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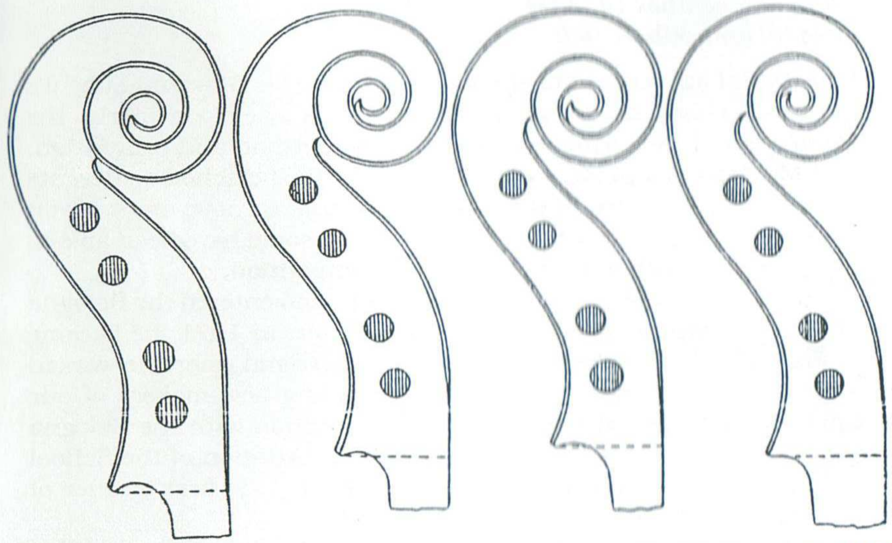
VIOLINS, VIOLAS, CELLOS and their BOWS



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THE USE OF EMPIRICAL AND SCIENTIFIC METHODS TO MEASURE THE VELOCITY OF PROPAGATION OF SOUND

Giovanni Lucchi

Friday, November 14, 4:00
Introduction: Albert Mell

Prof. Mell: I am pleased to see so many of you for Giovanni Lucchi's lecture-demonstration for two reasons: this afternoon marks the completion of the formal events of the competition and convention; and Mr. Lucchi's presentation was added to the scheduled events too late to be included in the printed program. By now, many of you have had the opportunity to meet him, and some have been able to try his bows which were entered in the competition.

Mr. Lucchi was trained as a bass player and entered the Bologna Theater Orchestra in 1968. Three years later, in 1971, he became interested in bow making and went to Switzerland where he worked with Siegfried Finkel, one of the outstanding bow makers of our time. In 1976, he gave up his formal connection with the Bologna Orchestra and went to Cremona, upon the invitation of the School of Violin Making, to become, as I understand, the first teacher of bow making in Italy.

His experiments with various woods, including ironwood, led him to believe it had many of the characteristics of elasticity and resonance that were similar to those of pernambuco. Experiments with woods continued into the early 1980s. In 1980, he developed the instrument, or invention you see before you, for measuring the musical factors associated with good wood.

Mr. Lucchi's lecture-demonstration was not listed in the program. In the preparation of this revised version of his talk, Mr. Lucchi wishes to acknowledge the collaboration of the following: M. Alquati, of the Politechnic of Milan; M. Lucchi, a student of computer science at ITIS, Cremona; and D. Haddad, a violin maker in Cremona.

I think that I have given you enough information about his background and I will now simply turn the platform over to Mr. Lucchi.

Mr. Lucchi: One of the greatest problems in the construction of musical instruments has always been the choice of wood that will yield the best quality of sound. To solve this problem, the classic Cremonese makers experimented in various ways to determine the acoustic and mechanical properties of wood. Their empirical methods often yielded imprecise results. Upon completion of an instrument that does not possess good sound qualities, the disappointed maker is confronted with a myriad of questions: is it the choice of wood, its thicknesses, the varnish, bass bar, sound post, arching, volume of air, strings, etc., all of which influence the sound and playability.

