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WOOD FOR SOUND[1]

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The unique mechanical and acoustical properties of wood and its aesthetic appeal still make it the material of choice for musical instruments and the interior of concert halls. Worldwide, several hundred wood species are available for making wind, string, or percussion instruments. Over generations, first by trial and error and more recently by scientific approach, the most appropriate species were found for each instrument and application. Using material property charts on which acoustic properties such as the speed of sound, the characteristic impedance, the sound radiation coefficient, and the loss coefficient are plotted against one another for woods. We analyze and explain why spruce is the preferred choice for soundboards, why tropical species are favored for xylophone bars and woodwind instruments, why violinists still prefer pernambuco over other species as a bow material, and why hornbeam and birch are used in piano actions.

Key words: wood; acoustical properties; materials selection; musical instruments.

"[I]t appears probable that the progenitors of man, either the males or females or both sexes, before acquiring the power of expressing their mutual love in articulate language, endeavoured to charm each other with musical notes and rhythm...", wrote Darwin in 1871 (p. 880). So far we can only speculate, when our early ancestors started to perform music, on the role of music in our biology and evolution (Cross, 2001), and when the first musical instruments were made and from which materials. What we know for certain is that about 35 000 years ago, when the oldest surviving sculptures and cave paintings were created, flutes were played in the Geißenklösterle Cave in the southwestern part of Germany (Conard, 2004). The flutes heard then are universally accepted as the oldest musical instruments found so far. Of the three flutes found in the Geißenklösterle Cave, two are made of hollow swan wing bones, and the third of solid mammoth ivory that was first carefully separated into halves for hollowing, then glued together along a perfectly prepared, air-tight seam (Conard, 2004). All three flutes show not only early artistry in their manufacture, but experiments by Seeberger (2003) on modern reproductions of these flutes conclusively demonstrate that they are intricate musical instruments with which complex and aesthetically pleasing music can be produced.

The oldest surviving examples of musical instruments are those made from bone and ivory—probably not because they were the preferred material for flutes, but rather because purely organic materials decay much more quickly than their mineralized counterparts. Flutes of a similar design and other musical instruments were likely made from leaves, grasses, wood or fruits at the same time or even earlier than these oldest surviving ones. Plants, as do bird wing bones, have shapes suitable for musical instrument making, and additionally, plants have mechanical properties that would have made it even easier for our ancestors to shape them with relatively simple stone, bone, or antler tools.

The earliest surviving flutes were found in Europe. However, finds of similar and other musical instruments on all continents show that sound and rhythm have been an intricate part of human nature, independent of region and culture.

MUSICAL INSTRUMENTS

Over the millennia since the swan-bone and mammoth-ivory flutes, the range and color of sounds that can be produced by humans have increased immensely. The development of new and improved musical instruments has played an important part in this, and for many of them, the human voice has been the benchmark. Today, musicologists group the vast number and kinds of past and current musical instruments into five families based on a system devised by von Hornbostel and Sachs (1914). The initial four classes were (1) idiophones—instruments that make sound primarily by vibrating themselves, without the use of membranes or strings (e.g., xylophones); (2) membranophones—instruments that use a stretched membrane to create the sound e.g., drums); (3) chordophones—instruments that rely on a stretched string (e.g., violins, guitars, pianos); and (4) aerophones—instruments that rely on a vibrating air column for sound creation (e.g., flutes, clarinets and didgeridoos). More recently, a fifth class has been added to the Sachs–Hornbostel system: (5) electrophones—instruments that produce sound by electronic means (e.g., keyboard synthesizers).

Even though the range and sophistication of musical instruments has increased significantly, particularly during the last four centuries or so, the range of materials from which the instruments of all these classes are manufactured has changed remarkably little. Whenever music is made by hand, whatever the location and culture, from folk to classical, from jazz to rock and pop, the vital parts in most musical instruments are still made from natural materials and primarily from wood, despite the arrival of sophisticated alloys, polymers, and composites. There are a number of good reasons why this is so, as will be illustrated. We begin with a brief description of the composition

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and structure of wood that give it its exceptional mechanical and acoustical properties.

WOOD AS AN ENGINEERING MATERIAL

The unique and desirable spectrum of physical and mechanical properties of wood that so far can only in exceptional cases truly be matched by manmade materials, make it the material of choice for a multitude of applications ranging from construction to sports equipment and musical instruments even today. Wood is advantageous in its comparative abundance and in being relatively easy to shape with simple tools. One feature that sets wood apart from most manmade materials is that it is an orthotropic material, meaning that it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential. The longitudinal axis (*L*) is defined as parallel to the fiber (grain), thus along the length of a tree trunk; the radial axis (*R*) is perpendicular to the growth rings; and the tangential axis (*T*) is perpendicular to the grain but tangent to the growth rings. This orthotropy is due to the cellular structure of wood. Wood is primarily composed of hollow, slender, spindle-like cells, that are arranged parallel to each other along the trunk of a tree. The microscopic properties of the individual cells such as their composition and structure, their physical and mechanical properties, and their shape and connectivity determine the overall performance of wood.

