What intrigued me most about lutherie when I started was that most of the elements that determine a guitar’s sound go unseen. Its sound components include many structural features that are too small to notice or reside within the box. The player may not see them, but these elements have a profound sonic impact. What makes one guitar sound different from another, and what choices does a luthier make to set the instrument’s voice? Lutherie is a craft that transforms material and shape into sound. This article will explore structural and acoustic principles of the soundboard that influence that sound.

**Players as ballparks**

Players and luthiers often describe a guitar by its bracing pattern because it provides a shortcut that people find easy to conceptualize. However, information about bracing is not enough to predict a guitar’s sound. While people often conflate bracing pattern and overall design/style, they are not the same. For example, there are many styles of lattice-braced guitars. As we will see, bracing is only one element within a larger architectural framework that could more correctly be termed design or style.

Today, a dizzying variety of styles offers an unprecedented opportunity to match instrument to player. Certain styles can, and often do, predispose the tonal aesthetic of a guitar. Consider the sound of a fan-braced Hauser-style guitar versus an Australian lattice-braced or a double-top guitar. Now consider two ballparks—vintage Fenway Park in Boston and modern Marlins Park in Miami. Each provides a different experience. The architecture is radically different, yet the baseball fields inside have nuances that matter most to those playing the game: How short did the groundskeeper mow the grass? What is the shape of the pitcher’s mound? What are the distances to the fence? Like a groundskeeper, a luthier decides and shapes tonal nuances within the context of a larger tonal aesthetic. It is at this level of tonal nuance that we will focus our attention.

**The original resonator guitar**

You may have noticed while holding your guitar that the voice of a person in front of you or the sound of music can stimulate your soundboard to vibrate. For good guitars, the vibration can be strong and responsive to a wide spectrum of pitches. Similarly, efficient guitars amplify sound not through brute force movement of the strings but rather through the soundboard’s natural propensity to move at the same frequencies as the strings driving them. A good guitar top wants to move; it just needs frequency-specific instructions from the player’s hands communicated through the strings. The result is amplification of a signal far greater than the small amount of air that tiny strings alone can push toward your ears.

**Gears in your car**

To draw another analogy, think of a guitar’s collection of resonances like the gears in your car. Each gear supports a certain range of speed so if you are missing a gear, you cannot go those speeds. Likewise, trying to drive at speeds out of a gear’s range of efficiency makes the car shake or whine, begging us to shift to the next gear. Fortunately, a car has a whole collection of gears that overlap in efficiency to allow a continuum of speeds. Similarly, a guitar has a collection of different movements that are excited by, and amplify, specific ranges of pitch. The soundboard shifts from one movement to the next as it has an automatic transmission. If the luthier combines the movements well, you do not experience abnormally weak or strong notes. These movements supporting resonances are the physical basis for a guitar’s voice, and because the instrument’s structure can alter them, a luthier has the ability to manipulate that voice.

Returning to the example of feeling a guitar top resonate with someone’s voice, one can use a related technique to watch how a top moves. German physicist Ernst Chladni pioneered early versions of this technique in the late 1700s by sprinkling sand on metal plates and exciting the plates with resonating frequencies from a violin bow that instantly created wondrous geometric patterns. Whether using direct contact with a violin bow (or guitar string) or through space with the pitch of a voice, the phenomenon of sympathetic resonance is the same. Using a contemporary version of Chladni analysis, Figure 1 shows examples of some movements a soundboard makes at different frequencies. The guitar’s soundboard is uniformly covered with particles, in this case tea leaves. When a computer generates pitches near the resonant frequencies, with its
speaker pointed at the soundboard, the leaves rapidly jump in areas of movement and collect in regions of stillness. Regions on either side of the lines of tea leaves move in opposite directions relative to the plane of the soundboard. For this soundboard, a 228-Hz pitch most efficiently drives the lowest frequency resonance, also known as the main top resonance. Frequencies on either side of this maximum also stimulate movement but with decreased efficiency.

Figure 1: Chladni patterns from a guitar body exposed to different resonant frequencies generated by computer and speaker. The accumulation of tea leaves indicates regions of no movement. The frequencies shown are those that stimulate the maximum response. For brevity, the image shows only four of the ten patterns obtained within the range of 200–1,000 Hz. The guitar body, tested prior to gluing the bridge, has a spruce/cedar double top.