There are so many different components of a violin that every small error or imprecision can adversely affect the sound. There are also differences in taste and requirements among performers in respect to timbre and set-up. However, if an instrument truly sounds well, it will please almost everyone from the beginning, and, with small changes, it can be adjusted to suit an individual's taste and convenience.

What is remarkable about the work of Antonio Stradivari is the consistently high level of workmanship and tonal quality that one finds in his output. I believe that he recognized the velocity of propagation of sound as one of the most important criteria in the choice of his materials. Using only the empirical methods then available, he was able to achieve amazingly accurate results. These are apparent in the power and quality of the sound of his instruments, which derived from his optimal choice of materials as well as exquisite workmanship.

The simple but very effective method that Stradivarius probably used was that of hammering or scratching on one end of a piece of wood. By placing his ear at the other end, he could ascertain the intensity of sound (see Fig. 1). Using this method, an experienced listener could tell whether the wood in question possessed the necessary continuity of fibers that augured well for a good propagation of sound. Physically, this phenomenon is due to the fact that a vibration, or hammering at one end of a piece of wood, causes fibers to oscillate. These oscillations, according to the internal tension of the fibers, will transmit the sound to the opposite end. This vibration could be attenuated to a greater or lesser extent, or, in the extreme case of high acoustic resistance, be inaudible.

Using the same criteria as Stradivarius, the TESTER I shall demonstrate today was developed to measure the velocity of sound in wood by "nondestructive" means. Thanks to modern technology, one can now obtain precise and trustworthy results. In recent years, "non-destructive" methods of testing materials of all kinds have

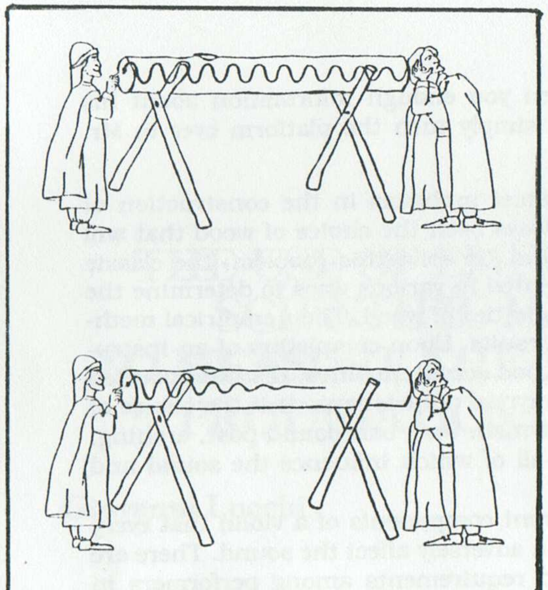


Figure 1. Testing the velocity of the propagation of sound.

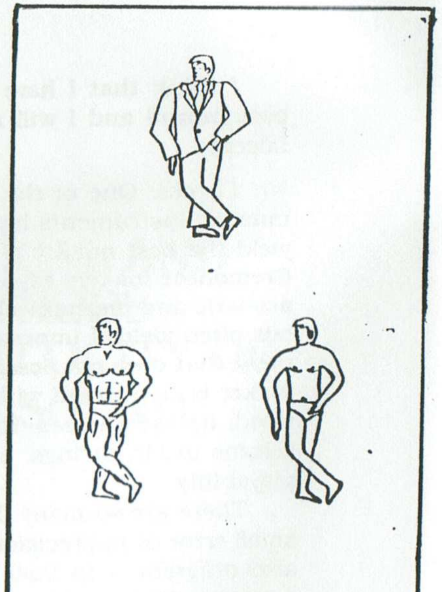


Figure 3. What the clothing may hide.