Wood is a hierarchically structured composite. The cell walls consist of cellulose microfibrils embedded in a lignin and hemicellulose matrix in which minor amounts (5–10%) of extraneous extractives (e.g., oils) are contained (Wood Handbook, 1999; Dinwoodie, 2000). Variations in the volume and chemistry of these ingredients, combined with differences in the amount and distribution of porosity, determine the structure and thus the density and mechanical properties of a wood. While the properties of a single wood species are constant within limits, the range of properties among species can be large. Worldwide, the density of wood ranges from about 100 kg/m^3 for balsa (*Ochroma pyramidale*) to about 1400 kg/m^3 for lignum vitae (*Guaicum officinale*) and snakewood (*Brosimum guianense*) (Wagenführ and Schreiber, 1989), a value close to that of carbon-fiber-reinforced polymers (CFRP) (Fig. 1). However, even in Europe, which has a small diversity of tree species due to a relatively recent ice age, the density ranges from about 400 kg/m^3 for willow (*Salix alba*) to about 800 kg/m^3 for hornbeam (*Carpinus betulus*) and 950 kg/m^3 for boxwood (*Buxus sempervirens*) (Sell, 1989). From these, our ancestors found, over the generations and by trial and error, the best wood species available for a given function. As today, their choices were not made on purely technical and mechanical grounds, such as the wood's decay resistance and dimensional stability and the ease with which it could be shaped and joined. Very important always were additional ones, such as the wood's appearance—its texture, grain pattern, and color. We will see later that these last, seemingly "soft" criteria are often the critical ones that determine whether a material will be accepted or not in cases of material substitution, even when the technical criteria are clearly met.

Physical and mechanical properties of wood—Many physical and mechanical properties of wood are correlated with density. The Young's and shear moduli parallel and perpendicular to the grain of this orthotropic material are among these and have been shown to be important for musical plate vibration. Lacking complete sets of measurements of these moduli for woods used in musical instruments, we concentrate on the Young's modulus parallel to the grain because it has been determined for a large number of wood species and because the Young's modulus, together with the wood's density, determines most acoustical properties of a material. Additionally, the side hardness is important whenever wood carries contact or impact loads, as is the case in xylophones, for example. For clear, straight-grained softwoods and hardwoods, the Young's modulus parallel to the grain and side hardness may be estimated from the density, ρ, in kg/m^3 according to the correlations in Table 1 (Wood Handbook, 1999). Figure 1, a plot of Young's modulus parallel to the grain vs. wood density, illustrates the modulus–density correlation; the diagonal line has a slope of 1.

Another important feature peculiar to wood and important for musical instruments is that it reacts and adapts to the environmental conditions to which it is exposed, particularly that it exchanges moisture with air. Material properties that are critical for the acoustical performance of a wood such as density, Young's modulus, damping, and shrinkage are highly dependent upon the wood's moisture content. Thus, important criteria during the material selection process are also how much and how quickly a wood exchanges moisture with the

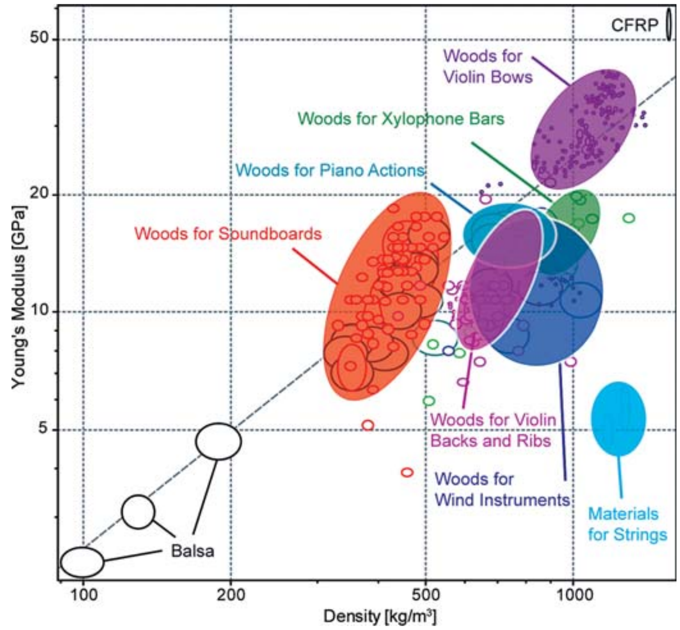

Fig. 1. A material property chart for woods, plotting Young's modulus, *E*, against density, ρ, for woods parallel to the grain. It illustrates that Young's modulus and density are almost linearly correlated. Figure created using the Natural Materials Selector (Wegst, 2004).

TABLE 1. Correlations of Young's modulus, hardness and density (ρ) in kg/m^3 for soft and hardwoods.

Property correlations	Softwoods	Hardwoods
Young's modulus [GPa]	$56.3 \cdot \rho^{0.84}$	$121.1 \cdot \rho^{0.7}$
Side hardness [N]	$0.229 \cdot \rho^{1.5}$	$6.48 \cdot 10^{-3} \cdot \rho^{2.09}$

environment and how the moisture affects its dimensional stability and mechanical properties. In general, the speed of moisture sorption decreases with increasing density and content of extractives (Sell, 1989). The rate and amount of water uptake along with the dimensional stability of wood can further be controlled through treatments with waxes or oils.

Acoustical properties of wood—The acoustical properties of wood, such as the volume, quality, and color of the sound of xylophone bars and soundboards are determined by the mechanical properties of the material from which they are made because the sound is produced by vibrations of the material itself. The properties on which the acoustical performance of a material depends are primarily its density, Young's modulus, and loss coefficient. They determine the speed of sound in a material, the eigenfrequencies of a wooden bar, and the intensity of the radiated sound.

The most important acoustical properties for selecting materials for sound applications, such as musical instruments and building interiors, are the speed of sound within the material, the characteristic impedance, the sound radiation coefficient, and the loss coefficient:

- The speed, c, with which sound travels through a material, is defined as the root of the material's Young's modulus, E, divided by the material's density, ρ:

$$c = \sqrt{\frac{E}{\rho}}. \tag{1}$$

- Incidentally, this ratio, which describes the speed of longitudinal waves in a material, also characterizes the transverse vibrational frequencies of a bar.
- The impedance, z, of a material, is defined as the product of the material's speed of sound, c, and its density, ρ:

$$z = c\rho = \sqrt{E\rho}\,. \tag{2}$$

- The sound radiation coefficient, R, of a material, is defined as the ratio of the material's speed of sound, c, to its density, ρ:

$$R = \frac{c}{\rho} = \sqrt{\frac{E}{\rho^3}} \tag{3}$$

- The loss coefficient, η, measures the degree to which a material dissipates vibrational energy by internal friction. Other measures of damping include the quality factor, Q, the logarithmic decrement, δ, and the loss angle, ψ. For excitation near resonance and small damping, these quantities are related as (Newland, 1989):

$$\eta = \frac{1}{Q} = \frac{\delta}{\pi} = \tan\psi\,. \tag{4}$$

Speed of sound—As we saw in Eq. 1, the speed of sound is directly related to the modulus of elasticity and density. It is roughly independent of wood species, but varies with grain direction. The transverse Young's modulus of wood is only between 1/20 to 1/10 of the longitudinal; consequently, the speed of sound across the grain is only c. 20 to 30% that of the longitudinal value. Generally, the speed of sound in wood decreases with an increase in temperature or moisture content and proportionally to the influence of these variables on Young's modulus and density. It decreases slightly with increasing frequency and amplitude of vibration (Wood Handbook, 1999).

Characteristic impedance—Like the speed of sound, the characteristic impedance is directly related to the modulus of elasticity and density of a material. This quantity is important when vibratory energy is transmitted from one medium with impedance z_1 to another with impedance z_2. The first medium could be a string and the second the soundboard of a musical instrument. The ratio of the reflected sound intensity, I_r, to the incident intensity, I_0, can be expressed as a function of the impedances of the two media:

$$\frac{I_r}{I_0} = \left(\frac{z_2 - z_1}{z_2 + z_1}\right)^2. \tag{5}$$

And the ratio of the transmitted sound intensity, I_t, to the incident intensity is

$$\frac{I_t}{I_0} = \frac{4z_2z_1}{(z_2 + z_1)^2}\,. \tag{6}$$

From these equations, we see that the transmitted intensity goes to zero if there is a large mismatch between z_1 and z_2, thus either $z_1 << z_2$ or $z_2 << z_1$ (Fletcher and Rossing, 1991).

The soundboard's impedance is proportional not only to the characteristic impedance of the material from which it is made, but also to the square of the soundboards thickness. As a result, soundboards with considerable thickness, such as that in pianos, for example, have an impedance significantly larger than that of the strings. To achieve a high sound quality, the impedances of the strings and the soundboard must thus be controlled very carefully. This is not a trivial undertaking, because two conflicting requirements must be met: sufficient vibratory energy must be transmitted from the string to the soundboard to make the strings vibrate audibly, while the energy should not be transmitted too readily or too rapidly, causing the vibrations of the string to die down quickly and their sound to resemble that of a thud (Benade, 1990).

Sound radiation coefficient—The sound radiation coefficient describes how much the vibration of a body is damped due to sound radiation. Particularly in the case of idiophones, such as xylophones and soundboards, a large sound radiation coefficient of the material is desirable if we wish to produce a loud sound. To maximize loudness, we need to maximize the amplitude of the vibrational response of the soundboard for a given force, a quantity that is described by the frequency response function (Barlow, 1997). According to Skudrzyk's (1980) mean value theorem, the mean value of the amplitude is equal to the driving-point admittance, which for an infinite isotropic plate is

$$Y = \frac{1}{4h^2}\sqrt{\frac{3(1-\nu^2)}{E\rho}}, \tag{7}$$

where h is the thickness of the soundboard or the bar and ν is the Poisson's ratio of the material from which it is made. Assuming that we do not wish to change the timbre of the instrument, we need to ensure that the modal density of the soundboard has the correct value (Manning, 1997). For an isotropic plate, the modal density (in frequency space) is

$$n(\omega) = \frac{A}{h}\sqrt{3(1-\nu^2)\frac{\rho}{E}}, \tag{8}$$

where A is the area of the soundboard. Rearranging Eq. 8 and substituting it for h in Eq. 7 yields an expression that describes how the mean amplitude for a soundboard of a given area and the modal density depend on the soundboard's material properties:

$$Y = \frac{n(\omega)}{4A^2}\sqrt{\frac{E}{\rho^3}\frac{1}{3(1-\nu^2)}}. \tag{9}$$

Thus, if we wish to maximize the average amplitude or the average loudness of a violin for a given modal density and prescribed soundboard dimensions, assuming the term in parentheses equals 1, we need to maximize the combination of materials properties which was earlier defined as the sound radiation coefficient, R:

$$R = \sqrt{\frac{E}{\rho^3}}. \tag{10}$$

If we wish to maximize the peak response of a soundboard or a bar, rather than the average response, we need to maximize the ratio of the sound radiation coefficient to the loss coefficient, η (Barlow, 1997).

Incidentally, the quantity that we need to maximize if maximum stiffness per unit weight is sought is the same as that represented by R. In soundboard design, this means that the one that radiates the loudest sound also is the stiffest per unit mass, thereby ensuring that the thin top plates of violins, which typically are only 2–3 mm thick, can support the 70 to 90 N (c. 7 to 9 kg) load of the strings with minimal deflection.

Loss coefficient—When a solid material vibrates, it is strained and some of its mechanical energy is dissipated as heat by internal friction. The mechanism by which this occurs in wood is complex and depends on the temperature and moisture content within a sample and on the type and amount of extractives characteristic for the wood species. The value of the loss coefficient ranges from about 0.1 for hot, moist wood to about 0.002 for air-dry wood at room temperature. Unlike the three acoustical properties described earlier, the loss coefficient, which quantifies the damping of vibration due to internal friction, is independent of density and Young's modulus, as Fig. 4 illustrates.

