

Acoustics 101 for Architects

A presentation of acoustical terminology and concepts relating directly to the design and construction of an architectural space. Low-tech descriptions, explanations, and examples.

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This essay is tailored to the one group of people who have more influence over a building's acoustics than any other; architects.

The focus is on Architectural Acoustics, a field that is broader than most imagine. To do justice to the theme, we must briefly touch on many subordinate topics, most having a synergetic relationship bonding architecture and sound.

This paper is based on fundamentals, not perfection. It covers most of the basics, and explores many modern and esoteric matters as well. You will be introduced to interesting and analytical subjects; some you may know, some you may never have considered. Here are a few examples of what you'll find by reading on:

- What is sound and why is it so hard to manage or control?
- The length of low- and high-frequency sound waves vary by as much as 400:1. Why does this disparity matter?
- How and why do various audible frequencies behave differently when interacting with various materials, structures, shapes and finishes?
- There are three acoustical tools available to both the architect and the acoustician. What are they? How can they benefit or hinder the work of each craft?
- Room geometry: Why some shapes are much better than others. Examples and explanations.
- Reverberation and echo: How do they differ? Which is better, or worse, and why? How much is too much, or too little?
- Speech intelligibility: We all know it matters. What can architects do to help or hinder?
- Three simple tests: Quick, easy ways to evaluate the basic acoustical merits of a room.
- Opportunities and tradeoffs: Blending architecture, acoustics and pragmatism.
- Acoustical priorities: One man's wish list.
- Modern materials: Acoustical glass coverings, acoustical plaster, CMU diffuser block, graphic imprinting on acoustical products, and much more.

It's easy to think that sound is completely removed from the fundamental principles of architecture. Nothing could be further from reality.

Consider this: If a person were seated in an amazingly beautiful structure at night, one without illumination, they would see few, if any, of the features, shapes, materials, colors, textures, or workmanship that was created. However, given that same dearth of light, all audible sounds remain unaltered, for better or worse.

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1.0 ARCHITECTURAL ACOUSTICS DEFINED

- 1.1 Architectural Acoustics (AA) can be defined as the science, study and application of acoustic principles as they are implemented inside a building or structure. In the context of this tutorial, the terminology focuses on built environments that will be used for live, creative performances, or the audible presentation of other useful information.
 - A. Beyond performance and presentation communications, AA also encompasses core elements such as noise control, speech privacy, passive and active sound reinforcement, paging, and emergency communications.
- 1.2 This paper has four main goals:
 - A. First, this essay endeavors to put the essential terminology and concepts of AA into the hands of the architect, owner, or anyone else who would like to have a better understanding of this subject.
 - B. Second, to introduce the incredible range of wavelengths that exist between the lowest and highest audible sounds. Once defined and established, we then can overlay this dimensional understanding of sound waves onto the physical structures they touch.
 - C. Third, to teach architects how to visualize the relationship between the physical shapes and dimensions of their work, and why those design decisions impact the qualitative behavior of sound.
 1. Example: Architecture requires three-dimensional thinking and implementation; yet sound is a four-dimensional experience that must coexist within a three-dimensional structure.
 2. The fourth dimension, time, being significant because the speed of sound is so slow that the size and shape of a built environment can often dictate the quality and clarity of sound within.
 - D. Fourth, to explain the importance of interior symmetry.
 1. Sound propagation is an amazingly flexible phenomenon, but not something that is easily controlled once a group of sound waves begin to move in any particular direction. As a result, building symmetry is an important component related to the high-quality dispersion of sound.
- 1.3 AA and sound have an interdependent relationship. Once established by design, right or wrong, they are inseparable unless significant design changes are implemented. They coexist as a bidirectional, cause and effect engine.

2.0 WHAT IS SOUND?

- 2.1 Have you ever stopped to consider just what sound is, besides possibly being the second-most important of the five senses? The next few paragraphs will attempt to bring the bare elements of sound into focus.
- 2.2 Sound is not a tangible thing, it's a transformative experience.
 - A. Sound is a relatively slow-motion, push/pull, molecular chain reaction that starts with a simple oscillation or vibration. These vibrations are created by any number of animals or objects. The vibrations become a sound we can hear if they stimulate the nearby air molecules with enough energy to be detected.

- B. As an object vibrates, it pushes the neighboring air molecules out of its way. The molecules don't really move much, they squeeze together to create a small area of higher and lower air pressure.
 - 1. On the opposite side of the pushing motion, the corresponding "pull" causes the air pressure to decompress a little, effectively lowering the nearby pressure.
 - C. The stronger, or more violent, the oscillating motion, the greater the pressure. This results in a louder version of the vibration or sound.
 - D. Barring obstruction, these tiny changes in air pressure move away from the source vibrations, and travel through the air, until they strike another set of objects that vibrate sympathetically. Those sympathetically-vibrating objects are our eardrums.
 - E. In its most rudimentary form, the transformative circuit that culminates in audible sound looks like this: A vibrating object > a chain reaction of air molecules pushing toward, and pulling away from one another > one or more sympathetically-vibrating eardrums > brain.
 - F. The experience: Sound is created when air molecules are pushed around and perceived by our ear/brain system. The air molecules themselves make no audible sound.
- 2.3 Sound can also be thought of as a force, somewhat like gravity or magnetism. But unlike gravity with its ubiquitous downward force, or magnetism with its bi-polar forces, think of sound as a force that generates molecular chain reactions. When man-made, a force that can easily be activated or deactivated, when and if required.
- A. Sound can easily move through air in any direction; can be manipulated and steered into relatively definable areas; and with proper care and handling, is generally adaptable and responsive to our needs.
- 2.4 There must be some type of compressible medium for sound to exist. It doesn't matter what type of medium or atmosphere, as long as there are molecules that can be pushed around, or stimulated into distinct patterns of greater and lesser pressure.
- A. Water is a good example of a medium that easily transmits sound. So are steel and concrete under the right conditions.
 - B. A vacuum has no atmosphere therefore, sound does not exist in a vacuum.

3.0 SOUND PROPAGATION

- 3.1 Grasping the principles in this section and the next (3.0 & 4.0) is critical to the information being conveyed throughout this paper.
- 3.2 Sound propagates, or travels through air, in waves. The waves are formed when the air molecules closest to the vibration source are pushed into their neighbors, and those neighboring molecules push against their neighbors, and so on.
 - A. Each individual air molecule barely moves. Each molecule is pressed forward, and compressed, just enough to bump its neighbor and start, or continue, a chain reaction. There is just enough to transfer its energy and momentum to the next molecule. Imagine a microscopic version of Newton's Cradle.

- B. These waves aren't so hard to visualize if you picture a long line of dominos all standing on edge, ready for the first one to get knocked over. As we all know, this starts a chain reaction that causes one domino to fall into the next.
- C. Add to this picture the idea that the dominoes can immediately bounce back to their previous, upright position, so they can be pushed over again and again. Each domino barely moves, yet the net result is a wave of falling dominoes that can travel a sizeable distance if unobstructed.
- D. If you are able to visualize this, you are beginning to understand the basics of sound propagation.

3.3 Frequency, wavelength, and the speed of sound:

- A. Fundamental sounds can be defined by either "frequency" or "wavelength". Every discrete frequency has a corresponding wavelength. While frequency and wavelength are directly correlated, and interchangeable, each word defines something different.
 - 1. When identifying a specific frequency, in cycles per second, the unit of measurement is Hertz (after Heinrich Hertz), which is abbreviated Hz in most applications.
 - a. To say that a sound has a frequency of 500 Hz means something is vibrating, back and forth, 500 times each second.
 - b. A number, followed by Hz, defines how fast something is vibrating. No other movement is required.
 - 2. When traveling through air, the speed of sound has a "generalized" constant. The number used, or referenced, throughout this paper is 1,127 feet per second. This number will fluctuate slightly based on temperature and humidity, but not enough to be meaningful in the context of this paper.
 - a. The complex waves of music and speech all travel through air at the same speed, regardless of frequency.
 - 3. As any discrete vibrating frequency is produced, and propagates or moves outward at the speed of sound, the linear distance required to complete one full, sinusoidal wave cycle, is its wavelength.
 - a. Thus, the wavelength of a 500 Hz tone is about 2.25', and a 2.25' wave is a 500 Hz tone. They are identical in size and sound.

3.4 Sound wave modeling:

- A. Sound travels through air in longitudinal waves. While these waves may not be too difficult to visualize at the most basic level, their behavior can be quite difficult to accurately calculate and predict in three-dimensional space.
- B. Architectural Acoustics correlates the myriad frequencies and wavelengths of audible sound with the complexities of architectural geometry, and the influences of multiple finish materials. Together, these factors are nearly impossible to compute, using manual methods.

- C. Today, we rely heavily on computer-based calculations and simulations to help model and solve for the most critical and complex acoustical questions.
1. "Ray tracing" theory, and software algorithms, are used to model the behavior of sound as it radiates from a virtual sound source, and bounces around in a computer model of an enclosed structure.
 - a. The virtual rays that are used in modeling programs can be thought of as discrete beams of light. Imagine a star burst of light beams, with each beam expanding out from a virtual source; like a large fireworks artillery shell bursting in the night sky.
 - b. Most modeling programs emit these beams at a spherical density that represents between 1 and 5 degrees of separation between each beam. The resolution depends on the available resolution of the program, its data, and the amount of detail that needs to be evaluated
 - c. Each ray can represent a narrow band of frequencies, or a broadband-range of frequencies. The modeling programs allow the operator to select and adjust the frequency groupings as needed.
 2. These virtual rays can effectively approximate the behavior of direct and reflected sound as it travels through air. But there's a catch: ray tracing is best used to represent only a portion of the audible frequency spectrum. More specifically, only about 7 of the 10 total octaves of audible sound (between 20 Hz and 20 kHz) can be modeled, with reasonable accuracy, when using ray tracing or other modeling techniques.
 - a. An "octave" is a musical term. All musical notes have a correlated frequency and wavelength. When a musical note is halved or doubled, its corresponding frequency and wavelength is halved or doubled.
 - b. An octave below A440 is A220. An octave above is A880. The numbers represent the fundamental frequency of the notes.
 3. When computer modeling is used to evaluate the lowest three octaves, the results become less and less accurate.
 - a. One reason is that loudspeaker modeling data is often limited, or non-existent, for the lowest two and half octaves.
 - b. It's also very difficult to get accurate data reporting if a room's dimensions are not sufficiently large to include the very long wavelengths of the lowest octaves.
 - c. An example of this is a room model that has major or defining dimensions that are nearly equal to, or less than, the wavelength dimensions that need to be evaluated. You'll get a better sense of this concept in Section 4 below.

3.5 Delivery methods:

- A. There are three primary yet distinctly different methods of transmitting the sounds of a performance or presentation to a live audience. They are:

1. Acoustically - with no electronic reinforcement.
 - a. Pure acoustic reinforcement is generally reserved for very sophisticated rooms, and end users, such as symphony orchestras or operas. These rooms require very strict design criteria and construction techniques, and though important, are not the primary focus of this paper.
 2. Point source, or line array, sound reinforcement systems.
 - a. This paper is written with these reinforcement systems clearly in mind, as they represent the most commonly-specified technologies used in facilities that seat more than about 50 people.
 - b. These are also the systems that are capable of producing the widest frequency response, the greatest power, and that will generally benefit most from being installed in a good acoustical environment.
 3. Overhead, distributed loudspeaker systems.
 - a. These too are common systems, but are typically specified to support background music, light foreground music, and/or speech-only sound reinforcement.
 - b. These systems are often specified when limited frequency response, and/or power requirements are needed.
 - c. The overhead, distributed loudspeaker system is often the most effective approach when a low, flat ceiling is required.
- B. There are other delivery methods, but they usually operate independently of a room's architectural acoustics.

4.0 LOW-FREQUENCY WAVES VS. HIGH-FREQUENCY RAYS

- 4.1 There is an extremely important distinction between low- and high-frequency sounds. That distinction is based on the physical size of the various wavelengths. This concept is a major theme of this paper.
- 4.2 The classic representation of audible sound is stated as 20 Hz to 20 kHz.
 - A. When discussing AA, and sound reinforcement systems, the most usable range of frequencies is a little more limited.
 1. Most professional sound reinforcement systems are designed for optimum performance in the range of frequencies between 40 Hz and 16 kHz. Therefore, when relating to AA, these frequencies represent wavelengths that are our greatest concern.
- 4.3 Pay particular attention to the wavelength disparity between the three octaves of sound between 40 Hz and 320 Hz, and the two highest octaves centered at 8 kHz and 16 kHz.
 - A. Each halving of 320 Hz is an octave down, and a doubling in wavelength size. Examples:
 1. A 320 Hz wavelength is a slightly longer than 3.5'.

