421.22. The H-S system suggests including with the latter those Native American flutes that have an internal *and* an external duct, but they are so different that it seems better to give them their own designation as 421.23. And if duct flutes with a stopped end without fingerholes are 421.221.31, then those Moroccan flutes that *do* have fingerholes, the lowest of which is not fingered but provides a side-hole substitute for the open end, should be 421.221.32.

The reed instruments we have to leave as they are, despite the comments above, but among the reedpipes with free reeds, 422.3, we might place the side-blown horns that use a free reed rather than the player's lips in a group of their own since they have only a single hole in the apex (like many African side-blown horns) rather than the number of fingerholes that those of bamboo or cane possess, and call them 422.33.

With trumpets, one has to ask, what is a "natural trumpet"? In H-S, it is an instrument "without extra devices to alter pitch." If a fingerhole is an "extra device to alter pitch," however, we need to recognize that not all conch trumpets are natural, as we saw above from Fiji, and that many, perhaps even most, African side-blown horns have a hole in the tip for that purpose.

We also have to delete the word *throughout* in the definition of 423.231, valve bugles: "The tube is conical throughout." The inventor who can produce a conical tuning slide will make a fortune. And as Arthur Benade pointed out, today it is the horn whose tubing is predominantly cylindrical and the trumpet that is predominantly conical, but if we keep the H-S numbers and names and forget those definitions, which apply only to our own orchestral instruments, do we with our own instruments know what is a horn and what is a trumpet.[21]

It was precisely such additions, amendments, and discussions that Hornbostel and Sachs were expecting when they published their *Systematik* as *Ein Versuch*. They expected, too, that we and others would expand their categories to cater for the finer and more precise definitions. For example, several of their categories go down to 9 figures, and with suffixes to show how the instruments are played to even more; others have no more than three figures. This is not because those are simpler categories but because it is left to us to do some of the work of classification, to look at those groups of instruments and to see the smaller piles and heaps for which they have given us only the mounds. They provided, in their introduction, an example of how this might be done among the members of the xylophone family. There is still much for future generations to do in this area.

Scales and Music

However many instruments we have, we cannot produce music until we decide what notes they can or should play. There is an infinite number of potential notes in the octave, and every musical culture has to decide which of them to use. Almost all peoples of the world do recognize the octave, even if only as the difference between what men sing and what women sing. We speak of "singing in unison," but when men and women sing unisons together, they are not true unisons (*unison* means "as one"). They are singing the same note-name, but at that distance apart that we call the *octave* (from the Latin for "eight," because we have eight notes when we go from A up through the alphabet to G and then to the next A), the women an octave higher than the men.[22]

Other peoples have different numbers of steps to the octave. Five steps, a pentatonic scale (from the Greek *penta*, "five"), is very common (four is much less usual and three very rare). One often sees references to *the* pentatonic scale, meaning the equivalent of the five black notes of our piano, and something like this is not unusual in many parts of the world, although which note you start on makes a big difference to the order of different sized steps, whether you start on F♯, C♯, or any other note. This is not the only pentatonic scale, however, because the widths of the five steps vary quite considerably from one people to another. In some places, the steps are nearly equal, for instance, in Java where they have two different scales, one of which, *slendro*, has five steps that vary only slightly in size.

To measure intervals we use a unit called the "cent," our equivalent of the millimeter and equally artificial but equally useful. There are 100 cents in an equal-tempered semitone (any one of the steps from note to adjacent note, white or black, of our piano) and 1,200 in an octave.[23] Five equal steps would each cover 240 cents, but while three of the steps in the slendro scale are usually around that size, one is usually wider, up to about 260 cents, and another rather narrower, perhaps as little as 220 cents.[24] Since 10 cents (one tenth of a semitone) is usually reckoned to be the smallest interval that most people can perceive, the difference of 20 cents, and usually less, between the average step and the wider or the narrower step of the slendro, is very little. The other Javanese scale, *pelog*, has seven steps—although they often use only five, or occasionally six, of these—but these seven unequal steps are very different from our unequal seven steps. They are different, too, from the steps of some other heptatonic (Greek *hepta* = "seven") scales of the Southeast Asian mainland, where, as in parts of Central Africa, one finds equi-heptatonic scales, seven equal steps.

Our heptatonic major scale is unequal, with steps of two sizes, whole tones from C to D, D to E, F to G, G to A, and A to B, with semitones, only half as wide, from E to F and B to C—a scale with seven equal steps sounds very different.

