Photo by Akira Kinoshita

Cremona Revisited: The Science of Violin Making

by Andrew Hsieh

Itzhak Perlman in concert.

The lights dim, and a hush falls over the concert hall. The concertmaster rises, and as the orchestra tunes, the faint rustling of programs is heard in the background. Tonight's concert features one of the greatest living soloists performing with the orchestra, and the anticipation is palpable. The conductor appears and is duly acknowledged by the crowd; but he is not the one they are waiting to see. Finally, the soloist emerges, leaning on a pair of walking sticks, and takes his seat at center stage to thunderous applause.

It is the distinguished violinist Itzhak Perlman, and the instrument in his hands is one of the finest string instruments ever made: the "Soil" Stradivarius, crafted in 1714 by the Italian master Antonio Stradivari. Even before the first notes have been played, members of the audience are transfixed by the sight of the violin, its brilliant red varnish and the stunning "flame" pattern of its back catching the eye as they reflect the bright stage lights. The conductor raises his baton, and as the first notes reverberate through the hall, they complete the image of the renowned virtuoso and his legendary instrument.

Each violin, viola, cello, and bass is a masterpiece, simple lumber converted into a sublimely expressive musical instrument. Most were made long before the musicians playing them were born. Musicians and violin makers claim that a violin's sound improves with age, and therefore it is not entirely surprising that most musicians prefer older instruments.

The best-known string instruments, with only a few exceptions, are the work of either Antonio Stradivari or Giuseppe Guarneri, both active in Cremona, Italy, in the first half of the 18th century. Their violins were often passed down from virtuoso to virtuoso and sometimes named after famous past owners. Both Stradivari and Guarneri generated a sort of mystique about themselves by selling their instruments only to virtuosi or to extremely wealthy customers, and the quality of instruments such as those played by great soloists past and present has served to not only perpetuate but to increase the "Cremona mystique." The two men maintained an extraordinary level of secrecy throughout their lives, suggesting that they might never have revealed some of their techniques to the world. The possibility of such secret techniques existing continues to provoke vigorous debate and experimentation, even after hundreds of years.

A Brief History

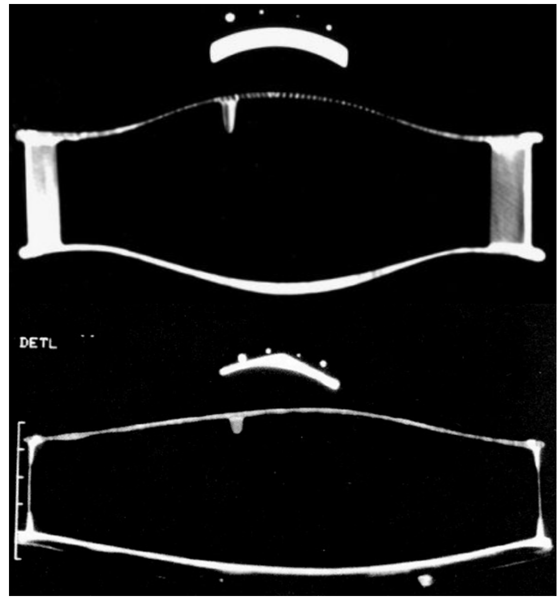
The violin family first appeared in northern Italy in the first half of the 16th century, and has changed little since the 1550s. Instruments made as early as 1560 are still in regular use today and are in most respects identical to their more recent counterparts.

The years from 1650 to 1750 were a golden age of violin making. Nicolo Amati (1596–1684), the last and greatest of the Amati line of violin makers, was almost single-handedly responsible for the emergence of the many famous masters of the era; his students included Antonio Stradivari (1644–1737) as well as Andrea Guarneri (ca. 1626–1698), grandfather of the better-known Bartolomeo Giuseppe Guarneri (1698–1744).

Antonio Stradivari and Giuseppe Guarneri departed significantly from previous designs, which had very highly-arched front and back plates, by building instruments with relatively flat bodies. These were better able to withstand high string tensions and had greater carrying power in large concert halls. Stradivari's violins were known for their brilliant tone color; Guarneri's for their full, dark character.