2. An octave lower is a 160 Hz, with a wavelength of about 7'.
 3. The next octave down is an 80 Hz wavelength, which is a little more than 14' long.
 4. Drop one more octave and you're at a 40 Hz. This wave is roughly 28' in length.
- B. For perspective, here are the wavelengths for the two highest octaves of usable sound:
1. The 8 kHz wavelength is a little more than 1-5/8 inches long.
 2. A 16 kHz wavelength is a little less than 7/8 of one inch in length.
- C. To summarize, compare the 28' wavelength of a 40 Hz tone to the 7/8" wavelength of a 16 kHz tone. Dimensionally, that's a ratio of 400:1, or about nine octaves in musical terms.
1. Contrast this to the wavelengths of visible light (from red to violet), which are at opposite ends of the visible spectrum. Dimensionally, the ratio is 2:1, or one octave in musical terms.
- 4.4 It should now be obvious that there are enormous differences between lower- and higher-frequency sounds and their corresponding wavelengths. This is the primary reason why sound waves are so much more difficult to manage and control than light waves.
- A. Moving forward throughout this document, sounds that are at or below 375 Hz will be categorized as *LF waves* (low-frequency waves). Mid- and high-frequency waves, those above 375 Hz, will be recognized as *HF rays* (high-frequency rays).
1. The wavelength of a 375 Hz tone is significant because it is 36" long. For this paper, 375 Hz was chosen because 36" is a very easy dimension for most Americans to relate to, and visualize.
 2. Please note that 375 Hz is a somewhat arbitrary value. A one meter wavelength (343 Hz) could just as easily been used. So could any other frequency between 250 Hz (52") and 400 Hz (32"). The point is to define a transitional wavelength to separate the two *wave* groups being represented.
 3. The delineation between *LF waves* and *HF rays* is an important distinction to remember. Not the exact values, but the concept that there are two distinct groupings.
- B. Because of the size and propagation differences between *LF waves* and *HF rays*, any discussion related to AA must include and embrace the appropriate treatments that each requires.
- 4.5 Size matters:
- A. Understanding the size of various frequencies is very important, because sound interacts and behaves differently based on the physical structures and materials it comes in contact with.
- B. As stated above, 36" represents one full wavelength of a 375 Hz sine wave tone.

1. Another way to understand this is to know that a 375 Hz tone requires 36" of linear distance to complete one full cycle, and about 3 milliseconds to travel that distance.
 2. For those with a musical background, 375 Hz sits just slightly below A-440, and a little above middle C on a piano.
- C. Now picture a flashlight shining a cone of light on a wall that is 36" in diameter.
1. It's fair to say that 36" is a fairly small dimension when related to most public venues. Why do we care? Because every architectural element, which has any dimension of 36" or larger, will have a noticeable acoustical affect on frequencies that are equal to, or higher, than 375 Hz.
 2. In fact, architectural elements and finishes that are a mere 9" in size will also impart some acoustical affect on that 375 Hz sound. We'll delve into why this is true in section 4.7 below.
- 4.6 Ray trace modeling is most accurate when evaluating the *HF-ray* group of frequencies.
- A. When using ray tracing to simulate the behavior of sound waves in a computer model, you might visualize each representative ray as a laser beam that has a diameter of 1/16". Not actually 1/16", but good enough for this visualization.
1. As each 1/16" diameter ray travels through the virtual airspace of the model, it can represent, with reasonable accuracy, any frequency or group of frequencies that are around 375 Hz or higher.
- B. Unfortunately, modeling sound waves that are longer than about 36", becomes less and less reliable. This is because the rays don't accurately represent the longer waves.
1. Picture this: A 100 Hz tone has a wavelength that is a little more than 11' long. Wavelengths of this size simply wrap around small objects and structures. Acoustically, those small objects simply don't exist.
 2. However, when ray tracing is used to model a 100 Hz sound, one or more rays may land on that same small object or structure, and return a value that is reported, but misleading.
- C. When propagating wide-ranging wavelength dimensions onto architectural features, finishes, and acoustical treatments, it becomes necessary to evaluate, design, and/or remediate with these dimensional relationships clearly in mind.

4.7 Acoustic Shadows:

- A. Acoustic shadowing occurs when objects block the direct sound path between a sound source, and one or more listeners.
1. This subject comes into play more often than might be imagined. The most common examples are seen in large assembly areas that have columns, truss beams, and/or large lighting pendants or chandeliers.
 2. This scenario is easily demonstrated and understood by using this simple test: If a listener cannot see all of the nearest loudspeaker or sound source, some or most of the *HF ray* content will be blocked. This condition is what creates an acoustical shadow.

- B. The specific calculations needed to quantify the problem are too complex for this paper, therefore let's stick with these basic concepts:
1. The largest dimension of an obstruction is not necessarily the most "significant" dimension. The most significant dimension is the one obstructing sound from getting to one or more listeners.
 - a. Example: For any given seat, the significant dimension of a 12" round column, which is 15' tall, is almost always 12", not 15'.
 2. There are three qualities related to acoustic shadowing - Full blockage, partial blockage and no blockage.
 - a. Full blockage: If the most significant dimension of the blocking structure is equal to, or greater than, two times the wavelength dimension, most or all sound at those frequencies will be blocked.
 - b. Partial blockage (technically known as the "diffraction zone"): When the most significant dimension is between one-quarter and two times the wavelength dimension, those frequencies will be partially blocked or diffracted.
 - 1) The diffraction zone includes those wavelengths that are able to partially wrap around the obstruction in question, but without full power and fidelity. These frequencies may be audible, but will be distorted in time and energy relative to the unblocked sound in the same general area.
 - c. No blockage: When the most significant dimension is smaller than one-quarter the size of the wavelength dimensions in question, then no significant blockage will occur.
- C. The grand takeaway: There should never be an object that blocks the line of sight between any listener position, and the sound source or loudspeaker that is providing direct coverage to those seats or positions.

5.0 THE THREE ACOUSTICAL TOOLS

- 5.1 The three acoustical "tools" are: absorption, reflection and diffusion. Technically, these are not actual tools, but rather they represent the acoustical properties and interactive behavior of various surface materials. These three words translate into materials and application techniques that can be used to manage how sound behaves in an enclosed space.
- 5.2 Absorption: This tool is used to soak up sound. It describes the action that happens when sound waves strike an absorbent wall, panel, boundary or barrier of some type. If the surface is a soft and/or porous material, some of the *HF ray* frequencies will become absorbed or trapped inside the fibers, pores or pockets of that material or structure.
- A. Most materials that absorb sound are only partially effective. Each type of material has a different absorption coefficient, which is a fancy way of saying the material is able to absorb more, or less, sound at various frequencies.

- B. Materials and techniques that are most effective at absorbing *HF rays*, are generally least effective at absorbing *LF waves*. The inverse relationship is also true.
- C. Mineral wool, or spun glass insulation, is a very useful absorption tool when properly specified and installed.
 - 1. R-11, R-19 and R-30 batt insulation are effective, especially in the *HF Ray* range of frequencies. However, these materials deliver little or no acoustical benefit if fully enclosed in a wall, or placed above a hard-lid ceiling.
 - 2. When specified as a sound absorber, these insulation materials must be exposed, directly or indirectly, to the air and sound within the room.
 - 3. Indirect exposure is effective when open vaults, cavities, soffits and traps are created in a room. In these areas, batt insulation can be used to line the walls, floor and/or ceiling areas as necessary.
 - 4. The soft, fuzzy side of the insulation should always be mounted outward, so it is exposed to the air as much as possible, and not facing the structure to which it is attached.
- D. Semi-rigid fiberglass panels are very effective sound absorbers too.
 - 1. These products are typically specified with a density of either 3pcf, or 6-7pcf. Other densities exist, but are less commonly used.
 - a. AC duct liner is an example of the 3pcf material.
 - b. Fabric-wrapped wall panels, sometimes referred to as "sound soak" panels, are usually constructed from the 6-7pcf fiberglass boards.
- E. Not all "insulation" works as an absorber.
 - 1. In the construction trade, the term insulation can describe two different materials: one is useful to the acoustician, and one is not.
 - 2. Closed-cell, Extruded Polystyrene (XPS), rigid foam insulation should never be specified or used as a sound absorber. This rigid foam material will absorb little or no sound, and is therefore useless as an absorption tool.
- F. *LF wave* frequencies can be absorbed too, but not easily by using soft/porous materials alone. This is true because the size and depth requirements needed for effective absorption are generally unavailable or aesthetically unacceptable.
- G. There are *LF wave*-range absorption materials, devices and techniques. One method is to construct an assembly of materials that create a "limp mass" structure. A limp mass assembly, or structure, consists of materials that have the following properties: size, weight, and a freedom of movement.
 - 1. Sufficient size is required to catch or collect the long wavelengths of sound. Minimum size requirements are generally based on quarter-wavelength dimensions.
 - 2. Weight (mass) is required to give the long sound waves something substantial to push against. Thin, lightweight materials don't work well.
 - 3. Freedom of movement allows the mass to vibrate easily when pushed by the *LF waves*.

- H. *LF* wave absorbers are typically damped-vibration panels; not designed to sustain or reinforce the waves that strike the surface.
 - 1. When properly assembled, the vibration of the flexible panel converts *LF* wave energy into heat, via the friction that exists between the panel and its mounting attachments.
 - 2. Additional energy loss occurs through the mechanical strain and deformation of the panel.
- I. Perforated panels are another excellent choice to consider when a hard, smooth, flat and/or curved surface is desired, along with some amount of absorption.
 - 1. Perforated (perf) panels offer a combination of architectural, aesthetic and acoustical properties that are hard to ignore.
 - a. Perforated, curved-wall (or ceiling) finishes offer a unique combination of all three acoustical tools: absorption, reflection and diffusion.
 - 2. Manufactured perf panels are commonly available, and can be used as a non-structural finish material, which can be applied to ceilings and/or walls.
 - 3. There is a nice variety of base materials, hole sizes, and hole shapes and patterns to choose from. Most panel types can be painted, or wrapped in acoustically-transparent fabric, as needed to best correlate with other room finishes.
 - 4. Perf panels are available in a variety of material compositions, including: metal, polypropylene, fiberboard, and plasterboard.
 - 5. Perf panels have a specification labeled "% Open Area". From the most basic perspective, this number indicates how much sound will be absorbed, versus how much will be reflected or diffused. The higher the % Open Area, the greater the absorption. 20% - 40% open area is the typical range in this application.
 - 6. For proper performance, there is one detail to keep in mind: perf panels should always be mounted with airspace behind them, and the airspace should be lined or filled with mineral wool or spun glass insulation.
 - a. Use these values as initial airspace guidelines: 2" = bare minimum. 4" = nominal. 6" or more, optimal.
 - b. The greater the airspace depth behind a perf panel, the greater the absorption performance in the *LF* wave range.
 - 7. In most cases, a perforated metal roof deck is a much better solution than a standard, metal roof deck.
 - a. Be sure to specify a sound absorbing filler material, not XPS-type rigid foam (thermal only) filler.
- J. Mounting locations, and material quantities (square footage), are the remaining keys to the successful use of absorptive materials.
- K. Air is also an effective *HF* ray absorber, but we won't discuss this in detail quite yet.

- L. One of the keys to the effectiveness of all absorption products is the thickness of the materials used. Thicker materials absorb more sound, but more is not always the goal.
- 5.3 Reflection: Acoustically-reflective materials are probably the most widely used surface type. These materials are very commonly applied in modern construction, and are often the least expensive to purchase and install.
- A. Reflective surface materials are generally smooth and rigid. Concrete, tile, glass, wood, metal, and sheetrock are common examples.
 - B. When exposed to sound, the classic Law of Reflection applies here: The angle of incidence is equal to the angle of reflection.
 - 1. If you shine a flashlight at a mirror, or throw a golf ball against a concrete wall, you will get a reflection or bounce that is similar to what happens when sound bounces off a smooth, reflective surface.
 - 2. These are sometimes described as "specular" reflections.
 - C. When *HF rays* strike a reflective surface, the sound bounces off with nearly the same energy that it had before it struck the surface.
 - D. To be highly effective at reflecting *LF wave* frequencies, finish materials must also be very-rigidly mounted.
 - 1. Common construction methods are generally insufficient if effective *LF wave* reflections are required.
 - 2. Think about designs that require double or triple layers of sheetrock. Such wall densities are usually specified to create an acoustical environment that requires efficient and supportive *LF wave* reflections.
 - E. In some situations reflective finishes can be an effective acoustical tool. However, in many applications, they create more problems than they solve.
- 5.4 Diffusion: Diffusion has existed since the beginning of time, but has only recently been identified and classified as an effective, quantifiable, acoustic tool.
- A. Diffusion transforms a singular, specular reflection, into hundreds, if not thousands of mini-reflections.
 - B. To visualize this, imagine sound waves being exploded, and evenly scattered in many directions, after they strike a boundary.
 - 1. Another visualization is to imagine a stream of water, from a squirt gun, striking a screen door. A narrow stream of water comes out of the nozzle, but a much broader, "scattered" spray of water is what is seen after the water passes through the screen.
 - 2. Diffused sound waves don't go through a wall or barrier, they bounce back into the room after they have been exploded into many smaller waves, each having less pressure or energy than the original wave.
 - 3. Much of the scattered sound energy is still "alive", and actively moving through the room. However, significant amounts of energy also get trapped in the complex geometry of the diffusive boundary, and are thereby absorbed.