Pitch and timbre of sound—The loudness or intensity of a sound depends on the square of the amplitude of the vibration, as described earlier. The pitch of sound of a musical instrument is determined by the spectrum of frequencies it radiates and transmits into the air. Each body has its own particular set of eigenfrequencies defined by the size of the vibrating body, the material from which it is made, and in the case of strings, on its tension. The timbre and quality of the sound that a vibrating body produces is due to the presence of eigenfrequencies, also termed overtones or upper partials, and their relative strengths. Which overtones of a sounding body are excited depends on what causes the body's vibrations: whether it is hit by a soft or a hard mallet and whether the vibration is caused by a plucked or a bowed string. The harmonics also depend on the shape of the body and on the material from which the body is made, as is explained next.

MATERIAL SELECTION FOR MUSICAL INSTRUMENTS

When we plot the various physical and mechanical properties and acoustical quantities described earlier against one another for the woods commonly used for different types of instruments, we can illustrate the design requirements for these instruments and analyze why certain species are especially suited for particular sound applications and therefore traditionally chosen by musical instrument makers. The scales of the charts are logarithmic to accommodate a large range of materials and to be able to represent the acoustical criteria with straight lines. The materials are represented as bubbles and grouped by colors, which indicate the traditional use for a material. Data sources for information on materials and their properties are Haines (1979), Richter (1988), Finscher (1994), Yano et al. (1997), Sadie and Tyrell (2001), Oberhoff (2003), Rujinirun et al. (2005) and Bucur (2006).

Figure 1 shows Young's modulus, E, plotted against density, ρ, for woods parallel to the grain. From the chart, we read that soundboards are made from low density woods, which have a relatively high Young's modulus, that woods for wind instruments and xylophone bars have a high density, and that woods for violin bows have both an exceptionally high density and a high Young's modulus. The reasons for these choices are described in detail later.

Figure 2 shows the speed of sound, c, plotted against density, ρ, allowing two additional acoustical properties to be read from this chart. Lines with slope 1 represent the ratio c/ρ, the sound radiation coefficient, R. Lines with slope -1 represent the product of the two, $c\rho$, the characteristic impedance, z. All materials on an individual line with a slope of 1, or -1, have the same value for this property, thus they radiate the same amount of sound, or have the same impedance, respectively. Materials above a line have a higher value for the respective property than those below. Woods for soundboards stand out. They have both an exceptionally high speed of sound and a remarkably high sound radiation coefficient.

Figure 3 shows the sound radiation coefficient, R, plotted against the loss coefficient, η. Lines with slope 1 represent the ratio of the two, the peak response of a sounding body, rather than its average response represented by R. All materials on an individual line have the same value for this property. Materials above a line produce a louder peak response than those below. The chart reveals that woods for soundboards have both a high average and a high peak response and that soundboards, xylophone bars, and violin bows all have an exceptionally low loss coefficient.

Figure 4 shows the Young's modulus plotted against the loss coefficient, η, illustrating that these properties are not at all correlated. The chart also shows that woods for violin bows are unique in their combination of an exceptionally high Young's modulus with a very low loss coefficient.

In the next sections, these four material property charts are used to explore which of the depicted properties dominate the material choice and quality of sound produced by woodwind instruments, xylophone bars, soundboards, piano actions, and violin bows.

Woods for wind instruments (aerophones)—Wind instruments made from wood are, for example, the recorder, the flute, the oboe, the clarinet and the bassoon. We concentrate on these, since the principle of sound production applies to all other instruments which, like these, use an air column as a resonating body to produce and radiate the sound. The sound characteristics of these instruments that allow us to distinguish one from the other are due to the mode of air column excitation (whether by blowing over the column for the flute or through a single reed for the clarinet or a double reed for the oboe), on the shape of the air column (whether it is cylindrical or conical), on the length of the air column (controlled by opening and closing the finger holes on the instrument), and very importantly, on the exact shape and design of the finger holes (Benade, 1990; Fletcher and Rossing, 1991).

Traditionally, the woods from which these instruments are made are dense, have a fine structure, and a high dimensional stability, particularly when exposed to high levels of moisture. Before the arrival of tropical wood species in Europe, boxwood (*Buxus sempervirens*) and fruit woods such as pear (*Pyrus communis*) and plum (*Prunus domestica*), and in exceptional cases the material of the oldest surviving flute, ivory, were used. Since the arrival of the denser tropical species, African blackwood or grenadill (*Dalbergia melanoxylon*), Brazilian rosewood (*Dalbergia nigra*), and Macassar ebony (*Dyospyros celebica*) have been favored for oboe and clarinet, while the large bassoon has always been and still is made of maple (*Acer platanoides*) (Table 2).

Why were these woods chosen? Their mechanical properties differ vastly, by almost a factor of two between the least and the most dense. The reason for their use is their structure. All these woods can be turned and drilled with great accuracy, and they are sufficiently dimensionally stable under the influence of moisture. These characteristics are critical because for these instruments, the material determines the sound quality of the instrument not by vibrating itself—the acoustic pressure of the standing wave in the air column is by far too weak to excite and couple to vibrations of the thick wooden tube of wooden instruments to produce audible vibrations—but the sound quality is determined by the interaction of the material with the enclosed column of vibrating air.

The tube material influences the sound of the instrument and its playability significantly and mainly by two mechanisms: by vibrational damping due to air friction at the tube walls and by turbulence in the vibrating air at the edges (Benade, 1990). Vibrational damping is lower in tubes with a smooth finish. Turbulences, which also dampen the vibration and affects the tonal quality of an instrument, are reduced when the edges can be cut precisely and finished slightly rounded as for finger holes, for example. The best wood for a wind instrument thus has a high density and a fine grain to obtain an optimal finish of the tube walls and finger holes. Because the breath of the musician introduces significant amounts of water into the air column, the material should further absorb a little moisture since water droplets on the tube wall spoil the sound. At the same time, the material should be dimensionally stable when exposed to moisture, so that the instrument remains tuned over a significant amount of time. All the woods named earlier have these qualities to a larger extent than others. Their resistance to moisture is frequently further improved by oiling or by impregnating with paraffin.