Many other heptatonic scales exist, or have existed in the past, using all sorts of intervals. Ellis was the first to publish precise measurements of exotic scales.[25] Since then, many other sets of measurements have been published in the ethnomusicological literature, sometimes as the basis for equally exotic hypotheses.[26] The one thing that all the measurements have in common is that while an equi-heptatonic scale has steps of 171 cents each, if some steps are going to be narrower than that, others must be wider if all are going to fit into a 1,200-cent octave. Thus if on our piano we want to keep to our conventional seven steps, some of which are to be whole tones, we cannot have more than five of them, and the others must be semitones. If all steps were whole tones, we could fit only six of them into the octave, a hexatonic scale (Greek *hexa* = "six"), as Debussy did when he wrote music using the whole-tone scale, six steps to the octave (C, D, E, F♯, G♯, A♯, C, if one starts on C).

The 100-cent semitone and 200-cent whole-tone steps of our current equal-tempered scale are a very modern convention. They were first devised between 1550 and 1600 by a number of theorists, but they were used only sporadically thereafter until the mid-nineteenth century. In our modern orchestras and choirs, they are used only when the presence of a piano or other modern keyboard instrument, or the performance of atonal music, makes them necessary.[27]

Every musical culture has its preferences and its own conceptions of the ideal of being "in tune." Ours is a pure consonance with the absence of beats, those vibrations that are heard when two people playing the same note are slightly out of tune and that are also heard when two or more different notes of the harmonic series are played together but again slightly out of tune. This absence of beats can only be achieved by using a scale made up precisely of those intervals of the harmonic series that correspond to the notes of a scale. A more complete series can be seen in figure 0.1 in Explanations and Definitions; here we include only those useful for this purpose (see figure AW.1). It will be noticed that three harmonics are missing here, numbers 11, 13, and 14. These do not fit our preferred series of pitches, as we have noted previously. The pitches that they would represent can be determined from the others: if G is a fifth up from the lower C, F is a fifth down from the upper C, and so on.

If we start a scale on the eighth harmonic, where the notes of the series come close enough together to do so, we can build a scale with "natural" steps and produce chords with beautifully pure intervals.[28] This works very well melodically and harmonically with voices, for example in a church choir, and with any instrument whose pitches were not preestablished by a tuner and then fixed. It cannot work on, for example, a keyboard instrument that has been tuned to these "pure" or "natural" intervals starting on C, because the moment one wishes to change key from C major (in which it sounds lovely), one immediately strikes a problem. If we use the numbers of each harmonic as the integers of a ratio, it becomes obvious that the ratio 10:9 must be smaller than 9:8, and so we have two different sizes of whole tone: from C to D, a major tone of 204 cents, and from D to E, a minor tone of 182 cents. If our scale is to begin major tone, minor tone, semitone, as the harmonic series provides, we cannot start it on D on a keyboard that has been tuned to C because the first step, D to E, has been fixed by the tuner as a minor tone whereas we now want a major tone.

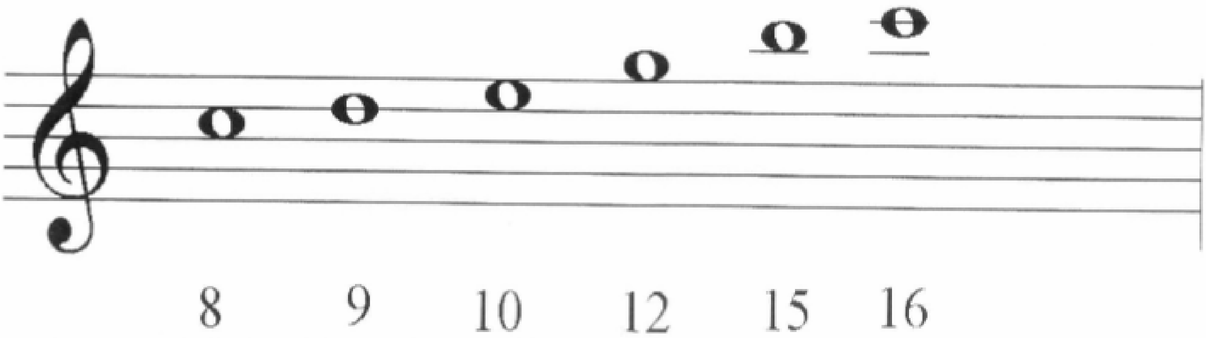

Figure AW.1. Harmonics from Which to Make a Musical Scale

This had already been recognized as a problem in ancient Greece, where the philosopher and mathematician Pythagoras came up with the logical solution of having only one size of whole tone, the major tone of 9:8 that measures 204 cents. However, the interval of a pure major third, C to E, 10:8 or 5:4, measures 386 cents, the sum of the two different whole tones, the major tone (204 cents) plus the minor tone (182 cents). Pythagoras's two major tones, 204 + 204 cents, produced a horrible third of 408 cents, wildly sharp. The sevenths were also very sharp, but, for melodic use, a sharp leading note, the base for the last step of the scale, was rather liked because it pushed the music on toward the keynote.