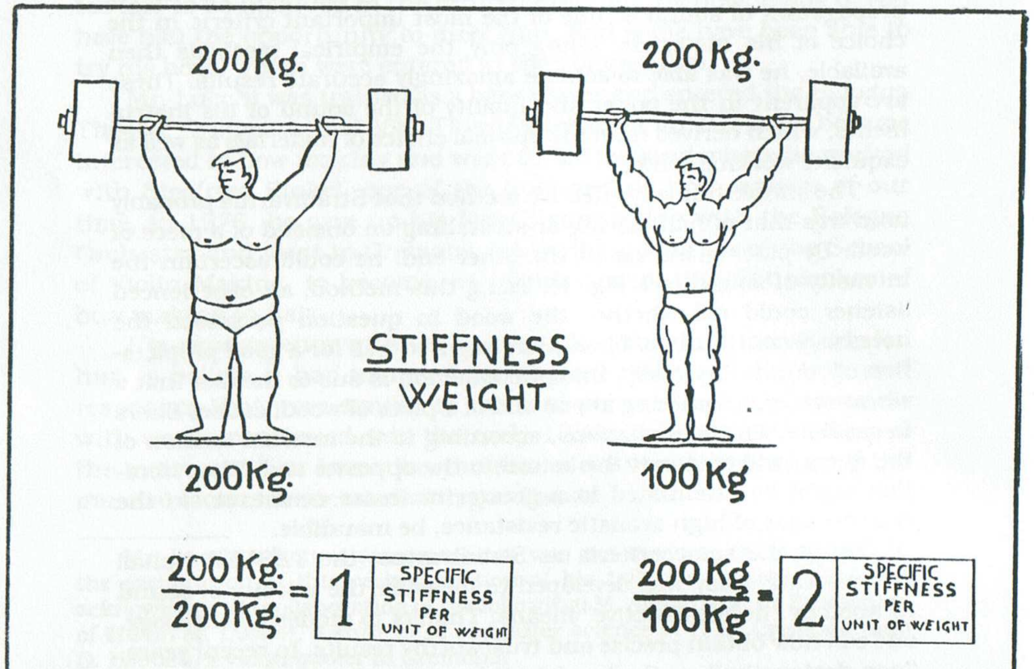


Figure 2.

begun to replace the traditional ones. There are examples of such changes in the investigations of paintings and frescoes, in aeronautics, and in the study of musical instruments, as well as in many other areas. These methods include the use of laser beams, ultraviolet radiation, radiography, and ultrasonics, among others. It is with the application of ultrasonics to musical instruments that our research has been concerned.

In recent years, ultrasonic techniques have been used with increasing frequency to reveal defects in materials of all kinds: to check the accuracy of soldering, and to test the landing gear of airplanes as well as for excessive loads. In research on musical instruments, ultrasonics have been used to study the characteristics of elasticity in the materials used. These investigations have revealed that the velocity of the propagation of sound is an important parameter in determining elasticity. We are now able to determine Young's modulus, the modulus of specific elasticity, the quality factor or coefficient of resonance, and the modulus of rigidity.

The latest TESTER model contains a microprocessor. The time taken for an impluse transmitted by a probe to reach a receiver probe is measured by a timer. The microprocessor elaborates the data and the results are shown on digital display. In this way the operator can, without further calculation, obtain immediate indications of the mechanico-acoustic properties of the material in question.

One may ask what the utility of an apparatus of this nature can be. This can be best answered by an example: in the past, airplanes have been constructed using spruce. Table 1 shows that ebony has the same Young's modulus as spruce and, therefore, the same mechanical characteristics. But the weight of ebony is four times that of spruce: therefore, an airplane using ebony in its construction would require a much more powerful motor that would lead to a greater expenditure of energy, not to speak of other problems related to the greater weight.

As you may have noticed in Figure 1, I like to use simple, if not amusing ways of illustrating my points. Figure 2 shows two weight lifters exerting the same force in lifting 200 Kg. Note that one man weighs 200 Kg., while the other weighs only 100 Kg. Calculating the ratio of his weight, we see that weight lifter no. 1 lifts the equivalent of his weight, while lifter no. 2 lifts twice his own weight. Therefore, lifter no. 2 has a specific force (per unit of weight) twice that of no. 1. He is not only considered more athletic and agile, but also avoids the stress of carrying superfluous weight of his own. We can draw the same comparison in our understanding of wood. Some woods contain inert structures comparable to superfluous weight and are, therefore, mechanically unusable because of poor mechanico-acoustical properties, a low force/weight ratio and low value of specific force (low specific elasticity).