Because African blackwood is an endangered species, plain and wood-filled polymers have recently been introduced as a substitute material for the manufacture of clarinets. Makers and players tend to claim that they can hear differences in sound quality between instruments made from different woods and alternative materials. Such differences can be due to differences in surface and bore properties of the instrument or due to the wall material's thermal properties, because sound waves involve temperature fluctuations, which, due to the thermal inertia in the walls, produce a damping effect. Appropriate material selection and the optimization of the manufacturing process should make it possible, however, to manufacture polymer instruments that can produce a sound similar in quality and timbre to that of wooden ones. Current reservations of musicians toward polymers use for top quality instruments might have an additional, more subtle reason: the "feel" towards an instrument made from synthetic "plastics" as opposed to the natural material wood.

Woods for xylophones (idiophones)—The xylophone consists of wooden bars mounted horizontally and supported by a soft material at the two nodal points of its lowest eigenfrequency. The fundamental frequency of vibration of an individual xylophone bar is determined by its length. Bars of identical length and shape have vibrational frequencies that scale with the speed of sound from the chosen material. An arch is cut into the underside of xylophone bars for two reasons: to reduce the bar length required for low pitches and to tune the overtones (Fletcher and Rossing, 1991).

Xylophone bars are impulsively excited instruments. The energy that causes the bar to vibrate is transferred to it in a time span that is very short in comparison to the decay time of the bar's vibration. As a result, the choice of the mallet used to excite the bar has an enormous effect on the color and quality of the sound produced (in a way similar to the quality of the felt on the hammers in a piano). A hard-headed mallet produces a bright and penetrating sound, while a softer mallet produces a more mellow sound that is often preferred for the lower notes. This effect is due to the frequencies excited on impact. The harder mallet has a shorter contact time upon impact and excites a spectrum rich in overtones characteristic for a given material, while the softer excites only the harmonically tuned lower partials and dampens the higher partials due to its longer contact time.

If a significant loudness and reverberation time of an impulsively excited instrument is to be achieved, the best materials are those that radiate sound well. Additionally, bars with a low loss coefficient will result in a brighter sound because the higher partials are less damped than in a material with a high loss coefficient (Richter, 1988; Bork, 1995).

Figures 3 and 4 show that xylophone bar woods (Table 3) have a low loss coefficient and high value of peak sound radiation, but not of the average sound radiation coefficient, and that woods for soundboards (Table 4) have much higher values for both. What are the consequences of these differences and why are xylophone bars not made from soundboard woods? For two reasons: the first is that soundboard woods have a very low density (Fig. 1), and as a result a low side hardness (Table 1). Low-density species hit by a mallet would dent easily or even split, and the bars' tuning and damping properties would suffer as a result. Thus we seek a wood with

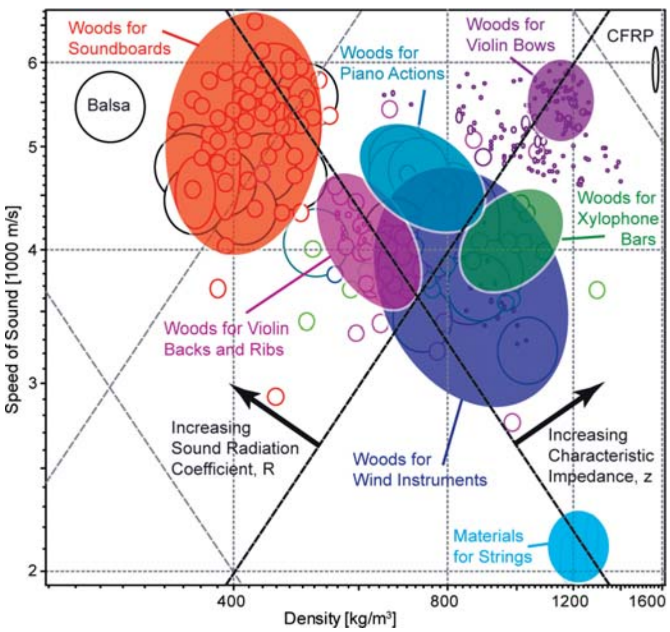

Fig. 2. A material property chart for woods, plotting the speed of sound, c, against density, ρ, allowing two additional acoustical properties to be read from this chart. Lines of slope 1 represent the sound radiation coefficient, $R = c/\rho$. Lines of slope -1 represent the product of the two, the characteristic impedance, $z = c\rho$. Figure created using the Natural Materials Selector (Wegst, 2004).

a high side hardness, a design requirement best met by high-density tropical species (Holz, 1996). The second reason is also related to density: the sound of xylophone bars should decay sufficiently slowly, a criterion of less importance in a continuously excited string instrument, for example. Figure 2 shows

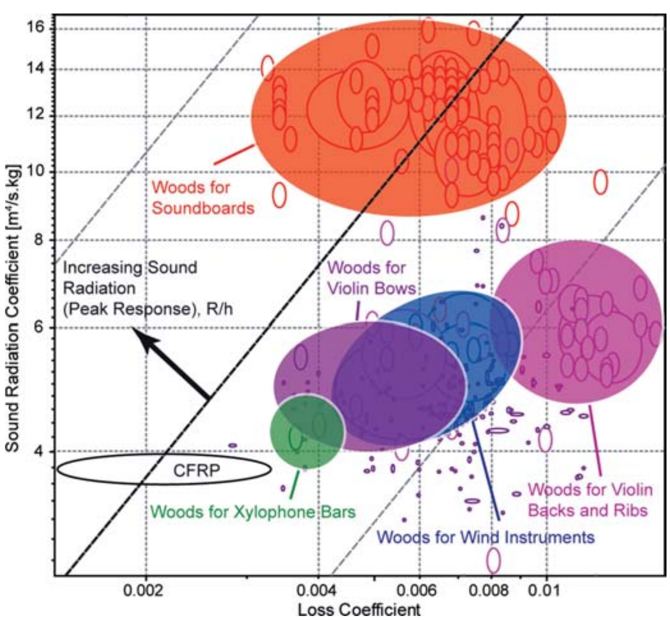

Fig. 3. A material property chart for woods, plotting the sound radiation coefficient, R, against the loss coefficient, η. Lines of slope 1 represent the ratio of the two, R/η, the peak response of a sounding body. Figure created using the Natural Materials Selector (Wegst, 2004).