This process, changing the tuning of one or more notes of the scale to produce more practical results, is called tempering, so this example is known as the Pythagorean temperament. Once the use of the organ became common in church choirs, from the ninth century on, the Pythagorean temperament had perforce to be adopted, and its use spread into instrumental music also, with the invention of the string keyboards, such as the harpsichord, in the early 1400s.

The major third was regarded as a dissonance in the Middle Ages, and this was because in the Pythagorean temperament, at 408 cents, it was indeed dissonant. This had not mattered in ancient Greece, where they did not use harmony as we do, but in the Middle Ages it did matter. When harmonic theory progressed to the stage where it wanted to use the third, the Pythagorean temperament had to be abandoned so that one with a better third could be adopted in its place. Nobody, though, wanted to go back to two different whole tones, for keyboard instruments were by then in use everywhere, and therefore a new size of whole tone was constructed, dividing a pure major third (386 cents) in half, taking its average or mean. This is why it is called the meantone temperament.

This is not the place to go into the full history of European temperament, nor into the mathematical problems behind it. It may suffice to say that the problems are inherent in Nature because our pure, beat-free intervals do not add up as we would wish them to do. A fifth, C to G or the ratio 3:2, measures 702 cents; an octave, C to C, 2:1, measures 1,200 cents. And so if we pile fifth upon fifth, C to G, G to D, D to A, and so on, we shall never return to C, only, after the necessary twelve steps, to B♯, 24 cents higher than C. The major third measures, as we have said, 386 cents, and piling three of them on top of each other, C to E, E to G♯, and G♯ to C, give us only 1,158 cents, woefully flat of the octave, 42 cents short. As we try to tune our instruments, the better in tune the thirds are, the worse the fifths become, and vice versa. The history of temperament since the late fifteenth century has been that of compromise: to make the fifths as pure as possible without rendering the thirds intolerable.

Our modern equal temperament has fifths that are almost pure (700 cents instead of 702) and thirds that are not quite as bad as Pythagorean (400 instead of 408) but still quite nasty, a lot worse than pure (386). The thirds are bad enough that organs were still tuned in meantone in the 1850s, albeit a meantone that was a better compromise than the one that had been first devised in 1523.[29] Harpsichords and pianos have sounds that die away fairly quickly, so that the built-in pulsations of the equal-tempered third are no worse than unpleasant. Because the organ can sustain a chord almost indefinitely, however, those thirds were intolerable to a musician's ear, hence the adherence to a form of meantone or other unequal (often called irregular) temperament.

Even though meantone had been improved over the centuries by making the thirds slightly wider than pure and thus improving the fifths, as composers became more adventurous and wanted to change key more often during the course of a piece of music, if they had started in a key where the note between A and G was tuned to G♯, they might need to have an A♭ instead. The resulting chord was so out of tune that the beats between the E♭ and the G♯ were so fast that they howled like a wolf. And so some keyboards had the G♯/A♭ key cut across its middle and provided with two strings or pipes, so that one could be tuned to each note. The same might be done to D♯/E♭ because these four notes were the worst affected by meantone. For the same reason, all the flutes that Johann Joachim Quantz built for himself and for his royal master, Frederick the Great, had two keys on the foot joint, instead of the more usual one, one for E♭ and the other for D♯.[30] A number of other makers followed his example. Both Pythagorean and meantone scales, because of the way they are constructed, have to have two different sizes of semitone, with the result that sharps and flats, normally just one note on the keyboard, are not the same as each other. In meantone, the difference between them is the 42 cents that we met a few lines above.