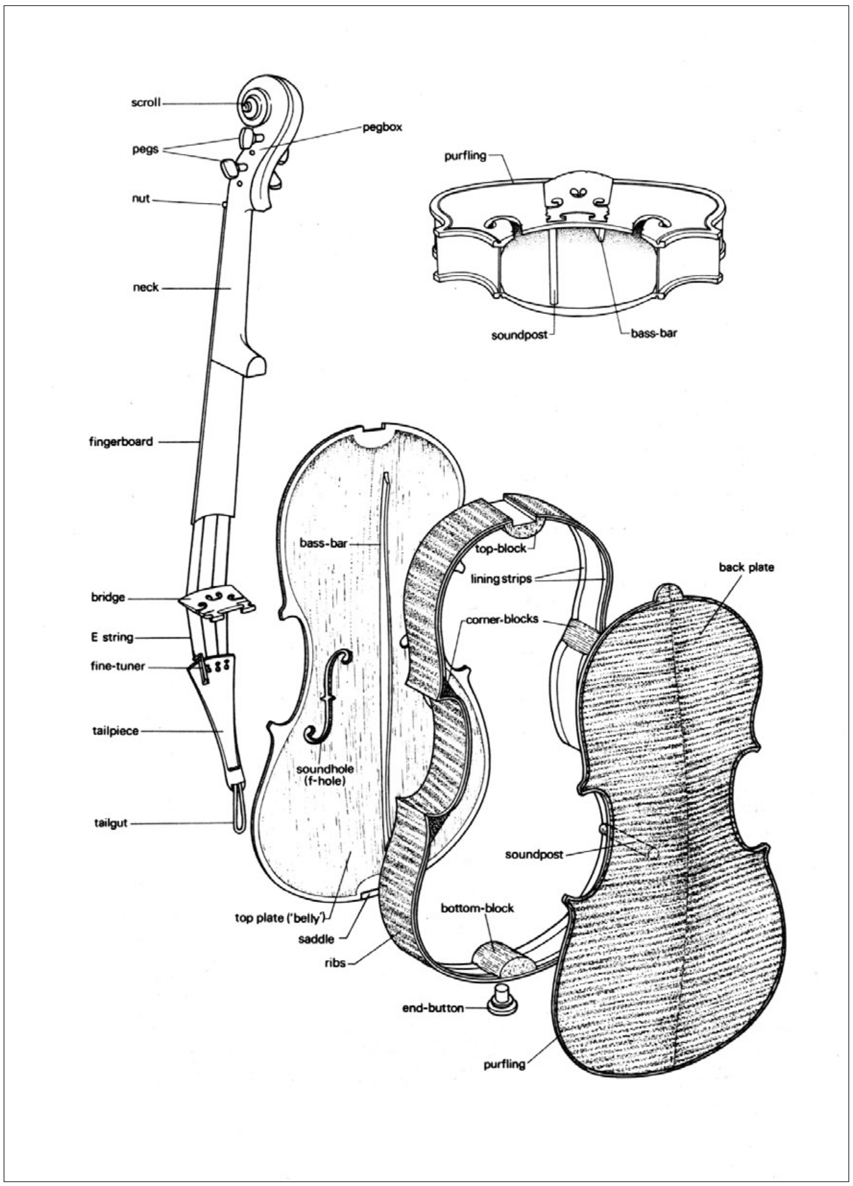
With the deaths of Stradivari in 1737 and Guarneri in 1744, the Cremonese school of violin making came to an abrupt end. Since then, their violins have been frequently copied. Some makers even built reputations for producing high-quality

Right: X-ray cross sections of a 1654 Amati violin (top) and a 1698 Stradivari violin (bottom), showing the more gentle slope of the front and back plates in Stradivari's instrument.



Images courtesy of Steven A. Sirr, M.D.

Below: The parts of a violin.



From David Boyden *et al.*, *The Violin Family* (New York: W. W. Norton & Co., 1989) p. 4.

replicas by painstakingly measuring every aspect of the old instruments. However, while the copyists could duplicate the appearance of the Cremonese violins, they could never duplicate the sound.

Building a Violin

The violin appears simple at first glance, but it is one of the most complex musical instruments, built from more than 70 separate pieces of wood that are shaped and assembled by hand. No two violins are exactly alike; a trained ear can distinguish between individual violins. Whether it is a centuries-old masterpiece or a mass-produced fiddle, each violin has its own unique "voice."

