Technical Note

Note: Technical notes are aimed at promoting discussion. The views expressed are not necessarily those of the editors or the Australian Acoustical Society. Contributions are not formally peer-reviewed.

MATERIALS AND MUSICAL INSTRUMENTS

Neville Fletcher
Research School of Physics and Engineering, Australian National University, Canberra

Many of the musical instruments with which we are familiar today have derived their basic structure from "natural" objects, and their detail has depended upon the materials from which they can be constructed. This brief exploration of the musical instrument scene shows how this both underlies and perhaps limits their future development.

INTRODUCTION

The evolution of musical instruments over the ages has depended in large manner upon the materials available from which they could be made. It is interesting, therefore, to examine the dependence of the behaviour of musical instruments upon these materials and to see in what ways they restrict or enhance the instrument performance.

PERCUSSION INSTRUMENTS

Music probably began in the humanities as a form of song, imitating to some extent the songs of other animals but with the addition of meaningful words so that the song told a story. The oldest musical instruments were probably made to enhance these songs by the addition of rhythmic sounds and began the evolution of percussion instruments. The first of these were simple sticks of wood clapped together, like Australian Aboriginal clap-sticks, but other cultures had hollow logs that could be beaten with heavier sticks, and these instruments were gradually evolved to more sophisticated forms. The peak of the evolution of these wooden percussion instruments was probably the xylophone and its partners, in which wooden planks of graded length were carefully supported so that they produced some form of musical scale when struck by a wooden hammer. These planks were further refined by thinning the central section so that several modes were in nearly harmonic relation, thus giving a more pronounced musical pitch.

These developments depended upon many of the intrinsic properties of wood, particularly that it was fairly consistent in elastic properties from one piece to another of the same species and quite low in internal damping so that the sound would not decay too quickly. It also needed to be easily shaped by the available woodworking instruments and long lasting enough for the efforts to be worthwhile. Since these early times, wood has been used in a large variety of other musical instruments, as will be discussed later, but it has always stood out as a readily available, simply workable, and long-lasting mechanical material.

Later in the evolution of humanity came metals, and these were of greater variety. Setting aside the "precious metals" gold and silver, those that were readily available from mining operations were copper, tin, lead and zinc, with iron entering the scene much later. Pure metals are too soft for most uses, so alloys were developed for use in making domestic or military objects. The most useful of these alloys were pewter (typically 85% tin and 5% lead), brass (typically 60% copper and 40% zinc) and bronze (typically 88% copper and 12% tin). Pewter had a low melting point and was rather soft, so that it was good for making domestic items, while brass and bronze were largely used by the military for armour and weapons. Brass was a "tough" alloy that would bend under stress, while bronze was more brittle and likely to crack, but both had melting points low enough (900–950°C) to make them useful casting alloys. When iron later became common it was widely used, but had a higher melting point which made manufacture more difficult.

Brass and bronze were the obvious candidates for making various percussion instruments since they could be melted and cast into shape in a fairly simple way. Bronze was the preferred material for large heavy objects such as bells, since it was very dense and had low internal loss, giving a sustained sound. Many bell shapes were developed, with different traditions in different countries. We are most familiar with the West European church bell, the shape of which is designed to produce a mode sequence close to 0.5, 1.0, 1.2, 1.5, 2.0,... with the 1.0 mode being the nominal pitch. One significant thing is the mode 1.2, which is a minor third above this nominal and gives the bells their particular sound. Bells from other cultures have different shapes and different sounds, but bronze casting is straightforward and gives sustained sound, and bronze bells last for thousands of years. Without bronze we would not have the bells we know today.

For percussion instruments with rather thin walls, such as gongs and cymbals, special bronze alloys are required, since brass will often deform under the impact and normal bronze might break. The sound of these instruments is very much different from that of bells, largely because of the fact that their vibration amplitudes are comparable with or larger than their material thickness, so that nonlinearity leading to harmonic production and even chaotic oscillation is common, giving impressive sounds to highlight important events in musical performance.

The final form of percussion instrument to be mentioned is the drum, which originally consisted of a piece of animal skin stretched tightly over some sort of retaining edge. Apart from the development of tuned instruments such as the tympani and the use of elastic polymer sheets instead of animal skin, very little has changed over the centuries.

STRING INSTRUMENTS

Much more important for modern music than are the percussion instruments are the string instruments, which include plucked stings such as the guitar, bowed strings such as the violin, and hammered strings such as the piano. In all cases the string itself is unable to radiate appreciable sound intensity because its diameter is so small compared with the sound wavelength involved, so that it is necessary for the vibrational energy of the string to be transferred to some much larger structure that can radiate efficiently. In nearly all cases this radiating structure is made of wood.

