Most of the ideas in this book are not my own. Many are common currency, having been part of musical instrument building practice for years and years. Others I have picked up in my extensive contacts with other instrument makers, and through familiarity with their instruments and writings. These makers are knowledgeable, skilled and inventive individuals — and terribly generous too, every one of them. This book owes an incalculable debt to all who have shared their ideas and experience with me over the years. By rights the list should be much longer, but here are a few of those people:


Equally essential to the making of this book have been the people who read and criticized the manuscript prior to publication. Donald Hall, David Kreimer, Skip La Pante, Michael Meadows, Jon Scoville, Stephen Golovnin and Dennis Waring reviewed and corrected the manuscript for practical, technical and scientific accuracy. Without the assurance of their expertise, not to mention their myriad ideas and suggestions, I could not have presented much of the material contained here. Kate Buckelew, Janet Hopkin, and especially Nan Hopkin, along with the others just mentioned, provided invaluable stylistic and editorial criticism. Chaz Bufe, my editor at See Sharp Press, gave it the final polish with just the right instinct for simplifying and clarifying the language. Without their guidance, this book would have been a far more awkward and less inviting thing to read.

To all these people, my heartfelt thanks and appreciation.

To my wife, Janet, and my son, Shane, who offered boundless support and patience during the long and arduous preparation of the manuscript, my love and thanks.
INTRODUCTION
by Jon Scoville

So ... you've opened this book, flipped through its pages, looked at its illustrations, tables, charts, and sidebars, and have seen that there's a universe of sound here for the making. And now you're sitting down with the intention of actually reading it. (In this computer-driven age, it's still the normal way our old flat-bed brains scan stuff into the corporeal PC.) But before you enter Bart Hopkin's Wonderful World of the Ways and Whys of Sound, allow yourself an imaginary journey:

Close your eyes, lean back, and imagine a group of musicians tuning up, then launching into a loud, glorious fanfare . . . with your choice of instruments, of course. Strings and brass and timpani? Sure. But how about instead a vast orchestra of saws and wobbleboards, mirlitons, rattles, marimbas, tongue drums, and tuning forks? Arising from it is a clangor and cacophony full of overtones and implications — as busy as an urban street corner, but as bright with possibility as a sunrise on a glistening sandy beach.

Those waves of sound arising in your imagination, be they made by traditional instruments or by something as improbable as a balloon-mounted bar gong, are all following predictable and logical laws of acoustics (at least in this corner of the galaxy — I can't vouch for that parallel universe lurking just around the corner). This book that you hold in your hands (as you dream of new solar systems of sound) is really a guide to unfold those patterns and laws of sound, to explain some of the mysteries, and to give you the tools to create new ones.

There is an ancient imperative lodged in our DNA which asks us to make music. Our intuitive understanding of being alive on this blue planet is most poetically expressed in our songs and dances. In our instinct to organize sound and movement we fully express both the ambiguities and certainties of life. Making the instruments that make the music that makes the soundtracks to our lives is one of the ways we reconnect ourselves with the world and with our ancient heritage. Thus we join that long tradition of (mostly) unknown instrument makers who gave birth to drums, violins, lutes, bamboo zithers, steel drums, gamelan, and the countless other instruments that produce our planet's songs and symphonies.

Yet the principles and procedures of instrument construction are often viewed as being as incomprehensible as those involved in building a car or a computer. The beauty of this book is that it gives you a Rosetta stone to understand the tools, resources, and formulas that will equip you to enter the world of instrument construction. The poetry of how your instruments will look, and, more importantly, what kind of music they will play, is left up to you. Dive in. The water is deep, but warm and inviting. The universe of sound is yours for the making.
This book is a guide for anyone interested in musical instrument making.

In the chapters that follow we'll survey the fundamentals of instrument design. In the process, we'll get to know the acoustic relationships that underlie familiar musical instruments, and a host of new and unusual instruments as well. My goal is that this book will help you gain an acoustical sense that will serve you well in the creation of all kinds of acoustic instruments, both traditional and innovative. This book will also fill a continuing role as a handy reference for practical information on instrument design and construction.

Musical instrument design is a vast topic. The accumulated lore about violin making alone would fill an encyclopedia. This book will not tell you how to make a violin, and it will not serve as a course in musical acoustics. What it does, that other resources do not, is gather under one cover a body of broadly applicable design principles, coupled with practical ideas and suggestions for making specific instruments. If you are interested in exploring instrumental sound, building something musical from scratch, or composing and performing with anything other than the usual commercially made instruments, then you will be glad to have the information provided here. So will anyone, for that matter, who simply wants to better understand musical sound.

Acoustical phenomena in the real world are complex. It isn't easy to describe sounds in terms detailed enough for scientific analysis. But on a broader and less exacting scale, there is a world of practical information about the behavior of sound and sounding bodies. This information may be cruder than the physicist's analysis, but it is immensely useful in musical instrument design. This book operates on the level of that broader understanding. The information contained here may be challenging for those new to the field, but my hope is that anyone, regardless of technical background, will find it comprehensible and, above all, useful.

And what about people who lack the construction skills called for in fine instrument building — is the world of instrument making beyond their reach? It is true that workshop skills will give you a head start in making ideas come to life. But many wonderful instruments can be made by complete novices, including quite a few of the instruments described in this book. You will find that musical sound is frequently right there for the taking; it is a most inviting world to explore. And beginners often show a disconcerting knack for coming up with fresh ideas and overlooked approaches. As for special equipment, while power tools are faster, you can do an awful lot with basic hand tools. After all, instrument makers since the start of time have worked with nothing more.

The early chapters of this book are devoted to principles of acoustics as they relate to instrument design. We will need to understand these in our subsequent examinations of different instruments. The succeeding chapters, forming the bulk of the book, deal with specific instrument types and their design principles. At the end are several appendices designed to codify important information and provide easy reference. Among them are a section on instrument building materials and where to get them, a chart relating wavelength, frequency and pitch name, a glossary, and much more. Here and there, alongside the main text, are separate items I have called "Sidebars." These are discussions of topics worth noting, but peripheral to the flow of the text. Scattered throughout the main text and sidebars you will find ideas and informal plans for instruments you can make.
In order to think intelligently about sound production, we need to understand certain things about how the ears and brain make sense of the sounds that reach them. This will also help us to develop better analytical listening skills, which are invaluable in instrument making.

**SOME BASICS**

Sound is created when something causes small, localized fluctuations in air pressure. The fluctuations propagate outward from the source as pressure waves in the atmosphere. Should there be any ears in the vicinity, the pressure waves cause movement in the sensitive membrane that is the ear drum, and, following a series of bio-mechanical and neural transmissions, the event is interpreted as sound by the brain. A single pressure pulse doesn’t amount to much of a sound; it takes a series in rapid succession to give the ear something it can respond to. The arrival of a series of pressure waves causes air molecules at a given location to move back and forth with each pulse; thus the association of sound with vibration.

An important property of vibrations is frequency, normally expressed as the number of vibratory cycles per second completed by whatever it is that is vibrating. Think of frequency in terms of complete vibratory cycles: for a vibrating object beginning at some central point, moving to one side and back to the center constitutes a half-cycle. To complete the cycle it must continue through the center point and on to the other side, and return once again to the center point. The term Hertz, abbreviated Hz, is commonly used to represent cycles per second (after the 19th century physicist Heinrich Hertz). Thus, for instance, 200 cycles per second = 200 Hz.

Humans are responsive to frequencies falling within a range extending roughly from a lower limit of about 20Hz to perhaps 16,000 or 20,000Hz for a typical young person (this upper limit drops with age). Within this range, lower (slower) frequencies are associated with low, or bass sounds, and higher (faster) frequencies are associated with high, or treble sounds. In general, through most of the range, the human ear's acuity is quite impressive: it picks up sounds representing truly minuscule amounts of energy; and at the opposite extreme it withstands sounds carrying billions of times that energy before serious discomfort or hearing damage occurs. The ear's sensitivity is not uniform through the hearing range, however. It tapers off at both ends, and has a broad peak in the range of about 2,000Hz to 5,000Hz, corresponding to a medium-high part of the range. This means that sounds within this band sound much louder than sounds carrying comparable energy at higher or lower frequencies.

When a sound vibration occurs at a single steady frequency, you hear it as having a recognizable "note" or pitch. Pitch, in other words, is the brain's way of interpreting vibrational frequency. The ascending series of notes that you hear when someone plays a scale on a musical instrument actually represents the instrument's ability to produce sounds at a series of specific frequencies, each a little higher than the one before. (Appendix 2 at the end of this book contains a chart giving frequencies for each of the pitch names used in the standard Western musical scale.) Human ears and brains are amazingly good at recognizing steady-frequency vibrations and distinguishing one frequency from another. Frequency differences of less than one percent are easily recognized by people with no special training. This acuity diminishes toward the extremes of the hearing range.