In musical instruments like the violin, a correct force/weight ratio is responsible for the support of the pressure of the strings; allows the harmonic box to vibrate freely; and yields low acoustic resistance, and, therefore, a good quality of sound.

In Figure 3, we can see a clothed person; but under the clothing there may be a great surprise, for the clothing may hide two people of completely different and contrasting physiques. Wood, also, has a kind of covering we cannot remove, but we seek only to understand what it may be hiding. In the same way, we cannot know the sonorous characteristics of a violin until we set the strings in vibration.

On the basis of the brief remarks I have made, we can conclude that Young's modulus—that is, the load supported per unit of area—is not the important factor. It is the load supported per unit of weight, the modulus of specific elasticity, which is the important consideration. Thus, in a violin, the following characteristics that are required are similar: a high resistance value together with a light weight; and the important resonance factor (quality) calculated from the ratio of longitudinal (or radial) velocity of sound and density. The acoustic quality of wood is determined on the basis of these factors.

The latest study of the coefficient of resonance (or quality factor)—by using ultrasonics to test the properties of materials used in the construction of musical instruments—is revealing particularly interesting results. A significant example of what is meant by the quality factor may be seen by comparing styrofoam and polystyrene. If one rubs styrofoam, one can hear a loud noise. But polystyrene, which has a much higher density (about 1, approximately that of water), does not have a good coefficient of resonance and therefore cannot amplify the sound. Light woods, such as spruce and balsa, have a high quality factor. Therefore, we can conclude that the lightness of wood is a characteristic of resonance. With this in mind, one would advise the use of spruce that is not highly resinous, since resin increases density and thus reduces the sonorous quality factor.

The Violin Bow

Like the harmonic box of the violin, the bow should also have a ratio of maximum strength (stiffness) to its minimum weight. In this way it will have the agility and bounce that facilitates the execution of spiccato and the other bow strokes, while at the same time allowing the strings to vibrate freely and fully in order to obtain a full and powerful sound. It is well known that different bows used on the same violin will completely change the timbre and volume of sound in addition to differences in playability.

Using the specific modulus, it is possible to calculate the ratio of force (stiffness) to weight (stiffness divided by weight); in other words, how much force is distributed in a given number of grams.

Table 1

Materials	Velocity Longitud.	Density	Resonance Quality (Q)	Specific Stiffness	Young (E) kg/cm²
Spruce	6.300	0.30	210	396	119
Ebony	3.140	1.20	26	98	119

Table 2

Materials	Velocity Longitud.	Density	Resonance Quality (Q)	Specific Stiffness	Young (E) kg/cm²
Spruce	6.300	0.30	210	396	119
Spruce	4.280	0.65	65	183	119

Table 3

Materials	Radial Velocity	Density	Resonance Quality (Q)	Specific Stiffness	Young (E) kg/cm²
Spruce	2.100	0.30	70	44	13
Spruce	700	0.65	10	4	3

Units of measurement used in the tables:
Velocity of sound: m/sec
Density: kg/dm³ (dm³ = cubic decimeter)
Young's modulus: kg/cm²

It is important go have a high stiffness value in a small amount of weight. If a given material lacks a sufficient stiffness value, it will be necessary to increase the thickness and thus the weight.

Table 1 shows that both spruce and ebony have a rigidity of 119 Kg/cm², that is, the same elasticity characteristics. However, we also note that spruce has a specific stiffness (per unit of weight) of 396, while ebony has a value of 98. Compare also the values for the resonance factor: 210 for spruce and 26 for ebony. Although the Young's modulus for these two woods is identical, note the marked differences in the values for quality factor (resonance) and specific elasticity. Therefore, we can only conclude that one chooses spruce for musical instruments not because of its high Young's modulus, but because of its specific modulus of elasticity (which enables it to support the pressure of the strings) as well as its resonance factor.