- C. *HF ray* diffusion is accomplished by deploying highly-complex geometrical shapes across one or many areas of interest.
 - 1. While the total square footage of treatment may be moderately large, the individual cavity dimensions are usually quite small; typically measured in inches.
 - 2. Round columns, and other convex structural features, make excellent *HF ray* diffusers too. This is not true of concave structures. Convex features scatter sound; concave features "focus" sound.
 - 3. Architectural features that focus sound are rarely desirable.
- D. *LF wave* diffusion is accomplished by deploying large, moderately-complex geometrical shapes in one or more areas of interest.
 - 1. The wavelength of a 100 Hz signal (baritone voice) is a little over 11'. A low bass guitar note (50 Hz) is double that wavelength. Because the wavelengths are so long in this region, *LF wave* diffusion requires treatment materials that are many times larger than what are needed for *HF ray* diffusion.
 - 2. It's not always necessary to construct full-wavelength *LF wave* diffusers. To be at least moderately effective, only one-quarter of the target wavelength is needed.
 - 3. A structure that is at least 5.5', in its smallest dimension, can provide useful diffusion for frequencies of 50 Hz and above.
 - 4. For most public facilities, large building features or structures are often the only practical application of *LF wave* diffusion. For some rooms, large ceiling clouds can serve this purpose. In others, balconies, pews, stairways and stages can all contribute to *LF wave* diffusion.
- E. Diffusion is a very effective tool when properly applied. It can also be more expensive to implement than either of the other two treatment tools.

5.5 The Square Footage Challenge:

- A. Regardless of the acoustical tools or materials used, the true effectiveness of the various treatments is based on the total square footage of each treatment, and the location(s) in which it is placed.
- B. The formulas used in calculating a room's reverberation time rely heavily on the total square footage of each finish material applied.
 - 1. When a facility is built without a specific AA plan, the base-line acoustical characteristics will be defined by the room's dimensions, geometry, and the sound absorbing-, reflecting- and/or diffusing-properties of the construction materials and furnishings. Typically, these are materials such as: carpet, drapes, sheetrock, glass, padded or un-padded chairs, steel, wood, tile, and concrete. All are architecturally-driven decisions.
 - a. The acoustical properties of each material listed above is different. Though some might be quite similar, some are very different.
 - b. The greater the total square footage for each material, the greater that material will influence the overall reverberation time in the room.

- c. By pure random accident, it is possible to build a venue that is too reverberant, too "dead", "dry" or non-reverberant, or something in between.
 - 2. For any reason, if additional acoustic treatment is required, and the ratio of treated to untreated footage is too large (large areas untreated : small areas treated = a large ratio), the treatment will be ineffective, and potentially a waste of money.
 - a. Rule-of-thumb: To be statistically significant, any generalized acoustic treatment must represent at least 10% of the total surface area of the room. Yes, there are exceptions.
 - C. Added or specialized acoustic treatment(s) should be considered under these conditions:
 - 1. The whole room needs to be adjusted to a more appropriate Reverberation Time (T60), "Room Tone", or "Time Slope". (See Sections 11.3 and 11.4 for more on T60, Room Tone and Time Slope).
 - a. This is the scenario under which the 10% rule applies.
 - 2. Acoustical zones or spot treatments are required.
 - a. There are situations that may require a small, dedicated, acoustical zone that differs from the overall room requirement. A choir loft or drum booth are two possible examples.
 - b. There are also conditions that call for a spot treatment of absorption or diffusion material, in order to improve a small problem, in an otherwise well behaved room.
 - c. The 10% rule does not necessarily apply under these conditions.
 - 3. Appropriate calculations can be run by any competent acoustician. However, it is important to note that acoustical calculations are just estimates. They are only valid when specific conditions, parameters and assumptions are being considered.
 - D. Location, location, location.
 - 1. If a venue requires additional, overall acoustic treatment(s), the results will benefit greatly from the proper distribution of the various treatment materials. Bunching the materials together on one wall, or in one confined area, is usually not productive, recommended, nor cost effective.
- 5.6 Please understand that loudspeakers are not one of the acoustical tools listed above.
- A. With the exception of the electronic, variable acoustic systems outlined in Section 15 below, no loudspeaker, nor collection of loudspeakers, can be used to "improve" the acoustics of a room.
 - 1. No electronic system can actively defeat, reduce, or remove the negative effects of excess reverberation, echo, or bad acoustics in general.

2. The best that loudspeakers can do is minimize the amount of unusable sound they broadcast into a room. This is accomplished through accurate selection and placement of all loudspeakers, and properly managing their sound radiation.

6.0 WHERE DOES ALL THE UNUSED SOUND GO?

6.1 Once a sound gets started, and moves past the audience's ears, does it go on forever? If not, why not? The answer is no, it doesn't last forever. If it did, our world would sound like an infinitely-long reverberation chamber; a literal cacophony.

A. Presuming an enclosed space: When sound reaches any sizeable absorptive or diffusive, boundary or barrier, some or much of its energy is captured and spent. The remaining energy is reflected and/or diffused away, and continues on its new path until it strikes another boundary. This process continues until the remaining sound energy becomes inaudible, then completely gone.

1. Once caught up in some type of absorbing material or structure, sound loses its energy because of friction that is created between the air molecules as they try to escape from the captivity of the material's fibers.
 - a. The physics: In simplistic terms, friction is the transfer function that converts sound energy into heat. Heat is inaudible. This all happens at extremely small human scales. You really can't see the movement or feel the heat, but it's there.
2. As noted in Section 5.1.A.5 above, depletion of *LF wave* energy also occurs when these longer waves impact items that bend or flex, causing a loss of kinetic energy through very small mechanical strains and material deformations.
3. Even without absorptive and/or diffusive materials, sound energy is depleted by the friction that exists between air molecules as they are pushed through the air.
 - a. Air absorption consumes *HF ray* energy the most; much less so for *LF wave* energy. This is one of the main reasons why you hear the *LF wave* energy from the neighbor's party in significantly greater amounts than the *HF rays*.

B. One other important factor exists: sound transmission through walls.

1. The construction materials and techniques used in most buildings allow a certain amount of sound to escape the structural envelope. This is generally not by design, nor is it necessarily a good thing, however it is one more way that sound energy is attenuated.

6.2 Anechoic chambers: Anechoic chambers are rooms built and used for the controlled testing of various devices. These rooms are designed for one unique purpose - to absorb the energy that is produced by a device being tested, so the acoustic properties of the room do not otherwise influence the test results.

A. These rooms are very effective at catching and dissipating sound. An anechoic chamber can absorb nearly 100% of the sound energy that initially strikes its interior surfaces.

- B. These chambers are only useful for product testing and other scientific applications.
 - C. A reverberation chamber is exactly the opposite of an anechoic chamber.
- 6.3 A reverberation (reverb) chamber is constructed using very hard, rigid, reflective surface materials and construction techniques. In these rooms, sound is supposed to bounced and scattered around for many seconds, with little loss of energy.
- A. When the sound in a reverb chamber finally dies out, it's because air absorption, and very small reflective transfer losses, eventually cause the initial sound energy to completely dissipate.
 - B. It is not uncommon for a true reverberation chamber to have an audible reverb tail in the range of 10-15 seconds. In the UK, the National Physics Laboratory has a reverb tail of 30 seconds. The Taj Mahal, in India, is said to have a 25-30 seconds of reverb.
- 6.4 What about outdoor sound?
- A. Air particles, and other natural and man-made structures absorb, reflect and diffuse outdoor sounds. The amount of absorption will vary over time, distance, direction, temperature and humidity, but eventually, the sound gets caught, or completely worn down.

7.0 AUDIO VOLUME CHANGES - WHAT DO THE NUMBERS MEAN?

- 7.1 Let's define some basic concepts related to audio volume or loudness.
- A. The unit of measurement used to describe volume, and changes in volume, is the decibel, which is abbreviated as "dB". The capital B is used to honor the works of Alexander Graham Bell.
 - B. The dB value represents a ratio of two numbers; one fixed, known or standardized, the other measured. The dB can be used to express several electro-acoustical values. Here, the nomenclature is attached to acoustical sound power or sound pressure.
 - C. Sound Pressure Level (SPL).
 1. SPL is a acronym that may precede or follow some dB rating or measurement.
 2. While the decibel is a common unit of measurement, SPL is often the subject of the measurement. Changes in sound pressure are what the ear/brain system perceives and translates into more or less volume, or loudness.
 3. As an example, someone may use a sound level meter to measure the volume of a musical performance, and state the results as being "85 dB SPL". Or they might say, "the SPL is 85 dB".
 4. Some form of sound level meter is used to measure SPL. There are many makes and models. The most common are handheld devices that can be purchased for a few hundred dollars or less.
 - D. When referencing a sound level meter, the following are measurements and observations that can be made:

1. 1 dB represents a very small change in audio volume. So small that the average untrained listener will be unable to hear any difference, when compared to the same sound received prior to a 1dB change.
 2. 3 dB is considered to be the smallest change the average untrained listener can consistently recognize.
 3. 6 dB is considered to be half again louder (or softer) than the original sound sample.
 4. 10 dB is considered to be twice as loud (or soft) as the original sound sample. 20 dB doubles the perceived volume change yet again.
 5. Though the values stated above are all based on subjective evaluations, they are widely accepted references. They have been researched, studied, "normalized", and attached to the pro audio lexicon as a way of communicating common values and concepts related to audio volume.
 6. A more objective scale is not really possible given that no two people perceive sound in exactly the same way.
- E. Ratio clarification: Throughout this essay, the word "ratio" represents both mathematical and proportional values.
1. The 400:1 ratio expressed in Section 4.3.C is mathematical. One number is 400 times greater than the other.
 2. When used to reference various audio terms, such as shown in Section 7.1.D above, the values are proportional. An audio ratio of 6 dB SPL does not mean that one sound is 6 *times* louder than another. It means that one sound is 6 *decibels* louder or softer than the other.
 3. Mathematical and proportional ratios should not be confused, nor can they be used interchangeably.

7.2 The Fletcher-Munson Curve:

- A. The human ear/brain system is not uniformly sensitive at all audible frequencies. The Fletcher-Munson Curve (after Harvey Fletcher and Wilden Munson, 1933) quantifies this fact, and was the first standardized reference to define the non-linearity of human hearing.
1. The Fletcher-Munson Curve is but one of three ISO (International Organization for Standardization) curves. Generically, the phrase "equal-loudness curve (or contour)" applies to each.
 2. The equal-loudness curves account for different hearing sensitivities based on the SPL of a sound at different frequencies.
 3. The equal-loudness curves do not take into account hearing abnormalities due to advancing age, or any form of hearing damage or disease.
- B. Without getting too granular, here are a few noteworthy points that are represented by each of the equal-loudness curves:
1. Our hearing is least sensitive at low frequencies that fall into the *LF wave* region of sound. This is particularly true within the bottom three octaves of audible sound (20 Hz to 160 Hz). Because of this low sensitivity, it takes more volume (louder) to be perceived as equal in volume to sounds containing higher frequencies.

2. Our hearing is most sensitive in the mid-frequencies that fall into the range of sound between 500 Hz and 5,000 Hz. This range also happens to incorporate all the most important frequencies required to achieve good speech intelligibility.
3. Our hearing is less and less sensitive as the frequency range continues up beyond 5,000 Hz. By the time a sound reaches the highest octave of audible frequencies, 10 kHz to 20 kHz, four things work against us.
 - a. Our ears are nearly as insensitive as they are in the *LF wave* region.
 - b. Sound sources, and reinforcement systems, become less efficient at creating and reproducing this octave of sound.
 - c. Air absorbs these frequencies much more efficiently than at any lower frequency. As a result, sounds absorbed by air may never reach some areas of a large audience.
 - d. As we grow older, our hearing becomes less acute to sounds above 10 kHz.
4. For these reasons and more, the very important frequency range between 10 kHz and 20 kHz presents significant challenges to the acoustician and sound system designer.