The word “interval” refers to the perceived distance between two pitches, or how much higher one pitch is than another. People in most musical cultures seem to perceive equal musical intervals between pairs of pitches when the ratios of their frequencies are the same. The best example is the octave. The musical interval of an octave is associated with a frequency ratio of 2:1. Double the frequency of any pitch, and you get the pitch an octave above. Double it again, and the pitch is now two octaves higher than the original, while the frequency is four times as great. Just as 2:1 corresponds to the octave, a musical interval of a third is associated with a frequency ratio of 3:2, a fifth with a frequency ratio of 4:3, and so forth. Any musical interval can be defined as a frequency ratio. The tunings chart in Appendix 2 gives ratios for all of the most important musical intervals.

**TIMBRE AND OVERTONES**

Most sounds in the real world are complex, and are comprised of vibrations of many frequencies. The ears do not generally hear a complex sound as a group of separate pitches at different frequencies, however, but as a single sound possessing a characteristic timbre, or tone color. That tone color results, in part, from the blend of frequencies present. In some cases the blend creates a sensation of pitchless noise. In other cases the ears and brain hear a multi-frequency sound as a single “note” or pitch, focusing on one frequency from among the many present as the defining tone.

Let’s look at these phenomena more closely. We can start by describing several general vibration types.

**No steady frequency present:**

In some sounds no recurring pattern arises — just flames of disordered air movement. The ear hears such unpatterned sound as unpitched noise. The noise may seem trebly or bassy, depending upon the general frequency trend. Maracas (shakers) provide one example of this sort of sound. Try shaking a maraca and humming back the note you’ve heard. You can’t do it, because in that rush of shaker sound there is no steady, dominant frequency.

**One steady frequency present:**

In most natural sounds there are one or more recognizable steady frequencies present. Steady-state vibrations need not maintain the same frequency more than a tiny fraction of a second; the ear is very quick about recognizing them.

Where there is but one frequency present, the aural effect is a well-defined pitch and a timbral quality which is not unpleasant, but rather colorless. Sustained vibrations at a single pure frequency are hard to achieve by acoustic means, although some flutes or blown bottles may come fairly close. Sounds that are much closer to the one-frequency ideal can be produced electronically. Some of the beeps and boops of early electronic music are examples.

**Several steady frequencies present:**

If there are many frequencies present as components of a single sound from a single source, the listener usually does not get a sense of plurality, but hears the blend as a single tone having a particular timbre. The nature of that timbre depends in large part on the relationships between the frequencies within the tone. Here things become rather complex, and some key questions arise. Will the ear interpret the multi-frequency sound as having a defined pitch? What qualities in the timbral blend allow the ear to do so? And which factors determine what the perceived pitch will be? In answering these, we begin by defining some terms.

**WAVE FORMS**

Most sounds are blends of many different frequencies sounding simultaneously. It might be difficult to envision how this actually happens physically. One can easily picture a particle of air vibrating back and forth at a particular frequency, but how can a single particle vibrate at ten or more frequencies simultaneously?

To express multiple frequency vibration, the particle engages in a complex movement which can be mathematically interpreted to be the sum of the several frequencies it is supposed to be manifesting. This mathematical interpretation may seem like an artificial construction. Is the complicated dance the particle is performing really the same as vibrating at multiple specific frequencies? But this interpretive model does correspond to the ear’s subjective response. Presented with a complex vibratory motion that can be shown mathematically to represent the sum of several frequencies, the ear and brain do indeed hear those several frequencies.

To aid in the study of such motions, acousticians draw graphs, plotting the pattern of vibratory movement through time. Different types of vibration yield different graphic patterns, called wave forms. The sine form for a single pure frequency is a wavy line of very regular and smooth curvature, known as a sine wave (because it matches a graph of the sine function in trigonometry). Sounds with strong harmonics show wave forms that are more angular, but still quite regular. More complex timbral blends, with non-harmonic frequencies or added noise components, have correspondingly more complex and irregular wave forms. With highly complex wave forms it becomes difficult for the ear and brain to recognize the recurring
In a sound with multiple frequencies present, the individual frequencies are called partials. The lowest of those frequencies can be called the fundamental. Additional frequencies arranged above are overtones. Overtones fall into two important categories: harmonic and inharmonic. Harmonic overtones are those that have frequencies equaling some integral multiple of the fundamental frequency. This defines a series of harmonic overtones. For a fundamental frequency, the harmonic overtones have frequencies 2f, 3f, 4f, 5f, ... and so on indefinitely. That is the harmonic series (illustrated in Figure 1-3); and you will be hearing a lot about it before you finish this book. In their aural effect, harmonic overtones blend closely together, creating the feeling of a single tone. Inharmonic overtones (those whose frequencies are not multiples of the fundamental frequency) do not seem to blend as closely into the overall tone, giving the resulting composite timbre a spicier, edgier, or more dissonant quality.

FIGURE 1-1: The first five partials of the harmonic series over a fundamental of 100 Hz. For a fixed fundamental, the usual partials and frequencies would differ, but the same intervals would hold. Small arrows align some notes that are successively a major or minor 2nd of the related partials.

<table>
<thead>
<tr>
<th>Harmonic No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>600</td>
<td>700</td>
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<td>1,000</td>
<td>1,100</td>
<td>1,200</td>
</tr>
<tr>
<td>Frequency</td>
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<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>600</td>
<td>700</td>
<td>800</td>
<td>900</td>
<td>1,000</td>
<td>1,100</td>
<td>1,200</td>
</tr>
<tr>
<td>Pitch name</td>
<td>C1</td>
<td>D1</td>
<td>E1</td>
<td>F1</td>
<td>G1</td>
<td>A1</td>
<td>B1</td>
<td>C2</td>
<td>D2</td>
<td>E2</td>
<td>F2</td>
<td>G2</td>
</tr>
</tbody>
</table>

And now, back to the question of perceived pitch in multi-frequency sounds. There are many possibilities here, and many factors at play. Here are some governing considerations:

Rule #1: In general, lower-frequency components play a greater role in establishing the perceived pitch of a tone, while higher-frequency components contribute more to its coloration. Most commonly, the lowest frequency present, the fundamental, establishes the pitch.

Rule #2: Harmonic overtones lead to a well-defined pitch sense. To whatever extent the overtone frequencies can be construed as falling into the harmonic pattern, the tone will sound coherent, full, and well defined in pitch. Familiar instruments having harmonic overtones include most string instruments and the standard woodwinds and brass. The perceived effect of the composite tone quality depends in part upon which harmonics are most prominent: where the higher harmonics predominate, the tone will be brighter, with a more metallic sound; where higher harmonics are subdued, the tone will be rounder, as with a nylon string guitar.

Rule #3: In tones possessing multiple inharmonic frequency components, the perceived results are quite variable. They depend on the relative prominence of the different components, the pitch relationships between them, and the degree of crowding in different parts of the spectrum. In such cases, the ear sometimes succeeds in picking out the fundamental as the defining pitch, but hears it as part of a peculiar timbre. Sometimes the ear tracks another tone as the defining pitch. Sometimes the ear doesn't focus on any one tone as the defining pitch, and the sound is perceived as pitchless. Figure 1-2 provides examples.

Tuned carillon bells (such as the sets used in church towers) provide a wonderful example of an instrument possessing prominent frequencies not arranged harmonically, but still interpretable to the ear as having a single defined pitch. The tone is highly distinctive — nothing else sounds like cathedral bells — and it is one that many people find enchanting. It also can be musically confusing, in that the ear may occasionally track the wrong overtone as the defining pitch. When you have an opportunity, try listening closely to the tone of a set of big bells, mentally isolating the pitches present, making note of their relationships, and — this is an important part of the perception of the tone — observing which overtones sustain longest, and which die out quickly.

Many "pitchless" percussion instruments are better described as having ambiguous pitch. This includes most drums, some cymbals, cowbells, triangles, and so on. With a little concentration, a listener can often pick out one or more pitches in such sounds, and these pitches, even if one tries to ignore it, take on meaning in musical contexts. In addition, it is surprising just how many everyday sounds have at least some component of identifiable pitch. To test this, try knocking, banging, squeaking, and scraping everything in a room, listening as you go for pitch among the noise. Give each item a couple of tries: sometimes the definite pitch components are elusive, but you might be surprised at how often you find them.

In the ambiguous territory between clear pitch and pure noise, a great many disorienting effects occur. There can be indistinct tones, which seem to shift pitch depending upon musical context or a change in one's perceptual predisposition. There can be tones which seem to have pitch in one musical context but degenerate into pitchless jangle in another. There can be tones for which two people disagree as to what their pitch really is. There can be tones which seem to have pitch, but which have so much pitchless noise mixed in that the resulting timbre is bizarre. There can be tones in which the components blend seamlessly, and tones in which several pitches retain a degree of individuality, sounding gong-like or even chordal. And there can be anything in between.