The main top resonance corresponds to a simple pumping motion in the lower bout, which moves in and out 228 times per second. 228 Hz (about A#) is also one of the predominant frequencies you hear if you tap the top. As we will see, the stiffness and weight of the soundboard determine resonant frequencies. If this guitar were assembled and strung, the motion of the 228-Hz resonance would be responsible for amplifying the notes played on the third string and many of those close in pitch on the fourth and second. As higher pitches play, the soundboard shifts to the next movement, and so on. In Figure 1, only the first, fourth, sixth, and ninth of ten soundboard motions detected are shown. Even with this limited set of examples, one can see that top movements change with increasing frequency to support different ranges of pitch and become increasingly complex.

Luthier as structural engineer
The job of the builder is to control resonances through a variety of structural techniques. These techniques shift the resonances up or down the frequency range to change the bass-to-treble balance, and promote or inhibit certain resonances to normalize note-to-note strength and tonal color across ranges of pitch. Spatial distribution of stiffness and weight influence soundboard movements and thus resonances. More specifically, the frequency range that can excite each resonance relates directly to the ratio of stiffness to mass. The consequence is that stiffness and weight have opposing effects, and it is necessary for luthiers to understand which parameter changes faster relative to the other during each building step.

Figure 2 presents hypothetical adjustments that a luthier could make to a soundboard. All else being equal, the table outlines the expected change in brightness (increased treble-to-bass balance) and, often, treble clarity, manifested by changes in stiffness, weight, and resonant frequencies. In every case, increasing the amount of any of the soundboard features tends to produce a brighter sounding guitar with potentially more defined trebles. Conversely, decreasing the amount of any of the soundboard features tends to increase warmth, richness, and bass strength.

<table>
<thead>
<tr>
<th>Soundboard Feature</th>
<th>Brightness (Treble Orientation)</th>
<th>Soundboard Stiffness</th>
<th>Soundboard Weight</th>
<th>Resonant Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased thickness</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Increased wood density</td>
<td>Generally ↑</td>
<td>Generally ↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Increased bracing</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Increased arching</td>
<td>↑</td>
<td>↑</td>
<td>No change</td>
<td>↑</td>
</tr>
</tbody>
</table>

Table: How increased amounts of different soundboard parameters affect brightness and other physical properties. The size of the arrow indicates the magnitude of the effect.

Soundboard thickness and stiffness
Increased thickness changes the stiffness of a soundboard faster than the weight gain, so increased thickness generally produces a brighter sounding guitar. In practice, luthiers start with thicker material than desired and gradually reduce the thickness to a target. But what is the target? Each luthier has his or her own idea. The late GFA Hall of Fame awardee Manuel Velázquez calibrated soundboard thickness with a highly developed sense of feel between his thumb and finger combined with feeling the board’s resilience.1

Because the stiffness of different cuts of wood can vary significantly, builders such as GFA Hall of Fame awardee Daniel Friederich place target thickness secondary to directly measuring stiffness; then they thin to a target flexibility.2 This approach works equally well for spruce

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or cedar soundboards. **Figure 3** shows a stiffness measuring system similar to that used by Friederich. The accompanying measurements demonstrate the relationship between thickness, stiffness/flexibility, weight, resonant pitch, and the variability among different soundboard blanks. **Figures 3a and 3b** show spruce soundboard blanks of identical dimensions suspended across two long blocks spaced a standardized distance apart, with the grain of the board perpendicular to the blocks. A two-pound weight bends the boards so that the bending distance, as measured by a dial caliper, provides a value related to strength. Although both samples are four millimeters thick, Sample 1 is stiffer compared to Sample 2 because it bends less.

Perhaps more relevant than stiffness to the guitar’s sound are the resonant pitches of the raw boards when they are tapped or measured by Chladni analysis. Stiffer Sample 1 is pitched higher at B3 (247 Hz) compared to more flexible Sample 2 at A3 (220 Hz). At this stage, the thickness of the boards is approximately twice what they will be in assembled guitars. The measurements provide the luthier objective criteria to use in board selection and in deciding how to work the material.

A guitar built with Sample 1 at the same thickness as Sample 2 will generally sound brighter and have potentially clearer trebles because stiffer soundboards tend to shift all resonances to higher frequencies and accentuate the trebles. Have you ever noticed that guitars with bright trebles tend to have a very stiff feel in the right hand? Our hands are ultra-sensitive to the flexing of the top when we strike the string, so we are able to notice the correlation between stiffness and high frequency. It is not surprising that certain bright, treble-oriented guitars feel “tight.”