7.3 Is it really too loud?

- A. One interesting psychoacoustic phenomenon (see Section 16 for more on psychoacoustics), which this author has observed on many occasions, is that the measured (objective) sound pressure levels are not the only, or even the primary reason for most sound complaints. More often than not, it's the style, source, quality, or instrumentation, which is the basis for the complaints, not the SPL.
 1. A person that complains about a rock or blues band playing at 90 dB SPL, may just as likely be thrilled by an orchestra, pipe organ, or choir performance measured at exactly the same volume, or even louder.
 2. One first-hand experience revealed a very restrained DJ rig (playing hip-hop and disco) in a shopping mall, while operating at 80 dBA SPL. Also measured, in the same venue, was a "featured" water fountain display splashing away at a continuous at 85 dBA. The DJ rig got all the complaints, while the fountain was generally loved by one and all; young and old. The sound of the splashing water was not even a consideration, let alone an object of annoyance.
 3. On another occasion, while a wedding reception was in progress one evening, sound levels were measured at the property line of a church community room. The neighbors had filed noise complaints based on similar, previous events. The audio levels at the property line averaged in the mid-50 to low-60 dBA range. Same as the crickets, and a little less than the traffic noise from the nearby roadway.
- B. The acronyms dBA and dBC are used when a "weighted curve" is applied to an SPL measurement.
 1. When measuring "quiet" sounds, the "A" weighting is used to represent the hearing sensitivities described by the Fletcher-Munson curve.

2. When measuring "loud" sounds, the "C" weighting is used to represent the hearing sensitivities described by the Fletcher-Munson curve.
3. There is a "B" weighting for "medium" volume sounds, but it is rarely used.
4. An unweighted SPL measurement will simply be expressed as dB, with no weighting letter.

8.0 THE INVERSE SQUARE LAW

- 8.1 The inverse square law is one of the fundamental concepts used in the business of sound and acoustics. Fundamentally, this is what the inverse square law describes:
 - A. Every time the physical distance between you and the sound source doubles in distance, the sound will be 6 dB lower (softer).
 - B. The opposite holds true too. As the distance is cut in half, the sound will get louder by 6 dB
 - C. There are exceptions, but they are not critical to this discussion.
- 8.2 Here is a very basic example: Start with a sound source that is 86 dB when measured 3' in front of the source. Measure again at a distance of 6' and you will get a measurement of 80 dB, which is 6 dB lower. Move from 6' to 12' and the measurement will be 74 dB. Move from 12' to 24' and you get 68 dB. See the pattern? All this reverses when you move toward the source of the sound.
- 8.3 Critical Distance: In the glossary of audio terminology, "critical distance" defines the point at which direct sound energy and reverberant sound energy have the same SPL. A one-to-one energy ratio has been located.
 - A. The inverse square law only hold up as long as the measurements are taken between the direct sound source and the point at which the critical distance is found.
 - B. In a highly-reverberant room, critical distance may be achieved quite close to the sound source or a loudspeaker. This, however, is usually not a good arrangement. In most cases, the 1:1, critical distance ratio should never be found within the essential seating areas of a venue.
 - C. If found outdoors, critical distance may be a considerable distance from the direct sound source. This is because a reverberant field generally doesn't exist. It's more likely a variant of critical distance will be found at the point where the direct sound and the ambient noise become equally loud.

9.0 ROOM MODES AND RATIOS

- 9.1 Room modes are one of the more difficult acoustical ideas to understand. However, some understanding is important because the topic appears throughout the remainder of this tutorial. Here are some very simplified notes to help explain the creation and management of room modes:
 - A. A room mode is a low-frequency resonance that is created within an enclosed room or space.

1. The wavelength of each resonant frequency is directly related to one or more of the room's primary, dimensional boundaries.
 2. Most significant modal activity is found below 300 Hz.
- B. Almost every room (larger than a broom closet) has modal resonances. The specific modal complement is based on physical dimensions and the complexity of the room geometry.
1. A room with very simple geometry, i.e. a "cubed" rectangle, will almost always have the fewest number of resonant, modal frequencies. While this may sound like a good thing, it is not. The optimum goal is nearly the exact opposite. It is desirable for room modes to be reasonably-dense, and evenly spaced, throughout the *LF wave*-region of the frequency spectrum.
 - a. A room with dense, evenly-space modal resonances will be perceived as having more "warmth", or a "warmer" sound. This is generally a good feature.
 - b. These resonances must also be damped and contained in duration. This means the decay time of the various modal resonances must be well controlled so they properly match the venue's desired T60 range, and the audio material being performed or presented.
 2. One other important goal is to minimize the excess strength of any specific modal frequency, or cluster of frequencies. When this is an issue, very targeted absorption or diffusion treatments may be required.
 3. Room ratios (9.3 below) are the primary controlling factor related to the density and spacing of the modes.
- C. It is not overly difficult to calculate the room modes of an empty, rectangular room, having a flat floor and ceiling. It is, however, extremely difficult to calculate room modes for a room with complex geometry.

9.2 Naming the three room modes:

- A. In a rectangular room, modes are calculated based on three possible geometric pathways of sound reflection. Those pathways are called: axial, tangential and oblique.
1. These words define the reflective pathways traveled by *LF waves*, depending on whether they bounce between two, four or six walls.
 - a. A two-surface bounce is defined as an axial mode.
 - b. A four-surface bounce is defined as a tangential mode.
 - c. A six-surface bounce is defined as an oblique mode.
 2. Don't try to remember these terms, just be aware they are real and are the basis of room mode calculations.

9.3 Room ratios:

- A. Primary room dimensions are expressed in terms of height, width, and depth (HWD). A room with dimensions of 8' x 20' x 30' has this set of ratios – 1.0:2.5:3.75.
 - 1. The smallest dimension always represents the 1.0 place holder. The other dimensions are multiples of the first value. The sequence of the numbers is insignificant.
- B. There are many “optimum” ratio sets stated in the technical references. Here is one example: 1.0:1.4:1.9.
 - 1. In this case the room might have a 10' ceiling, and be 14' wide and 19' deep. This would be a very nice rectangular room shape to work with. Need a bigger room? Double all these dims so the room becomes 28' x 38', with a 20' ceiling. The ratio set stays the same.
 - 2. Depending on the overall room size being planned, many other good-to-optimum ratios exist, so there are several options to be considered. Your friendly, local acoustician can help you find the best ratio set for your project.
 - 3. Designing around one of the optimum ratios is not the only factor to consider, but it's a good place to start if you are building a rectangular room that will be used for some type of sound generation or reproduction.
 - a. If a venue is only going to be used for speech-range applications, the importance of using good room ratios is less significant.

10.0 ROOM GEOMETRY - THE GOOD, BAD AND UGLY

- 10.1 It's very hard to separate these two fundamental topics: architectural geometry and AA. At the most basic level, it's safe to say that any room having complex, yet symmetrical, interior geometry will complement sound better than a room with simple and/or asymmetrical geometry.
 - A. The rectangular, “shoebox” room is a very common shape; having only six major walls or faces. Each pair of walls are parallel. All corners are set at 90 degree angles; a very simple three dimensional shape, and typically, very cost-effective to build.
 - B. When a more complex interior geometry is suggested, we're talking about convex curves, acute and obtuse angles, tilted walls, alcoves, balconies, non-flat ceiling structures, sloped or stepped floors, etc.
 - C. With the concept of simple and complex internal geometries in mind, let's now consider various room shapes. The following list includes many possibilities. Not all are particularly usable, but they do illustrate many key acoustical concepts relating to the ideas being expressed.
- 10.2 Sphere - The inside of a sphere is generally the worst acoustical shape. Because this isn't a practical building shape for most commercial venues, it is rarely seen, and not worth much further commentary other than these two points.

- A. If you are seriously considering the design of a spherical room, one of your first phone calls needs to be to an acoustical consultant. There will be much work required to make this shape sonically tolerable.
 - B. Conversely, the outside of a sphere is an excellent shape when located inside of almost any room. It becomes a very effective, convex diffuser.
- 10.3 Cube - This is the worst of the realistically-usable room shapes. The problem is that all three dimensions are equal, and that each of the three dimensions are parallel. Though it may not be obvious, a cube-shaped structure will result in all kinds of nasty sound problems if it has hard, reflective surfaces.
- A. Massive echo problems, and very-poorly distributed room modes, are the main issues with this shape. Much work will be required to make a cubed room sonically viable.
- 10.4 Cylinder - A round room with a flat floor and ceiling. This is a difficult shape for any sound-related activity.
- A. Without significant absorption or diffusion materials incorporated into the vertical walls, this footprint will likely be unusable for public assembly. Oval rooms have very similar problems.
 - B. The primary issue with cylindrical and oval rooms is the focusing of sound, toward a fairly small area, near the center of the arc radius. This is caused by the concave side walls. Once again, much work will be required to make this shape sonically feasible.
- 10.5 Dome - Picture a literal dome or a cylinder with a domed roof. These shapes have all the same issues as the sphere and cylinder, but are even worse because of the concave ceiling. Again, without the addition of specific acoustic treatments, these shapes are nearly unusable for most public activities.
- A. If at all possible, never build a commercial space with a dome- or pyramid-shaped ceiling. This may look creative and artistic, but it will almost always result in a room that doesn't work well for good sound reproduction.
 - B. If it must be done, be sure and include an acoustical consultant on your engineering team, and a budget for some "creative" acoustical treatment within the envelope of the dome or pyramid.
- 10.6 Rectangle (2D floor plan) - This is probably the most common shape for commercial venues. Picture the common shoebox geometry, as referenced above.
- A. The geometry of a rectangular room is simple and obvious. Hopefully, the height, width and depth dimensions will be different, and be designed around a good set of ratios.
 - 1. Contrary to popular belief, parallel walls are not automatically a negative acoustical factor. However, there are potential problems if the room is not designed with some care beyond the basic construction requirements.
 - a. As noted above, the HWD ratio set is the first item of interest. While there are a number of complementary ratio sets, there are also many sets that are quite bad. Whenever possible, try and preview the primary ratios you may be considering.

B. Flutter echo:

1. In rectangular rooms, another significant area of concern relates to minimizing or eliminating audible echoes. Echo, sometimes called "flutter echo", occurs when sound bounces rapidly, back and forth, between hard, parallel surfaces. See more on Echo in Section 11 below.
 - a. To minimize or eliminate discrete echo, any number of diffusive and/or absorptive finishes or treatments may be employed.
 - b. Fear not. Flat, sound soak panels are not your only option.

10.7 Triangle (2D floor plan) - A true triangle is not a common building shape, but it does present one nice feature; the side walls are about as far from parallel as possible. Flutter echo shouldn't be a problem, unless it occurs between the floor and ceiling.

- A. Warning: Triangular- and pyramid-shaped rooms present modal problems, much like cube-shaped rooms. This is especially true for equilateral, triangular enclosures.

10.8 Quarter-round and half-round (2D floor plan) - In recent years these shapes have become popular for performing arts and house of worship venues.

- A. While these shapes can be quite good when considering sightlines, and a need to put the audience as close to the stage as possible, they can present acoustical challenges too.

B. Any concaved, interior wall surface presents an acoustical paradox.

1. If the concave surface is on the back wall of a stage, it may serve as an effective acoustical reflector, which may possibly enhance certain styles of musical performance.
2. If the back wall (opposite the stage) has a concave shape, it may not be a good acoustical element, and will probably need some specific treatment in order to minimize the negative effects (arc radii focusing) of the reflected energy bounding off the curved shape.
3. Regardless of the fact that the back wall is a true curve, or a faceted curve, the detrimental effects are similar.

10.9 Trapezoid (2D floor plan) - Like the quarter-round shape, the trapezoid room has one notable advantage: at least one set of walls is not parallel. This will help break up flutter echoes, and create more complex modal behavior in the *LF wave* region.

- A. The greatest disadvantage of the trapezoid shape is that the front and back walls are often either parallel, or one or both are built with a concave curvature. Both of these conditions will require further evaluation, and treatment, if not properly factored into the initial design.

10.10 Pentagon (2D floor plan) - The pentagon shape is this author's favorite because it's the shape that offers a large seating area, good sight lines, and no major, parallel or curved walls.