Other makers and players went much further. Vicentino's *arcicembalo* of 1555 divided every key, some more than once, so that every interval might be in tune on that harpsichord. There have been modern equivalents with thirty or more keys to the octave, such as the Janko piano, but these like the arcicembalo, as well as being expensive, tend to tax the player's memory to an excessive extent, trying to remember which key went with which other key to be in tune in any particular context. Pianists and organists today (few of whom tune their own instruments) put up with equal temperament, and most other musicians, save when playing with piano or organ, keep as well in tune as they can with their colleagues, keeping intervals as pure as possible by making notes a little sharper or a little flatter, as may be needed, than they would be in equal temperament on the piano.

String players can move a finger very slightly up or down a fingerboard, and singers have no problem with it, but wind players have to fudge things by lipping the pitch a little up or down. This is why it is a mistake to make wind instruments too rigidly "in tune," even though that might make things easier for beginners. They need to be flexible enough to allow for a little variation in this way.

One effect of equal temperament was the loss of color in music. With earlier temperaments, each key was slightly different in its intervals. Even without having perfect pitch, one could tell a difference between the keys; some were brighter, some were darker, and composers would often choose a key accordingly. This was certainly true in the various meantone temperaments, and it remained so in what are called the irregular temperaments, as may be heard in works such as Bach's *Well-Tempered Clavichord*, where the music in each of the preludes and fugues suits the character of each key.[31] This is also the origin of the numerous theories and conceptions of color in music—a difference of tuning produced a perception of a different color and led to the invention of the color organ that Scriabin included in some of his music. It was a purely subjective perception, though, for few composers ever agreed in assigning the same color to the same key.

With our own scale so firmly fixed to the harmonic series and our musical harmony so heavily biased toward thirds, fourths, and fifths, it is difficult for us to comprehend the musics of those other peoples who do not hear things that way. And yet, around the world, it is only in the Indian subcontinent that we hear music akin to our own. There, tuning is even more precise than ours, for they commonly work against a drone as we have already discussed. In their theoretical basis for scales, dividing the octave into 22 *srutis*, they have a similar concept to our major and minor tones, with some whole tones larger than others.[32]

But India is the exception. In most other cultures, the fifth and third simply do not exist. This is a permanent puzzle for musical psychologists. The sounds of the natural harmonics are all around us. If one listens with care to any musical note one can hear at least a few overtones, and for most instruments, these are the notes of the harmonic series (but not with percussion—and especially not for the idiophones, for most of their overtones are inharmonic). In Africa, all the pitches produced by the musical bow are those of the harmonic series, and yet this has had little effect on their music. Why this should be, we do not know, but this, and the preference for monody over harmony, are the main reasons that so many musics sound so strange to us, and ours, of course, to them.

The Sounds of Science

The main problem with most of our published studies of musical acoustics is that—apart from the excellent explanations of how sound waves behave and the basic facts about instruments such as the larger or longer, the lower-pitched—the major part of the information is *post hoc*. The books explain what has happened when sounds are made on known instruments, not necessarily what will happen or might happen with an instrument that has not been seen or studied before. Thus the behavior of many instruments from cultures other than our own remains unexplained because they are not instruments that the acousticians have encountered, and they have no theoretical, or *propter hoc*, basis upon which to form any opinions.

We shall not try here to cover all these lacunae, partly for reasons of space, but chiefly because many of the problems have yet to be studied and the answers remain unknown, though we shall be forced to enumerate some, at least, of the anomalies. We shall also try to explain simply and untechnically the basis of how instruments work, at least insofar as we need to do so to amplify or elucidate remarks in our text.

Let us begin with flutes, all those instruments that one sounds by blowing across a hole, as children do with a bottle or pen top, or for that matter a whistle or a recorder. If, as well as a pen top, one has an open-ended tube of the same length and diameter, that tube will sound about an octave higher than the pen top. Leaving aside all the technicalities (these can be found in any book on musical sound),[33] the sound has to go to the bottom of the pen top and then back up again to the top to escape and thus travels twice as far as it does from one end of the open tube to the other, equating with a tube twice as long and so an octave lower. It is not *exactly* an octave, because the air column has an impetus of its own and continues for a very short distance beyond the open end of the tube, just as, when a car brakes suddenly, we are forced forward in our seats because we have an impetus independent of that of the car. This, on the instrument, is called "end correction." If the tube were doubled in length, the end correction would also double, whereas that of the pen top remains single. So to produce an exact octave, the length of the end correction has to be taken into account as well as that of the tube.