In a real-world scenario, the luthier might strive to build two similar sounding guitars from Samples 1 and 2. **Figure 3c** shows how thinning Sample 1 to give the same resonant pitch can help achieve this goal. Even after thinning Sample 1 to the same resonant frequency, the total weight of Sample 1 is significantly heavier due to its higher density. The increased weight yields a slightly different result—perhaps less power and a more sluggish right-hand response but potentially more sustain since the energy would not dissipate as quickly.

<table>
<thead>
<tr>
<th>Thickness:</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 1 Thinned</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 mm</td>
<td>4.0 mm</td>
<td>3.7 mm</td>
<td></td>
</tr>
<tr>
<td>Bending:</td>
<td>2.2 mm</td>
<td>3.5 mm</td>
<td>2.7 mm</td>
</tr>
<tr>
<td>Pitch:</td>
<td>B3</td>
<td>A3</td>
<td>A3</td>
</tr>
<tr>
<td>Density:</td>
<td>0.45 g/cm³</td>
<td>0.38 g/cm³</td>
<td>0.45 g/cm³</td>
</tr>
<tr>
<td>Weight:</td>
<td>190 g</td>
<td>158 g</td>
<td>174 g</td>
</tr>
</tbody>
</table>

**Figure 3**: The relationship between soundboard thickness, stiffness (as measured by bending), resonant pitch, and density. Soundboard stiffness and resonant pitch are highly dependent on thickness but can be highly variable from board to board because of variability in density. In panels a and b, both samples are Engelmann spruce boards of identical dimensions. In panel c, Sample 1 was thinned.

**Wood density**

Wood density is notoriously variable and something that challenges the skill of the luthier on a quest for consistency. To illustrate this point, consider again our Samples 1 and 2 in **Figure 3**, cut from different trees. The density of Sample 1 was 0.45 g/cm³; Sample 2 was 0.38 g/cm³. The stiffness and resulting pitches from these identically sized pieces are markedly different. Fortunately, soundboard density is highly correlated with stiffness and is an extremely useful parameter when selecting boards. Although density is calculable, Manuel Velásquez preferred to estimate a soundboard’s density by holding it up to a light, noting the amount of light penetrating the wood. In general, it is highly advantageous for builders to obtain large stocks of soundboard material of similar density.

**Bracing**

Bracing provides not only high strength relative to its weight for countering string tension but also control over direction and stiffness. Thus, it serves as a useful tool for manipulating a guitar’s voice and response. Torres masterfully integrated (diagonal) fan bracing, which not only adds strength in the direction of the string tension but also promotes a variety of side-to-side motions, resulting in a broad pallet of tonal color. By contrast, guitars built in the Viennese tradition employed simple, horizontally positioned ladder bracing, which inhibits side-to-side...
motions, resulting—at least to my ear—in a drier, less colorful voice.

Braces increase resonant frequencies by adding stiffness. After the luthier glues braces to the soundboard, he or she carves them downward to introduce flexibility and lower the resonances in frequency. Nearly all bracing schemes employ this approach. The exact amount and location of the carving depends on the luthier’s intent toward introducing spatial differences in flexibility. The stiffness of a brace is extremely sensitive to height, so small changes made by shaving the height can drastically change the local stiffness. Combined with positioning, brace stiffness in key areas can normalize the strength and timbre of notes across the range. Bracing treatment is highly personal, and because of the potentially confounding influence of braces on the multitude of patterns of soundboard movement, the exact effects are too complex to predict, especially in higher registers. Thus, luthiers typically develop bracing schemes empirically.

**Figure 4** shows the bracing adjustments I made on one of my soundboards that markedly improved the strength, note-to-note evenness, and sustain of notes above the twelfth fret. My intent was twofold: (1) to reposition the right closing bar to increase horizontal stiffness in order to raise upper range resonant frequencies, and (2) cross the fan bars to integrate the top in order to enhance note-to-note evenness. In this instance, intuition and experience led to success. In lutherie, the second guitar in a series is always more important than the prototype because an improvement has little value unless the effect can be reproduced. Fortunately, this positive result has proven to be extremely reproducible.

In traditional fan-braced guitar tops, the board is the heavier component compared to the bracing—approximately eighty-five percent board and fifteen percent bracing. As in the case of a building’s floor, it is more weight-efficient to add beams to strengthen the floor than increase the thickness of the floor. Lattice-braced and double-top soundboards push this principle to the extreme by investing weight in an extensive network of braces or a honeycomb core to drastically reduce soundboard plate thickness(es). The overall weight savings can result in additional power and speed of right-hand response but will affect the resonances, which will require compensation through other means.