- A. As nice as this shape may appear on first glance, there are still potential acoustic issues to be considered. These are based on:

1. The dimensions of the wall segments

2. The symmetry of the layout
 3. The height and potential slope angle of the ceiling
 4. The potential slope angle of the floor
 5. The location of various key elements such as a stage, and the seating layout
- 10.11 Hexagon (2D floor plan) - More facets is not necessarily better. The hexagon plan falls back into the rectangular group of shapes because it has multiple, parallel walls. All the same precautions must be taken related to flutter echoes and room modes.
- 10.12 Heptagon (2D floor plan) - Much like the pentagon, a potentially good acoustical shape to consider. However, now construction costs start to climb, but with no real acoustical improvement.
- A. The heptagon shape also begins to more closely resemble a cylinder, which as noted above, can be problematic.
- 10.13 Octagon - See hexagon and heptagon.
- 10.14 Concave and convex planes - There is no question that architectural structures take on many other, more complex shapes than those outlined above. Therefore it is appropriate to summarize the relative merits of these two, plane curve shapes.
- A. Concave plane curves: Almost all concave planes are acoustically challenging, especially if they are finished with hard, reflective materials.
 1. As noted earlier, concave surfaces can concentrate reflected sound energy into a fairly small area. The density of concentration, and the size of the focal point, are largely determined by the arc radius of the plane, and the overall size of the curved surface.
 2. Focusing reflected sound is usually not desirable, and should be avoided in most situations. Yes, there are exceptions to this guideline, but they are rare, especially in multi-use facilities.
 - B. Convex plane curves: Convex planes bring the exact opposite results, and are generally encouraged, where and whenever possible.
 1. Convex planes are inherently diffusive, which is good. More often than not, convex planes result in improved acoustics and sound.
 2. Faceted convex planes are less complementary, but still can be beneficial. The number of facets, and the arc radius of the curvature, will determine the relative benefits. More facets generally bring better results.
 3. If a building's design is able to include two or more, mirror-image, convex planes, regardless of location, the need for additional diffusive or absorptive materials may be greatly minimized.
- 10.15 Symmetry - Yes please. If the purpose of a room is to support live performances or the presentation of other useful, audible information, it helps tremendously to design a symmetrical interior shell.
- A. One of the prime goals and challenges, for the sound system designer, is that of delivering even sound coverage to all seating areas.

- B. There are significant performance, cost, and aesthetic benefits achieved when a room is designed with mirror-image symmetry along the center line axis of the stage or platform.
- C. Later, in the section on psychoacoustics (Section 16), the importance of "time" will be further developed. But in the context of symmetry, it is important to note these points:
 - 1. Good quality sound reinforcement requires careful analysis and implementation in the time domain. A sound system that is not properly "time-aligned" is analogous to a photograph that is out of focus.
 - 2. Every major building element or feature, which introduces significant asymmetry to the floor plan, ceiling, and/or the audience seating area(s), can add cost and complexity to a room's sound system requirements.
 - a. Asymmetrical sound propagation generally translates into time-domain challenges that must be resolved.
 - b. Additional sound devices, labor, structural points, and aesthetic anomalies, can all become unexpected challenges brought on by the need to support an asymmetrical structure. Obviously, each of these adds cost and technical complexity to any sound system.
- D. To reiterate. Within the guidelines for achieving a good acoustical environment, complex interior geometry is a beneficial and much desired objective. Conversely, asymmetrical complexity is not an appropriate goal.
 - 1. Example: The exterior of the Disney Concert Hall, in Los Angeles, is anything but symmetrical. However, upon closer inspection, you should notice that the performance area within the hall is very symmetrical, while also providing strikingly-complex structural geometry.
- E. Asymmetrical rooms can often result in unwanted or inconsistent acoustical areas or zones. If a room is designed with random, asymmetrical shapes and finishes, there is a good chance the acoustical results will be less than desirable.
 - 1. Do note, there are some exceptions; times when specifying "zoned acoustics" is an appropriate and desirable goal. Application-specific, acoustic zones need to be carefully planned, and purpose-built.

10.16 Ceiling Layout - Ceilings are another important element within the acoustical environment.

- A. Ceiling symmetry is just as important as floor plan and wall symmetry.
- B. If a room is to have a single, interior ceiling slope, it's extremely helpful to have the highest point in the room located above the stage or platform, with the downward slope moving away from the stage.
 - 1. The slope ratio should be in the range of 1:12 to 3:12. Anything having less slope is acoustically insignificant. A ratio that's too steep has its challenges too.
 - 2. If there is a sloped or stepped floor planned, slant the floor and ceiling in opposite directions so the angles open widest above the stage.

3. Gradual, yet acoustically-significant slope changes are much preferred over dramatic changes.
 - a. One challenging example can be seen in buildings that have a central clerestory, with a significantly lower ceiling structure beyond.
- C. The A-framed, peak-ridge roof structure:
1. If a room design calls for an A-frame ridgeline, please, please, please DO NOT set the peak to run perpendicular to the center line of the stage or platform.
 - a. All kinds of presentation and propagation challenges are created when the peak ridge is turned sideways.
 - b. A peak ridge, which runs parallel to the center line of the stage, is perfectly fine as long as the lowest point of the slope is equal to or greater than about 50% of the ceiling height at the peak. Read a shallow, not steep slope.
- D. Dome and pyramid ceiling shapes are very problematic. See Sections 10.5 and 10.7 above to review why.
- 10.17 Elevations - Last, but far from least important are the room's overall interior elevations.
- A. If only one AA wish could to be granted, this designer would opt for more usable ceiling height. No other single, structural parameter makes the presentation of good sound, video and lighting more difficult, and expensive, than the lack of adequate vertical space; especially above a platform or stage.
- B. The larger the room, the more ceiling height that's needed.
1. If good results are desired and/or expected, a 20' ceiling should be considered a minimum guideline for a 5,000 square foot room that is being designed for presentation or performance.
 2. At 10,000 square feet, the usable ceiling should be at least 30'. Here, the term usable means unobstructed.
 3. Yes, of course, there are exceptions. Exceptions become workable solutions when greater expense and careful planning are allowed to coexist.
- C. Try to avoid adding any type of soffit that runs directly above the stage and/or primary seating area(s). Even a small drop soffit, running above any key areas, can effectively define the lowest point for the entire room or platform.
1. If an important goal is good sound propagation, a mid-room soffit can easily translate into a more complex and expensive sound system.
 - a. Example: If a room has a general ceiling height of 30', but has a soffit running through the middle of the room that finishes at 24' AFF, effectively, for all sound-related purposes, the room has a ceiling height of 24'. Without additional speakers being added, the *HF* rays may not be able to reach very far beyond the soffit.

2. If soffits can be pushed out to the far edges of a room, along the walls and away from the seating and staging area(s), this concern is significantly minimized.

11.0 REVERBERATION AND ECHO

11.1 Reverberation and echo are often perceived as two separate acoustical phenomena, but in reality they are very much the same thing; just perceived differently because of the size and geometric characteristics of a room.

- A. Reverberation (reverb) is highly-diffused sound energy that has reflected off of several surfaces or structural boundaries.
- B. Echo is non-diffused, reflected sound energy, which exceeds our ear/brain "integration time".

11.2 For spoken word, the human ear/brain system perceives direct sound, and reflected sound that arrives within a range of about 30-60 milliseconds (ms), as being one in the same signal. The two discrete time arrivals are integrated or merged into one. The time arrival of the two is so close that we can't tell them apart.

- A. 60ms represents the upper limits of this integration time, after which the late arriving sound is perceived as a discrete echo.
- B. Based on many factors, the integration time for music can be slightly longer than 60 ms, but speech integration, and therefore intelligibility, are almost always the dominant concern.

11.3 Both reverb and echo are caused by sound bouncing off various room surfaces.

- A. Echo is more easily heard in small rooms, especially rooms with little or no geometric complexity.
 1. A repetitive echo is sometimes called "flutter" echo because percussive sounds, like a hand clap, bounce rapidly between one or more sets of parallel surfaces, producing a "fluttery" sound.
 2. Flutter echo is most obvious and problematic when two or more parallel walls are finished using hard, reflective materials.
 3. Absorption and/or diffusion can be used to mitigate problematic echoes.
- B. Reverberation is usually found in larger rooms.
 1. A naturally-reverberant space will typically be voluminous. In most cases, the more cubic feet of air, the longer the reverb time.
 2. Reverb time is measured in seconds, and represents the amount of time it takes a test stimulus signal to drop 60 dB below the initial SPL of the stimulus.
 3. The unit of measurement is commonly referred to as T60. You may also see it as RT60, which today is somewhat dated terminology. The "T" is short for time, as in reverb time. The 60 represents 60 dB of SPL attenuation.
 4. When fully stated, a measurement result might look like this: "The room has a T60 of 1.5 seconds", or "this room has a 1.3 second T60".
 - a. Modern tools and techniques allow us to achieve similar results when using T30 and T20 measurements too.

5. When a single T60 number is stated, it represents an average of two frequencies: 500 Hz and 1 kHz. See Section 11.4 below for more detail regarding frequency-specific T60 measurements.
- C. In medium and large rooms, with simplistic geometry, it's common that both discrete echoes, and measurable reverberation, are present. When these conditions exist, it's common for the reverb to "mask" or cover up the echo.
 1. This condition is typically found when the density and length of the reverb tail is equal to, or greater than, the intensity of the discrete echoes.
 2. In such rooms, the misapplication of simple absorptive materials can reduce the reverb, but do little or nothing to mitigate the undesirable echoes that persist at a lower intensity.
 - D. If given only one option, design and treat to eliminate echo. Reverberation is less problematic.
 1. Both echo and reverb can be effectively managed by properly selecting and applying one or more of the acoustic tools mentioned above.

11.4 Reverberant Time Slope (RTS):

- A. Ultimately, the goal is to design for an overall package of reverberant energy that fits both the appropriate time value (a T60 target relevant to the venue's primary uses), and the appropriate RTS.
 1. The RTS represents the shape, or trend line, throughout the range of measured octaves; from lowest to highest.
 2. Reverberation specifications and measurements are typically confined to one-octave frequency centers beginning at 63 Hz, which continue up to 8 kHz.
 - a. 63 Hz is used because it is the closest non-fractional frequency that's one octave below 125 Hz.
 - b. The remaining frequencies are: 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz.
 - c. Some measurement devices detect only six octaves, between 125 Hz and 4 kHz.
- B. For most rooms, and applications, the natural RTS should be very slightly *LF* wave-range strong or long.
 1. This is accomplished by designing for, or manipulating the T60 so the lowest frequencies are ever-so-slightly longer than the *HF ray*-range of frequencies.
 2. Some of this manipulation happens naturally and easily because of air absorption affects, and the inclusion of various soft finish materials.
 3. Achieving a more precise RTS goal requires specific, collaborative, and carefully-coordinated design efforts between the architect and acoustician.
- C. As a general guideline, we're talking about RTS variations in tenths of a second.
 1. If a room has been specified to need a mid-band T60 of 1.5 seconds, that single number represents the median value across the eight, octave centers.

2. When charted individually, this 1.5 second room should have about 1.7 seconds of reverb at 63 Hz, and maybe 1.3 seconds at 8kHz. These are not absolutes, but reasonable guidelines. There should also be a fairly smooth, linear trend line between the lowest and highest frequencies.
- D. Never should the variation between the longest and shortest T60 be as much as one full second.
1. One classic problem arises when a room is designed or treated with absorption materials that capture too much reverb in the *HF ray* spectrum, while ignoring the *LF wave* region.
 - a. An example would be a 1.5 second room with 2.5 seconds of reverb at 63 Hz, and 1.1 seconds at 8 kHz. In this example the *LF wave*-region has a T60 that's more than double the highest region of frequencies. This would not be good.
 2. Think of the RTS as a teeter-totter, with the mid-band T60 being the pivot point. Ideally, neither end of the seesaw should be too high (long) or low (short).
- E. For rooms that will be mainly used for the performance of high-energy, fast-paced music, the RTS should be pretty flat throughout the T60 spectrum. In other words, almost no T60 variation, from lowest to highest.
1. *LF wave*-energy containment is a significant challenge during high-energy performances. The problem exists because of the massive amounts of subwoofer energy (typically 40 Hz to about 100 Hz) being produced.
 2. If the room can't absorb or otherwise dissipate the subwoofer energy, at nearly the same rate it's coming out of the sound system, the building will be flooded with *LF wave* energy. The result is a performance that sounds very "boomy" or "muddy". You've all probably been there.
 3. Controlling and/or dissipating residual *LF wave* energy is both a reverberant and modal challenge. Quite honestly, this is a challenge that the pro audio and acoustics industries are still learning how best to manage.
- F. In some rare cases, the opposite can occur. If too much *LF wave* energy is absorbed, the result is a room that sounds "thin", "tinny" or "harsh" when excited with program material that is otherwise natural-sounding.