In Table 2, we have two types of spruce, each having the same Young's modulus. But they have very different elasticity values due to their different densities (.30 and .65) and stiffnesses (396 and 183). Another fundamental characteristic is that of resonance (quality), with figures of 210 and **65**. These factors contribute to the marked differences in the crucial criterion of velocity of sound. We can, therefore, observe that the factors of resonance and elasticity in two samples of the same kind of wood can be significantly different in respect to their potential for good sound even if they have the identical Young's modulus. These differences also clearly demonstrate the wide variety of mechanico-acoustical properties that one can find in material of the same botanical family.

A further advantage of using nondestructive tests is that they enable us to evaluate the characteristics of materials used by the classical makers. Such tests have also shown that choosing violin-making materials on the basis of Young's modulus alone is incorrect. A confirmation of this statement is found in the book by James E. Gordon, *La Scienza dei Materiali Resistenti* (The Science of Resistant Materials). Gordon states that although carbon fiber is often described in newspapers and on television as a dream of a fiber because of its exceptional resistance, carbon fibers, in reality, are not particularly resistant; more than that, they are a little less resistant than glass fibers. Furthermore, per unit of weight, carbon fiber is eight times more rigid than glass or any other metallic material used in engineering. We emphasize, therefore, how important the modulus of specific elasticity is in choosing materials to resist, per unit of weight, an applied force.

Some violin makers are convinced that the skill of a good and experienced craftsman can produce a good sounding violin, even if the material used is not of the best quality. I find this belief, as I hope I will be able to convince you, is absolutely false.

If a violin is made from material which is not sufficiently elastic (lacking in strength and stiffness) and is, therefore, thinned excessively in order to make it sound well immediately, its harmonic plate

will be unable to support the pressure of the strings. Instead of improving with time and playing, as the older well-made instruments did, this instrument will weaken and deteriorate. On the other hand, if the harmonic plate is strengthened by increasing its thickness (thus also its weight and mass), the structure will not weaken with time. But this instrument will not have a good quality from the outset because of its high percentage of inert material. An instrument made from a good choice of materials, and constructed correctly, should sound well from the beginning and will improve with age and good playing.

Many attribute the defects that we often encounter in a just completed violin to its newness and its need to mature. It is true that, with time, the quality of sound of a well-made instrument tends to improve gradually. This is the result of several causes: the complete drying of the varnish and the vibrations that the instrument has been subjected to during use by a player who knows how to draw a good sound and plays well in tune.

