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William F. Fry: A Physicist's Quest for the "Secrets" of Stradivari

By Kameshwar C. Wali

The origin and early history of the violin remain shrouded in mystery despite much research and speculation. The instrument appeared in its present form in the early sixteenth century, predominantly in Italy. Two schools of luthiers flourished: that of Gasparo Bertolotti, or Gasparo da Sal (1542-1609) in Brescia, and that of Andrea Amati (c. 1511-1581) in Cremona. The Cremona school dominated the scene for the next two centuries. Amati and his descendants ushered in an extraordinary period of violin making, which peaked between 1650 and 1750. All the violin makers lived and worked side by side around a courtyard in front of the St. Domenico church, where they produced instruments of great beauty and exquisite sound. The most celebrated of all, Antonio Stradivari (1644?-1737), brought unsurpassed perfection to the instruments he built.

Since that time, well-known luthiers have attempted to replicate the Cremona violins. Although some of them have made excellent copies, the general consensus is that they have not come close to reproducing the distinct voices, carrying power, and responsiveness of the Cremona instruments. This apparent lack of success has given rise to myths of unknown and unknowable secrets concerning the source of the wood and its treatment and the particulars of varnish; there exists a vast amount of pseudo-historical and pseudo-scientific literature filled with incredible claims.

Many legitimate scientific researchers have also attempted to demystify the Cremona instruments. Although studies of the separate components, or "mechanical subsystems," of the violin --- the bridge, soundpost, frequency modes, top and bottom plate resonances, action of the bow, radiation patterns, wood, varnish, and strings --- have provided valuable knowledge regarding how a violin works, they have failed to give any clues about what makes a particular violin stand out among others, let alone revealing the secrets of a Stradivari violin. "Violin research is not directed to the question of what makes a violin a great or good violin," said Gabriel Weinreich, professor emeritus of physics at the University of Michigan. "It is directed toward understanding how a violin works by definition, although that is not orthogonal to the question of what makes a violin good."

A violin is essentially a set of strings mounted on a wooden box containing an almost entirely enclosed volume of air (the parts of the violin are shown in figure 1). When a violinist draws the bow across the strings, the vibrations are communicated to the box; corresponding vibrations are set up in the air space, and they in turn generate the amplified sound waves that reach the listener. This simple description, however, hardly conveys the complexity of the instrument. Indeed, for a violin maker, no formula, however detailed, could describe the multitude of variables involved in the design and construction of a violin. Making a violin is considered to be a matter of experience and intuition, artistry and craftsmanship. There could be no such thing as an exact copy of a famous model, if for no other reason than that no two pieces of wood are identical.

William F. "Jack" Fry, professor emeritus at the University of Wisconsin-Madison, is well known for his pioneering research in high-energy physics and his work in astrophysics, but during the past three decades he has also pursued research on violins. Fry has been immensely successful in understanding the delicate interconnectedness of the different parts of the violin. His holistic approach to its acoustics, although rooted in solid physics principles, contrasts markedly with the conventional, reductionist approach. Fry is committed to a scientific probe and an analysis in terms of physical principles because he [p. 12] believes that the Cremona masters must have known, consciously or unconsciously, what they were doing when they were making their violins. With new insights, he has come closer than anyone before him to reproducing the sound of the great Italian violins.

William F. "Jack" Fry. Courtesy University of Wisconsin-Madison Archives.

Fry was born in a small town near Des Moines, Iowa, and raised on a farm. As a young boy he had two strong interests: music and building radios. "The isolation of a farm heightened my interest in music," said Fry. "Listening to the radio not only connected me to the outside world, but it also brought music into my life. My ears developed in two ways both at the same time, forming the roots of my scientific and aesthetic interests." At the age of seven, he decided that he would like to play the violin. His father bought him a fiddle, and Fry took lessons from a local farmer, an enthusiastic amateur fiddler. When the farmer realized that the young boy had talent, he advised him to receive formal training. Soon Fry was playing simple melodies at community events. In high school, Fry continued to pursue his dual interests in music and electronics, taking violin lessons and toying with chemistry and electronics in his basement laboratory.

In his freshman year at Iowa State University, Fry had the opportunity to take violin lessons from a professional, Ilse Niemach, who had been trained in Europe and had studied with Jascha Heifetz. He learned superior techniques and developed a deeper appreciation for classical music, but observing Niemach's standard of playing convinced him that he lacked the combination of will and talent required to be a professional musician. He decided to concentrate on his scientific interests and to pursue an engineering career.