Many of the features of the violin that appear merely ornamental are highly functional. The low vaulting of the front and back plates is essential for strength and for amplification of sound. The narrow middle bout, or waist, allows the player more room to bow on the highest and lowest strings. The purfling—the decorative trim around the edges of the instrument—protects the body from cracking, but also changes the dynamics of vibration considerably. Cutting the groove in which the purfling is inlaid allows the plates to vibrate as if they were hinged rather than clamped at the edge.

The process of making a violin begins with the selection of materials. Choosing wood is an art in itself: it must be strong, flexible, and as dry as possible. Wood for violins is always cut during the cold dormant months, when the amount of sap in it is at a minimum, and "seasoned" for years under very dry conditions. The wood used in the best instruments is aged at least ten years, and sometimes as long as fifty years.

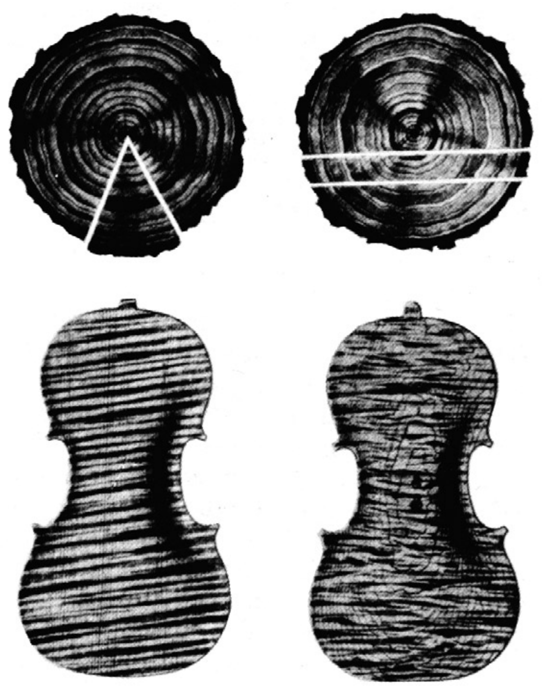
Equally important is the process of shaping the front and back plates. The front plate is made from a softwood, typically spruce, while the back plate is normally maple. The arched outer surfaces are carved rather than formed by bending. The arching gives the thin front plate increased resistance to the lateral force exerted by vibrating strings, and subtly alters the modes in which both plates vibrate. The violin maker carefully "tunes" the front and back plates, tapping the plates with the knuckles, listening for the characteristic "tap tones." The pitches of different harmonics are adjusted by scraping away material as necessary. Tuning the front and back plates is easily the most demanding part of making a violin, and takes years to master.

From Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments*, figure 3.13, p. 79.

IMAGE NOT LICENSED FOR WEB USE

Above: The resonant modes of a square plate with free edges. The X mode and the ring mode are the second and third ones, respectively, in the top row. The numbers below each mode are frequencies corresponding to the modes, relative to that of the first mode. Lines represent nodes, or places that remain stationary as the plate vibrates at a given frequency.

Below: Quarter-cut (left) and slab-cut (right) sections of a log, with the look of a violin back made from each. These are the only cuts of wood used in violins; the softwood front plate is traditionally quarter-cut while the hardwood back plate may be quarter-cut or slab-cut. In either case, the longitudinal axis is in the plane of the plate.



From David Boyden *et al.*, *The Violin Family* (New York: W. W. Norton & Co., 1989) p. 6.