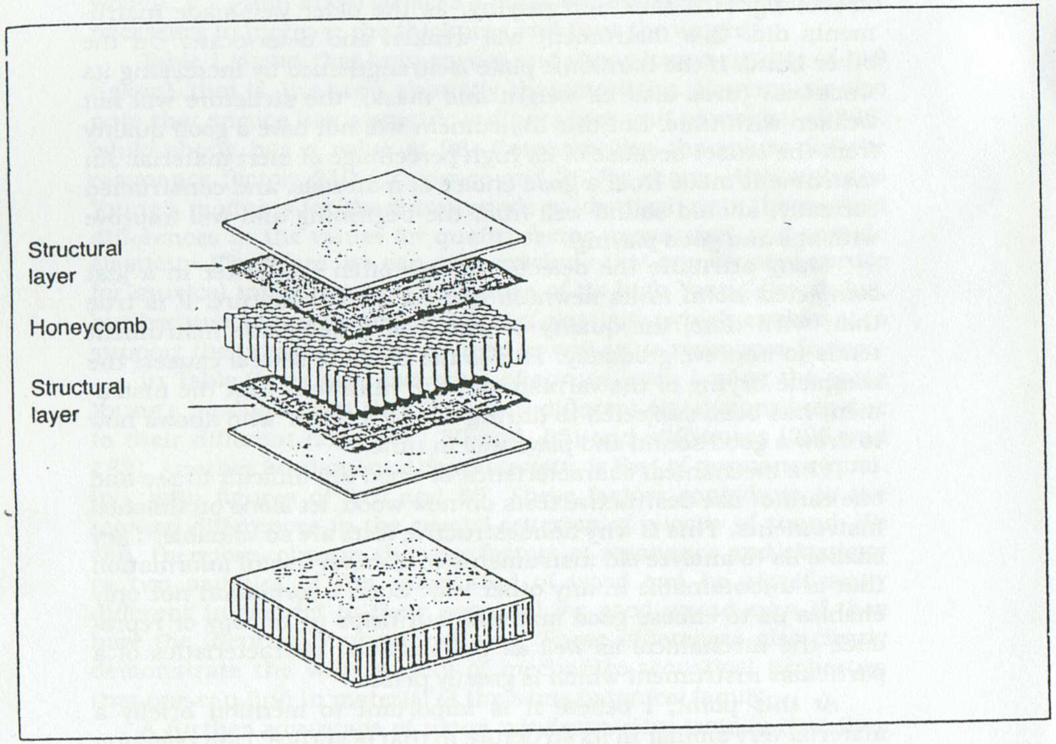
The mechanical characteristics of wood are difficult to see and one cannot use destructive tests on new wood, let alone on finished instruments. This is why nondestructive tests are so valuable. They enable us to analyze old instruments to discover useful information that is unobtainable in any other way. Such information not only enables us to choose good material, but helps us to copy or reproduce the mechanical as well as the aesthetic characteristics of a particular instrument which is greatly prized.

At this point, I believe it is important to mention briefly a material very similar in its structure to that of spruce: I am referring to the structure of a beehive. A hive is composed of two very resistant outer layers of fiber with a very light honeycomb layer in between. The various examples in Figure 4 show that by widening the distance between the outer resistant layers and enlarging the size of the honeycomb filler, there is a significant increase in resistance and the parity of weight as the specific modulus grows exponentially.

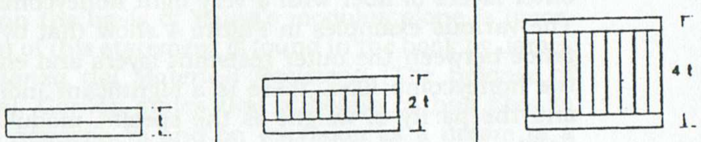
This type of beehive construction can be considered to be a kind of artificial spruce, consisting of very resistant material with another that is very light. In this way, one has obtained a composition with optimal acoustical qualities.

Measuring the Drying Time of Varnish and Residual Elasticity

The Giovanni Lucchi elasticity tester enables us to use ultrasonics to measure the drying time of varnish. This also enables us to avoid the danger of setting up the instrument and subjecting it to the pressure of the strings while the varnish may still be wet and the fibers still weak. This is a significant improvement over the superficial methods of the past that were used for ascertaining



Influence of the thickness of the structure on the ratio of weight characteristics



Relat. stiffness	100	700	3700
Relat. resistance	100	350	925
Relat. weight	100	103	106

Figure 4. One of the latest and most interesting structures in aeronautic technology

drying time. It is also possible to discover if a varnish, when really dry, has in fact weakened the fibers and, therefore, lowered the earlier values of elasticity of the material.

For example, if one submerges a piece of sonorous spruce in water, the elasticity decreases. However, as the wood dries, its elasticity gradually assumes its original value. If the same test is done with oil instead of water, the elasticity will also be lowered, but it will not return to its original value because the oil will have weakened the fibers of the wood. Therefore, in violin varnishes which are considered justly to be one of the secrets of classical Italian violin making, the composition of the varnish is of fundamental importance. The varnish has to leave the elasticity of the wood intact without penetrating too deeply.

In Stradivari's lifetime, life was much less frenetic than it is today. He and his contemporaries worked on consignment, were not so pressured, and were able to allow ample time for their varnishes to dry. Oxidation and playing in the several centuries that have passed since that epoch have undoubtedly made their contribution to the marvelous tonal qualities of these old Italian instruments we enjoy so much today.