FIGURE 1-2: Some characteristic vibration types and their perceived pitch and sound quality effects.

The role of overtones in instrumental tone quality gives rise to an important question: Do musical instruments typically produce the same set of overtone relationships for all their sounding pitches? When the instrument moves from one note to another, does the whole family of overtones move together, retaining the same relationships? The answer is yes and no. In most cases, the overtone relationships are fairly well preserved, ensuring similar timbre from note to note. But at the same time, the relative prominence of the different overtones tends to change. Each instrument, by its nature, radiates sound particularly effectively within certain general frequency ranges. Components of the sound that happen to fall within these ranges ring out fully, while those falling outside are de-emphasized. As different notes sound from a given instrument, different overtones are highlighted as they fall within the ranges of particular functional pressure areas.
emphasized frequencies.

Such regions of heightened response are called formants. Along with overtone mix, formants are another important part of our sense of instrumental timbre. As an example, consider the violin. The violin does a particularly good job of radiating sound in two prominent ranges. Whatever mix of frequencies the string may deliver to the soundbox, the soundbox always radiates most effectively whatever part of the input happens to fall in those ranges. The resulting fullness of tone in those ranges is an essential identifying characteristic of violin sound.

The best way to illustrate how we, as listeners, are tuned in to formants is through speech. The human voice is one of the few instruments in which formant frequencies do undergo marked changes rather than remaining fixed. Altering the shape of the oral cavity during speech has the effect of selectively enhancing certain frequency ranges within the vocal tract, and this is the basis for the production of distinct vowels.

The difference between “at” and “ah” lies in which formant frequencies the speaker enhances. People are so well attuned to the differences that they effortlessly distinguish the two.

You can familiarize yourself with some of the effects of different formants by singing sustained tones and altering the shape of your vocal cavity (raising and lowering the tongue, changing the position of the lips, raising or lowering the soft palate, etc.), and listening closely to the resulting tones. Try to pick out the predominant overtone components for different tone qualities. You may even acquire the skill of overtone singing — that is, bringing specific overtones so much to the fore that the ear begins to hear them in their own right, harmonizing with the fundamental, rather than merely as part of the timbral blend.

Sidebar 1.2

A BALLOON-MOUNTED BAR GONG

Here’s a simple construction that will allow you to experiment with an extraordinarily rich array of partials from a single sound source. (Remember that the term “partial” refers to any of the individual tones or frequencies that make up a complex sound.) The instrument consists of a single long metal tube or bar held in a manner that allows extremely free vibration and enhanced lower frequency radiation. Thus, the struck tube reveals a rainbow of tones. Through various techniques, the player can bring different partials to the fore with each stroke, for a kind of melodic movement in both tone color and pitch.

The drawing shows the basic assembly. What can one use for the metal sounding element? Many sorts of tubing or metal bar stock can serve. For convenience and availability, I suggest a 10-foot length of 1” thin-wall aluminum metal conduit, commonly called EMT (widely available in hardware stores). The long tube rests on two battens. Best is the long lumpy-bumpy-elongated “knot,” looking like a bracelet that has been squashed by a box cracker. They should be fairly large and strong. To prevent the battens from rolling, place non-melting objects, like wooden blocks or books, alongside them.

You should find that each note, while soft, begins with a loud attack. Begin by experimenting with a variety of tubes, with the idea of finding the ones that bring out the best in the bars. Try regular percussion mallets, or household items like screwdrivers held by the blade. Look through Chapter 3, “Balloon, Station & Friction Mounds” for more ideas.

The key to the colorful potential of the bar is to bring out different partials and combinations of partials with each stroke. Do this, first, by striking at different locations along the bar. Different striking points excite different partials. Second, by pitching the bar firmly between thumb and forefinger of the free hand at different points as you strike, releasing immediately after. Doing this imitates most of the notes, while allowing a few sought ones to sound clearly. Some striking points kill most of the sound, from an unresponsive reed. Others allow a mix of tones to come through each mix having its own distinct pitch and timbre. But the talker, listen closely. Keep track of the combinations of stopping and striking points that produce the best sounds. The rich spectrum of partials naturally exists, in potential at least, in all hard metal tubes and rods. But the full array usually remains inaccessible, because vibration is damped by whatever holds the bar or whatever it rests on. Balloon mounting overcomes the damping problem entirely by being the most compliant support system imaginable. In addition, most bars in themselves lack sufficient surface area to radiate their lower-frequency vibrations effectively to the surrounding air. But the balloons provide a larger surface area: the bar transmits its vibrations to the balloon, and the balloon radiates them to the air. Low frequencies that would have been lost suddenly become audible.

In the next chapter we will discuss more fully the acoustic principles at play in the bar gong, and you will find a follow-up discussion of the instrument in Sidebar 1.2. “Balloon-mounted Bar Gong Revised.”

A BALLOON-MOUNTED BAR GONG

This chapter has focused on tuning and treatment of strings. Through this chapter I have used the word “noise” to describe sounds that lack definite pitch. The rich spectrum of partials naturally exists, in potential at least, in all hard metal tubes and rods. But the full array usually remains inaccessible, because vibration is damped by whatever holds the bar or whatever it rests on. Balloon mounting overcomes the damping problem entirely by being the most compliant support system imaginable. In addition, most bars in themselves lack sufficient surface area to radiate their lower-frequency vibrations effectively to the surrounding air. But the balloons provide a larger surface area: the bar transmits its vibrations to the balloon, and the balloon radiates them to the air. Low frequencies that would have been lost suddenly become audible.

In the next chapter we will discuss more fully the acoustic principles at play in the bar gong, and you will find a follow-up discussion of the instrument in Sidebar 1.2. “Balloon-mounted Bar Gong Revised.”

Sidebar 1.3

FORK CHIME

Here is another instrument that will force you to listen carefully. It combines the vibrating patterns of a tuning fork and a simple tube chime, giving rise to a complex array of frequencies. You can tune the frequencies as you make the chime (albeit roughly), and bring out different frequencies in the tone by how and where you strike.

All you need to make fork chimes is metal tubing. Aluminum or brass tubing will work well, but you can also make a fine instrument with the same steel conduit recommended for the bar gong described in Sidebar 1.2. Get enough tubing to make several chimes.

The drawing shows the design of the fork chime, with typical dimensions. Start by cutting the tube, drifting the suspension cord hole at about 22% of the length from one end, running a bit of cord through and tying it to form a loop for hanging the tube. At this point you have a simple chime, which will produce a nice tone when suspended and struck with a hanger. Next, cut the slit in the opposite face, and using a hack saw or saw, try to make it straight and even, but don’t worry if it isn’t perfect. Make the cut about 20% of tube length initially. Support the tube by the cord and strike near the split end. A new tone emerges. It comes from the two halves of the split end engaging in the pattern of vibration normally associated with tuning forks. The chime tone is still there (though slightly raised in pitch due to the cutting), and you can hear it by striking it near the center. Other slightly coarser tones appear when you strike in different places, most of them being overtones of the basic chime center.

Send a few moments striking the fork chime in different ways, and listen to the tones you can get. Do you like the musical relationship between them? If not, you can change them. Cut the slit longer to lower the fork tone. Raise the chime tone by cutting a small amount of tubing from the opposite end. If you cut a significant amount, drift a new suspension hole at the new 22% point. Experiment until you find a set of tones that form an attractive blend. When you have made several fork chimes with pleasing relationships both within themselves and among one another, hang them some place where you can occasionally play them as you pass by.
We will be studying the vibrating patterns of chimes and tuning forks in Chapter 4, “Idiophones.”
The description given here of displacement, restoring force and inertia at work provides sufficient understanding for a lot of musical instrument design work. But we can deepen our understanding by looking at the situation from another perspective. In a more sophisticated view of the same events, the simple back and forth motion of vibration can be seen as a wave of displacement running rapidly through the vibrating medium or object. Consider a rope lying along the ground. Someone holds one end and gives an abrupt vertical shake. The curved hump that scoots from the shaker's hand on down the rope is a traveling wave. In classic wave-like fashion, each point on the rope engages in only a small movement, up and down again, as the hump passes. But this series of localized movements gives rise to the progressive movement of the wave as a whole.

There are two important differences between the rope and the musical wave media that we are interested in. One is that the rope's wave occurs on a large scale and progresses relatively slowly, making the wave observable. The other is that the wave in the rope dissipates all its energy along the way and at its end. If the rope were anchored rigidly at both ends and held in the air under tension, the energy would not dissipate so fast. Instead, the wave would reflect (bounce back) at the far end, and would then be seen running back in the opposite direction along the rope, only to reflect again at the near end, continuing in a back-and-forth movement until all its energy is dissipated. (Sidebar 3-3, "Watching Waves" describes further experiments along these lines with observable waves.)