Let us begin with the violin family, the most important of all string instruments in a modern orchestra. The strings are traditionally made from animal gut, which had a considerable influence on tone quality since it had large internal losses at high frequencies. Modern violins mostly use synthetic polymers, which have less loss at high frequencies and so produce a brighter sound. The higher strings are even made of metal, which further reduces the high-frequency losses.

The violin body is made from wooden plates with strong edge support, and the most important part is the slightly domed top-plate to which string vibrations are conveyed through a bridge with one of its posts supported by a peg running through to the back plate, this converting the sideways forces produced by the bow-excited vibrating strings into vertical forces that excite plate vibrations. A very important thing about wood is that it is elastically very anisotropic, with the bending modulus being nearly ten times as large along the grain as it is in the transverse direction. This means that the lowest vibration mode should ideally have a shape about three times as long in the grain direction as in the transverse direction, and this is approximately the shape of a traditional violin. This lowest mode can therefore be efficiently excited and gives a strong fundamental sound to the instrument. Of course things are much more complex than this, for the back plate is also excited into vibration, and the enclosed volume, vented through the "f-holes" contributes another important resonance. The shape of the violin is also, of course, influenced by the need to allow access to all the strings by the bow, which gives the overall "figure-eight" form.

The wood used for the violin has been the subject of extensive study, particularly in relation to the excellent violins produced by Stradivari and Guarneri in Cremona, in the early eighteenth century. Was there something special about the wood used – grown in the "Little Ice Age" of the seventeenth century? The answer is not yet clear, but modern violins can now be made that surpass the perceived quality of these "old masterpieces" as judged in "blind" playing and listening tests. Modern experiments with different kinds of wood show that this does have a pronounced influence on tonal quality, as is indeed to be expected from the variations in elastic anisotropy and vibration losses. Much study is still in progress since modern makers want to produce the best possible instruments.

All these principles apply in equal measure to the viola, cello and double-bass, the larger instruments of the standard string group. In a famous development, American violin maker Carleen Hutchins and Harvard physicist Frederick Saunders expanded the scope of the violin family to a total of eight members using the acoustical principles underlying the classical Italian violins, and this "New Violin Octet" covers a range from that of the standard double bass to one octave above the violin. Quite a number of these octets now exist around the world.

Since elastic anisotropy is important in reproducing the quality of classical violins, this rules out many materials for their construction – one could make a violin body out of thin metal sheet, for example, but it would sound very different! The most likely contender is fibre-reinforced plastic composite material, since the elastic properties, and particularly the anisotropy, can be adjusted in the design. Quite good violins have been made using such composites for the body, but they do not possess the beautiful appearance of high-quality wood.

Very much the same principles apply to the materials from which the bodies of guitars are made, and for very much the same reasons. One major difference is that the top-plate of a violin is curved to support the stress of the string tension, and this raises its vibrational mode frequencies, while a guitar top plate is flat and stiffened by a set of carefully arranged braces. There are thus somewhat different criteria to be used in choosing appropriate materials.

Taking one step further, instruments such as the harpsichord and piano also rely upon a wooden soundboard to translate the vibrations of the strings into radiated sound. Many more compromises are needed here, however, because of the large size of the soundboard and the fact that the great tension produced by the large number of metal strings is supported by a frame made either of wooden or steel beams. The soundboard is stiffened by a pattern of braces but there is still an influence of the material properties upon its vibration and consequently upon the sound produced.

WOODWIND AND BRASS INSTRUMENTS

Wind instruments became popular long ago because of the sustained loud sounds they could produce. Their introduction into music appears to have been achieved because of the natural occurrence of structures that could make loud tonal sounds when blown. An early example is the conch shell, which has the structure of a conical tube wound in an elongated spiral. Blowing through a hole made near the narrow end of this spiral could produce a loud trumpet-like sound, and this is still widely used in ceremonies in some Buddhist temples in Asia, only one or at most two different pitches being produced. In this case it is the structure rather than the material that is important and the derived musical instruments generally used metal when evolving into their modern form.

A related but very different case evolved in Australia, where termites hollowed out the centre material of the trunks of small Eucalypt trees. The hollow trees could be detected by tapping on the trunk and then cut down to produce tubes typically about 150 cm in length and with slightly flaring internal diameter, typically about 4 cm at the narrow end. Figure 1 shows a picture of such a tube called a didjeridu.