Advantage is taken of this octave difference between stopped and open tubes by organ builders. As we have seen, many organ pipes are duct flutes. The pipe for the C below the bass stave, two octaves below middle C, must be eight feet long and organists therefore call it the 8-foot C; the C an octave lower is the 16-foot, and so on. Since these are the speaking lengths, from the lip to the end, one also needs another foot or more in length for the pipe to stand on. Pipe metal is expensive, and when one remembers that one needs a pipe for each note of each rank of pipes, or stop, the cost mounts up very rapidly. Replacing the 16-foot ranks with stopped 8-foot pipes represents a considerable saving of cost, as well as of space, and replacing the 32-foot with stopped 16s and the 64-foot with stopped 32s saves even more.

There is a difference of tone quality due to the different harmonic content. A stopped pipe loses its even-numbered harmonics, or at least greatly weakens them. However, the savings in cost and space far outweigh this, and the different tone qualities are themselves advantageous in creating different combinations of sounds.

As we observed with the panpipe in chapter 3, a player can tip the top of the instrument against the lower lip, so slightly covering it, reducing its aperture and thus slightly altering the pitch. This is because, all other things being equal, the wider the aperture, the higher the pitch produced, and the narrower the lower. This is also one of the ways organ pipes are tuned. The tuner has a set of solid and hollow cones. Inserting a solid cone into the end of the pipe opens it slightly and sharpens the pitch; placing the hollow cone over the end constricts it slightly and flattens the pitch. We described this effect of the area of the open hole, here the end of the organ pipe, in chapter 3's discussion of vessel flutes.

Turning to the reed instruments, a woodwind instrument of cylindrical bore that is reed driven (flutes behave quite differently) will function as what organists call a "stopped tube." It sounds an octave lower than a flute of the same length, and when overblown (blowing harder, increasing the airspeed, so that the pitch jumps up to the next overtone), it sounds a twelfth, an octave and a fifth, above the fundamental, or lowest note. A reed-blown tube that widens from the reed to the bell, often called a conical bore or conoidal (conoidal because it widens conically rather than being exactly a cone), however, overblows to the octave and while its fundamental sounds lower than that of the flute of the same length, it is not as much lower as that of the cylindrical tube.

To take practical examples, if one had a flute, an oboe, a soprano saxophone, and a clarinet all with the same length of bore (in other words ignoring the length of the flute from the cork to the top of the head), the clarinet would sound an octave lower than the flute, and the oboe and the saxophone would sound much the same as each other (the saxophone has a wider bore that makes some difference) and a little lower than the flute. The reason that the oboe and saxophone are lower than the flute is that, although one may refer to them as being of conical or conoidal bore, this is not strictly true; a cone comes to a point and these do not, because there has to be room for a mouthpiece or a reed and staple. The explanation seems to be that when they are blown, the cone or conoid completes itself partway down the player's gullet and that this, rather than the body of the instrument, is the true length; the pitch would be the same as that of a flute of that same length.

We shall return shortly to what happens next on "our" instruments, but we must emphasize here that the type of reed has nothing whatever to do with this behavior; it is solely a matter of the shape of the bore: the saxophone, with its clarinet-like mouthpiece and single reed, behaves in exactly the same way as the oboe with its double reed; both oboes and bassoons may be, and sometimes are, played with special single-reed mouthpieces adapted to their size (see figure 4.1) without this having any different effect on their musical behavior.

The problem, with which we started this afterword, is that the above statements do not always hold true with instruments from other cultures. We have, for example, already met the forked shawm, where a mainly cylindrical body is rendered acoustically conoidal by the use of a series of short cylinders, each a bit larger than the previous, so producing a stepped cone. So why does this not happen with the instrument we called in chapter 4 by one of its more common names, the *zummāra*? Here, too, we have a mainly cylindrical body, with at least two smaller-diameter steps, and yet it behaves cylindrically, rather than conically. Even more perturbing, if a cylinder is long enough in relation to its bore, it seems to forget that it is a cylinder and starts to overblow octaves, not twelfths. This can easily be demonstrated with lengths of plastic tubing of suitable diameters to accept reeds or mouthpieces, and most of us have heard hosepipe trumpets demonstrated in this way.

Trumpets and horns are also types of reed instrument, for the player's lips are functioning as a dilating or retreating reed. The reeds on oboes, clarinets, and bassoons stand open in their position of rest. As the player blows, they close, and then bounce open, due to their natural elasticity; the frequency with which they do this, closing and opening, controls the sound.[34] The player's lips, on the other hand, start from a closed position and are forced apart by the airstream, bouncing closed again by the action of the buccinator muscles of the mouth.[35] Other examples of a dilating reed are ephemeral instruments such as grass or reed stems with longitudinal slits that open and close when the player—often with these instruments, a child—blows into the end of the stem. Thus one would expect trumpets and horns to behave in a similar fashion to the other reed instruments, but when one looks at alphorns, for example, they all behave in much the same way whether the bore expands, as it does on the well-known Swiss instruments, or is almost entirely narrowly cylindrical, as on the Scandinavian ones. Some help is given to these by the short conical termination of the bell (like that of a hosepipe trumpet when one puts a kitchen funnel into the end), but more seems to come from the determination and strength of the player's lips that force it to behave in the way intended.