On the basis of our study of spruce for violins, we have come to the following conclusions: that longitudinal elasticity determines the mechanical characteristics for the support of the force of the strings, while radial velocity determines the characteristics of timbre and volume of sound (see Table 3).

The radial or medullar rays are responsible for the radial velocity. The maple used for violin bridges provides a good example of this. The dark radial rays transmit with more or less velocity the sound from the strings to the harmonic box. Therefore, we can conclude that a bridge with long medullar rays, as seen in Figure 5, will yield a good and powerful sound, although it is often erroneously thought that a darker bridge also if it has dots may have, as in Figure 6, more favorable characteristics. It is not always true that a dark coloration corresponds with a continuity of fibers.

Similarly, in the construction of the violin top plate, the continuity of the medullar rays of the spruce is of utmost importance. If these rays have been severed, the quality of the instrument will be impaired. The medullar rays of spruce are formed as the plant absorbs silicates from the soil during its growth. However, our conclusion is that superficial treatment of the wood with various forms of silicate does not improve the sound because these substances do not penetrate the wood and thus do not enhance the continuity of the fibers.

The use of technology in the study of various materials is the same in all areas. What is most important, however, is to know with precision what is exactly needed for each special use. In conclusion, I would like to stress again the importance of using nondestructive tests in order to gain a greater understanding of the genius of the

Table 4

Materials	Velocity Longitud.	Density	Resonance Quality (Q)	Specific Stiffness	Young (E) kg/cm²
Carbon Fiber	7.500	1.10	68	562	618
Aluminium	6.200	2.70	22.90	384	1.037
Iron	5.210	7.70	6.70	271	2.090
Lead	1.570	11.40	1.30	24	280

These values can vary greatly with melting and casting process and changes in the alloy percentage or through thermal processes.

The vibraphone has the same requirements as the violin, that is, high specific modulus and high resonance factors to yield, on the one hand, a high internal tension and, on the other, a good quality of sound. Airplanes, like vibraphones, are made from aluminum to achieve a high specific elasticity and quality. Lately, carbon fibers are used together with aluminum in some parts of airplanes to improve their mechanical characteristics.

Table 5

Materials	Velocity Longitud.	Density	Resonance Quality (Q)	Specific Stiffness	Young (E) kg/cm²
Brass	3.640	8.56	4.20	132	1.134
German Silver	4.760	8.70	5.40	226	1.970
Silver	3.600	10.50	3.40	129	1.360
Gold	3.240	19.32	1.60	104	2.028

If one asks whether a gold flute would have a more beautiful sound than one made of silver or German silver, the answer is seen in this table. The flute should have a low resonance factor in order to vibrate minimally so as not to disturb the column of air, which is the only source of sound. The same principle explains why lead with its low resonance value is used for organ pipes. Ebony, with the lowest resonance value of all types of wood, is used in flutes and clarinets (see Table 1).

Table 6
Specific Stiffness in Different Materials

Materials	Density	Spec. Stiffness
Carbon Fiber	1.1	562
Spruce (for Violin)	0.3	397
Pernambuco Wood (for bow)	1.1	368
Aluminum	2.7	384
Steel C 40	7.8	291
Glass	2.6	287
Iron	7.7	280
Copper	8.93	161
Bronze	8.4	122
Cast Iron	7.8	114
Brass	8.56	112
Lead	11.4	24

These values can vary greatly with the melting and casting process and changes in the alloy percentage or through thermal processes.

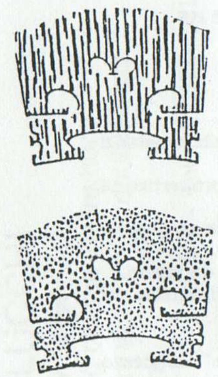


Figure 5 & 6. Medullar rays in maple for bridges.