This same sort of motion occurs in musical strings. It is also closely analogous (though harder to picture) to what happens in drumheads, music box prongs, marimba bars, wind instrument air columns.
Vibration patterns of this sort can be called standing waves. Standing waves are the steady-state vibrations that arise as a result of traveling waves reflecting back and forth in a string, air column, or other medium of finite dimensions. The interacting wave fronts reinforce or cancel one another to varying degrees all along the medium at each instant to create the standing wave form. It is not intuitively obvious, but the cumulative effects of the multiple reflections can account for all the complexity of the vibration patterns we see in musical instruments, including the presence of multiple frequencies (fundamentals and overtones) in the vibrating object.

**Resonance**

Most natural vibrating systems show a preference for certain frequencies and not others. These natural frequencies are the frequencies at which the system will oscillate if given some sort of initial impulse and then left to vibrate on its own, as, for example, a guitar string will vibrate at a certain frequency each time it is plucked. Resonance is a function of this property. To illustrate, consider a tube that has one stopped end and one open end. The air in a tube has a springy quality. If it is momentarily compressed into the tube by some inward movement at the open end, increased pressure within will cause it to surge back out; in doing so it overshoots slightly, creating a relative vacuum that pulls it back in again. As this continues an oscillation of the air results just as if one had compressed and then released a coil spring.

Now let's add to this system a driver — something that will repeatedly force air in and out of the open end of the tube, driving the enclosed air at some specific frequency. As an example, we'll use a piece of wood mounted so as to act as a marimba bar. Marimba bars flex up and down at the center when struck. If one is placed over the opening of a tube a short distance away, it has the effect of pushing small amounts of air in and out as it vibrates. Like most vibrating systems, the bar has a natural frequency at which it "wants" to vibrate, and so does the air column below.

What happens with the air in the tube now if someone strikes the bar? The answer depends on the relationship between the natural frequency of the bar and the natural frequency of the air column. In the likely case that the two frequencies are different, the air responds minimally. The bar is trying to drive the air at a frequency the air doesn't want to go at. If the frequencies are roughly the same, however, the air joins the bar in oscillating at the frequency they now share. The intensity of the tube's response can easily be heard in the resulting sound: the bar tone is greatly enhanced and augmented by the air sound from the tube. (Creating a good coupling between bar and resonance tube is one of the joys of instrument making.)

This is a good example of resonance response. The word resonance refers to an oscillating system's enhanced response to a driving force at or near any of its natural frequencies. It comes about because of the fact that if the driving frequency matches the oscillator's own natural frequency, the driver can consistently impart energy at just the right time and in the right direction to maximize its effect. A classic analogy is that of pushing a child on a swing. The child-plus-swing, like all pendulums, follows the rules for oscillation described earlier, and has its own natural frequency of oscillation. (That frequency, of course, is well below the hearing range.) The driver for the system is the person doing the pushing. If the pusher times the pushes so that the direction of the pushes always contributes to the swing's natural motion, the imparted energy will accumulate and the swing will go higher and higher. This is an instance, in the middle of the swing's back swing — the two forces cancel. Then, rather than building up, the swing's motion diminishes. This inevitably happens at least some of the time if the pushes consistently come at a frequency very different from the natural frequency of the swing. If the pusher's frequency is close but not identical to the swing's natural frequency — say, just a little too fast — then some accommodation will be reached in which each swing cycle is slightly foreshortened by the too-early push. It will oscillate a little faster, but with less amplitude, as part of each push will be wasted in countering rather than contributing to the swing's natural movement. We can sum this up by saying that the swing shows an enhanced resonance response when driven by the pusher at the swing's natural frequency; the response diminishes rapidly if the pusher's driving frequency departs slightly from the swing's natural oscillation frequency, and drops very nearly to nothing for any pusher so willless as to push at some completely unrelated frequency.

The same sort of interaction happens with the marimba bar driver and the tube resonator. After the bar's first downward flex has initiated an oscillation in the air at the mouth of the tube, then — if the driver frequency and the natural frequency of the tube are close to matching — each subsequent downward flex comes at about the right time to reinforce the air's next inward movement, one vibratory cycle later. The recurring reinforcement perpetuates and increases the tube vibration.
result will be a longer-lasting sound of lesser volume. Musical instruments can be deliberately designed to achieve damping. The greater volume is coupled with lesser sustain. In other words, if the vibration is not continuously with the bow.

Fingerboards (witness the sound of violin pizzicato), but the player compensates by injecting energy away, because the player continuously injects energy into the system by blowing. The same is true of instrument tubes and the like, to ensure mat instruments dependably and unambiguously produce their intended pitches. The violin string wouldn't do its job as a driver of precise and controllable frequency if it weren't frequency-specific. On the other hand, you need the more generalized response typical of soundboards in cases where you want to pick up, resonate and amplify not a single frequency, but a broad range of frequencies. A soundboard whose resonance response shows isolated spikes separated by deep valleys means trouble: the pronounced frequency biases will scarcely allow some pitches injected by the player to sound, while making others disproportionately strong, and distorting still others in time or pitch. A gentle peakiness or a great many overlapping peaks in something serving as a resonator can be valuable, in that the peaks may lend character and an attractive color to the sound.

**Damping and Radiation**

An important factor in resonance response is damping. Acousticians use the term to refer to the rate at which a vibrating system dissipates energy. The more heavily damped a vibration is, the more rapidly it spends its energy, and as a result, the shorter its duration. A vibration with zero damping would sustain itself forever without needing more input energy, but this, of course, is beyond the capabilities of mortal instrument makers. Energy dissipation can take various forms, but the important distinction for us is between 1) dissipation through radiation or transmission of the vibration, and 2) dissipation through mechanisms like friction.

Radiation (1 above) may be to surrounding air, or it may be to other solid bodies which can in turn radiate to the air. With musical instruments, the hoped-for result is that the vibration becomes audible, as when a string transmits its vibratory impulses to a soundboard, and thence to the air. Damping due to friction (2 above) is energy lost without contributing to sound. It can occur within the original vibrating medium, or it can occur indirectly, as when the initial vibrating object spends itself in driving some other friction-laden object. Simply stopping the strings of a guitar with one’s hand works that way, providing so much frictional damping through the soft flesh that the string's vibrational energy is absorbed virtually immediately, stopping the sound.

Damping, and the related question of transmission-vs-frictional loss, are central considerations in the functioning of musical instruments. Let's summarize their effects:

1. Heavy damping corresponds to little sustain for a given vibration. If there is not continuous additional energy input into the system. Thus, vibrations in heavily damped plucked or hammered strings die away quickly, as do vibrations in wooden vibrating bar instruments, plucked rods like kalimba lines, and so forth. On the other hand, wind instrument vibrating systems can be heavily damped without dying away, because the player continuously injects energy into the system by blowing. The same is true of members of the violin family: the string vibration is heavily damped by the player's fleshy finger on the fingerboard (witness the sound of violin pizzicato), but the player compensates by injecting energy continuously with the bow.

2. When damping is heavy and energy loss is due primarily to internal friction, then a relatively small part of the total vibrational energy goes into audible sound in the atmosphere. This makes for an inefficient sound maker, with relatively little sustain and most likely a small maximum volume level. That's why pillows make poor musical instruments. Hit a pillow as hard as you like; inject as much energy as you can. Most of that energy is lost to internal friction, and the sound is unimpressive.

3. When the damping is heavy because the system is radiating sound energy rapidly to the surrounding air, then the initial result is greater volume. (This may be contrary to your intuitive sense of the word "damping.") The greater volume is coupled with lesser sustain. In other words, if the vibration rapidly shoots off all its energy as sound radiation, the result will be a short, loud sound.

4. When damping is small, which is to say that the vibrating body releases energy only slowly, the result will be a longer-lasting sound of lesser volume. Musical instruments can be deliberately designed...
MÖDES OF VIBRATION

In Chapter 1 I spoke of the ear's response to complex vibrations involving many simultaneous frequencies. Now we can talk about how such vibration patterns arise. This kind of acoustic behavior is easiest to describe in connection with musical strings, so we will start with them. But bear in mind that these phenomena have their parallels in membranes, winds, and solid vibrating materials as well.

Within the tone of a typical musical string, a sharp-eared listener can pick out the fundamental tone along with a few audible overtones above it. (The fundamental is normally the most prominent and the easiest to focus upon, and its pitch is heard as the pitch of the overall sound.) Now, these multiple tones must come from somewhere; they must somehow reflect patterns in the string's movement.