11.5 Direct to Reverberant Ratio (D/R)

- A. Earlier, in Section 8.3, critical distance was described as the physical location in a room where direct sound energy and reverberant sound energy have equal SPL intensity. A close correlation exists between critical distance and the D/R values found throughout a venue.
1. If the D/R ratio is one-to-one (1:1), critical distance has been found.
 2. As the D/R ratio improves (gets larger) sound clarity improves.
 3. Depending on the venue, and the type of performance or presentation given, a D/R ratio of between 4:1 and 6:1, is a reasonable goal.
 - a. In this instance, 4:1 means that the direct sound energy is 4 dB SPL louder than the reverberant energy.

- B. There are many nuances tied to the scope and importance of D/R ratios. This, however, is not the medium to further expand on the subject.
- 11.6 To summarize: Reverberation that is well behaved in the time domain, and is presented in an appropriate D/R ratio, can and will complement the sound of any performance or presentation.
- A. For the architect and owner, the most important question to resolve is: What single T60 target is most appropriate for the majority of the venue's uses and functions?
 - B. If there is no single, appropriate target, then variable acoustics may be required. See Section 15 below for more on variable acoustics.

12.0 SPEECH INTELLIGIBILITY

12.1 When it comes to the good and bad of acoustics and sound reinforcement, few subjects receive more scrutiny than "speech intelligibility".

- A. Simply put, the phrase 'speech intelligibility' references the average* person's ability to understand what is being said when another person is speaking their native language. (* Requires average hearing, average intelligence, and the absence of a heavy dialect or accent.)

12.2 Loudness vs. clarity:

- A. When talking to new clients, one of the most common complaints we hear is: "Our people can't hear the pastor (or presenter) who is preaching (or teaching)."
- B. Nine times out of ten, they can "hear" but they can't "understand" what is being said. This is a perfect illustration of loudness versus clarity. Good speech intelligibility and good clarity are pretty much one in the same, and neither requires excessive loudness.

12.3 The spoken English language is almost entirely dependent on the quality and clarity of the consonants communicated within each word; not the vowels. Here's a written example. See if you can figure out this phrase using only the vowels. e e ea e y e ea o_e, i_e e ai i ai o i ue . (See 12.4.B below for the complete phrase.)

- A. When the consonants are not clearly received, words are missed or confused with other words. Sometimes this can be a significant problem.
- B. Examples of poor speech intelligibility arise quickly and easily when two or more consonants rhyme. We've all experienced this at one time or another. The letters P, B, T, D are easily confused. M and N often get crossed up, as do F and S.

12.4 Articulation Loss of Consonants (ALcons):

- A. Speech clarity and intelligibility are so important that real, objective tests have been devised and established as industry standards.
 1. One such test is based on a long list of unpredictable, rhyming words. The lists are devised to gage the percentage of lost consonants (%ALcons) that might exist in an acoustical environment.

2. Other intelligibility measurement tests and techniques exist (STI and RASTI are two), but the %ALcons rating was the first devised, and still has significant relevance today. The acronym was adopted as a unit of measurement to describe and document the test results.
3. A score of zero %ALcons is considered perfect. Every person engaged in the listening test can hear and understand every word perfectly. Zero percent of the words were misunderstood. Any number above zero is less than perfect.
4. A %ALcons score of 10 means that 10% of the words were heard and written down incorrectly, because their consonants were not clearly understood.
5. A %ALcons score of 5 is considered to be very good, 10 is considered to be fair at best. A score of 15 is poor, and anything above 15 is bad.

B. From Section 12.3 above: "She sells sea shells by the sea shore, while the rain in Spain continues." Doesn't make any sense you say? Wasn't meant to.

12.5 Three Simple Tests: There are three easy tests that can be used to quickly judge the basic acoustical merits of a room. We'll call these tests, "the two talker", "the hand clap", and "the room mode analyzer".

A. The two talker test - This assessment requires two people, and is used to evaluate speech intelligibility and clarity, room noise, D/R ratio, and even the need for amplified sound reinforcement.

1. The procedure goes like this: Two people face each other, spaced an arm's length distance apart. The beginning location is not overly critical, but let's start the procedure in the middle of the room.
2. Begin a conversation at a normal speaking volume. After a few short exchanges, move apart by about five paces each and continue the conversation. Again, after a few short exchanges, move apart by about five more steps each.
3. Continue this process of talking, and moving apart, until you reach a point at which the conversation becomes either unintelligible or inaudible.
 - a. If you begin experiencing lower and lower intelligibility, before reaching the physical limits of the space, you are most likely at or beyond the point of critical distance. This means you're hearing more reverberant energy than direct sound from the other talker. See Section 8.3 to review the concept of critical distance.
 - b. Presuming you have not reached critical distance, as you move further and further apart, you may find a point where the other person's voice is just too soft to clearly hear. If this happens, it's an indication that a sound reinforcement system may be needed to amplify the spoken word.
 - c. If neither scenario occurs, you are probably evaluating a fairly small room, with reasonably good acoustics.

B. The hand clap test - This activity can be done solo. It is used to evaluate the presence of problematic echoes, and give a rough idea of the room's T60.

1. The procedure for this test is no more difficult than having the ability to produce a single, loud, hand clap.

2. Walk around the venue. Occasionally stop and clap your hands one time. Then just listen. In almost all locations, you should hear and notice either echoes, reverberation, or both.
 - a. If it's echoes you hear, with little or no reverb, look around for any large, hard, parallel surfaces you may be standing between. These echoes are symptomatic of acoustical problems that, at the very least, will reduce clarity and intelligibility. Move around the room and repeat as needed.
 - b. If you hear a smooth, obvious, reverberant tail after the hand clap sound, without any obvious echoes, try and count the number of seconds it takes for the reverb tail to become inaudible. Count up from zero, as in 'zero Mississippi, one Mississippi'. If you get to more than about 1.5 "Mississips", this is an indication the room probably has too much reverb for good speech clarity and intelligibility. Count silently to yourself. Move around the room and repeat as needed.
 - c. It's not uncommon to hear both echo and reverberation. When you easily hear both, it usually indicates that the T60 is under about 2.0 seconds, but greater than 1.0 second. If this is the case, treatments should focus on minimizing the echoes.
- C. The room mode test - This exercise requires a sound system and a sine wave generator. It's used to uncloak and reveal a room's modal characteristics.
1. This test is very easy if you have access to a venue's sound system, and perhaps a sound tech to help with the implementation.
 2. Ask to have a 60Hz sine wave tone run through the system. It doesn't have to be loud, pick any comfortable volume.
 - a. Walk around the room and listen. This test is so interesting and powerful the outcome won't be described here. You just have to experience it at least once in your life.
 - b. The experience will be similar in most rooms, though in some it will be more dramatic; others, less so. In a perfect room, the variations in what you hear will be quite minimal. Perfect rooms are very rare.
 3. Have the frequency changed, up or down, by 10Hz or so, and listen to what happens. Try a few other frequencies, at or below 100Hz. As the frequency changes the experience changes too.
 4. The underlying cause of this unique listening adventure is the modal nodes and anti-nodes, which are resonating throughout the room, and changing based on:
 - a. The stimulus frequency; your position in the room; the room's dimensions and ratios; the architectural finishes; and the acoustic treatments applied. (See Section 9 for more on Room Modes and Ratios)

13.0 NOISE

13.1 Noise is sound that is unwanted, uncomplementary and/or distracting.

- A. Noises can be either short or long in duration. Regardless of length, it's still noise.
 - B. A room's signal-to-noise ratio, and its speech intelligibility scores, go hand in hand.
- 13.2 Signal-to-noise (S/N) ratio: As the name implies, this is the ratio of direct, desired program material (signal) to the total, aggregate noise package (noise).
- A. A S/N ratio is most often expressed using dB as the unit of measurement. If the program material averages 85 dB SPL, and the noise measures 75 dB, then it is said that the S/N ratio is 10 dB.
 - B. General industry guidelines suggest that a S/N of 10 dB is the absolute minimum allowable for any speech comprehension. This is not meant to imply that 10 dB is remotely acceptable, but more, it has been shown to be the minimum value that would result in some minimal speech intelligibility, under the most extreme emergency conditions.
 - C. Most acousticians and audio system designers are looking for a minimum S/N ratio of 50 dB, or more, when possible.
 - D. Coherent early reflections and reverberation are not noise.
- 13.3 When reverberation and echo become noise:
- A. In the right setting and D/R ratio, reverberation is coherent and complementary to the desired program sounds. In excess, reverberation can distract from the quality and clarity of the direct sound signals, thereby becoming much like any other background noise.
 - 1. In most situations the longer a room's T60, the worse the intelligibility of spoken words.
 - B. When other background noise(s) is introduced into a reverberant space, the signal-to-noise-ratio becomes even worse.
 - 1. All noises mix together, regardless of their source, tonality, quantity, or location of origin. When combined, and sustained by excess reverberation, these noises can create a din of random sound, making even the most articulate performance indistinct.
 - C. Acoustic echo may be somewhat coherent, but is generally considered a non-complementary component of good sound quality and clarity.
- 13.4 Examples of common structural and environmental noises are:
- A. HVAC hum, vibration and wind-velocity noise.
 - B. Electrical transformers, and lighting buzzes and hums.
 - C. People talking, coughing, sneezing, clapping, crying or being generally restless.
 - D. A noisy sound system or electronic instrument.
 - E. Water features, fountains and pumps. Especially water that splashes.
 - F. Elevators
 - G. Outside road, rail, airplane, or other environmental noise.

- H. Neighboring or adjoining rooms that transmit loud or noisy activities.
- 13.5 Noise Criteria (NC): The term Noise Criteria is used to describe an industry-standard collection of measurement points and values, which somewhat follow the sensitivities of human hearing, as defined by the Fletcher-Munson curve. (Section 7.2)
- A. NC calculations and projections are used to express minimally-acceptable environmental noise specifications. These are often the first line of defense in defining and establishing good S/N ratios.

14.0 INTERNAL VS. EXTERNAL NOISE

14.1 The methods and materials used to minimize or contain noise are generally divided into two main classes, based on the need to control or mitigate internal or external noise.

14.2 Internal noise:

- A. Noise that is created, and stays within the envelope of a given room, is internal noise. The first five items listed in Section 13.4 above are examples of internal noise.
 - 1. Internal noises often can and should be removed or reduced at their source.
- B. Unwanted noise(s), which cannot be mitigated at the source, can be minimized somewhat, using absorptive treatment on the walls, floor, ceiling, etc.
 - 1. Once transmitted into a room, only absorptive or damping treatments are effective for noise mitigation.
 - 2. The more reverberant a room, the more obvious and pervasive any and all noises will be.

14.3 External noise:

- A. External noise, which is received from an outside source, is just as problematic as internal noise. The last three items listed in Section 13.4 are examples of external noise.
- B. Depending on the noise, and the location of the noise source, blocking it from entering a building can often be more challenging and expensive than any of the internal acoustical treatments mentioned earlier.
- C. The most effective way to stop noise from getting into a room is to identify the potential problem before any construction begins. At this point, an acoustical consultant can evaluate the potential problems, and specify the appropriate construction materials and methods needed to block most or all of the unwanted sound.
 - 1. If you are working with an existing structure, blocking external noise can be quite complicated and expensive. Because they are misapplied, many of the most common and "obvious" AA treatments are ineffective, and a waste of money.
 - 2. Blocking out external noise is most often an exercise in the art of frequency-dependant vibration isolation, not sound absorption.

14.4 Sound Transmission Class (STC):

- A. Many construction materials have an STC rating. The STC rating describes how effective the material is at blocking various frequencies that might try to pass through any given material.
- B. Material STC ratings are not generally relevant to the management of internal room acoustics. They are, however, very relevant to controlling sound that tries to get in or out of a specific room.

15.0 VARIABLE ACOUSTICS

15.1 The phrase variable acoustics (VA) means that the acoustical characteristics of a room can be adjusted, or changed, to better match the requirements of a performance or presentation. This can be a very useful feature.

15.2 VA is a topic that's most often considered for implementation when designing a performing arts venue, though many other facilities could be candidates too. Beyond the basic technical requirements of audio, video, lighting and staging, there is a great deal more that goes into managing these type venues.

- A. More often than not, the ideal goal in this market segment is to build and maintain a venue that can support the widest possible range of events and performances.
- B. In almost all cases, venues that can effectively accommodate a diverse programming agenda are the ones booking the most calendar dates; ultimately making them more commercially-viable and profitable.

15.3 Historically, the acoustical characteristics of most rooms have been static and unchangeable. Beginning with Wallace Clement Sabine, in the early 20th century, acousticians began studying the qualities and properties of various finish materials, and how they affected a venue's acoustics. It didn't take long before people started trying to manipulate the reverberation time in a facility by adding or removing various absorbent materials.