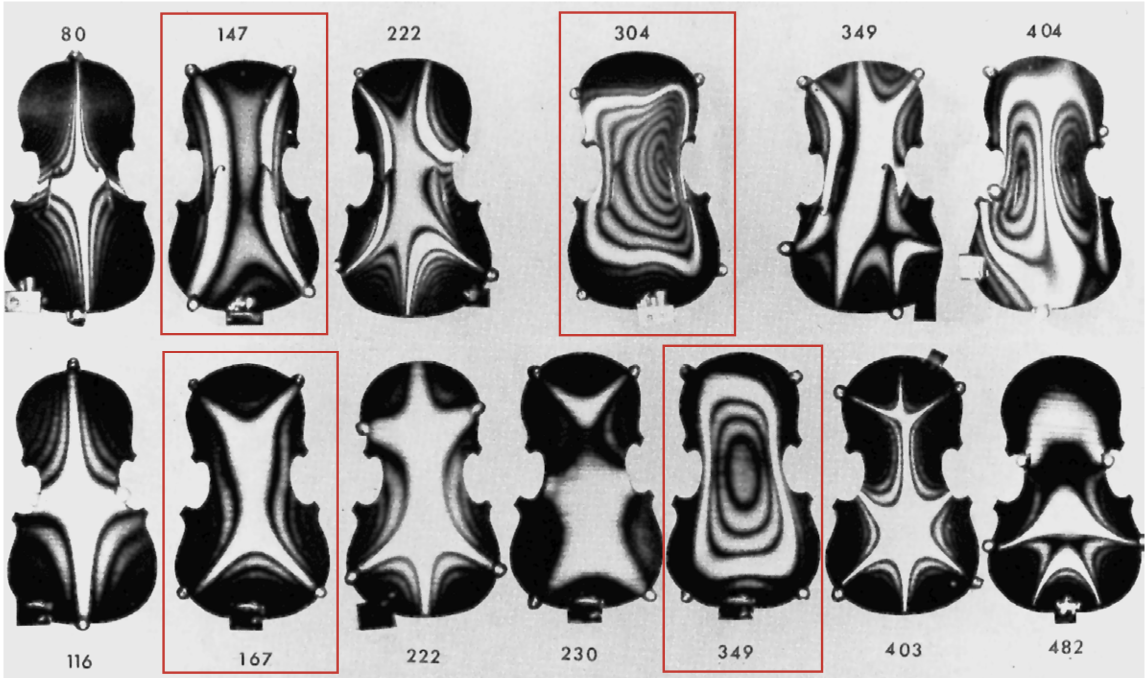
Violins and Sound

A vibrating string alone produces almost no sound, as it is too thin to sufficiently disturb the air. Therefore, it is not the string itself, but the body of the violin, that actually generates its sound. When a string vibrates, the bridge rocks back and forth at the same frequency. The soundpost immobilizes the front plate directly beneath the right foot of the bridge, so that the right foot remains stationary, and the front plate is driven rapidly up and down by the left foot's "pumping" motion. The bass bar, mounted lengthwise under the left foot of the bridge, reinforces the front plate and couples the upper and lower bouts so that they move together.

The body of the violin has a number of resonant frequencies, or natural vibrational frequencies, at which a weak stimulus can cause large vibrations. Forced vibration of the top plate produces some amplification at any frequency, but the amount of amplification at a given frequency depends on how well it corresponds to one or more of these resonant frequencies. The bridge transmits a whole set of harmonics from a vibrating string to the front plate, and each harmonic is amplified according to the resonance generated at that frequency. The violin's relative response levels to different frequencies create the instrument's unique timbre by preferentially amplifying some harmonics and damping others.

The resonant frequencies of the violin body as a whole depend most strongly on the resonant modes of the front and back plates. The plates themselves can be modeled most simply as two-dimensional panels, free to move at all points out to the edges. Just as a string vibrates in harmonics corresponding to standing waves on the string, a two-dimensional panel vibrates in specific resonant modes; the graphic above left shows the calculated resonant modes of a simulated square panel.

In violins, there is a further complication: wood has very different mechanical properties along different axes. Its mechanical properties are determined entirely by its cell structure. Wood is made up of long, thin cells with walls composed of the polymers cellulose, hemicellulose, and lignin. Cellulose, a carbohydrate that forms long straight



From C. M. Hutchins, *et al.*, "Clarification of Free Plate Tap Tones by Hologram Interferometry," *Catgut Acoustical Society Newsletter*, No. 16 (1971), p.15. Reprinted with permission of the Violin Society of America.

