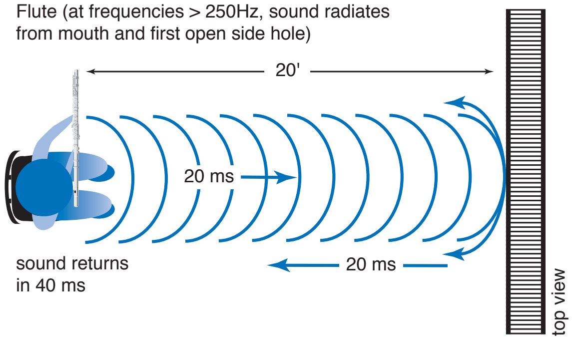
SOUND GENERATION

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.

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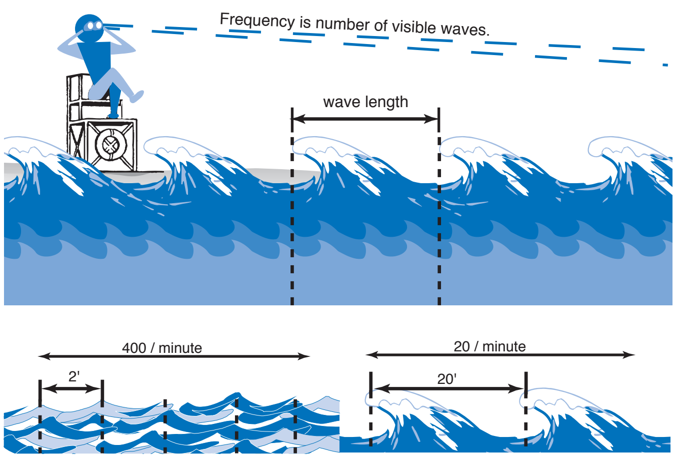
FREQUENCY AND WAVELENGTH

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.

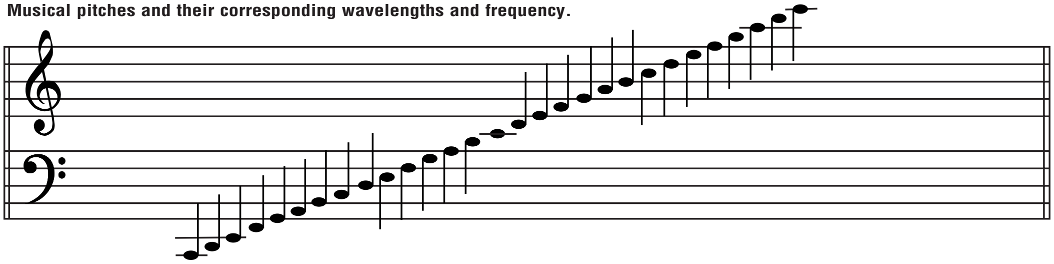
Relevance:

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.

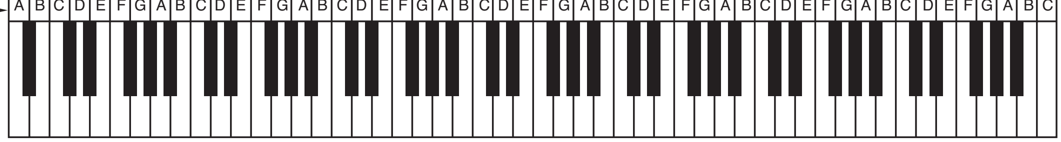


PHYSICAL WAVE LENGTH OF SOUND	40.4	36.5	34.2	30.5	27.5	25.7	23.1	20.5	18.2	17.4	15.5	13.8	13
FREQUENCY (Hz) TO NEAREST 1.0	28	31	33	37	41	44	49	55	62	65	73	82	87
MUSICAL NOTE	A	B	C	D	E	F	G	A	B	C	D	E	F

PHYSICAL WAVE LENGTH OF SOUND	11.8	10.3	9.2	8.6	7.7	6.8	6.5	5.8	5.1	4.6	4.3	3.8	3.4
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	2.9	2.6	2.3	2.2	1.9	1.7	1.6	1.4	1.3	1.2	1.1	11.5
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