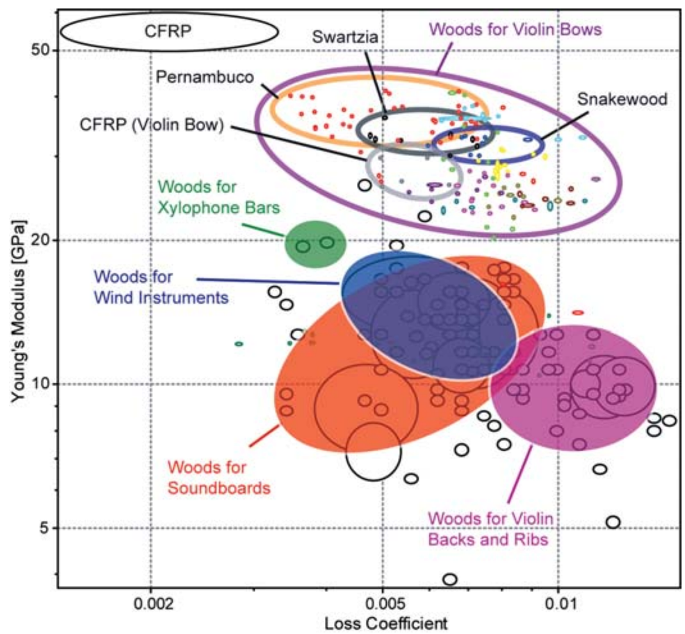

Fig. 4. A material property chart for woods, plotting Young's modulus against the loss coefficient, η, revealing that these two properties are not at all correlated. Figure created using the Natural Materials Selector (Wegst, 2004).

that, due to their higher density, woods for xylophone bars are much less damped by sound radiation than soundboard woods, resulting in slower sound decay. Additionally, the higher impedance characteristic of these woods (Fig. 2) also means that they lose less energy through the supports because the impedance mismatch is greater. Consequently, tropical species with high density, high peak response, and low loss coefficient such as Amazon rosewood (*Dalbergia spruceana*), Honduras rosewood (*D. stevensonii*), African padauk (*Pterocarpus*

TABLE 2. Woods traditionally used for wind instruments.

Common name	Taxon
Norway maple	*Acer platanoides*
Sycamore (curly) maple	*Acer pseudoplatanus*
Ma-had	*Artocarpus lakoocha*
Cocuswood	*Brya ebenus*
European boxwood	*Buxus sempervirens*
Castella boxwood, castelo	*Calycophyllum multiflorum*
West Indian boxwood, zapatero	*Casearia praecox*
Brazilian kingwood	*Dalbergia cearensis*
Bahia rosewood	*Dalbergia decipularis*
Indian rosewood	*Dalbergia latifolia*
African blackwood, grenadill	*Dalbergia melanoxylon*
Brazilian rosewood	*Dalbergia nigra*
Ching-chan	*Dalbergia oliveri*
Brazilian tulipwood	*Dalbergia variabilis*
Cocobolo	*Dalbergia retusa*
Macassar ebony	*Dyospyros celebica*
Bubinga	*Guibourtia tessmannii*
Red chacate	*Guibourtia schliebenii*
Pear	*Pyrus communis*
Plum	*Prunus domestica*
Olive	*Olea europea*
Indian kamba	*Stephegyne parviflora*

Table 3. Woods traditionally used for xylophone bars.

Common name	Taxon
Granadillo	*Dalbergia cubilquitzensis*
Amazon rosewood	*Dalbergia spruceana*
Honduras rosewood	*Dalbergia stevensonii*
Merbau	*Intsia bijuga*
Wenge	*Millettia laurentii*
African padauk	*Pterocarpus soyauxii*
Cristobal	*Platymiscium pinnatum*
Pau rosa	*Swartzia fistuloides*

Table 4. Woods traditionally used for soundboards, sides, and backs.

Common name	Taxon
Silver fir	*Abies alba*
King William pine	*Athrotaxis selaginoides*
Norway spruce	*Picea abies = P. excelsis*
Sitka spruce	*Picea sitchensis*
Pine	*Pinus sylvestris*
Douglas fir	*Pseudotsuga menziesii*
Woods traditionally used for sides and backs of violins	
Silver maple	*Acer saccharinum*
Sycamore (curly) maple	*Acer pseudoplatanus*

soyauxii), Ching-Chan (*D. oliveri*) and Ma-Had (*Artocarpus lakoocha*) perform well by these criteria.

Woods for soundboards (chordophones)—The sound that a single plucked or bowed string produces is barely audible because one string sets only a small volume of air into motion. To produce sounds with satisfactory volume for our ears, the string must be coupled to a resonator, which has a better coupling to air to transmit the vibratory energy of the string and radiate the sound. In the violin family, the string is coupled via the bridge to the top plate of the instrument, the soundboard, which usually is a piece of softwood with the grain running parallel to the strings. The bridge transmits the vibrations of the string to the soundboard, which is connected to the back plate by the sound post and the ribs. The back plate is part of the vibrating structure and as such also contributes to radiating the sound. The shape and material of the body strongly influence the sound quality and the way in which it is radiated into the room. The *f*-holes in the top-plate, for example, have not only a direct influence on the vibrations of this soundboard, but also provide a passageway through which the air enclosed in the instrument's body communicates its oscillations to the outside.