**Doming**

Close inspection of soundboards built since Torres’s time reveals at least a remnant of a slight dome built into the top. The peak of the dome usually centers near the bridge, approximately two millimeters higher in elevation compared to the edges, for increased stiffness without adding weight. Luthiers introduce arching while gluing and clamping the braces to the soundboard. Once the glue is dried, the braces continue to hold the arch radially. Much like a musical saw that is flexed into a curve, the more severe the arching, the higher the pitch of the resonances. Varying the amount of doming is an effective way to control the relative richness or aggressiveness of the voice. Often over time, the dome may deform under string tension and transform into an S-curve with a dip in front of the bridge and a hump toward the tail. Nonetheless, since the maker established tension in the top during assembly, the sonic result typically remains similar regardless of the shape.

**Bass vs. treble: more than just metal vs. nylon**

If the soundboard only resonates in the range from approximately 200 Hz (open third string) and above, what resonances support the bass notes played on strings four through six? Air in the body moving in and out of the soundhole supports notes played on the bass strings, not soundboard movement. However, soundboard movement enhances air movement in such a way that the resulting main air resonance shifts to lower frequencies. A consequence of this coupling effect is that building a more flexible top increases bass response, warmth, and richness. The main air resonance is typically most efficient near 100 Hz (near G2 on the sixth string). Main air resonance and main top resonance (discussed earlier) are often confused; although they are spaced about an octave apart, both often land near the note G.
**Which approach is best?**

Luthiers often categorize themselves as “intuitive” or “scientific” in approach. Does this mean intuitive builders synthesize less information than scientific ones? Doubtful. For every measurement taken by a numbers-oriented luthier, the intuitive builder uses an equal sensitivity of touch, hearing, and memory. Luthiers have created great guitars with approaches ranging from highly intuitive to highly data-intensive. Each approach is valid as long as the luthier can reproduce or move the voice as desired. In theory, any structural change will affect a guitar’s resonant properties, which may not be large enough for players to perceive. The challenge for all luthiers is to discover which structural parameters have the strongest or most meaningful influence on sound and manipulate them in a way that is highly reproducible and controllable. It is not necessary to understand the physics, but it is important to understand the correlations.

The ability to change a guitar’s sound, even a small amount toward a desired target, is one of the most advanced skills a luthier can develop. Often, the idea of a new tonal target grows out of a close partnership with skilled and perceptive players who are able to articulate their needs. Moving sound *per se* is as simple as changing one structural feature. Changing structure to achieve a tonal goal is an entirely different matter. At some point in a luthier’s career, he or she might ask the decisive question: Am I building a guitar (structure) in search of a sound, or building a sound in search of a structure? In order to achieve the latter, the luthier might need to build a minimum number of variations and evaluate the sonic results in order to draw the correlations. Since the guitar is an infinitely complex system—far too complex to describe with a computer—the more correlations the luthier establishes, the clearer the solution becomes. Many data points—measurable or tactile, recorded or memorized—are valuable. Wood variation can cloud the picture, so at a minimum the luthier’s technique needs to be exacting enough that execution does not become the bigger variable.

**Luthier as sound engineer**

If you gave five skilled luthiers the same plan, specifying scale length, box dimensions, and bracing pattern, then told them to select their wood from a large stack of spruce and East Indian rosewood, chances are very good that each individual would create a different sounding guitar with each instrument bearing some familial resemblance to the others. Think of each structural or material feature as a slider on an audio mixing board. The luthier as sound engineer contemplates and sets the position of each slider to create a unique sound profile. Although different slider combinations could theoretically produce identical sounding guitars, more likely the results will be distinguishable. When the luthier replicates his or her intent over a large body of work, the voice becomes the luthier’s signature sound—the product of decision-making, technique, execution, experience, and most importantly, conviction. Now add five players for the five guitars. Likely, there would be no overwhelming consensus on the favorite guitar since each player gravitates toward the guitar that complements his or her style of playing. Just as there is no best player, there is no best guitar—just better matches in a world of captivating variety.

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Based in New Jersey near New York City, Garrett Lee has been building classical guitars since 1999. Originally trained as a biochemist, he transitioned to full-time lutherie in 2006. His primary interest is in controlling sound, response, and expressiveness through manipulation of the guitar’s structural elements. Gary’s instruments incorporate traditional approaches with modern design, such as double-top soundboards and adjustable-action necks. He handcrafts ten guitars a year, which are in demand by some of today’s top concert artists. For more information, visit LeeGuitarWorks.com.