The vibrating string, fastened at both ends and stretched tightly between its two anchors, is capable of several modes of vibration. Each mode is a pattern of vibration movement in the standing wave. The simplest and most prominent mode, labeled as the string's first mode of vibration, is the one in which the entire vibrating length of the string flexes from side to side, assuming at the extremes of each half cycle something like the curved shape of left and right parentheses, as shown in the top part of Figure 2.5A. This first mode is responsible, it turns out, for the pitch that we hear as the fundamental in the string's tone.

Additional modes of vibration involve subsections of the string engaged in smaller movements, as shown below in Figure 2.5A. The second mode takes the form, at the extremes, of shallow S shapes. The two sides of the pattern work together at a single frequency, and so this second mode, despite its seeming dividedness, is responsible for a single pitch -- ideally, an octave above the fundamental.

We can now highlight an important aspect of such vibrating patterns. In the second mode, as in all standing wave patterns, there are points of maximum and minimum movement. The center point in this second mode is virtually immobile; it merely pivots. Points of maximum movement appear one quarter of the way from each end. These defining points have names. The point that does not move is a node, and the points of maximum movement are called antinodes. Remember the meanings of these words if you are not familiar with them already; you will encounter them many times before we get to the end of this book.

A CENTER-BRIDGE HARMONICS GUITAR

Musical strings produce harmonic overtones. Normally these harmonics blend into the overall string timbre and do not stand out as separate tones. But there are ways to hear individual harmonics. The following instrument design takes advantage of a simple but elegant technique that isolates string harmonics over an extended range. It was developed by guitarist and composer Glenn Branca.

The instrument is a simple six-string board with a middle bridge dividing each string into two half-lengths. Under the strings on one side there is an electromagnetic pickup (such as electric guitars use). The player plucks the strings on the no-pickup side, varying the pitch with a Hawaiian-guitar-style steel slide. The vibration on the no-pickup side is scarcely audible, since the box resonates sound poorly. But any tones matching the harmonics of the half-length string will start a sympathetic vibration on the other side, to be sensed by the pickup and amplified. Because the system does very well at isolating tones high up in the harmonic series, where the tones are close together, the player will find a vast array of pitches waiting to come forth, making for a very rich musical palette. Just plucking the string and sliding the steel over its length produces a cascade of audible pitches. The tone, as it comes through the amplifier, is clean and lucid, with no plucking sound at all.

Materials

Remember to look in Appendix 1, “Tools and Materials,” for sources. You can vary dimensions and the number of strings to suit your needs or taste.

One six-foot 2x4 board.
One electric guitar pickup with cable and jack.
Foam rubber, 1/8-inch thick and about 2” by 4” rectangular.
An electric guitar amplifier — or, alternatively, you can hook up to your stereo or whatever else will serve.
Two 1/2- or 1/4-inch steel rods or equivalent, 3” long, to serve as end bridges (large nails or bolts with the heads cut off will do).
One section of 3/8- or 1/4-inch outside diameter metal rod or tubing, 3” inches long, to serve as the middle bridge.
Six tuning pins, and a tuning wrench or crescent wrench to turn them. Six 1-inch #8 roundhead wood screws.
Music wire — enough for 6 strings each about seven feet long. Use several different gauges, between about .010” (designated as #1 music wire) and .031” (designated as #13).
Six wooden end bridges, made from redwood or similar hardwood.
Six hard rubber slides, all about 5/8” thick, 2” long, to serve as the end bridges.
Wall of sound — enough for six strings each about seven feet long. Use several different gauges, between about .010” (designated as #1 music wire) and .031” (designated as #13).
Six wooden end bridges, made from redwood or similar hardwood.
Six hard rubber slides, all about 5/8” thick, 2” long, to serve as the end bridges.

Construction Procedure

Cut the 6-foot board. If necessary, carve out a seating with chisels or router to fit the pickup, so that the pickup with them beneath it will be about 1/2” below the strings in the finished instrument. Drill holes at one end for the tuning pins as shown in Figure B, small enough for the pins to fit firmly. For the most common other pin size the appropriate hole size is 1/8”. Tap the pins part way in, then screw them the rest of the way in (taking advantage of the fine threads on the pins'). In the equivalent locations on the opposite side, place six string wood screws, screwed down so that the heads are ½” from the board surface. Pull the smaller rods for the end bridges in place and secure them with screws, epoxy or any other effective means. Mount the pickup in its seating, with the foam rubber behind (but low enough to see it). Use Unigrip fencing nails to fix the few free inches of cord to the 2x4, to prevent allowing the wires where they join the pickup. Attach the strings end to end, from screws to pins, as indicated in Figure D and its caution. Use the tuning pins to tighten them moderately tight, then wedge the larger nod that forms the center bridge beneath them at the midpoint. You may derive your own tuning for the strings. Plug the jack from the pickup into an amplifier and turn it on.

Playing Technique

Position the board in front of you as shown. Pluck near the bridge to your right. Move the steel slowly along the strings as you pluck, in order to hear the barest of harmonics that appears over a relatively short sliding distance. There's no need to pluck hard in order to apply great pressure with the steel.

When you pluck the string on the no-pickup side, any harmonics having a node at the point where you place the steel will be excited, and will sympathetically excite the matching harmonics in the half-length on the other side of the bridge. The pickup there senses it, and it will be amplified. The first few harmonics — the second through the eighth or so — sound readily, and their nodal locations are not confusingly crowded together. The higher harmonics become increasingly difficult to locate, but with practice you will be able to control them as well. To aid in locating the steel for the different harmonics, you can mark off the nodal positions on the board beneath the strings, creating a chart similar to that shown in Figure E. The locations are as follows: the second harmonic has a node at the half-length's midpoint; the third harmonic has nodes at the half-length's 1 and ⅔ points; the fourth has nodes at the ½, ⅔, and ¾ points... and so forth.

Acknowledgements

The German guitarist Hans Reichel has developed a “Pick-behind-the-bridge Guitar” based upon the same principle as Glenn Branca’s harmonics guitar described here. While the beauty of the Branca instrument lies in its simplicity, Hans Reichel’s instrument is more complex, and demanding both to make and to play — but with huge musical potential amply demonstrated in Hans’ own playing.
In addition to the node at the center, the second string mode has a node at each end, since these points too are immobile. The first mode, which we looked at earlier, has but one antinode (point of maximum vibration) at the center, and the two nodes at the ends.

The third mode of vibration for a stretched string takes the form of three string segments, as shown in the third drawing in Figure 2-5A. This mode is responsible for the next higher overtone, ideally sounding at the interval of a 12th above the fundamental. You can see the form of the fourth mode in Figure 2-5A as well, and you can easily imagine what the higher modes will be. One could go on with this indefinitely, but in practice the strength of the vibrational modes diminishes as they get higher. Overtones above about number 16 are significant in relatively few instruments, and in many only the first few overtones play an important role. Notice, by the way, that the string overtones form a harmonic series.

These modes of vibration don't normally occur in isolation; the string vibrates in many modes at once. It does this in a manner analogous to that described in connection with a vibrating particle of air, in Sidebar 1-1. The forces at play in the several modes operate on the string in an additive manner, augmenting or counteracting one another in varying degrees at each point along the string and at each instant in time, to produce a single complex vibration pattern. When that pattern is transmitted to the ear (via soundboard and air), the ear manages to extract the frequencies associated with the subsidiary modes that are present, and recognizes them as the fundamental and overtone pitches.

These same principles apply not only to strings, but to most instrument types. For instance, a rigid rod fixed at one end, as in a kalimba tine, manifests its first four modes of vibration as shown in Figure 2-5B. The resulting overtone pitches in this case are distinctly non-harmonic, with the second and third modes producing pitches at just under two octaves and a minor sixth, and just under four octaves and a major second above the fundamental. Circular membranes, as in drum heads, show a set of modes which are somewhat analogous to string modes, but with more variations deriving from their two-dimensional nature (Figure 2-5C). The resulting overtone series once again is non-harmonic. Fuller information on these and vibrational modes for other instruments appears in the chapters devoted to the specific instrument types.

The modes of vibration just described can be called transverse modes. "Transverse" here refers to the fact that the movement of any point in the vibrating object is side to side. But relative to what? Relative to the direction of travel of the traveling wave in the vibrating medium. If you look back at Figure 2-2, you'll see this effect in a transversely vibrating string: as the traveling waves move lengthwise along the string, each point in the string accommodates the wave with a lateral movement. As a practical matter, transverse vibrations are the most musically useful sort of oscillation in solid vibrating materials such as strings, bars, rods and membranes.