The fourth type of reed is the free reed, where a blade of metal or cane vibrates freely to and fro in a close-fitting slot. Most books say that the free reed can produce only one pitch, and this is true of the way in which we use it, but in other parts of the world, mostly in Southeast Asia, it is used on a tube with fingerholes, where it behaves exactly like any other reed because it is designed to couple to the air column of the instrument just as are double and single reeds.

When fingerholes are opened on a tube, starting with that farthest from the mouthpiece, the length of tubing beyond that hole is effectively cut off and the air column is shortened to that extent. The pitch therefore goes up because the longer the air column, other things being equal, the lower the pitch; the shorter the air column, the higher. The extent to which the pitch rises will depend on the position of the hole on the tube, and especially on the relative diameters of the fingerhole and the instrument's bore. If the hole is as wide as the bore, it is almost totally effective in cutting off the tubing below. However, this is seldom useful in practice because the hole may then be too wide to be stopped securely with the finger. It also means placing the holes in their correct acoustical positions to produce the desired scale, and they are then almost certain to be too far apart for the fingers to reach them. So the best design for woodwinds without keywork (by far the most common around the world, and true for ours as well until the mid-nineteenth century) is to compromise and to position the holes along the tube where they will best suit the player's hand, and then tune the notes produced by adjusting the diameters of the holes.

Basic string acoustics are rather simpler. The pitch depends on the length, mass, and tension of a string: the longer, the lower; the greater the mass, the lower; the tighter the tension, the higher. Ideally an instrument with several strings would have them all at around the same tension. This can improve tone quality (the best sound, in our culture, is said to be produced by strings that are near the breaking point, but they must not be so near that they break too often) and also prevent distortion of the body of the instrument, for if the strings at one end or on one side are tighter than those at the other, the body will twist under the strain. However, this does not often work out in practice, even if most instruments come as near to the ideal as possible.

If all strings are also to be the same length, as they are on a violin or guitar, they must differ in mass, and a glance at any such instrument shows that they do. There are different ways of achieving this. There are limits to the thickness of a gut or metal string; too thick a gut string would be so stiff that it would produce a dull thud; too thick a metal string, and it would be halfway to the bar of a glockenspiel or orchestral bells. Twisting a gut string more tightly makes it more flexible and therefore better sounding. Taking a thinner string and loading it with something to increase its mass is a better solution, and this is why we have covered strings in the bass of all our instruments.

If some strings can be longer than others, this makes design easier, but not as much as one might hope. If two strings of the same mass and tension are to be tuned an octave apart, one must be twice the length of the other. A piano made that way would stretch the whole width of the concert platform. So varying the length alone can seldom be a useful answer. Again compromise is used, varying both length and mass, as one can see on the piano or harp and, regrettably since it eventually damages the body of the instrument, also with some variation of tension.

If one touches a string lightly at its midpoint, it vibrates in two halves, sounding an octave above the basic pitch; touching it one-third of the way along makes it vibrate in three parts, sounding a twelfth above the fundamental. These ratios, 2:1, 3:1, and so on, are those also of the harmonic series, and of the frequencies produced.

A few string instruments are played in this way. Our *tromba marina* works entirely in this manner. The small studs set into the soundboard of the Chinese *qin* show where to put the finger to obtain these harmonics. Their use is a common effect on our violin and other instruments. Woodwinds also work similarly; a small hole opened on the body of the instrument will encourage the air column to break into parts in very much the same way as does a string. Partly opening the thumbhole of a recorder, "pinching" it, opening the speaker key on a clarinet, and so forth, help the instrument to overblow to a higher harmonic without having to blow harder and thus play louder.