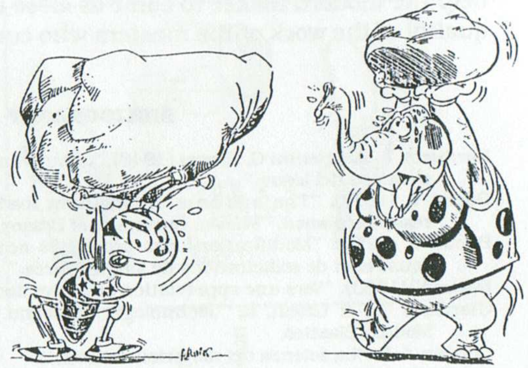


Figure 7. The ant and the elephant are good examples of specific force. It is well known that the ant is capable of lifting an object from 10 to 20 times its own weight.

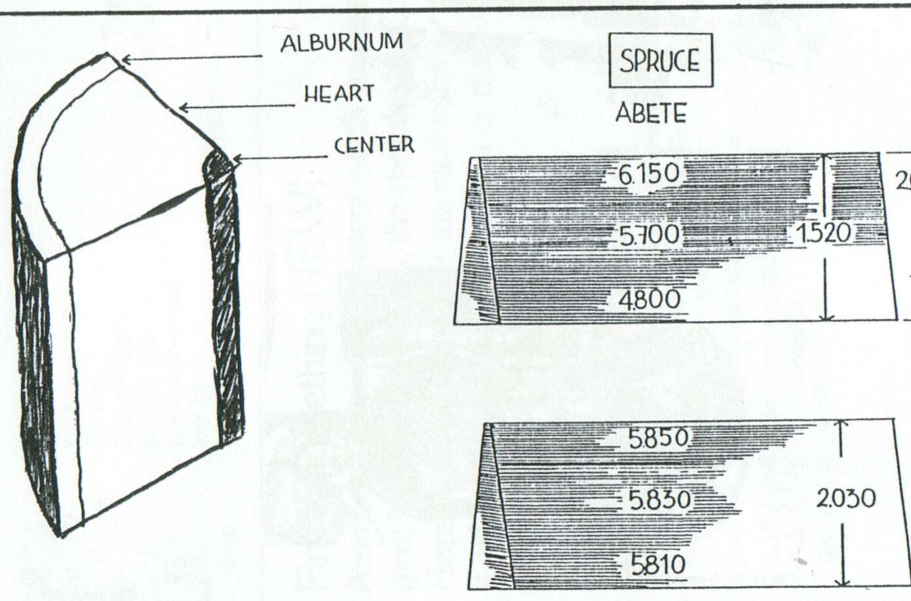


Figure 8. In the same wedge of spruce we can find completely different mechanical characteristics in its parts: the alburnum, the heart and the center.

great classical makers who arrived at such a high level of art and creativity through empirical and intuitive means. Such tests should help the modern maker to come as close as possible to the ineffable quality of the work of the masters who continue to inspire us.

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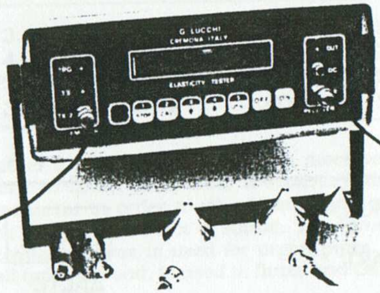

Figure 9. The Lucchi Tester

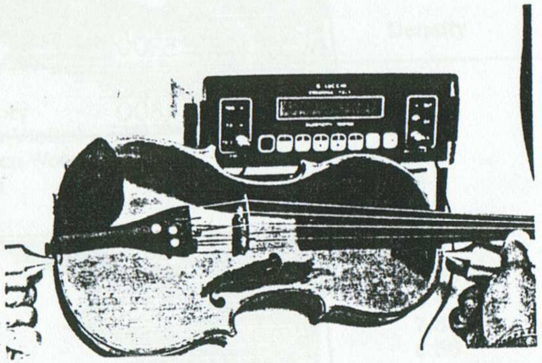

Figure 10. Uses for the Lucchi Tester