After college, Fry spent four years (1943-47) at the Naval Research Laboratory in Washington, D.C., where he built radio-jamming devices and a huge transmitter designed to misguide radio-guided German missiles. Fry soon realized, however, that his real interests lay not in building things but in understanding the principles behind them. He began taking night courses in physics at George Washington University, where, as luck would have it, he had as a teacher George Gamow, one of the most charismatic figures of twentieth-century physics. Under his spell, Fry discovered physics as his true vocation. He went on to graduate school at Iowa State University, where he did research on high-energy cosmic ray physics. In 1952, Fry joined the faculty of the University of Wisconsin-Madison, where he established himself as one of the pioneering researchers in high-energy physics.

Fry had long ago given up playing the violin except occasionally in amateur groups. Then, one evening in Berkeley in 1961, a colleague, Wilson Powell, suggested they play some music. Since Fry had no violin with him, Powell borrowed two from the music school, a Stradivari and a Gagliano. "For the first time in my life," said Fry, "I realized how a good violin can [p. 13]

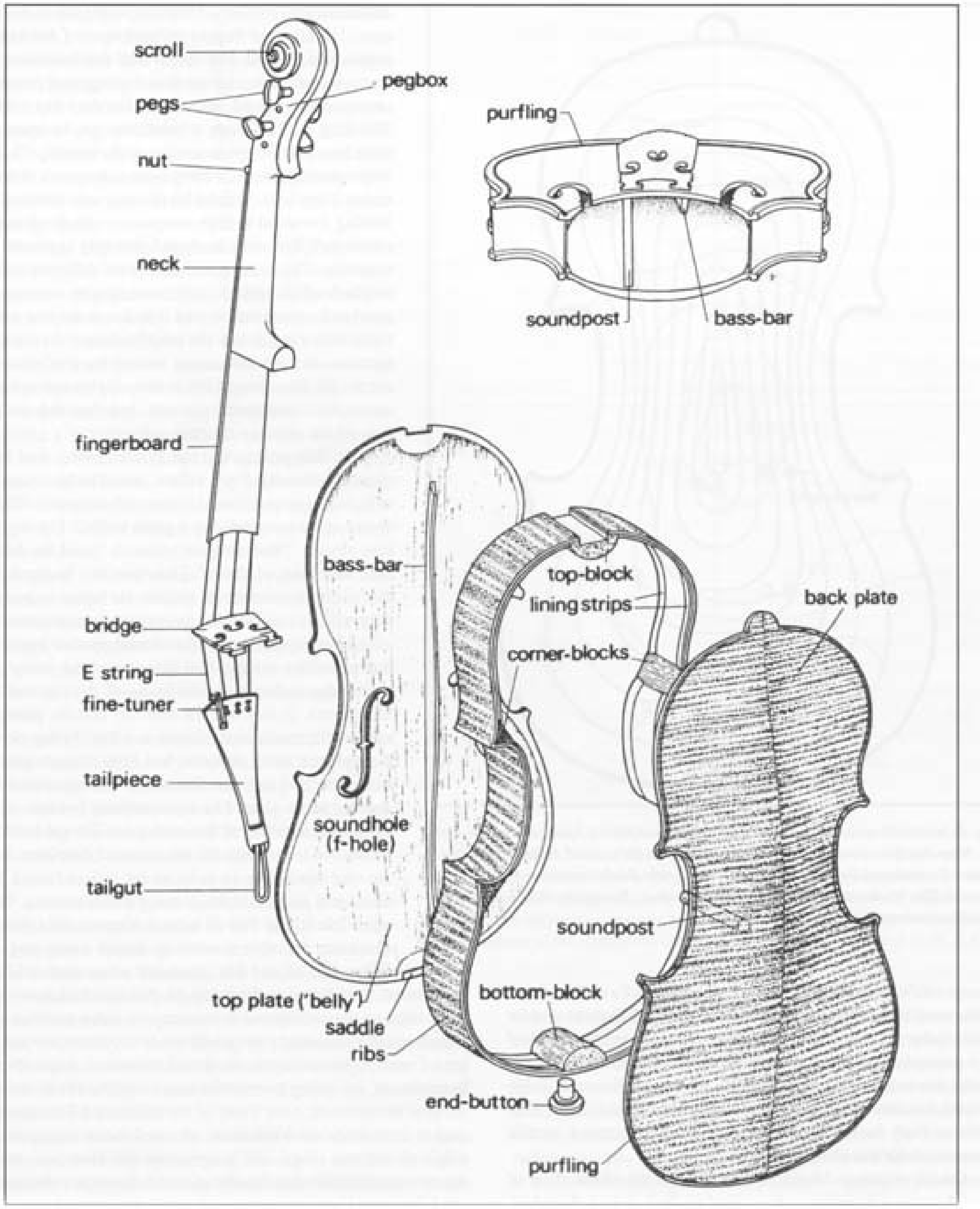