In addition to the transverse modes of vibration, there are longitudinal modes. Longitudinal vibrations are most important in air columns. (They can occur in strings, rods, and other long, thin media as well, but only rarely are they musically significant in these cases.) Longitudinal modes are those in which the predominant vibratory motion of any given point is along the same axis as the motion of the traveling wave in the vibrating medium. They simultaneously manifest themselves in a complementary form, as pressure waves traveling the length of the medium, giving rise to constant fluctuations of pressure at any given point. Despite the different orientation, longitudinal mode behaviors are closely analogous to those of transverse modes. They contain well defined nodes and antinodes, and are capable of the same sort of complex patterns manifesting several modes simultaneously.

Transverse vibrations and longitudinal vibrations can cohabit in the same medium, quite independently and with little effect on one another. For practical musical purposes you can usually focus on one and act as if the other didn't exist.

Longitudinal modes are harder to picture and describe than transverse, in part because they are more difficult to observe directly. The latter part of Sidebar 2-3 may help to paint the picture. Meanwhile, let's consider as an example one wonderfully outrageous longitudinal-mode instrument. The Long String
Longitudinal vibrations don't often play a primary role in string instruments, membrane instruments, or instruments using rigid materials, because of the extraordinary dimensions required. But longitudinal vibration is essential for the entire family of wind instruments. Pressure waves travel far more slowly in air than in solids, making it possible to have longitudinal mode wind instruments of reasonable lengths.

NODES AND ANTONODES: Practical Applications

For the past few pages we have been studying vibration patterns that arise in sounding bodies. Understanding these patterns is central in musical instrument design. It enables you to encourage the vibrations you wish to encourage, and discourage others. A key point to remember is that if you want something to vibrate freely in a particular mode of vibration, you must avoid inhibiting it at points that need to move for that particular mode. That means that if anything must touch the vibrating thing, it should touch only at the (stationary) nodes.

Here's a practical example: Consider a rectangular metal bar such as a glockenspiel bar. When such a bar vibrates freely, it manifests a whole array of natural modes of vibration, producing a corresponding array of sounding tones. The relationships between the tones are non-harmonic — such is the nature of vibrating bars — and the resulting timbre is somewhat clangy and dissonant. One of the modes is considerably lower than the others and may be louder; the ear naturally focuses upon it as the fundamental. It involves a pattern of motion like that shown in Figure 2-6.

Sidebar 2-2

BALLOON-MOUNTED BAR GONG REVISITED

In Sidebar 1-2, I described a balloon-mounted bar gong, an instrument producing a wideband array of audible overtones. In the accompanying discussion I focused on the acoustical effects of the multiple tones. Now that we have covered a bit more ground concerning modes of vibration, we can discuss the physical bases of those tones.

Each of the bar gong's audible overtones arises from one of its transverse vibrational modes. The steel bar has very little internal damping, while, in contrast, most strings have a large amount of internal friction. The string vibration involves complex motions that include transverse vibration, torsion, and even longitudinal motion along the length of the string.

In Sidebar 2-3, I described a coiled spring as a longitudinal resonant system, which is one of the major modes of vibration in musical strings. This mode is a transverse wave in a string, which travels from left to right and produces compressions and rarefactions in the string. These compressions and rarefactions are visible because the direction of propagation is perpendicular to the string.

Sidebar 2-3

ATTACHMENTS TO LONGITUDINAL WAVES

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Sidebar 2-4

WAVES IN AIR

The bar flexes at the center; the center dips and rises while the extremes rise and dip. There are two nodes, taking the form of nodal lines rather than points, crossing the bar at a distance of about 22% of the total length in from each end.

For most people's taste we can get the most musical sound from this bar by bringing out that lowest tone. For the past few pages we have been studying vibration patterns that arise in sounding bodies. Understanding these patterns is central in musical instrument design. It enables you to encourage the vibrations you wish to encourage, and discourage others. A key point to remember is that if you want something to vibrate freely in a particular mode of vibration, you must avoid inhibiting it at points that need to move for that particular mode. That means that if anything must touch the vibrating thing, it should touch only at the (stationary) nodes.

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SIDEBAR 2-2

The bar flexes at the center; the center dips and rises while the extremes rise and dip. There are two nodes, taking the form of nodal lines rather than points, crossing the bar at a distance of about 22% of the total length in from each end.

For most people's taste we can get the most musical sound from this bar by bringing out that lowest tone.
Once again, these principles don't apply only to metal bar instruments. For instance, the point at which a string is plucked makes a big difference in its sound. Imagine a string plucked exactly at its center point. That string will produce a strong fundamental, but the second and all higher even-numbered modes will be scarcely present in the tone. Why? The center point is a node for the even-numbered modes (to see this, look back to Figure 2-5a). Kinetic energy introduced there is useless to them. In contrast, a string plucked very near one or the other fixed end will be strong in the upper partials, giving it a more brilliant tone. That's because the energy is introduced relatively near a node (namely, the end point) for the lowest modes, whereas the same impulse is nearer to where the action is for the higher modes, with their shorter subsidiary vibrating segments.

### MORE ON HARMONICS

I introduced the idea of harmonic overtones in Chapter 1 when we were talking about timbre. In addition to its timbral effects, harmony also has acoustical implications of a mechanical nature. Harmonicity can be seen as a kind of alignment between the modes of vibration within a vibrating body, such as a string or an air column. If the overtones are harmonic, the second mode vibrates at twice the frequency of the fundamental, completing two cycles in the time it takes the first to complete one. They repeatedly arrive at the same point together, and the two reinforce one another. Mode 3 completes three cycles for each cycle of mode 1 for a similar reinforcing effect, and so on up the series. Vibrating bodies with harmonically related modes of vibration tend to be more responsive, having better sustain and a subjectively richer tone than those that do not. When harmonics are detuned, the sound body may not sing or ring out as well. As a familiar example, you can hear the effect of detuned harmonics in dull-sounding, stretched and worn-out nylon strings. The effects also appear in wind instruments, where a particular note may speak less willingly if it lacks reinforcement from well-tuned harmonics.

This is not to say that harmonic musical instruments are superior in some musical sense to those with inharmonic partials. Inharmonic timbres have their own character, and it would be a boring world if we didn't have them around to color the music.

This line of thought has yet another application. You can take advantage of the position of the antinode not only in the energy-input process, but also in the instrument's energy output. Consider once again the metal bar, and imagine that you want to bring out the fundamental mode, and have tuned an air resonator tube to that mode's pitch. The antinode for that mode happens to be the very center of the bar — that is where it vibrates with the greatest amplitude. If you are smart, then, you will center the bar over the resonator, putting it in the best position for the desired mode to drive the air within. One more example: Suppose you are attaching a lightweight contact microphone to a hanging chime. Where along the chime should you locate it? At the point where the mode you most want to hear is at its strongest — the antinode for the desired mode.

### PHASE RELATIONSHIPS

We have seen that most sounds in the real world are complex, comprised of many simultaneous vibrations. Another aspect of this complexity is that most musical instrument sounds involve the simultaneous action of not one, but several vibrating surfaces. For instance, a guitar string vibrates; it causes the soundboard to vibrate. The outer surface of the soundboard causes the air immediately in front of the guitar to vibrate, while the inner surface of the soundboard drives the air within the sound chamber for another, separate, air vibration. Furthermore, in its second mode, the string itself actually vibrates in two separate half-string vibrations, the two halves moving in opposite directions. The soundboard too has multiple subsections engaged in quasi-independent vibrations. And this list of semi-separate vibrating components could go on. Yet this situation is not as chaotic as it seems, because all these vibrations, in theory at least, are at the same frequencies as the driver (the string). But there are some important implications. Consider this one:

The external face of the soundboard pushes outward to create a pressure pulse in the surrounding air as part of each cycle. At the same instant, as part of the same action, the inner surface of the soundboard pulls away from the air enclosed in the chamber, creating a rarefaction (region of reduced pressure). By means of air flow through the sound-hole, this rarefaction is communicated almost instantaneously to the outer air. A half cycle later, the roles of the inner and outer soundboard surfaces are reversed. The inner and outer surfaces thus continually work against one another, with the sound coming out of the soundhole precisely counteracting the sound coming directly off the front face. Just how their interaction plays out is rather complex, but it is a fact that the total volume of the guitar is reduced by this contrary action. The guitar has a beautiful tone arising from the blend of the direct soundboard sound and the air chamber resonance — but it is purchased at the cost of this loss of acoustic efficiency.

When two simultaneous vibrations of the same frequency move in opposite directions like this, they are said to be out of phase. The phrase refers to the fact that the two vibrating bodies are at opposite phases of their vibratory cycles at any given instant. This illustrates one reason why two source sounds producing the same tone at the same volume are not twice as loud as one, and ten are not nearly ten times as loud. It is highly improbable that ten sound sources sounding the same frequency will be exactly in phase with one another for a listener at a given location. There is always at least some cancellation due to sound waves arriving at the listener's ear out of phase. Identical or near-identical sounds arriving from multiple sources do possess, subjectively speaking, a certain richness or fullness lacking in single-source sounds, but they are not as much louder as one might expect.