With trumpets and horns, when the air column is long enough, altering the lip tension (there is never-ending debate on just how this is done) persuades the air column to break into sections, and so to sound different members of this series of harmonics or overtones (there is dispute, too, over whether they really are harmonics, but in practice it is the various members of that series that are sounded). This is how natural horns and trumpets, those without valves and slides, were played in the Baroque and Classical periods. They are still played like this today, for though there are gaps between the harmonics, these are filled by lengthening the air column by the valves or a slide. Thus depressing a valve that opens access to a tube long enough to lower the pitch by a whole tone, or extending the slide of a trombone by the same amount, produces a harmonic series a tone lower than that of the instrument in its natural state. So, taking the trumpet, built in B-flat, as an example, depressing the second valve produces the harmonic series of A; depressing the first valve, the series of A♭; the third valve, or first and second together (but see below), the series of G; the second and third, of F♯; the first and third, of F; and all three, of E (all written a whole tone higher because the trumpet is treated as a transposing instrument, with the B-flat written as C).

But, and it is a big but, there is a problem here. The first-valve tubing is designed to be long enough to lower a B♭ tube by a whole tone, the second-valve tubing by a semitone. Once the first valve is depressed, the tubing is no longer about four feet, six inches long; it is around five feet, three inches. The second-valve tubing is not long enough to lower that by a semitone—it needs another half-inch or so. And it gets worse when the third valve is brought into action. This is why the better models of trumpets have rings or triggers to push out the valve tuning slides while one plays. This can be designed quite easily with the trumpet, though with more difficulty with the German orchestral trumpet because that is held differently. It is not practicable on the horn, nor on the instruments that are held vertically like the tuba. This is why some models of upright instruments have a fourth valve, to avoid the combination of first and third. However, the temptation then is to use the fourth valve in combination with the others, to fill the gap between, for example, the E we noted above for all three, and the bottom B♭. This makes things even worse. For this reason, the better models of tuba have complicated extra lengths of tubing on the valves such as the compensating system designed by David Blaikley for Distin and Boosey that automatically adds extra lengths of tubing to correct the pitch when more than one valve is depressed at a time.[36] Likewise, this is why Adolphe Sax, followed by some other makers, designed instruments with independent valves, to avoid the use of more than one valve at a time—some of them with independent tubing and bell for each valve, resulting in players looking as though they were surrounded by a nest of snakes raising their heads in the air.[37] Horn players can compensate by moving the hand in the bell, as they did on the handhorn.

Percussion acoustics are rather more complex. Skins and plates behave in very much the same way. There is little difference between a tightened drum-skin and a diaphragm of metal or other material. The bronze drums of Southeast Asia are indeed drums, not gongs as they are sometimes called—the circular metal plate behaves exactly like a skin drumhead. The overtones of all drums are inharmonic. When any instrument is played, if one listens carefully, one can hear the overtones in its sound; this is particularly easy on the Indian sitar, where one can detect as many as sixteen harmonics in the sound. Where these overtones are harmonic, the sound is enriched by them, and it is the different strengths of the overtones that give each instrument its characteristic sound. Where they are not harmonic but are inharmonic, the sound can jangle or jar.

With many members of the percussion family, there are ways to cheat their natural behavior, by varying the thickness in different places of a bar or bell, for instance (we have all heard bells where this has not been done, with a jarring sound as a result). Using an air column or air body as a resonator can help also, as with members of the xylophone family and with kettledrums such as our timpani. Many percussion instruments, with the exception of bells, have a short enough sound that this inharmonicity does not matter too much. However, the modern piano, whose string tension has increased enormously in the past fifty years in the interest of producing a louder sound, suffers very badly in this respect. While the overtones of a string are normally harmonic or not far off, those of a bar are not, and the strings of the piano, especially in the upper range, are so tight that their acoustic behavior is closer to that of bars than of strings. That is why the sound of the piano can jangle in the ear when one listens closely.

The best instruments are built empirically. "Perfect" designs, for example, woodwinds with an exactly even taper, are always out of tune, for it is essential to modify a "perfect" bore to allow for the quirks of nature. This is where the success of the best makers exists—the knowledge gained by experience of precisely where and how much to modify a bore that is theoretically perfect but out of tune in practice. Few really good instruments are the result of theoretical or scientific design; almost all require the extra cuts of the knife, the twist of the reamer, the tap of the hammer. Similarly, few good concert halls have been the result of the architects' acoustical studies; most have required tweaking before working well enough to satisfy musicians and audiences. For both, instruments and halls alike, the work of the experienced craftsman reigns supreme.