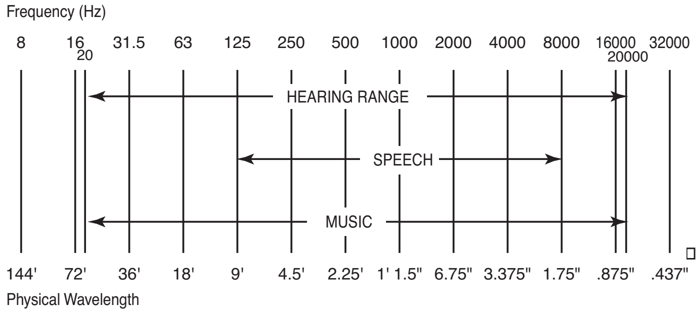
PHYSICAL WAVE LENGTH OF SOUND	10.3	9.7	8.6	7.7	6.9	6.5	5.8	5.1	4.9	4.3	3.9	3.4	3.2
FREQUENCY (Hz) TO NEAREST 1.0	1318	1397	1568	1760	1974	2093	2350	2637	2794	3136	3520	3951	4186
MUSICAL NOTE	E	F	G	A	B	C	D	E	F	G	A	B	C



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.

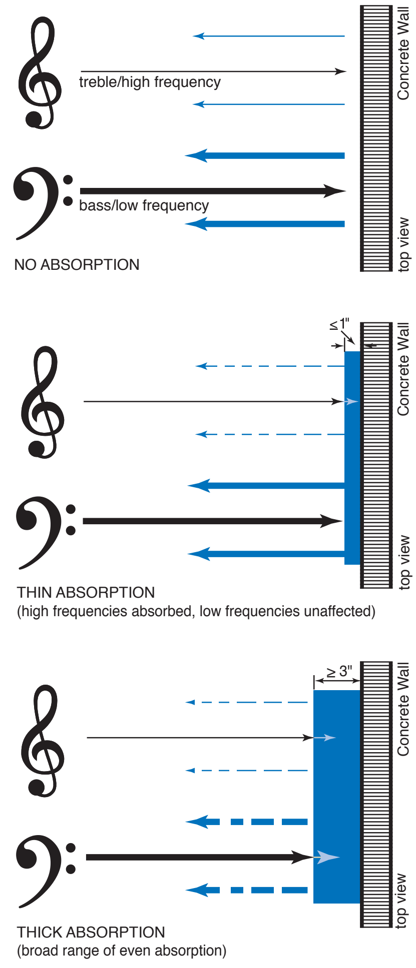
ABSORPTION

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.



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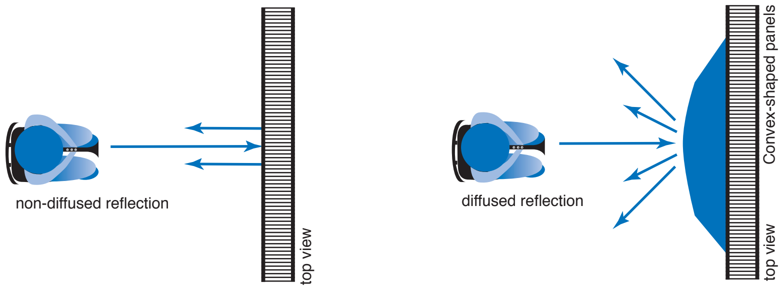
REFLECTING AND DIFFUSING SOUND



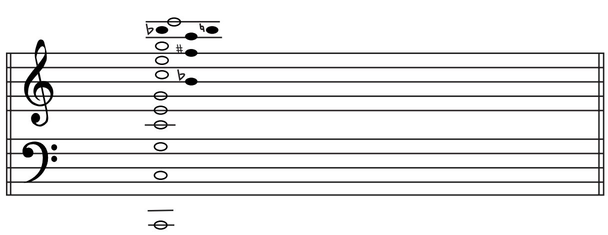
Concept:
The concepts of reflection and diffusion go hand-in-hand with, and in some ways are opposite to, absorption. Reflection occurs when sound strikes a hard, dense surface and is reflected at the angle of incidence, just like shining a flashlight into a mirror. Diffusion occurs when the shape of 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.

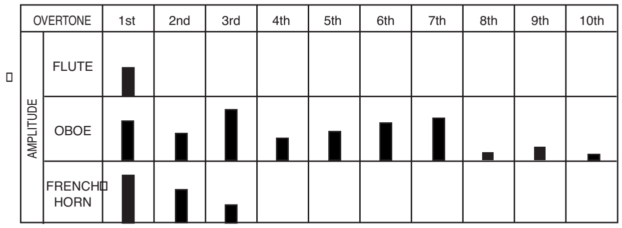
TONE COLOR AND THE HARMONIC SERIES

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

Concept:

Cubic volume is the floor area (square feet) of a space multiplied by the ceiling height (feet). For example, a 44' X 58' rehearsal space with a 20' 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	1,800 sq. ft.	28,800 - 36,000 cu. ft.
Band/Orchestra Rehearsal	60-75 students	18-22 feet	2,500 sq. ft.	45,000 - 55,000 cu. ft.