Figures 2 and 3 illustrate this. Soundboard-quality woods are not only the best sound radiators of all, but they also have a low characteristic impedance. A low impedance is beneficial for sound transmission into the air. The impedance of spruce (*Picea* sp.) is very similar to that of maple, the traditional material for the bridge, back plate, and ribs. Maple also radiates sound well; its characteristic impedance is sufficiently high to act as a reflector for the air oscillations within the corpus of the instrument and to help radiate them into the room through the *f*-holes in the top plate (Table 4).

A closer look not only at the holes in the top plates of string instruments, but also at their overall shape reveals a feature common to almost all wooden musical instruments: both the instrument itself and the holes cut into it are either round or composed of arcs. Such instrument design is not only aesthetically pleasing, but it is also prescribed by the orthotropic nature of wood. The softwoods commonly used for soundboards, such as spruce, very readily split parallel to the grain, particularly when they have the shape of a plate and a modest thickness of 2–3 mm, as is typical for violin and guitar soundboards. By cutting curves and circles, the instrument maker avoids creating the stress concentrations associated with sharp corners.

Common beliefs are that regular playing and aging of wood improve the acoustical properties of musical instruments, that instruments that are exhibited in museums rather than played lose their quality, that "old fiddles sound sweeter," and that new ones need to be "played-in." Humidity and creep are believed to play an important role in this. Hunt and Balsan (1996) show experimentally that regular playing at intermediate or high humidities leads to an increase in stiffness and a decrease in loss coefficient. Beavitt (1996) presents experimental evidence to support his hypothesis that creep facilitated by humidity cycling results in changes in the overtone spectrum of the instrument, making it sound more sonorous and resonant. Segerman (1996, 2001) claims that creep in newly strung instruments affects the sound as it absorbs sound vibrations and that vibrations accelerate creep and thus help a newly strung instrument to settle in faster. Other research shows that the gradual decomposition and loss of hemicellulose with time lowers a wood's density without affecting its Young's modulus (Bucur, 2006). This avenue is being pursued further in current research to "age" soundboard wood by infecting it with a carefully selected fungus to lower the density at a constant Young's modulus and thereby improving the sound radiation coefficient and quality of the soundboards (Zierl, 2005).

Further research on the "playing-in" and ageing of musical instruments is required to explain conclusively the various observed phenomena in terms of the chemical, structural, and mechanical properties of wood and the environment to which it is exposed.

Woods for piano actions—So far we have considered the transmission of vibratory energy from the string to our ear via a soundboard. This leaves questions about how strings are excited and which role wood plays here. To produce sounds on a piano, the pianist presses down a key, which by a complicated mechanism, the piano action, sets a hammer in motion. The hammer strikes the string at a suitably chosen point and thereby excites it to vibrate. Over their lifetime, the various piano action parts, which consist of hundreds of small levers, are moved millions of times. The best materials for such an application are those that provide a reliable structure by having a high wear resistance in the moving parts, a long fatigue life, a high toughness to resist repetitive impact loading and, most importantly, that are dimensionally stable and shapable with great precision. For over 300 years, woods such as hornbeam (*Carpinus betulus*), beech (*Fagus sylvatica*) and maple (*Acer platanoides*) have been the prime choice for these applications because they fulfill all these requirements (Table 5).

However, not only mechanical requirements have to be fulfilled by the components of piano actions; some components are also chosen for their acoustical properties as described by Holz (2000). The hammershank, a stick 120 mm in length and c. 5.5 mm in diameter, holds the felt-covered hammer and is

TABLE 5. Woods traditionally used for piano actions.

Common name	Taxon
Norway maple	*Acer platanoides*
Silver birch	*Betula pendula*
Hornbeam	*Carpinus betulus*
Beech	*Fagus sylvatica*

traditionally made from birch (*Betula pendula*). First, its elasticity is tested by hand bending. Only those which return to their original shape are chosen, and these are then dropped onto a hard surface to excite their eigenfrequencies. Variations in density and modulus between sticks lead to variations in the eigenfrequencies by as much as a fifth for these fixed dimensions. The sticks are grouped as "dark," "medium," or "bright," depending on the sound produced and used in respective sections in the piano. Birch with its higher speed of sound is often preferred over hornbeam and maple for this application. How does the material for the hammershanks affect the sound quality of the piano, and why is a high speed of sound preferred, particularly for hammershanks in the descant registers of a piano? Might the higher speed of sound be an indicator of stiffness, and might the stiffness of the hammershank influence the contact time of the hammer and with it the sound produced? Lacking rigorous analysis, we can only speculate. So far, the only evidence in support of the hypothesis that hammershank "tuning" improves the sound quality of a piano is the long, continuing, and sometimes costly tradition of labor-intensive materials selection by an acoustic criterion.

Woods for violin bows—String instruments like the violin have the ability to produce steady tones when a bow is used to excite the string's vibrations. Originally, bows for string instruments had the same shape as musical bows and resembled those used for archery. The bow as we know it today is thought to have been developed by the French bow-maker François Tourte in the second half of the 18th century. He changed the shape of the bow from a concave to a convex curvature and is additionally thought to have been the first to recognize the qualities of the still preferred material for bows, the tropical wood pernambuco (*Guilandia echinata*, syn. *Caesalpinia echinata*), a wood that first reached Europe as a dyewood for red cloth in the 16th century (Table 6).

Mechanically speaking, the wooden bow stick acts as a leaf spring. It tightens the horse hair sufficiently so that by pulling it across a string the player can excite and control its transverse oscillations (Pitteroff, 1995; Wegst, 1996; Wegst and Ashby, 1996; Oberhoff, 2003). This interaction of string and bow is highly complex and still not fully understood. Neither are the complete requirements for the bow stick material. Generally, the quality of a bow is judged by the ease with which a top-quality sound can be achieved on a violin by an experienced violinist. Factors influencing the playability of a bow are partly structural (shape, point of balance) and partly material dependent (mass, stiffness, mechanical damping) (Woodhouse, 1993a, b).