When two vibrations in the same medium are close in frequency but not identical, another phase-related effect comes into the fore. The two may start out in phase, reinforcing one another, but with the faster one completing each cycle more quickly, they gradually pull out of alignment, until they are out of phase and canceling. As the process continues, they keep moving in and out of phase, alternately canceling and reinforcing, to create in the cumulative effect a continuous rise and fall in volume, a sort of gentle tremolo. This phenomenon is called beating. You can experiment with the effect using any pair of vibration sources with which you can produce controllable pitches near the same note. Try playing two strings on a string instrument, starting with them at the same pitch and then very slowly sliding one ever-so-slightly sharp.

The rate of beating depends on how close the two frequencies are. With identical frequencies there is no beating; when they differ just slightly the beating is slow; with greater differences the beating becomes faster until at a certain point it becomes too rapid to distinguish separate beats.

Beating phenomena are at the heart of choring effects. When two violins, for instance, play the same pitches in unison, they never really play precisely the same pitches. They constantly slip microtonally sharp and flat of one another, bringing the beating effects into play. The beating is not steady; it constantly shifts speed and intensity as the difference between the two sources varies, and this is, to most ears, an attractive effect. It's really nothing extraordinary; it's simply a part of the richer sound of ensemble playing.

When an entire string section plays in unison, the same interactions take place but in such abundance that individual manifestations tend to obscure one another, and the overall effect is smoother. Electronic choring effects operate on the same principles. A more highly refined version of the original signal is mingled with the original to create irregular beating. We'll talk about applying these ideas to acoustic instruments in Chapter 10, "Special Effects."
Just how loud an instrument is, or could be under the best of circumstances, is dictated in part by how much sound energy the initial vibrating body can absorb. Heavier objects can sustain more vibratory energy than light ones, so can objects which can vibrate at large amplitude without damage to themselves or their mountings; and so can objects which are stiff enough to spring back forcefully in response to an initial displacement. Musical strings, despite their other advantages, make an effective bad example here: The average string is simply too light to hold a great deal of energy. Plucking a string harder and harder, going crazy and plucking it ferociously hard, doesn’t add much volume beyond a certain point. There is only so much energy the little guy can absorb. As a result, it is difficult to make a loud string instrument. The exception here helps to demonstrate the rule: the loudest non-electric string instrument is a grand piano. Grand piano volume is achieved by using strings much more massive, and at far higher tensions (enabling them to spring back with great force), than other string instruments could possibly endure.

Vibrating bodies made of thick, solid, massive materials can absorb and then release a great deal of energy. Consider a large metal gong. You can hit the thing hard with a heavy mallet; it absorbs the blow and converts it into vibratory energy within itself without damage. All that sound energy within the gong is then available to be converted into pressure waves in the air that listeners can hear.

But the ability to absorb and hold large amounts of vibrational energy does not ensure a loud instrument. An object may have this capacity, but do a very poor job of communicating its vibrating energy to the surrounding air. Heavy, solid metal rods, for instance, can hold a very strong vibration; but without the assistance of some external radiator their sound may be anemic, especially in the lower frequencies. There are two reasons for this. One is that they don’t have enough surface area to move much air. The other is that with massive vibrating objects, a large amount of energy can take the form of a vibration of small amplitude. The aforementioned rod, then, might be vibrating with lots of energy, but not enough amplitude to have much impact on the surrounding air.

And so we come to the matter of vibration transmission. You can make the rod sound louder by using it as a driver for a secondary sound radiator, which will in turn do a better job of driving the air. That secondary radiator must have a lot of surface area, and it must be lightweight and compliant relative to the rod so that the rod can drive it easily. Because the vibrations in a heavy rod are so strong, it is not hard for such a rod to drive most radiators, given the right sort of mounting. Strings, by contrast, are more exacting in their requirements. Typically they can effectively drive only a lightweight radiator, such as the thin, springy softwood soundboards of guitars and violins, the drumhead-like soundboards of banjos and their kin, or unconventional super-light radiation surfaces like balloons or styrofoam.

The measure of how well a given initial vibrating body will drive a given secondary resonator is impedance. You can think of impedance roughly as an indicator of a vibration’s concentration of energy. High-impedance vibrations condense a great deal of vibrating force into what may be a relatively small amplitude vibration. Consider tuning forks:

The two prongs of a tuning fork vibrate in a complementary lateral motion, in which they alternately flex toward one another and then apart, at some set frequency. The handle of the fork is also vibrating, as you can verify by pressing the end of the handle against a table top: the table top then acts as a soundboard driven by the fork, and the sound becomes much louder. If you grab the ends of the tines, they are immediately damped out and stop vibrating. But why doesn’t holding the handle of the tuning fork (as you have probably been doing all along) kill the vibration in the same way? The answer is that the handle is engaging in a lower amplitude, but much stronger vibration — so strong that not only does the hand not damp it, it can even impose its will upon the table top. The prongs, meanwhile, vibrate at larger amplitude, but with a relatively weak vibration. Not only are they easily damped by the hand, but if you try pressing them against the table top, all you hear is a moment of clatter followed by silence — the table top easily wins the battle of wills.

The intense, low amplitude vibrations in the handle of the fork are high-impedance vibrations. Larger amplitude, weaker vibrations such as those in the tines are low impedance. Generally, high impedances are associated with larger masses and greater rigidity; low impedances with lesser masses and greater flexibility. (The relatively large amplitude and low impedance of the tines is associated with their willingness to flex.) An easy way to get a sense of the impedance of a vibrating object is simply to touch it: low-impedance vibrations are easily damped with the hand; high-impedance vibrations are not.

An initial vibrating body of high impedance easily drives a low-impedance body, while a low-impedance initial vibrator will have more difficulty driving a higher-impedance body. This has important implications for musical instrument design. For a secondary sound radiator, such as a soundboard, to work with any degree of efficiency, it must have lower impedance — that is, be lighter and/or more flexible — than its driver. The higher the impedance of the driver relative to the radiator, the more rapid will be the energy transmission, and the broader and louder the sound.

Shall we go through this one more time with another example? Consider the guitar. At the middle of the string, where it vibrates very broadly, the impedance is extremely low. Fortunately, at the bridge, where the string is attached, the comparative rigidity of the anchoring compresses the same vibrating energy into much smaller amplitude, and thus considerably higher impedance. This enables the string to drive the bridge and the attached soundboard. Still, given the lightness of the guitar strings, it only works because string instrument soundboards are made relatively low in impedance, being both light and somewhat flexible. Just how light and flexible can be varied according to the sound one wants to achieve: Flamenco guitars are deliberately made with relatively lightweight bodies and soundboards, to facilitate rapid delivery of energy from the string to the sound radiator, resulting in a loud, percussive tone with relatively little sustain. This is in keeping with the musical style. At the opposite extreme, most electric guitars (which can achieve great volume by other means) are made with heavy, solid wood bodies. The result is a far slower delivery of vibrational energy to the body of the instrument, and far longer sustain. The volume, in the absence of amplification, is quite small.
Before moving on to descriptions of specific instrument types, we need to consider two more topics. One is tunings, meaning scale and pitch relationships. This bears directly on the choices that builders make regarding what pitches are to be available on a particular instrument, the reasoning behind those choices, and the process of tuning the instrument to those pitches. The second topic is the spatial layout of the instrument. For some instruments the physical nature of the instrument dictates the pitch layout to a large extent, and the maker has little choice. But for others the design of the interface between player and instrument is an open question, and an important one.

## TUNINGS

The piano, guitar, and most other western instruments are made to produce a set of twelve pitches in each octave, collectively called the chromatic scale. It would be easy to think of this set of twelve as the entire gamut of pitches available for use in music, but that would be false. The range of possible pitches is a continuum, and between any two frequencies there are other frequencies. Most listeners can easily distinguish musical intervals far smaller than the piano's smallest interval, the semitone. So there is no reason not to make music with pitches other than those of the standard chromatic scale. And in fact people do this all the time. Western musics commonly use other tunings. *"Outside"* pitches appear in plenty of western music as well, the most conspicuous examples being in blues and its derivatives (for instance, "bent" notes on the guitar).

Musical instrument makers have to deal with this matter of tunings and tuning systems, as they decide what pitches their instruments are to produce. Many makers stick with pre-existing tunings, such as the western chromatic scale, and so have no need to further analysis. Some base their pitch choices on instinct and the untaught preferences of their ear, without reference either to existing models or technical analysis. Some enjoy working with arbitrary or random pitch sets. And some devise new but carefully rationalized tuning systems. Many makers regard the matter of tuning as an essential aspect of the character of the instrument and the creativity of its maker.