Figure 1. A didjeridu is crafted by termites that eat out the centre of the trunk of a small Eucalypt tree to produce a slightly flaring tube

The third, and perhaps most important, shaped material giving rise to wind instruments was bamboo, which grew smooth uniform tubes of various lengths and diameters with blocking partitions at intervals along their length. Once again the material here was not of great importance, but the existence of such varieties of tube lengths and diameters led to the development of instruments with a cluster of pipes of graded length which could be used to play tunes, as in the panpipe as shown in Figure 2, or single pipes with finger holes as in the Japanese shakuhachi or the middle-European flute.

Figure 2. A set of panpipes made from bamboo. These pipes are sealed at the lower end by a natural partition in the bamboo

Materials come into importance when these traditional instruments were formalized for modern use. Lip-blown instruments derived from the conch shell were mostly made using brass, because this material was readily available and, because of its non-brittle nature, it could be mechanically worked into flaring tube structures. These techniques have persisted until the present day with only minor variations to improve appearance and stop corrosion. The sound of a brass instrument is determined largely by its shape and that of the mouthpiece, but there is some minor influence from vibration of the thin walls of the flaring horn, determined more by shape and thickness than by material properties.

Wood is also widely used for the class of "woodwind" instruments, particularly the flute, oboe, clarinet and bassoon. The instrument is machined from the wood and desirable material properties here relate mainly to the smoothness of the wood surface inside the tube, for this influences acoustic losses. Durability and appearance are also important and hardwoods from rainforest environments such as ebony are particularly favoured. One other feature of some of these instruments is the fact that they are excited by vibration of a reed valve held between the lips, and the material properties of the cane used to produce this reed are of great importance. Reed-making is essentially a hand-crafting process and, while working reeds can also be made out of plastic materials, they are generally considered to be of low musical quality.

A relatively recent development in woodwind instruments was the mid-nineteenth century development of flutes made from silver alloy tubing by Theobald Boehm (Figure 3). His major contributions were actually a mechanism involving coupled soft-padded keys that was later transferred to other woodwind instruments, and the conversion of the tapered wooden flute tube to a cylindrical metal tube with a tapered head-joint. Because the flute tube is cylindrical there is little opportunity for wall vibrations to influence sound quality so flutes are typically made of silver-plated copper-nickel alloy or of silver with 5 to 10% of added copper to harden it. Silver flutes are generally superior to those made from copper-nickel alloy because they are made and adjusted by hand, not on an assembly line, but this has little to do with the materials involved. Despite this, top-quality flutes are often made of gold and perform rather better than silver flutes, not because of the material but because they are made and finished by the best maker in a top company. This progression has even been carried further to platinum, with a dedicated musical composition by Edgar Varese entitled "Density 21.5".

Figure 3. A classical wooden flute with simple finger holes and a modern silver flute with complex Boehm finger keys (not to quite the same scale)

The other "woodwind" instrument that uses metal instead of wood is the saxophone, developed by Rudolf Sax in the nineteenth century using the coupled-key system developed by Boehm. The instrument is made from a metal alloy, typically brass or bronze, and produces a loud mellow sound, but this is due to the widely tapering enclosed air column rather than to the material. Because of the shape of the saxophone, it would be difficult to make it from anything except metal, or perhaps plastic.

PIPE ORGANS

Pipe organs have been on the musical scene since the time of the Romans, two thousand years ago, and can be regarded as derived as a mechanical version of the panpipes. It is by far the largest present-day musical instrument, with perhaps the exception of the carillon. The Sydney Opera House organ, (a small fraction of which is shown in figure 4), contains nearly 10,000 pipes which are controlled by five keyboards and a separate pedalboard, while the Sydney Town Hall organ has a "square conical" longest pipe of 64 feet (20 metres) which produces a fundamental of 8Hz from the bottom key of the pedalboard. The sounding of the pipes in an organ is controlled by mechanical, pneumatic or electric links between the keyboards and the valves that supply air to the pipes, and varies from one organ to another. In the present context, however, the matter of interest is the materials from which the organ pipes are made.