The vibrational modes of the front plate (top) and back plate (bottom) of an unassembled violin made by a modern master craftsman are revealed by laser interferometry. Nodal areas appear white. The X modes and ring modes of both plates are highlighted in red. The numbers are the frequencies at which the resonances occur.

chains, is the main structural component of wood. Cellulose chains usually form microfibrils, fibers consisting of groups of parallel chains held firmly together by hydrogen bonding. In wood, cellulose microfibrils lie parallel to one another in four layers, and spiral around the cell in its long direction, with different angles of spiraling in each layer. Lignin and hemicellulose, which form highly cross-linked structures, act as a "glue" that holds together the cellulose components and binds adjacent cells together. The longest dimension of each cell runs parallel to the growth of the tree trunk, in the longitudinal axis, and therefore wood has its greatest tensile strength in the longitudinal direction. As a result, wood plates must be elongated along the grain of the wood, in the direction of greatest tensile strength, in order to achieve the same types of resonant modes that are observed in an ideal square plate.

Many modern-day violin makers use visualizations of resonant modes to aid in tuning a violin's front and back plates. During construction, modal patterns in a plate can be seen by covering the surface of the plate with a fine sand and inducing mechanical vibrations at various frequencies. As the plate resonates, the sand moves about, except at the nodes, which remain stationary. The sand collects at the nodes or is bounced away, creating much the same patterns as shown above.

Two particularly strong modes are the second and fifth harmonics of the plate, often referred to as the "X mode" and the "ring mode" for the shapes of their nodal patterns. These harmonics are the main components of a plate's tap tone. Recently, a number of violin makers have recommended tuning each plate such that the ring mode sounds exactly an octave above the X mode, in order to mimic the efforts of early violin makers, who would have tuned the most prominent modes to exact musical intervals. While the theory is difficult to test, it seems highly plausible because tuning tap tones to musical intervals requires no specialized equipment and therefore could have been done by even the earliest violin makers. In addition, the idea parallels Renaissance ideals of mathematical perfection, which may well have guided the Italian violin makers of centuries past.

Lumber Redux: Another Look at Wood

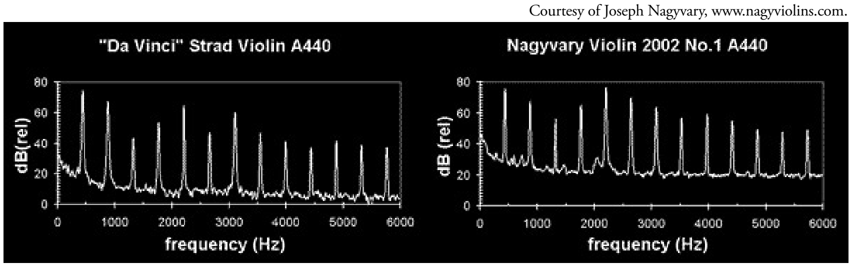
Do violins actually improve with age? The acoustical properties of the wood used in their construction certainly change with the passage of years.

Moisture in wood absorbs vibrational energy, converting it to heat energy by evaporation. Although the wood used in violins is already dry, minute changes in water content can have dramatic effects on violin acoustics: a 1 percent decrease in moisture content reduces damping by up to 3.5 percent. The long-term improvement of acoustical response depends mainly on the degradation of hemicellulose, the component of wood that adsorbs water most readily and degrades most dramatically over time. As hemicellulose degrades, the wood's maximum water content decreases. Even over very short periods, the sound of a frequently played violin may noticeably improve as small amounts of water evaporate from the wood.

Analyzing Cremona

Age, however, does nothing to explain the

Courtesy of Joseph Nagyvary, www.nagyviolins.com.



Above: The FFT spectra of the open (unfingered) A string on two violins, the 1725 Stradivari "Da Vinci" and a 2002 Joseph Nagyvary violin. (The A above middle C is tuned to 440 Hertz, a standard frequency also known as "international pitch.")

difference between Cremonese violins and their contemporaries. The recognized superiority of the Cremonese instruments must still be a result of unique acoustical properties.

One way to examine these properties is by performing a mathematical technique called a Fast Fourier Transform (FFT) on the waveforms that are generated when the violins are played. The sound waves produced by a musical instrument are the sum of the fundamental frequency of the note and all of its harmonics; the FFT breaks down a sound into its component harmonics and allows us to chart their relative strengths in what is known as an FFT spectrum.