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.

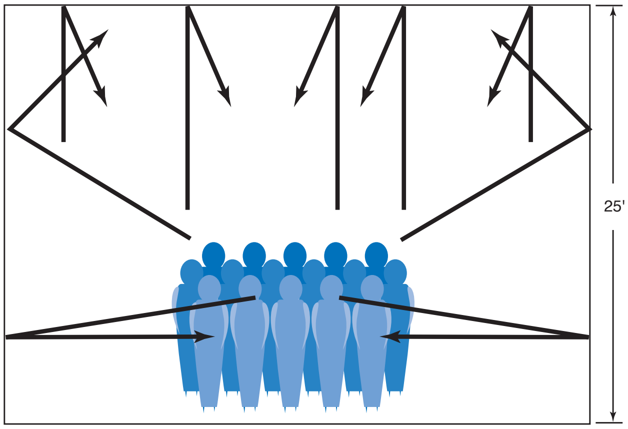
MUSICAL PRESENCE AND ENVELOPMENT

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 approximentaly 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.

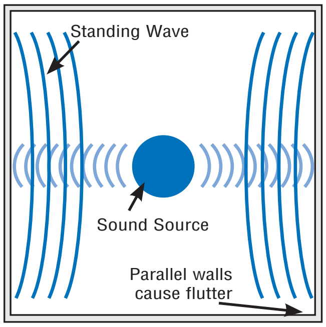
Relevance:

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.

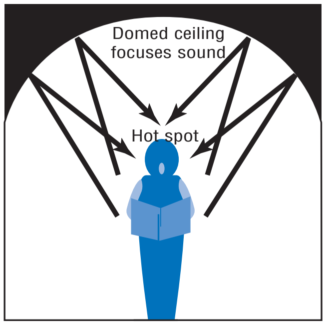


Choral performers immersed in sound. Reflections suporting mutual hearing should arrive after short delay of 30 - 80 milliseconds.

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.

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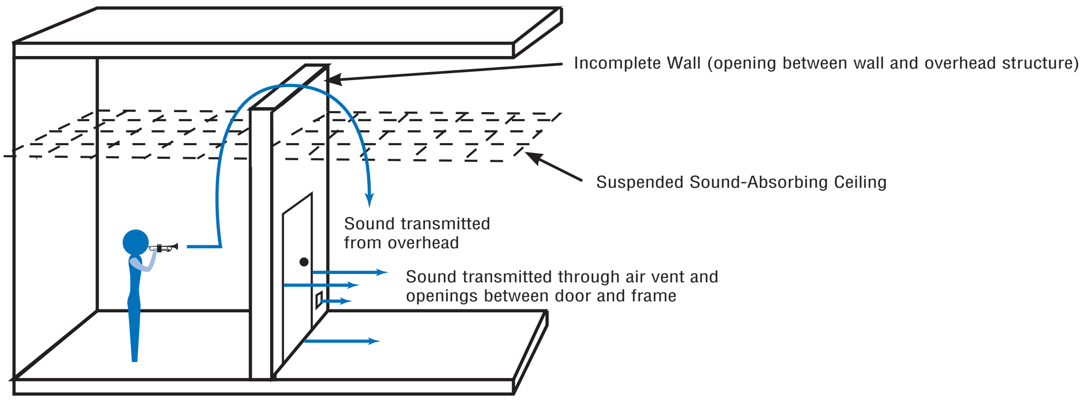
SOUND ISOLATION

Concept:

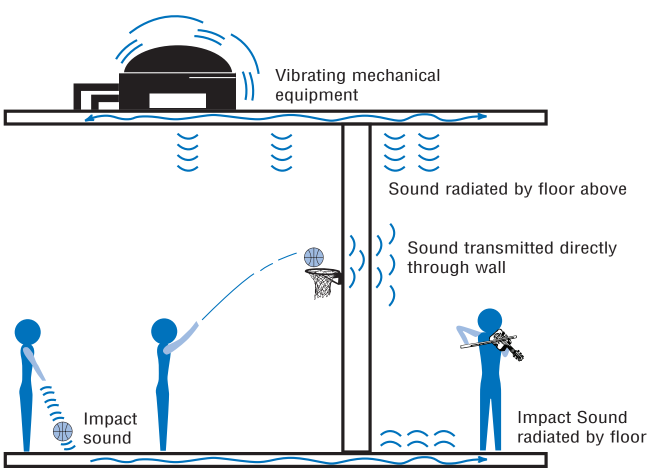
Sound isolation depends on how well the construction elements of a room (floor, walls, ceiling) keep sound created in the room contained and keep sound generated outside from penetrating into the room. Sound isolation is compromised by airborne sound leaking through any openings in your structure — doorways, 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.

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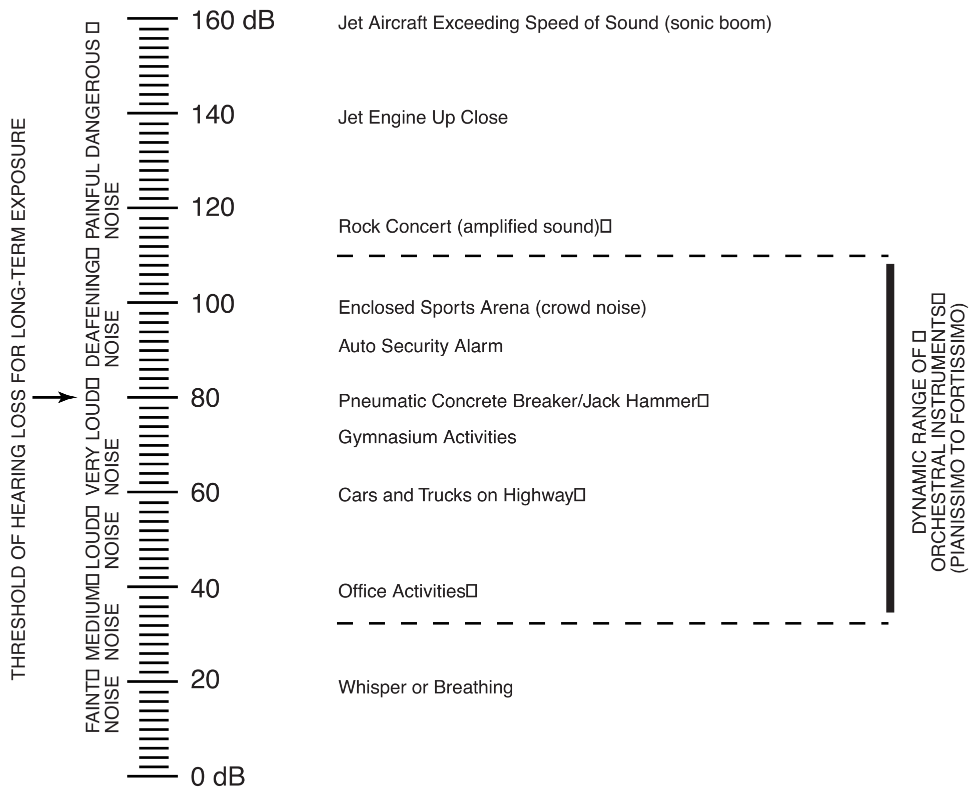
LOUDNESS

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.

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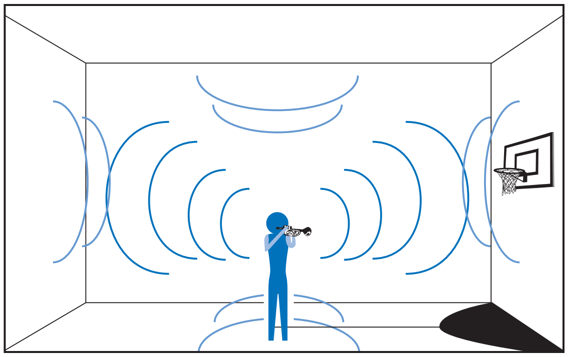
REVERBERATION

Concept:

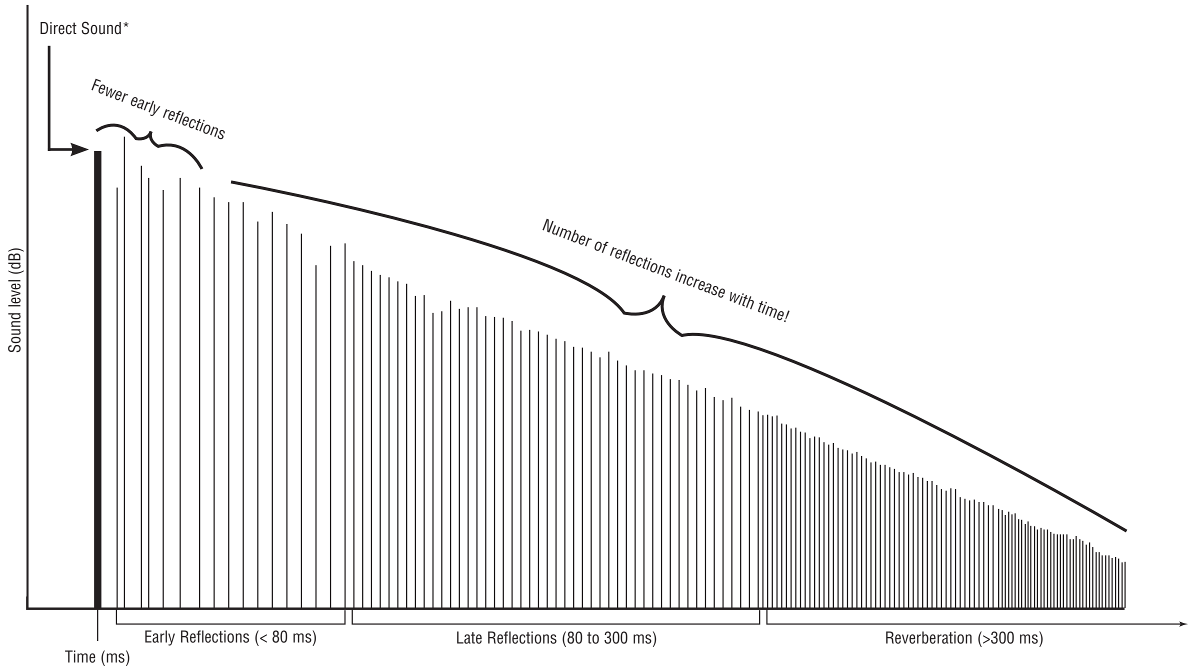
Reverberation is the persistence of sound in an enclosed space. Reverberation affects the character and quality of music. It is measured in seconds, from when the sound is generated to when it decays to the point of inaudibility. Reverberation is affected by the interior surfaces and size of a room, 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.

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BRIGHTNESS

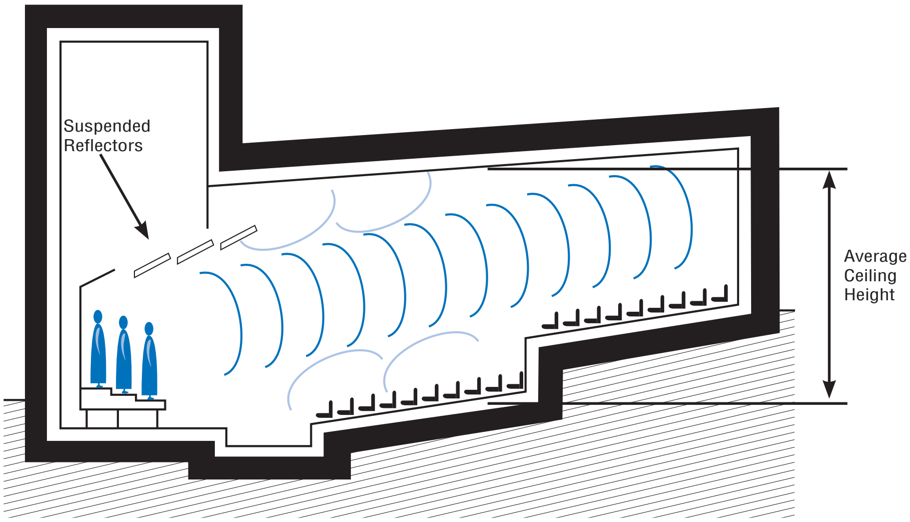
Concept:
Brightness describes the perceived loudness of higher musical frequencies (≥ 2000 Hz). When a room is bright, these frequencies are in balance with, and not overpowered by, lower frequencies. To achieve brightness in auditoriums, it is important that interior surfaces be heavy and massive.

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.

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