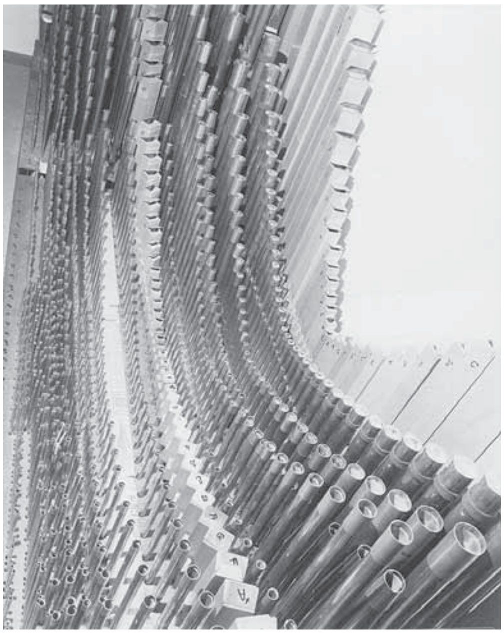

Figure 4. A small fraction of the ten thousand pipes making up the Sydney Opera House organ

From the discussion above, it is clear that, provided the material used has a smooth surface, it has little effect upon the sound of a cylindrical pipe. Some of the pipes of an organ, however, are square rather than circular in cross section and are made of wood. The walls of these pipes can be made to vibrate under the influence of internal acoustic pressures and so may have an effect upon tone quality when the playing frequency or one of its harmonics is a near match for a vibration frequency of the wall panels. The walls of these wooden pipes are generally sufficiently thick that this is not a significant matter, but the effect can be detected by acoustic measurements.

In the case of the cylindrical or conical pipes that constitute most of the organ, the material has little effect upon sound quality, though this might not be true if the walls were very lightly damped because the cylindrical symmetry is broken at the pipe mouth where there is an aperture across about half of the pipe diameter. Such resonances would be regarded as intrusive, so there is no desire except to ensure that they do not arise. The main problem with organ building, rather than design, is therefore to ensure that thousands of pipes of different sizes and shapes can be made as simply as possible and with opportunity left for detailed adjustment after the organ is assembled.

Many different metals could be used to make the pipes, but the alloy of choice is a tin-rich tin-lead alloy similar to pewter. It has the advantages of a low melting point, 170 to 230°C, and is both strong enough to stand upright for hundreds of years without distortion and soft enough that the pipe mouth can be easily adjusted by the organ builder using simple hand tools. To make the pipes, a rectangular box of liquid metal, with one of the sides having a gap of about 1mm along its bottom edge, is slid along a flat table of marble or other similar material and the result is a uniform layer of the tin alloy that solidifies in less than a minute. This layer can then be lifted up and cut into pieces that are wrapped around wooden rods and soldered closed to constitute organ pipes. These cylindrical sections are then soldered onto the smaller structures constituting the pipe mouth and supporting section. These techniques can be used over dimensions ranging from millimeters to meters.

Very few difficulties have been experienced with these methods or the resulting pipes, one of the few being interestingly known as “tin pest” in which the shiny tin pipes develop white powdery surfaces and may even corrode away. Interestingly this is not a true case of corrosion but rather of phase change in a tin-rich alloy at the sub-freezing temperatures that may be experienced in Scandinavian churches!

Since the metal from which the pipes are made has little effect upon tone quality, it is possible for some organs to be designed with display pipes made from copper or some other material of different appearance, or for them to be painted with appropriate decorations, none of this having any significant effect upon tone quality. Figure 5 shows a variety of organ pipes all sounding the same note but with differing sound quality because of their differing shapes.

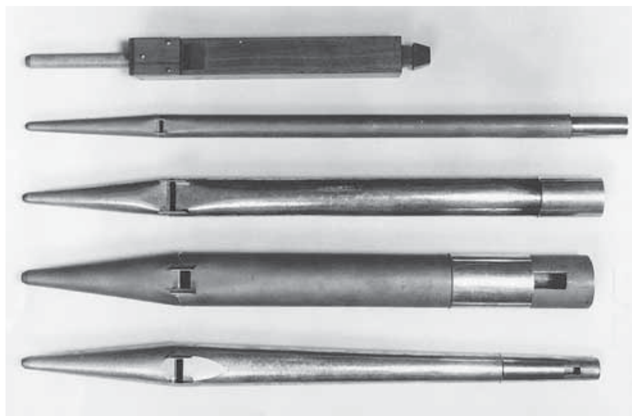

Figure 5. A variety of organ pipes all sound the same note. The pipe at the top is made from wood, the two shiny pipes are made from tin-rich tin-lead alloy and the two dull pipes are made from lead-rich alloy

CONCLUSIONS

The relationship between musical instruments and the materials from which they are constructed has a long history, and many instruments have evolved because of the prior existence of specialized materials or natural structures. Some aspects of modern musical culture have opted to divorce from this relationship and to produce “musical” sounds by purely electronic means that require no real instruments. While this certainly gives “musical freedom” to the composer, the absence of an identifiable instrument and performer detracts from the influence upon the listener. The next step, perhaps, is to bypass the electronic equipment and have simple “brain to brain” transmission of musical compositions through neural couplings. But perhaps not!