One final thought. The instrument that is built to be perfectly in tune is always a pig to play. "In tune" is always a matter of context. As we saw in the previous section on scales, these are always a compromise. Unless one were playing alone with only a "perfectly in tune" keyboard instrument as accompaniment, every note would need to be bent, even if only very slightly, to be "in tune" with whatever notes and harmonies other instruments, or for that matter voices, are sounding. The instrument that is "perfectly in tune" does not bend easily and is far more difficult to play than one that is designed to be a little flexible. And even the keyboard instruments are never perfectly in tune; octaves at the extreme top and bottom need to be stretched a little if they are to sound in tune. A keyboard that is tuned only against an electronic meter, however exact it may appear on the screen, will always sound out of tune to the human ear. The only true judge is the human ear, and it is essential to be flexible if one wishes to be really "in tune."

Notes

1. Alexander Pope, *Essay on Man*, Epistle 2 (1734). *Logos* is more literally "discourse," and thus *-ology* is perhaps better as "teaching," but one cannot teach unless first one should study.

2. The Royal Society began around 1650 with debates and experiments in Wadham College, Oxford, with the encouragement of the warden, John Wilkins, and participants such as Christopher Wren, Robert Boyle, Robert Hooke, and John Locke.

3. *Scientia*, Latin for "knowing," "discerning."

4. From the Greek *archaio*, "ancient."

5. As the "ordering of organisms into taxa on the basis of their similarity" (Ernst Mayr, *The Growth of Biological Thought* [1982], 185).

6. Margaret J. Kartomi, *On Concepts and Classification of Musical Instruments* (1990). See also my review of it and of two other works on classification in *GSJ* 49 (1996): 214–20.

7. Erich M. von Hornbostel and Curt Sachs, "Systematik der Musikinstrumente," *Zeitschrift für Ethnologie*, Jahrg. 1914, Heft 4/5 (1914): 553–90. This was translated into English by Anthony Baines and Klaus P. Wachsmann in "Classification of Musical Instruments," *GSJ* 14 (1961): 3–29. Other translations have also been published: in Finnish by Timo Leisiö ("Soitinten Luokitusjärjestelmä," *Musiikki* 1–4 [1974]: 1–73, with useful sketches); in Catalan by Maria-Antònia Juan i Nebot ("Classificació d'instruments musicals," *Fulls de Treball de Carraxa*, segona època 2 [1994]: 89–108); in Castilian, again by Maria-Antònia Juan i Nebot ("Versión castellana de la Clasificación," *Nassarre, Revista Aragonesa de Musicología* 14:1 [1998]: 365–87); and in Italian by Febo Guizzi ("Sistematica degli Strumenti Musicali," in his *Gli strumenti della musica popolare in Italia* [2002], 409–82), and doubtless others that I have not as yet encountered into other languages. There have also been numerous adaptations, expansions, and other variants.

8. Victor-Charles Mahillon, *Catalogue descriptif et analytique* (1880). This is the first volume of five that Mahillon compiled for the Brussels Conservatoire Museum. All five were reprinted in 1978.

9. Kartomi, *On Concepts and Classification*, 58.

10. The suffix *-phone* means "sound"; the first half of each word means "string," "skin," "air," and "self-," respectively.

11. The Greek *autos* means "self," whereas *idios* is stronger, meaning peculiarly to oneself. Kartomi, *On Concepts and Classification*, 137–38, gives the various other names, mostly Latin-based, that have been used in Europe since the early Middle Ages.

12. Francis W. Galpin, *A Textbook of European Musical Instruments* (1937), 27–36.

13. Jeremy Montagu and John Burton, "A Proposed New Classification System," *Ethnomusicology* 15:1 (January 1971): 49–70.

14. Kartomi, *On Concepts and Classification*, 183–84.

15. See Laurence E. R. Picken, *Folk Musical Instruments of Turkey* (1975), 557–609, esp. 560–62.

16. Oskár Elschek, "Typologische Arbeitsverfahren bei Volksmusikinstrumenten," *SIMP* 1 (1969): 23–40; Mantle Hood, *The Ethnomusicologist* (1971), 144–96. See also Kartomi, *On Concepts and Classification*, 204–9 and 184–86, respectively.

17. Baines and Wachsmann, "Classification of Musical Instruments," 14, 15.

18. Nazir Ali Jairazbhoy, "An Explication of the Hornbostel-Sachs," in *Selected Reports in Ethnomusicology* 8: *Issues in Organology*, ed. Sue Carole DeVale (1990), 81–104.

19. F. W. Galpin, "The Whistles and Reed Instruments of the American Indians of the North-West Coast," *Proceedings of the Musical Association* 29 (1903): 115–38. So far as I know,