TABLE 6. Woods traditionally used for bows for stringed instruments.

Common name	Taxon
Snakewood	*Brosimum guianense*
Pernambuco	*Guilandia echinata*
Massaranduba	*Manilkara elata*

Particularly, the damping performance of the bow material is thought critical for the bows playability. Additionally, the damping properties of the bow stick are thought to have a significant effect on the violin's sound. Of great mechanical importance is the bow's bending stiffness, which for a given geometry, depends on the Young's modulus of the bow stick material. Stiffness is important for three reasons. First, if a bow is too flexible, the desired horse-hair tension is reached only when the bow is almost straight. Second, if the spring stiffness of the stick-hair system is low, the control of the bow dynamics is reduced—this is particularly important for techniques in which the bow leaves the string, such as spiccato. And third, a low lateral stiffness leads to reduced bow control in this direction. Finally, the mass of the bow affects the bow's playability because it is considered advantageous if the lowest bow forces can be achieved by the self-weight of the bow and a small additional load applied by the player.

Pernambuco fulfills all these requirements. It has the desired density, bending stiffness, and damping behavior for the current violin bow design. However, like African blackwood, the most revered wood for clarinets, this tropical wood currently faces a high risk of extinction in the wild, which raises the question whether alternative materials for violin bows exist.

Figures 1 and 4 show that pernambuco is a wood with an exceptionally high Young's modulus for its density and a remarkably low loss coefficient, which is thought to be due to an exceptionally high amount of extractives (Matsunaga et al., 1996, 2000). Figure 4 also shows that alternative materials exist, which, on purely mechanical grounds, could make as good violin bows as pernambuco. Examples are the wood Swartzia (*Swartzia* spp.) and CFRP (violin-bow quality), to name but two. In the case of alternative woods, however, further experimentation is required to explore whether they fulfill the other important design requirements, namely, that they are straight and fine-grained, free from defects such as knots and splits, and whether they can be worked easily, whether they can be bent over heat, and whether they retain their curvature well. Trials by bow makers and musicians are needed for a thorough evaluation of alternative materials.

Other critical criteria are again those of "feel" and appearance. The alternative wood or material has to be acceptable to the musical community. As in the case of woodwind instruments, aesthetics plays an important role: new materials for musical instruments are generally not only chosen for mechanico-acoustical considerations, but also for optical ones. A wood which has the wrong look, color or feel may be rejected purely for these reasons—even if their performance was similar or even superior to other materials. CFRP initially suffered from such reservations and the fact that it is a synthetic material. Now it is more and more accepted by musicians, particularly for pieces that require a more forceful style of play. The CFRP bow's great advantage is that it is less prone to fracture than an old French pernambuco bow and that it can be replaced.

Wood and acoustics in buildings—Not only musical instruments produce sounds and noises. Buildings also do.

Everyone has heard the sounds of wooden floors and stairs that act as soundboards and amplify rather than dampen the sound of walking. To a building's inhabitants, they can be both a severe irritant or a charming reminder of the building's history. However, most often they are undesirable, unless they are part of a clever alarm system. Probably the best-known example of a floor deliberately designed to produce a noise, for added security, is the Nightingale Floor laid in Nijo Castle, Kyoto, Japan. Its sound is a very pleasant one, similar to the cheeping of a nightingale. It is produced when the nails on which the floorboards are freely suspended above the frame rub against the floorboards when walked upon (Yokochi and Yoshimoto, 2004).

Wood in concert halls—At least as much as we appreciate a home with pleasant room acoustics, we hope for sound optimization in a concert hall. The acoustics of rooms are complicated by the fact that the sound produced by musicians on stage reaches the audience not only directly, but also after many reflections on the surfaces of the room and the objects in it. Important quantities in room acoustics are the level of reverberant sound and the reverberation time because they determine the loudness, the clarity, and the liveliness of the sound (Rossing and Fletcher, 2004). Optimal reverberation times depend on the size and function of a room and range from 0.5 s for small practice rooms of up to 135 m^3 to 2.2 s in large concerts halls of 20 000 m^3 or larger, and also on cultural preferences: Europeans, for example, prefer 10% longer reverberation times than Americans (Knudsen, 1988).

Both the shape of the room and the acoustical properties of the materials and objects in it determine the reverberation time. Materials with a highly porous surface, such as carpets, drapery, and upholstery absorb well at high frequencies, while wooden panels act as reflectors and as resonators to absorb low frequencies. The use of wood for flooring, seating, reflecting panels, and wall panelling in concert halls in combination with the aforementioned textiles is thus not only aesthetically pleasing, but also necessary for the optimization of the sound field, the reverberation time, and the brightness of a concert hall for a wide range of frequencies.

CONCLUSIONS

Over the millennia, we have learned to use wood to its best advantage in musical applications. The musical instruments we know today are the result of the simultaneous optimization of material and shape for the expectations of musicians and audiences at a given time and in a given culture. Despite much scientific effort to illuminate the properties of universally accepted perfect instruments and their reproduction, we still rely mainly on the art, knowledge, and experience passed on from one generation of skilled instrument makers to the next. They have the expertise to judge the quality of the material for an instrument using eye, ear, and touch—and this often when it is still hidden in the trunk of a tree or in wooden planks.

The aim of this contribution is to illustrate the unique range and combination of mechanical and acoustical properties of wood, which still make it the material of choice for musical instruments and the lining of concert halls. Material property charts that plot acoustic properties such as the speed of sound, the characteristic impedance, the sound radiation coefficient, and the loss coefficient against one another for various woods are used to illustrate and explain why spruce is the preferred choice for soundboards, why tropical species are favored for xylophone bars and woodwind instruments, why violinists still prefer pernambuco over other species as a bow material, and why hornbeam and birch are used in piano actions.

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