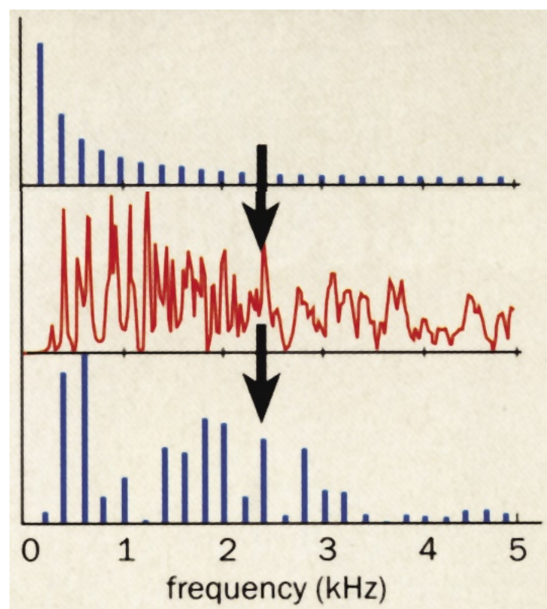
It is difficult to generate a steady waveform from a bowed string instrument, as the act of bowing the strings brings many unpredictable factors into play. Therefore, FFT spectra are never perfectly consistent; large variations can occur even in spectra produced by a single instrument. Such variations might be worked around by mechanically vibrating the bridge to simulate constant, perfectly consistent bowing. The resulting FFT spectrum is steady and can be used to create a response curve that represents the amount of amplification generated by the body at any given frequency, as shown at right. Peaks on the response curve indicate resonant frequencies of the violin's body, at which amplification is particularly high.

There are also easier ways to generate a response curve. Instead of simulating the full set of harmonics generated by the bowed string, one can produce the same results by vibrating the bridge at a range of pure frequencies, and measuring the resulting sound output in decibels. Ultimately, because body resonances are the main factor determining the tone quality of a violin, it is the response curves that provide the most insight into a violin's acoustical properties.

In 1985, German violin maker Heinrich Dünnwald compared the response curves of a group of Cremonese violins to two control groups, one of violins built by master violin makers and one of factory-made violins. The most striking contrast was seen at high frequencies. The Cremonese instruments showed a broad, strong maximum around 2500 Hertz (Hz), or vibrations per second, which is in the region of greatest human auditory sensitivity. There was a large reduction of response above 3000 Hz. Modern master-crafted instruments showed an overly strong response in the same range, which explains modern violins' widely-held reputation for shrillness; factory-made violins had a consistently dull response above 2000 Hz.

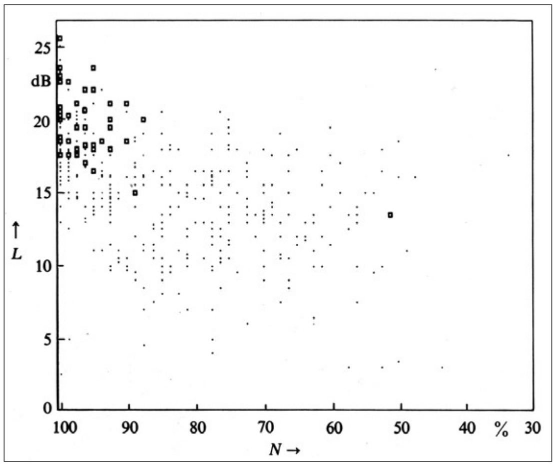
In a second experiment conducted the same year, Dünnwald found another characteristic trait of Cremonese violins: two of their response peaks are particularly strong. One peak, covering a fairly wide band located between 1300 Hz and 2500 Hz, was sufficiently strong that virtually any note played on the instrument had its strongest harmonic within that range. The other peak occurred at the air resonance frequency, the natural resonant frequency of the air inside the violin rather than of the violin body itself. Nearly every tested Cremonese violin showed a strong response at that frequency, as shown on the next page. In the vast majority of the other tested violins, both peaks were much weaker.

The Dünnwald experiments demonstrated conclusively that there is a clear acoustical difference between violins made by Stradivari and Guarneri,



Adapted from Colin Gough, "Science and the Stradivarius," *Physics World* (April 2000).

How a response curve corresponds to FFT measurements. The FFT of a vibrating string (top) decreases smoothly with increasing frequency. The violin's body (middle) amplifies harmonics that correspond to its resonant modes, while other harmonics are amplified very little. The sound we hear (bottom) thus has a very different FFT spectrum than does the string in isolation.