15.4 Over the past 70 years or so, concert halls and other performance venues have been installing *mechanical*, VA systems. The most common applications and techniques included:

- A. Drapes, which are opened or closed to expose or cover various reflective surfaces.
- B. The addition of purpose-built, auxiliary, reverberation chambers.
 - 1. These chambers are empty, highly-reflective annexes that share a common moveable, or shuttered, wall with the main venue.
 - 2. The shutters are then opened or closed to introduce more or less volume into the venue's airspace. The added volume is used to garner longer reverberation times.
- C. While these two approaches are seen as significant advancements over most static, acoustical options, they have several notable drawbacks:
 - 1. Cost of construction
 - 2. Loss of usable space
 - 3. A small range of variability

4. Slow and/or labor-intensive to adjust
 5. Somewhat difficult to repeat exact settings and conditions
- D. With these shortcomings, it's a wonder any owner would commit to the cost of this "new" technology. However, the need and demand for such acoustic flexibility was clear, and justifiable, when weighed against owning an unused venue; having only a single, static, acoustical trait.
- 15.5 Today, one of the more interesting and cutting-edge technologies available is commonly described as "electronic variable acoustics" (EVA). Consider these points:
- A. Apart from acoustics, all aspects of the technical systems in a performing arts facility, concert hall, house of worship, or other entertainment venue, are adjustable via real-time, human interaction. Today, we have access to tools and technologies that bring AA under our control too.
 - B. In recent years, the high-level implementation of digital audio signal processing has allowed manufacturers to explore the management and manipulation of room acoustics. This is done using various electronic components, micro-processors, and secondary loudspeaker systems.
 - C. Now, using presets, changes can be made quickly, easily, consistently, and with a much wider range of T60 and RTS parameters than ever before imagined.
 - D. This technology has sufficiently matured to the point that EVA solutions are now an extremely viable option; with no discernible, unnatural artifacts.
- 15.6 Ultimately, when someone mentions EVA, they are talking about adding and managing some amount of "man-made reverberation", within a very specific acoustical space.
- 15.7 Each type and style of performance is best expressed when delivered in a room with complementary, reverberant characteristics. Examples are:
- A. Spoken word - Short reverb, at or below a 1 second T60.
 - B. String or wind ensemble - Medium reverb time, between 1.5 and 2 second T60.
 - C. Unamplified jazz quartet - Medium short reverb, in the range of 1 to 1.5 second T60.
 - D. Rock, pop, blues, funk, hip-hop, soul or other, similar bands - Short reverb. The same or shorter than for spoken word.
 - E. Large choir, pipe organ, and/or orchestra - Medium to long reverb. 2 to 4 second T60.
 - F. Dramatic acting and musicals - Medium short. Between 1 and 1.5 second T60.
 - G. Motion picture theater - About the same as for a rock band or spoken word.
 - H. Without the implementation of an EVA system, there is no venue that can support this diverse range of acoustical requirements.
- 15.8 Because of the complexity of this topic, it would take far too much space to explain the subject in greater detail, but here are some basic takeaways for your consideration.

- A. Old -school mechanical VA systems are expensive to integrate, labor intensive to operate, and offer only minimal, functional variation.
- B. Modern EVA systems can also be expensive to integrate. Nevertheless, they provide a much greater range of adjustments, and they can be quickly and easily modified by recalling one of many presets. Presets are established during the initial EVA commissioning.
- C. There are currently no electronic products on the market that can reduce or eliminate excess reverberation. Therefore, to properly implement an EVA system, you must start with a room that has a short T60, i.e. about one second.
 - 1. Less than one second is okay. More is problematic because you can never get back to a shorter T60 than the venue naturally presents.
 - 2. If an existing room has too much reverberant energy it may first require the addition of absorptive and/or diffusive materials, in significant amounts, before an EVA system can be deployed.

16.0 PSYCHOACOUSTICS

16.1 No AA tutorial would be complete without touching on the subject of psychoacoustics.

16.2 The human brain is such an amazing computational tool that it's easy to overlook its role in audio perception. Loosely defined, psychoacoustics is the scientific study of how sound is perceived by the human ear/brain system. This subject has been extensively researched and documented, but for this paper only a few core concepts will be expressed.

16.3 It's safe to say that "time" is one of the most important components related to the quality of sound perception.

- A. Compared to the speed of light, the speed of sound is extremely slow. So slow in fact that the average listener can hear timing differences, between distant and nearby loudspeakers, when they are separated by as little as 34 feet. In some cases even less. As a result, time plays a critical role in the discussion of how sound is perceived.
 - 1. It may further interest you to note that 34', and the nominal 30 ms integration time noted above, are nearly identical. It takes about 30 ms for sound to travel 34'. That's 30/1,000th of a second.
 - 2. Beyond roughly 34', the brain gradually loses its ability to easily integrate the two speakers or sound sources as one; thus we begin perceiving them as two discrete signals.
 - a. If not electronically-corrected in the time domain, such delayed signals can easily reduce intelligibility and clarity.
 - 3. When the same two loudspeakers are moved from a front-to-back orientation, to a side-by-side orientation, a completely different set of psychoacoustic phenomena occur. Examples to follow.

16.4 Interesting examples of psychoacoustics in action:

- A. Phantom Center - To start, set up (or visualize) a stereo listening environment, configured as an equilateral triangle created by two speakers and your head, each separated by a few feet. Each speaker facing you and positioned at the same height as your ears.
1. Next, listen to a monaural audio signal (like a person talking) that propagates identically from the two speakers. What you should notice is that the talker appears to be positioned directly between the two speakers. The voice won't sound like it's coming from either of the individual speakers, but rather from a point directly in the middle.
 2. Because everything is equal, including the time arrival, your brain doesn't distinguish the sound as coming from two discrete locations. It integrates the two sounds into what seems to be a single phantom speaker, located between the two actual speakers.
 3. It doesn't matter if your eyes are open or closed, the phantom center does not move or change. Only if you move slightly to one side or the other will you begin to hear the sound move with you. Move a little right and the phantom center moves a little right too. Move too much, in either direction, and you may think that only the nearby speaker is on.
 4. The key to this phenomenon is time. As you move, it's the minute differences in arrival time that make the sound appear to move with you. This is one example of psychoacoustic at work.
- B. Time-related volume changes - Take the exact same setup as described above and add a very small amount of signal delay to only one of the speakers. Let's use 10 ms, which is $10/1000^{\text{th}}$ of a second. You won't be able to do this at home, but it's easily done with a professional sound system.
1. During this experiment, the signal will appear to be coming from the speaker that is not delayed, and the non-delayed speaker will sound louder, even though the volume of each speaker remains exactly the same. This is yet another example of time-domain psychoacoustics in action.
- C. There are other examples that could be used to described the role of psychoacoustics in AA and sound reinforcement, but these two should suffice for now.

16.5 How do psychoacoustics and Architectural Acoustics fit together?

- A. In a theoretically-perfect venue all listeners would sit in exactly the same optimal seat, and be presented with a single, four-dimensional "sound stage" that represents all instruments, voices, loudspeakers, and complementary acoustical artifacts. There would be nothing to interfere with the sound as it travels through the air. All sound would arrive with perfectly-coherent timing and fidelity.
1. Being the conductor of a symphony orchestra is probably the closest anyone comes to experiencing this ideal scenario. Maybe too, a recording studio engineer occasionally comes close to experiencing this phenomenon.
- B. Unfortunately, this ideal listening experience is never going to happen in a medium- or large-sized venue.

1. About the closest we can get to an ideal venue, and listening experience, is an unamplified music or vocal performance, presented in a modest-sized structure, with optimal acoustics. In this setting, each instrument and/or voice has a direct pathway to each individual listener.
 - a. There would be no perceptible "time smear" because there is a direct, one-to-one time relationship between each instrument or voice, and each listener.
 - b. Presuming a good D/R ratio, everything other than the direct sound is either an integrated early reflection, or highly diffused reverberation.
 - C. Once microphones, audio mixers, and loudspeakers are brought into the equation, two or more time-dependent pathways are created between the individual instruments and/or voices, and each listener. As a result, there are many more time-domain variables, and potential psychoacoustic distortions.
 1. If left uncorrected, these cumulative timing errors translate into uneven tonality and sound coverage, which further diminishes quality, clarity, and intelligibility.
 - D. Reasonable solutions become possible when architects work with purpose to distribute chairs, or seating areas, evenly and symmetrically throughout a venue.
 1. Audio system designers must also be allowed to place loudspeakers, in one or more very specific locations, so they can present everyone with the best possible blending of direct and amplified sound; all this while attempting to overcome the many timing, acoustical, spatial, tonal, budgetary, and aesthetic challenges that are ever-present.
- 16.6 Today's systems designers have many tools to minimize or eliminate the majority of these time-domain distortions, providing a room is built with good symmetry and acoustics. When asymmetrical room layouts comes into play, it complicates and/or exaggerates the timing variables, in some cases beyond what can be compensated for using today's sophisticated digital technology.

17.0 OPPORTUNITIES AND TRADEOFFS

- 17.1 Every project has it's opportunities and tradeoffs. Working with AA is no exception. Very few venues are ever built with "ideal" acoustics at the top of the priority list.
- A. AA is not an exact discipline, it's a mixture of the objective and subjective; a blending of art and science. For this reason, it's helpful to understand how to evaluate and prioritize the various opportunities and tradeoffs that might be proposed.
 - B. Because there are so many variables and priorities surrounding every construction project, pragmatic acoustic consultant's are generally happy if they can get 70% to 80% of their recommendations implemented.
- 17.2 Over the next several paragraphs a range of ideas will be presented that can provide reasonable, initial pathways to effective AA treatments. These are common prescriptions that should not overly tax the budget, the venue's functionality, nor the aesthetics of the architectural design.
- 17.3 Please understand that these are not complete, nor customized solutions, just guidelines that, in most cases, will do more good than harm.

A. Flooring

1. Carpet is often a great solution for large area, *HF ray* absorption.
 - a. A room without carpet can be challenging if there are not enough other, soft materials to help offset its absence.
 - b. In many cases, installing carpet in isles, entryways, and on presentation platforms, is better than none at all.
 - c. Very few other flooring materials provide the price/performance value of commercial-grade carpet.
 - d. If AA is the only consideration, adding under-carpet padding is seldom worth the expense.
2. In many venues, padded or upholstered chairs can be a reasonable alternative to carpet, providing sufficient numbers are used. Remember, this is a square footage issue.

B. Chairs:

1. Fully padded or upholstered chairs will provide many square feet of soft, sound absorbing material. Along with carpet, this is a great place to start managing the direct-to-reverberant characteristics (D/R ratio) in a large room.
2. Fully padded or upholstered chairs go a long way toward making the reverberation T60 more consistent, regardless of the size of the audience. This is a key point to remember, and a very helpful byproduct of upholstered chairs.
 - a. Presuming that good speech intelligibility is an important goal, any room that has a wide-ranging T60, from event to event, is going to be difficult to manage.
 - b. Like it or not, attendance becomes an undesirable form of mechanical, variable acoustics. The culprit is a venue that dramatically changes T60 based on the number of people in attendance.
 - c. People absorb sound. A fully padded chair absorbs about the same amount of sound as does a fully-clothed, adult human. When people sit in a chair, they become a direct substitute for the upholstered chair they occupy.
 - d. When people leave, the chair(s) become a direct substitute for the people. This dynamic plays out so the room's T60 has minimal variation, regardless of the number of people in attendance. This is a very desirable scenario.
3. In most cases, partially padded chairs are better than unpadded chairs.
 - a. Padding the back of a chair is slightly better than padding the seat if the loudspeakers are broadcasting from a platform area, or some point near the front of a room.

- b. The opposite is true if the speaker system is an overhead, distributed type, which has speakers that pointed straight down.
4. Adding sound absorbing materials to the underside of chairs or pews can be somewhat helpful, if other options are unavailable or unacceptable.
 5. For houses of worship, where congregational singing is usually encouraged, one of the best approaches is a combination of upholstered chairs, hard flooring under the chairs, and carpet applied in the aisles, on stage, and in other non-seating areas.
 - a. The hard floors help support the group singing, while the padded chairs and carpet help manage the overall D/R ratios.