Fig. 1. Diagram showing the parts of the modern violin. Reprinted, by permission of Macmillan Publishers Ltd., from David D. Boyden et al., *The Violin Family, The New Grove Dictionary of Musical Instruments* (London. Macmillan Press Ltd.; repr. New York: W. W. Norton & Co., 1989), p. 4. (N.B. Labels have been enlarged for clarity.)

scroll, pegs, pegbox, nut, neck, fingerboard, bridge, E string, fine-tuner, tailpiece, tailgut: bass-bar, soundhole (f-hole), top plate ('belly'), saddle: top-block, lining strips corner-blocks, bottom-block, ribs, end-button: back plate, soundpost purfling, soundpost, bass-bar [p. 14] change one's ability to play. That evening sort of awakened me. Here were two instruments which were so different, and so much better than anything I had ever played on. No one had ever pointed out to me that some of the problems of playing the violin are related to the problems of the violin itself." He became fascinated by old instruments. How could they be so different from the violins he had played? Was there a scientific explanation for the phenomenon?

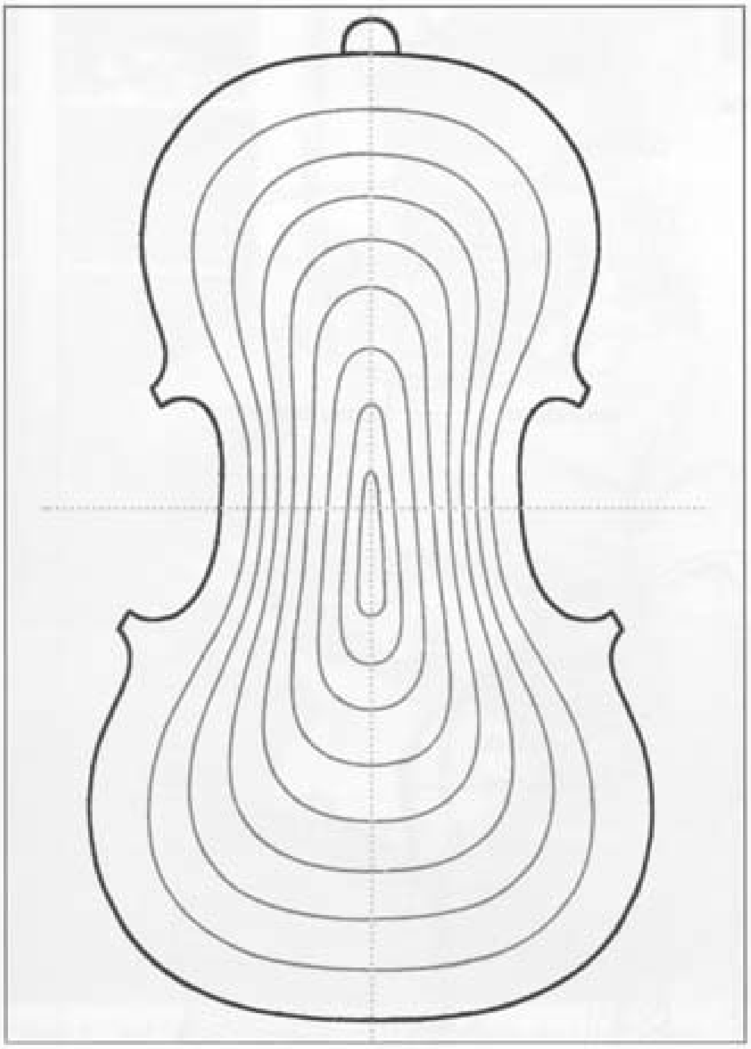

Fig. 2. Idealized contour lines of constant thickness for the back plate of the violin. Note that they are completely symmetric around a vertical axis through the center.