From H. Dünnwald, "Ein Verfahren zur objektiven Bestimmung der Klangqualität von Violinen," *Acustica*, Vol. 58, (1985) pp. 162-169.

Left: Dünnwald's second experiment. *L* is the relative strength of the air resonance frequency in decibels, and *N* is the percentage of possible notes for which the strongest harmonic is between 1300 Hz and 2500 Hz. Violins made by the old Cremonese masters are indicated by squares, and other violins are indicated by dots.

and contemporary violins. The characteristic Cremona sound appears to be the result of strong selective amplification of several key harmonics. The cause of this amplification remains an open question.

Varnish and Salt

For many years it was fashionable to study the varnish used by both Stradivari and Guarneri—the brilliant, reddish hue of their instruments suggested that their varnish was unique. The claim most commonly made by violin makers was that a secret recipe for varnish was the most important factor in tone quality. However, varnish is unlikely to improve the sound of a violin. Its only acoustical effect is to damp vibrations, and because its main function is to form a hard protective layer over the exterior of the instrument, it is highly implausible that any varnish could selectively damp very high frequencies. Furthermore, ultraviolet photography has revealed that most of Stradivari's and Guarneri's violins have lost much of their original varnish, and have been recoated in the last 150 years with modern varnishes. Since many modern violin makers believe that their violins sound better "in the white" than varnished, the best thing to do with varnish may simply be to use less of it.

The process of "stewing," or gently heating wood in a salt solution before drying, was also identified as a likely difference between the Cremonese school and the modern day. Analysis of wood shavings provides strong circumstantial evidence that Guarneri stewed his wood. The main effect of stewing is to substantially accelerate the degradation of hemicellulose, so the hemicellulose content of stewed wood should be far lower than is normal for its age. From comparison of growth rings to known climate data, we know that the wood in Guarneri's instruments cannot have been cut more than two decades before the instruments were made, yet the hemicellulose levels in the wood are what would be expected for wood three or four decades older.

But stewing was hardly a secret; on the contrary, it was a familiar process long before the 18th century. Evidence for it exists as early as 1580, when French chemist Bernard Palissy wrote: "Salt improves the voice of all sorts of musical instruments." The purposes usually stated for stewing were to prevent rot, to repel woodworm, and to stabilize water content. The last does not enhance acoustic response, but guards against cracking by preventing rapid changes in water content. Salt actually does this by hydrogen-bonding to water itself, slightly increasing the wood's water content and partially offsetting the effect of hemicellulose degradation.

The stewing theory has another flaw: there is no evidence that Stradivari stewed his wood. By the early 18th century the process was gradually passing out of standard practice. It has seen a resurgence in recent years, but still only a few violin makers practice it routinely.

The Second Coming of Stradivari?

If varnish and salt are not the answers, then Joseph Nagyvary, a biochemistry professor at Texas A&M University who moonlights as a violin maker, claims to be closer to knowing the secrets of the Cremonese masters. Recently he has gained notoriety in musical circles for making violins that show an amazing similarity to those of Stradivari himself. As a violin maker, Nagyvary was familiar with the extant literature on Cremonese violins; as a chemist, he gradually became convinced that physical characteristics alone could not adequately explain the Cremonese sound. He therefore hypothesized that Stradivari and Guarneri used some form of wood treatment that substantially altered the composition or structure of the wood itself. To test this hypothesis, he acquired and analyzed wood shavings from Stradivari instruments.

Nagyvary discovered that these instruments were made with wood containing extremely large quantities of embedded minerals, suggesting immersion in some mineral salt solution. However, he was unable to develop a wood treatment method that would cause sufficient penetration of minerals into the wood.

Photo by Kathleen Phillips, Texas A&M *AgNews*, August 2003.

Joseph Nagyvary applies varnish to a violin in his workshop in College Station, Texas.

Eventually Nagyvary stumbled upon an unexpected answer to this problem. He currently constructs violins with timber salvaged from the bottom of Lake Superior. For over three centuries logs were floated to lumber mills across the lake chained together in large "rafts," and some became sufficiently waterlogged to break away and sink to the bottom. Decades of soaking have left the wood heavily impregnated with a variety of mineral residues which, as Nagyvary discovered, closely matched the mineral content of wood shavings from one Stradivari cello.