C. Walls:

1. Much has been said about wall geometry in the sections above. Here are a few general guidelines relating to wall construction, materials, and techniques.
 - a. A metal stud wall will absorb slightly more *LF wave* energy than a wood stud wall.
 - b. A 24" OC wall will absorb slightly more *LF wave* energy than a 16" OC wall.
 - c. A single-layer sheetrock wall will absorb slightly more *LF wave* energy than a double-layer sheetrock wall.
 - d. Batt insulation, applied inside a finished wall, provides almost no *AA* benefit.
2. Mounting sound absorbing fiberglass panels on fir strips, so they stand a few inches off the wall, will be more effective than if the same panel is mounted flush to the wall.
3. Unpainted or rough-cut brick or cinderblocks will often deliver better sonic results than painted brick, cinderblock, marble, tile or slate. The porous surface will provide slightly better *HF ray* absorption, and possibly a little diffusion if the surface is rough enough.
4. When introducing non-standard, angled geometry, there are minimum values to consider. Offsets that create too small an angle will deliver no appreciable performance benefit.
 - a. As a guideline: 1:12 slopes or angles are the absolute minimum. 2:12 slopes, or greater, are much more effective. More is almost always better, unless the angle becomes too acute.
 - b. Try to work with obtuse, interior angles whenever possible, and try to limit acute angles to about 70°.
 - c. Mirror image walls, which are angled at a rate of 2:12, will produce the effective results of a single 4:12 slope angle. This can be very good.
 - d. All ratio-based slope guidelines are limited to the wavelength sizes they can affect. Smaller ratios (2:12 being smaller than 1:12) equal better

performance at lower frequencies. In addition, the angled surfaces must also be sufficiently-large, so they are not "invisible" to the longer wavelengths.

5. Convex plane-curves will almost always provide better results than concave plane-curves.
6. Perforated paneling and/or spaced slats can present a nice sonic and aesthetic character to a room.
 - a. Provide a minimum of 2 inches of space behind such panels or slats. More space is usually better.
 - b. Sound absorbing materials will typically need to be installed in the space directly behind these hard finish materials. Batt insulation or 3pcf duct liner work well in this application.
 - c. The slats and panels can be made of almost any acceptable material, and be painted or otherwise finished as desired.
 - d. Any added shape is also a plus. Perf panels and/or slats are a great treatment option when concave plane-curves are required.
7. Wall coverings such as paintings, drapes, tapestries, posters, etc., will all have different acoustic properties. Except for the drapes, most will have minimal impact - positive or negative.

D. Windows:

1. Windows are difficult to treat acoustically. This is because there are a limited number of acoustic materials that can be used without blocking a window's inherent transparency.
 - a. Some promising, translucent and transparent, window treatments are noted below under Modern Materials.
2. Almost any type of internal blind or mechanical shade material can be helpful in reducing the hard, specular, reflections that bounce off windows.
3. Direct application tinting is not at all helpful as an acoustic treatment.
4. Generally, windows that are located well above 8' AFF will present fewer acoustical problems than windows that are located below the 8' mark.
5. It is very helpful if windows can be angled so they are not perfectly parallel to other windows, or walls, on the opposite side of the room. The direction of the angle is generally not too critical, however the amount of angular offset is. See 17.3.C.4 directly above to review the specifics.

E. Ceilings:

1. Beyond what was listed above regarding ceiling geometry and symmetry, (Sections 10.16 and 10.17) ceiling finishes can also play a significant role.
2. Unless you are specifying an acoustical, perf-metal deck (which is highly recommended), a bare metal roof deck provides little or no acoustical benefit, and will probably be a problem area.

- a. If left untreated, a metal roof deck may very likely require other, post-construction, acoustical treatment.
 - b. Commercial buildings that have a thin roof structure will probably require some form of thermal insulation. This "thermal" insulation can be made from vastly-different materials; some acoustically helpful, some not so much.
 - c. Allowing your acoustical consultant to point out the best material for the job can be very helpful, and will most likely come with no negative impact on the thermal performance, nor construction cost.
3. T-grid ceiling tiles are now available in a wide variety of artistic colors, shapes, and finishes. If cost is not the only deciding factor, there may be some benefits to going with a more specialized product.
 4. Applying batt insulation above a T-grid ceiling will almost always bring additional beneficial results. To a lesser extent, so does spray-on, Monokote-type fire retardant.
 5. Within certain limits, *LF wave* frequencies can be absorbed by installing hanging baffles above a T-grid ceiling. There usually needs to be at least 4' of airspace above the grid to bring this idea to life, but it is a viable option to consider.
 6. Open truss/beam ceilings offer many possible opportunities for acoustic treatment.
 - a. This is valuable space that acousticians love to take advantage of whenever possible.
 - b. With floor and wall space usually being limited, and aesthetically sensitive, open plan ceilings often present the best opportunity to apply one, two or all three of the acoustical tools detailed above.

F. Plants and flowers:

1. Plants and flowers provide almost no acoustical impact or benefit.

G. People:

1. There is one unique and often overlooked acoustical fact: The quality and clarity of indoor sound can change dramatically, for better or worse, based on the number of listeners in attendance.
 - a. If this fact is just now hitting home, please review Section 17.3.B above.
 - b. There is nothing good or beneficial about a room that changes its T60, by a second or two, based solely on the attendance headcount. This is an important issue that you, the architect, have direct control over.

17.4 Commissioning and Training:

- A. Commissioning audio/video (AV) and acoustic systems is only properly done after the paint, carpet, permanent seating, drapes, window coverings, HVAC balancing, and fire alarm system testing are complete; after everything else is in place. Why? Because every tiny finish detail and noise plays a part in the evaluation and performance of these systems.
- B. Commissioning an acoustical design means the performance specifications are field-verified, to be within acceptable tolerances, relative to the specified goals and target values.
 - 1. Acoustical commissioning can't be started until all the architectural elements and finishes are in place.
 - 2. Further, the process of commissioning an audio system can't be properly started until all architectural and acoustical elements are finished.
- C. Architects can and should help manage everyone's expectations by carefully outlining the late scheduling requirements of the AV and acoustic systems commissioning, and AV training.
 - 1. Why is this important? Because it's an honest acknowledgement that just because the GC is done with his work, it doesn't mean the facility is ready for its first public use. It's not unreasonable, nor unusual, for these commissioning and training processes to happen after the owner has taken occupancy of a new facility.
 - 2. Very large projects can easily take two weeks for commissioning. For large and medium-size projects, one week is not unrealistic. Small projects may require one to two days.
- D. AV system operational training comes after the commissioning processes are successfully completed. Why? Because it's neither effective nor appropriate to train someone on a system that is not fully configured, tested and commissioned.
 - 1. Just like driving a car or using a computer, the AV system operator needs to have confidence the underlying systems are designed well, and operating correctly. AV system commissioning is the process of verifying that all systems are working at their best.
 - 2. The major components of a fixed AV system are not end-user adjustable. During the commissioning process, the main components and devices are optimized, then "locked down". Typically, only a limited number of operational controls are given to the operator or end user.
- E. Whenever possible, architects should discourage their customer's from scheduling a first use or "grand opening" event that is too close to the initial date of "completion".
 - 1. Thirty days after the actual TCO generally provides a reasonable amount of time for commissioning, operational training, and some technical rehearsals or dry runs to take place.

17.5 Value Engineering (VE) Issues:

- A. It's not uncommon for a sound system design to be based, in part, on the knowledge and expectation that all specified acoustical treatments will be properly installed. Problems arise when some or all the AA treatments are unexpectedly changed, or "value engineered" out of a project. This is not an uncommon story.
- B. This commentator can cite a few projects that didn't end well because customers refused to pay their sound contractor in full. Why? Once the construction was completed, significant speech intelligibility problems became apparent.
 1. The easy and obvious blame was placed on the sound system design or installation. However, the intelligibility problems were entirely the fault of missing or improperly-installed acoustic treatments. In each case, the necessary treatment was a part of the original plans and specs.
- C. If acoustic treatments are deleted or VE'd, the unintended consequences can be substantial and difficult to overcome. Three examples:
 1. Case one: A nearly-invisible ceiling treatment was VE'd out in the middle of the construction phase, without any consideration for, or communication with the acoustician and audio system designer.
 - a. The fix: Nothing was acceptable to the owner because of cost and the need to preserve the architectural aesthetics. Last checked, the problem still exists.
 - b. Because of all the finger pointing, and responsibility denials, it took almost a year for the AV contractor to receive full payment.
 2. Case two: A spray-on ceiling treatment was misapplied by the GC's sub-contractor. It's believed, to save money, the sub cut the specified application thickness by about 75%. In this large gymnasium, no one could tell there was a problem when looking up from the floor, and no one took the time to check the workmanship more closely.
 - a. When the construction was complete, everyone said the sound problem must be the fault of a poor sound system design or installation.
 - b. It took a little more than a year to fight through the politics and blame games; do site tests of the "as-built" conditions; spot check the workmanship, and finally have the responsible contractor re-apply treatment to the specified material thickness. That list doesn't include all the time lost, and money spent, to investigate the problem.
 - c. Final result after the fix: problem adequately resolved; sound contractor paid.
 3. Case three: Another near disaster avoided. As mentioned above in Section 5.1.A.8, not all "insulation" works as a sound absorber.
 - a. On this project, the insulation contractor chose to use XPS rigid foam, where 6-7pcf, semi-rigid fiberglass was specified to be installed behind a perforated-metal wall finish.

- b. An innocent mistake? Maybe, maybe not. Insulation is insulation, right? 2" XPS is just as good an insulator as 2" semi-rigid fiberglass, no? XPS costs about half, so who's to notice or care? These guys were the low bidder.
- c. This reporter happened to make an unscheduled jobsite visit, and noticed that the wrong materials appeared to be staged for installation the next day. Further evidence showed that installation of the XPS foam had already begun in a few small areas.
- d. To verify the concern, a quick phone call was made to the project's acoustical consultant, followed by calls to the architect and GC. Within a few hours the work was halted until the right materials could be acquired and installed. Fortunately, many additional days of rework were avoided.

18.0 PRIORITIES SUMMARIZED

18.1 The following are this commentator's list of AA priorities. All are equally important.

- A. More clear, usable ceiling height.
- B. Mirror image symmetry.
- C. Concise AA goals, and if necessary, a budgetary line item for acoustic treatments.
 - 1. This line item should be above and beyond the cost of the audio system and all standard finish materials.
- D. Once approved during the design phases, acoustical treatments should never be minimized or eliminated for budgetary reasons.
- E. Very low background noise.
- F. No large concave or domed surfaces.
- G. Negotiable opportunities to manage T60 and Time Slope.
- H. If specialized treatment is unacceptable or unavailable, design major surfaces to be non-parallel.
- I. Acknowledgement, and acceptance, of the time and scheduling needs for commissioning and training.

19.0 MODERN MATERIALS

19.1 Many new acoustical products have been introduced in recent years. In most cases, these products were specifically developed to encourage their use in architectural settings. Most are direct application, acoustical tools. Some require a backing layer to complete their acoustical usefulness.

19.2 An overview of these products includes:

- A. "3D" absorption panels, with complex geometric shapes, patterns, and colors
- B. Acoustical diffusers that also serve as clear, lighting diffusers

- C. Acoustically-absorbent plaster
- D. Bendable, semi-rigid fiberglass paneling, with fabric wrap
- E. Clear, translucent and artistically-printed films and foils
- F. Clear, translucent, and multi-color, diffuser block
- G. CMU diffusion block, with a structural rating
- H. Unique, complex, and customized, perforated metals and plastics
- I. Diffusion panels, with options for many geometric patterns, colors, and materials
- J. Digital print media on acoustical fabrics
- K. Dimensional metal surfaces
- L. Micro-perf, absorptive, translucent, window covers
- M. Perforated sheetrock, with multiple hole-pattern options
- N. Sprayable absorption materials, with color and thickness options
- O. Translucent art diffusers for lighting panels
- P. Very high-impact, fiberglass wall panels
- Q. Woven wire mesh, with multiple shape and color options

20.0 CONCLUSION

- 20.1 There is so much more to the subject of Architectural Acoustics than can be expressed in this limited format. If this paper has brought a new appreciation for the topics of Architectural Acoustics and sound, and the role they play in the buildings you design, then please bring this appreciation into each and every project you begin or assess.
- 20.2 Sound exists within the constraints of our primary, physical dimensions of space and time. Yet when isolated to any discrete listening position, it cannot be defined by height, width, depth, mass, time, color, smell, taste, or texture. As a result it is often underappreciated, and/or ignored, as something of critical importance within the three-dimensional confines of a building.
- 20.3 If you remember nothing else from this essay, please remember this: For better or worse, every architectural feature and finish influences sound.

References: This document is an original creation. No direct text nor quotes, from any previously-published materials, were used in its development. Similarities to other works are purely coincidental and unintended.

Five influential works have guided this author's knowledge and understanding of acoustics and the physics of sound. They are:

Architectural Acoustics - David Egan - McGraw-Hill, Inc. - 1988

Handbook of Architectural Acoustics and Noise Control - Michael Rettinger - Tab Professional Reference Books - 1988

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This paper was selected for presentation at the 166th Meeting of the Acoustical Society of America. December, 2013.

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