Reproduced, by permission of Verlag Erwin Bochinsky, from Simone F. Sacconi, *Die "Geheimnisse" Stradivaris* (Frankfurt: Bochinsky-Verlag das Musikinstrument, 1976), p. 66.

On his return to Madison, Fry went to the violin shop of Larry Lamay, who made and repaired violins, to look for a better violin for himself. There, he found a kindred soul. Lamay was also interested in solving the mysteries of the great violins, and he strongly believed that the secret lay in the varnish. He allowed Fry to varnish two of his instruments, and, indeed, Fry discovered that hardening the varnish and increasing the drying temperature changed the sound, making it harsher but louder. Thinking he had made a breakthrough, he spent the next few years experimenting with varnish. "I tried impregnating woods with various substances and varnishes," Fry said. "I did a lot of crazy experiments like heating the wood to high temperatures to dry it out, or shrink it." But soon he found that this approach led nowhere. The same process on two different violins might lead to entirely different results, sometimes good and sometimes so bad that the violin was essentially destroyed. It was not easy for Lamay to see a fair number of his instruments ruined by Fry's experiments. He also wanted Fry to keep their explorations a secret for commercial reasons, but that did not suit Fry, whose primary aim was scientific.

At this point, Wilson Powell, who had been closely following Fry's efforts, came to his rescue by offering unconditional financial support. "Don't worry about only making a great violin," Fry recalled him saying. "You do your research. Send the bills. I will take care of them." This was the beginning of Fry's serious research on violins. He formed a partnership with Powell and began systematic experiments.

Soon Fry thought he had found another important factor besides varnish that determined the sound of a violin: the variations in thickness of the top and bottom plates. It was known that the bottom plate has subtle differences in thickness and that the top plate is thinner and more uniform, but little importance had been attached to these features. Fry conjectured that the variations should be asymmetrical because of the off-center location of the soundpost. To test his ideas he needed to measure the thickness of the plates, but it was unthinkable to take apart a Stradivari or a Guarneri just to make these measurements. Once again his friend Powell helped him out, this time by inventing a simple measuring device using magnets. When Powell and Fry measured a Guarneri del Gesti instrument, they found to their delight that the thickness variations showed the anticipated asymmetry, in sharp contrast with the idealized symmetric patterns shown in the literature (see figures 2 and 3). Powell set to work and measured about seventy instruments, including twenty Cremona violins. He found that no new instruments, even those of the celebrated French violin maker Jean-Baptiste Vuillaume, showed these asymmetries, while all but two of the old instruments did. However, one of the two exceptions was a Stradivari violin from the collection of the Library of Congress that was famous for its great sound.

It became clear to Fry after additional experiments that asymmetry, although important, was only one of many parame- [p. 15] ters controlling the quality of sound of an instrument. "It took me a long time," Fry said, "to psychologically get over the idea that there were one or two simple secrets." During the last three decades, Fry has combined experiments with theoretical insights to create instruments with predictable qualities of sound. One of his important advances was to isolate certain "absolutes," along with the physical parameters they depend on, that are essential attributes of a great-sounding violin.