Nagyvary's revised theory is that Stradivari and Guarneri stored their wood in mineral-rich brackish water for years before beginning to dry it out. This storage allowed minerals to seep in and fill the empty space left as microbes digested hemicellulose in the wood. Nagyvary even suggests that 18th-century treatises calling for dry storage with no additional treatment may have been a deliberate deception aimed at obscuring the practices of the masters. The acoustical effect of embedded minerals is not yet well understood, but Nagyvary's experiments suggest that microscopic mineral crystals may modify resonant modes by stiffening wood in some directions and adding flexibility in others.

Baroque Tuning

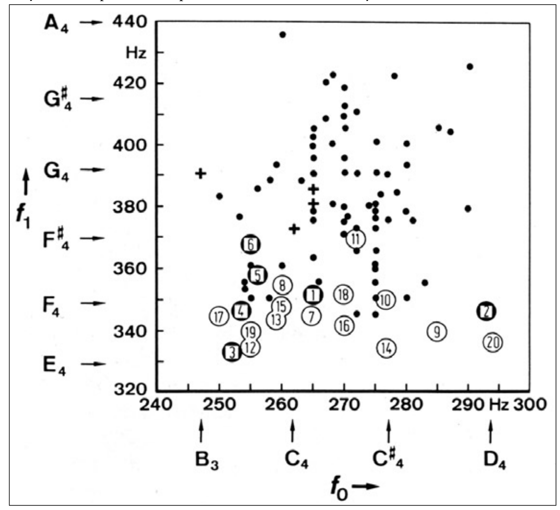
In addition to treating wood differently from modern practice, the Cremonese masters designed their instruments to fit specifications that distinguish them from their modern counterparts.

Most significantly, the tap tones of all early Italian violins are tuned distinctly lower than those of other violins. This in turn produces response peaks at lower frequencies. The difference is on the order of a half-step or a whole-step, which makes sense when one notes that Baroque orchestras commonly tuned to pitches that were approximately that far below modern standards. Violin makers may have begun to tune their tap tones to higher frequencies to match a late 18th-century rise in orchestral tuning pitch, affecting the violin's timbre in ways that they could not have predicted.

Coda

Although much has been discovered about the acoustics of violins in recent years, whether we have truly unlocked the secrets of Stradivari and

From J. Meyer, "The Tonal Quality of Violins," *The Journal of the Catgut Acoustical Society*, May 1984. Reprinted with permission of the Violin Society of America.



The distribution of the most prominent tap tones of 100 violins. f_0 is the air resonance; f_1 is the first body resonance. 17th- and 18th-century Italian instruments are marked with numbered circles; black circles indicate Stradivari violins.

Guarneri remains in question. Craftsmanship and design are likely as important to achieving high-quality sound as any purported secret recipe or technique, and there may be no substitute for three hundred years of graceful aging.

The present is an exciting time for violin makers and researchers alike. Acoustical analysis of Cremonese violins has, by revealing the specific patterns that define the Cremona sound itself, given violin makers a target to aim for. The exact way in which these patterns were achieved is still unclear, but new ways of looking at old instruments have generated plausible scientific explanations for many aspects of the art of violin making, as well as theories and avenues of research that could lead to further breakthroughs. Regardless of whether all the secrets of Stradivari and Guarneri are ever found, such technical advancements help contemporary violin makers fulfill every violin maker's ambition: to produce instruments that violinists might be proud to play three centuries from now. □

Andrew Hsieh (BS '04, biology) wrote this paper for the Core 1 science writing class. Hsieh plays both violin and viola, and is also active as a composer. He performed in both the Caltech chamber music program and the Occidental-Caltech Symphony Orchestra as an undergraduate. He is currently a member of the Division of Biology research staff and plans to go to medical school. Hsieh's faculty mentor for the paper was Jed Buchwald, the Dreyfuss Professor of History.

In the spring of 2004, the faculty modified the Core 1 requirement to emphasize technical writing for journals. A new course on science writing for the public, En 84, is now offered at the Hixon Writing Center.