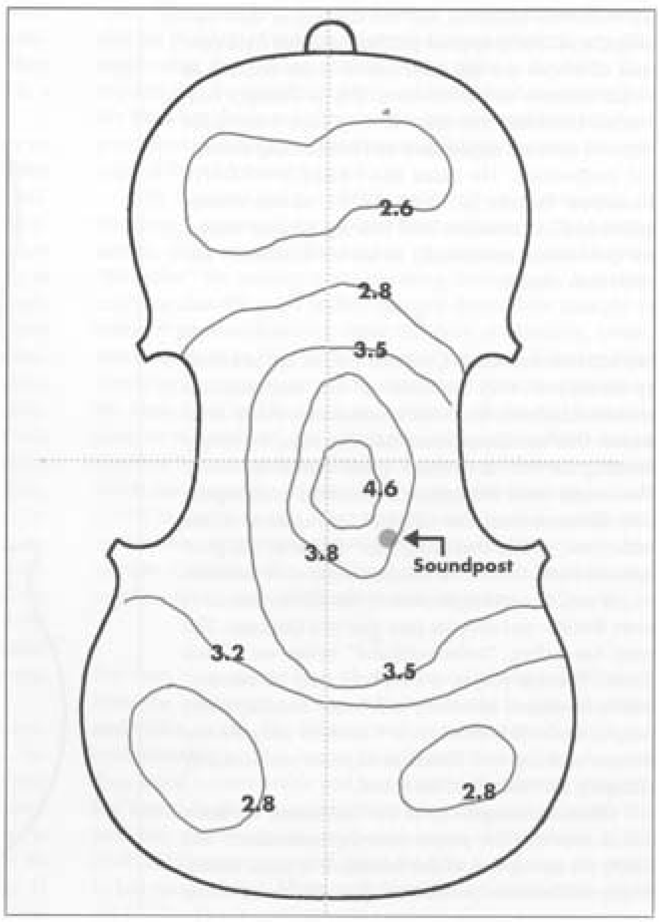

Fig. 3. Contour lines of constant thickness for the back plate of the violin as measured by W.F. Fry and W. Powell. Note that the contours are displaced slightly to the right and below the geometrical center of the back. Although this left-right asymmetry appears to be small, it represents a substantial difference in the left-right stiffness asymmetry, which partially compensates for the position of the soundpost to the right of the center line. Redrawn from a sketch by W.F. Fry.

The first important characteristic of a good violin is *carrying power:* it can be heard even over other instruments that put out more energy. This attribute depends upon the ability of the violin to radiate high frequencies (around 5000 Hz and more) efficiently and with as much power as possible. Instruments like horns generally put out less energy than violins in the high-frequency range. The high-frequency component produces a silky quality rather than the unpleasant shrill sound characteristic of the mid-frequency range (around 2500 Hz), to which the human ear is most sensitive. Thus, efficiency in radiating high frequencies gives a violin a refined sound as well as great carrying power.

A good violin also has *divided sound:* the low-frequency range, containing the fundamental, is well separated from the high-frequency range, and the middle range is suppressed. The low-frequency component gives the listener a feeling of pitch and fullness of sound; the high-frequency component, elegance and fineness.

Ringing, or the continuation of sound after the bowing stops, is extremely important for the player. It depends upon the ability of one string to excite the others: thus, if you play on the A string and then stop, the G string resonates because its first overtone coincides with the G note on the A string.

Even sound and *wide dynamic range* are two other attributes of a good violin. Such an instrument produces notes that are more or less uniform in intensity but sound distinctly different. On an instrument where certain notes stand out, the player has to produce evenness manually by playing some notes harder or softer than others. A violin with a wide dynamic range can be played very softly without losing its character or generating a hiss. The player should also be able to put more pressure on the bow to increase the volume without affecting the fundamental properties of the sound.

A good violin allows the *flexibility* for a violinist to project feelings and emotions by changing from a pure sound to a rougher one and by varying the texture. Without this flexibility, the instrument feels "frozen" --- always producing the same type of sound.

The final important characteristic is *response,* which concerns how quickly a note can be excited. A good violin responds almost instantaneously, as though, a violinist might say, "the note seems to start before I play it." The player does not have to "attack" the note. Another aspect of response concerns how a violin sounds to the player, which affects the sound that reaches the audience. The "local sound" surrounding the box is dominated by low frequencies, whereas the sound that radiates out has more of the high frequencies. If the local sound is too loud, the player will tend to play too gently to produce the high frequencies that carry out to the audience.

These acoustical absolutes have little to do with the physical appearance of the instrument. Most of the Cremona violins [p. 16] are extremely beautiful, and the shading of their varnish, the skillfully applied purfling, and the right contrast of woods are the most talked about features in violin auctions and exhibitions. Fry is strongly convinced, however, that there is very little correlation between outward appearance and outstanding acoustical properties. He cites the example of Carlo Giuseppe Testore (c. 1660-1720), whose cheap, unfinished instruments, still bearing scraper marks, are as beautiful acoustically as are his beautifully finished instruments.

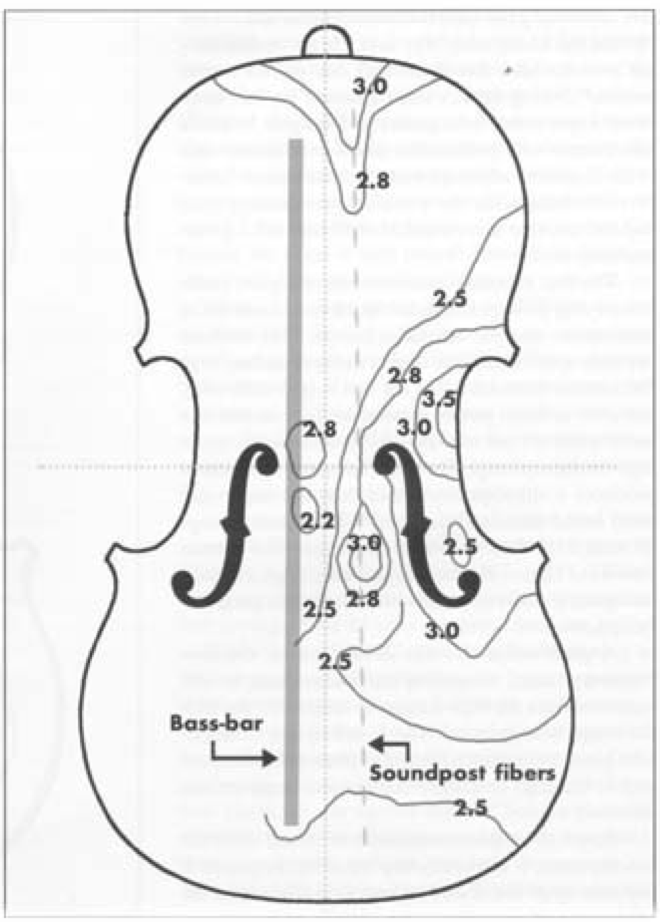

Fig. 4. The complex shapes of the constant thickness contours for the region around the bridge. The extra thickness on the inside area of the right f-hole and the increased thickness just above this f-hole are critical for the support of the soundpost fibers. Redrawn from a sketch by W.F. Fry.

Fry believes that many Cremona violins are in a class by themselves; they are different with respect to the acoustical absolutes from instruments made elsewhere. One can demonstrate this, Fry says, by simply drawing the bow at constant speed across the string. The sound from old Italian instruments is recognizably different from that of other instruments. At the same time, within that group, the violins of the great masters have their own distinct voices. A violinist might say, for example, that a Stradivari sound is more flexible and delicate than that of a Guarneri. The latter has a deep, "robust-colored" voice, but it feels frozen. For one player, a Stradivari may be too delicate to be played forcefully and hence lacks dynamic range, while for another, a Guarneri may be too frozen, making it difficult to express emotions by changing the "color" of the sound.

Given the complexity of the instrument, the interaction between the player and the instrument, and finally the perception of the listener, it appears forbiddingly difficult to provide recipes for constructing instruments with any degree of predictability. Yet Fry has been able to come close to this goal by departing from certain standard approaches. One approach to understanding sound quality has been frequency analysis using oscilloscopes and other techniques. However, such analyses reveal an extremely complex pattern of sound containing enormous numbers of frequencies. In addition, the pattern varies drastically from one violin to another, but has little or no correlation with the quality of the sound. After numerous experiments, Fry became convinced that frequency analysis was not the right approach and looked for a deeper understanding based on acoustics.

Fry drew an analogy with the human ear, a complex analyzer of sound. The ear perceives sound based not on one or two frequency components, but on groups of frequencies. Such groups are called "formants" by those who study human speech, and they are used to distinguish one voice from another. The concept of formants became an essential ingredient in Fry's work. He recognized and named three formants, each linked with a predominant mode of vibration of the violin:

The low-frequency range (200-1000 Hz), or the *breathing mode.* In this mode, the top and bottom plates move out of phase, pushing the air in and out of the f-holes. It is responsible for the bass quality of the violin sound.
The mid-frequency range (2000-5000 Hz), or the *rocking mode.* In this mode, the sound comes from a seesaw-like rocking motion of the top plate involving the rotation of the bass-bar around its center point. This is the shrill range.
The high-frequency range (>5000 Hz), or the *tweeter mode.* In this mode, the action is confined entirely to a small area on the top (the tweeter) around the bridge. This range gives the sound its elegant, silky quality.

[p. 17] All of these modes, however, are strongly coupled to each other by the forces exerted by the strings on the bridge that communicates with the plates. Fry emphasizes that understanding their interconnections requires understanding that the violin is a *driven system.*

A violin has several resonating components. The notes on one string resonate with those on another string. The confined air in the box resonates, as do the top and bottom plates. However, these resonances are not free, but are driven by external forces generated by the player's bowing. Their responses depend on how they are coupled to these forces. According to Fry, the human voice supplies an apt analogy. The vocal cords drive the resonating system of the lungs and the nasal and oral cavities. Each of the latter has its own resonating modes. However, a person's distinctive voice is not produced by these individual resonances but depends on how the vocal cords couple to and drive the resonating cavities. For Fry, the problem was to identify the parameters that couple the three basic modes and then to find ways to change and control them. For instance, if a violin sound is too soprano and a player wants it to be deeper, the amplitude of the breathing mode has to be increased. If it sounds shrill, the rocking mode has to be suppressed. To increase the carrying power and the elegance of the sound, the tweeter mode has to be enhanced. But because the modes are so strongly coupled, changing one requires changing something else. After much experimentation, Fry has been able to produce more and more predictable sound qualities.

Starting with the realization that the violin is a driven system, Fry thinks in terms of an idealized mechanical model. He envisions the top and bottom plates as a set of springs and masses, with the spring constants and mass values determined by the thickness of the plates. As a general rule, if a mass attached to a spring is subjected to a frequency lower than its natural one, its motion is governed by the spring constant. If subjected to a higher frequency, then it is the mass that matters. Fry can vary the spring constants and masses by varying the thicknesses of different parts of the plates, thus controlling how prescribed areas of the plates move.

To get a more concrete picture, consider the motion of the top plate, which is the most critical part of the violin for radiating high frequencies. Looking down on the violin top, the left foot of the bridge rests on the bass-bar, and the right foot rests near but not on the soundpost. Since the bass-bar is long, rigid, and massive, its inertia keeps it stationary as the left foot presses on it. The right foot, however, has no such support, and the fibers that pass under it are long and provide only weak support. Consequently, the right foot and the soundpost create a torque that tends to produce a rocking, rotational motion of these fibers that makes them less effective in exerting a driving force on the back plate. This in turn affects the motion of the back plate in the breathing mode, and the violin loses its depth. Remedying this requires increasing the stiffness of these "soundpost fibers" in the top plate. However, any support system for the soundpost fibers will affect the high-frequency mode; they must be free to perform the tweeter action. There is also the problem of reducing the mid-frequency, shrill range, by suppressing the rocking motion of the plate as a whole. This requires that the soundpost fibers not be coupled too strongly to the bass-bar. Fry's solution to this delicate problem involves prescribed thickness variations around the f-holes near the right edge of the violin (see figure 4).

Fry foresees the possibility of specifying parameters of thickness for areas of the top and bottom plates so that a violin maker, even with no knowledge of physics, would have a "blueprint" for making good-sounding instruments. It is conceivable that the great Italian masters themselves thought in terms of physics, however, since the ideas of elasticity, levers, and torques were familiar concepts at the time. Whether intuitively or through experiments, they must have thought along the same lines as Fry, since the contours of varying thickness patterns of Stradivari and Guarneri violin plates exhibit almost identical features to those that Fry has deduced from his experiments and reasoning. However, Fry's success must not be construed as implying that there now exists a precise mechanical method for turning out great violins, each sounding exactly like another. Craftsmanship, quality of wood, varnish, and attention to other details leave the final result open to wide variations.

Fry does his experiments with what he calls "old junk violins" from the nineteenth century, which he finds in antique shops and violin stores. He chooses older instruments because the craftsmanship is often better than in new violins, and because their wood is more stable and less affected by climatic changes. Fry's modifications may involve placing inlays or adjusting the bass-bar, the soundpost, or the thickness of the plates. If the modified instrument sounds good, he sells it and uses the profit to buy more violins. Many such transformed instruments are in the hands of young and upcoming violin players, who use them in concert playing. "I am not interested in making a lot of money," said Fry. "I am interested in making a contribution to the field and to making a large number of great-quality instruments available for young people at an affordable price." Fry is now able to produce superb violins, and friends have suggested that he could develop instruments with a distinct "Fry voice." Fry's personal goal, however, is to duplicate in a predictable manner the sound of an Amati, a Stradivari, a Guarneri, or a Bergonzi. This will be a true test of his scientific ideas, and if he succeeds, experts will acknowledge that Fry has finally solved the mysteries of the Cremona violins.

Source

Kolneder, Walter. *The* Amadeus *Book of the Violin: Construction, History, and Music.* Trans. and ed. Reinhard C. Pauly. Portland, Ore.: Amadeus Press, 1998.

The author has relied primarily on extended conversations with W. F. Fry, to whom he gratefully expresses his thanks.