To fulfill this last ideal, it is good to develop an understanding of tuning systems both conventional and exotic, and the rationales behind them. This can easily become a matter of intense study — the subject of tuning systems is a large, complex, and often arcane one. I won't provide a complete exposition of the topic, but in what follows I will provide a general overview as it relates to instrument design. Readers who wish to avoid the technical stuff, and who are content to work with random tunings or tuning by instinct alone, may choose to skip the sections on just intonation theory and equal temperament theory that follow.

### Underlying Concepts: Just Intonation & Temperaments

Over the last two centuries and some, a particular form of the chromatic scale has very much been the predominant tuning system in western music, especially in formal music circles. This is the scale known as 12-tone equal temperament. Not only is it the standard tuning for pianos and electronic keyboards, but it also dictates the spacing of frets on guitars, the tuning of commercially manufactured marimbas and xylophones, and so on. Most wind instruments are designed to reproduce the same scale, although they are usually a bit more flexible in practice; while instruments with sliding pitch like violins, trombones and slide whistles are, by their nature, not restricted to any particular scale.

Twelve-tone equal temperament is a system in which the octave is divided into twelve equally spaced intervals, providing twelve equidistant pitches before reaching the octave above on the thirteenth. To one who has been playing music in twelve-equal all his or her life, it may seem perfectly natural that there should be a single uniform intervalic unit — the equal-tempered half step, equal to 1/12 of an octave — by which all other intervals can be measured and constructed. It certainly is convenient. But scales need not be built around equal intervals, and in fact they rarely were before the relatively recent (historically speaking) introduction of 12-tone equal temperament. The scale systems that humans seem to have naturally gravitated toward, in most cultures and through most of history, have employed irregularly sized intervals between the scale steps. To understand this, we need to review some basics of intonation theory, and to come to terms with the distinctions among just intonation, temperaments like twelve-equal, and other intonation systems.

Recall that our ears interpret musical intervals in terms of ratios. For example, one hears the interval of a major third between any two pitches whose fundamental vibrational frequencies form the ratio of 5:4. It matters not what the actual frequencies are; as long as they are in that ratio, the interval will be heard as a major third. This kind of ratiobased perception seems to form the underlying basis of many, perhaps most, of the tuning systems that have evolved around the world. In such tuning systems, the frequencies of the pitches in the set all bear simple ratio relationships to the frequency of the tonic pitch around which the tuning is built. For instance, the frequency ratios for the seven pitches plus octave of the most basic form of major scale, each relative to the tonic, are 1, 9/8, 5/4, 4/3, 3/2, 5/3, 15/8, 2.

Tunings based on simple ratios like this are called just tunings, or are said to be in just intonation. (To clear up a common misconception: just intonation refers not to a single specific tuning; it refers to any tuning which meets this general description.) Many such tunings exist, although 12-equal is not one of them. Some just tunings have come into being because musical theorists invented them. Others — and these include many of the most important tunings historically and world-wide — have arisen naturally in various music cultures, and have been found upon analysis to be comprised of simple ratios. With the intervals of just tunings, the basic harmonies have what could be described as a smooth or restful sound. Twelve-equal, by contrast, possesses a certain roughness, especially in music of any complexity.

In just tunings, the scale steps inevitably fall in such a way that the spaces between the steps are irregular; no uniform intervalic unit exists. Is this a problem? It was never perceived as such for who-knows-how-many centuries. But following the Renaissance period, there emerged in European high culture music a growing interest in enriching the harmonic flavor of the music by modulating from key to key. This is difficult in tunings with asymmetric interval spacings, because to get the desired scale steps in each new key requires additional pitches that aren't in the original key, and the number of pitches called for quickly multiplies to an unmanageable number. It becomes impractical to build an instrument that produces many pitches.

One solution to this problem is simply to accept the limitation: build an instrument in one key and always play in that key, or modes thereof. Another is to add enough additional notes to allow for playing in perhaps just two or three additional keys. A third option is to find any cases where pitches in the new key almost match those of the original key, and use a single compromise pitch for both. This process — tuning certain pitches to compromise values to make them functional though not perfect in more than one key — is what is called tempering. Tempered scales are not just the temperings throw off the theoretically ideal simple ratios. But they typically are imitative of just tunings, designed to approximate the just ratios as closely as possible while still allowing some flexibility in changing keys.

Many different tempered scales were suggested and used in Europe in the 17th and 18th centuries. Most were not equal; the distances between the scale steps varied slightly from one to the next. When the idea of a twelve-tone equal temperament first gained prominence during the 18th century, many musicians, tuners and instrument builders were reluctant to use it. Their objection was that compromise values for certain important intervals — the thirds and sixths — were more seriously muddled than seemed acceptable. With the passage of time, this flaw has been increasingly forgiven and twelve-equal increasingly accepted as a standard. It has reached the point today where most westerners regard twelve-equal's thirds and sixths as perfectly normal. You can get some sense of the size of the discrepancy between just and tempered intervals by looking at the charts in Appendix 2, "Frequency and Tuning Charts."

The difference in sound between the two tuning types might seem a subtle one. But the change from the vanegated interval spacings and harmonies of ratio-based tunings to the uniformity of equal temperament was culturally and philosophically significant. As western material culture moved into an age of mass production, the technology of interchangeable parts was applied to the building blocks of...
For the temperament in question, just as we did for 12-equal above, you simply choose a starting pitch and use a constant factor to multiply it by repeatedly, just as you would to get to any step of a just temperament.

Equally spaced systems, as we have discussed, can be used to create equal temperaments — in which each step in the scale is the same distance apart (or equally spaced) — by simply repeated multiplication by the same factor. For example, if you start at 440 Hz, after twelve multiplications by the factor, you will arrive at its value. Sidebar 3-1 provides a chart listing the values for a range of equal temperaments.

Once you have established a tonic frequency, you can begin a process of simple multiplication to establish the frequencies of the other pitches of the set. For this example, let's take G-49.0 as the tonic, and the just major mentioned a moment ago as the set of ratios:

- **Tonic:** 1/1 * 49.0 Hz = 49.0 Hz
- **Major 2nd:** 3/2 * 49.0 Hz = 73.5 Hz
- **Major 3rd:** 5/4 * 49.0 Hz = 62.5 Hz
- **Perfect 4th:** 4/3 * 49.0 Hz = 65.3 Hz
- **Perfect 5th:** 3/2 * 49.0 Hz = 73.5 Hz
- **Major 6th:** 5/3 * 49.0 Hz = 81.7 Hz
- **Major 7th:** 15/8 * 49.0 Hz = 91.8 Hz
- **Octave:** 2/1 * 49.0 Hz = 98.0 Hz

That's one octave of the scale. You can find the second octave frequencies by multiplying the values for the first octave by two (recall that 2:1 is the ratio for the interval of an octave, and multiplying any frequency by two thus gives the octave above). Find the third octave by multiplying by two again, and so forth. (The octave duplication process applies only if you want the same pitches to repeat in the upper octaves. This is usually but not necessarily the case.)

**Equal Temperament — Theory**

Now let us go through the same processes with equally spaced tunings. We have spoken specifically about 12-tone equal temperament, but in fact you can have equal tunings with any number of divisions per octave. Each produces its own array of intervals, and each has its own characteristic sound. Usually, though not always, people use equal temperaments as approximations to just scales, favoring those that fortuitously happen to contain intervals closely approximating the just intervals they wish to hear. The standard 12-tone equal temperament is somewhat imperfect in this regard, matching some of the desired just intervals quite well and some not so well. But twelve has the great advantage that it is the smallest equal temperament number that does anything like a decent job of it. Other equal temperaments containing pitches closely matching important just intervals include 19, 24 (the quarter-tone scale), 31, 41, 53, and 72 (see Appendix 2 for more on some of these).

**Whole Tone Scale — Theory**

And what of all those other equally spaced systems, the ugly ducklings which don't happen to approximate important just intervals? While these have not been explored as much, there are composers who have taken an interest in them. Some enjoy the fact that such scales are without familiar reference points — no recognizable fourths or fifths or thirds — so the listener simply has to accept and appreciate the exotic intervals as they are, rather than trying to mentally resolve them into something familiar. It's an ear-stretching experience. Scales of 7, 10, 11 and 13 tones have been used with this effect in mind. Each has its own distinctive flavor or mood.

**Equal-spacing systems require a mathematical approach that is different from what we saw with just intonation. Here's how it works:**

By definition, each step in an equal temperament must be higher than the previous by a constant interval. This means that the frequency for each step must be multiplied by the same factor to get the frequency for the next successive step. (This factor works just like the frequency ratios in just intonation, but it is expressed as a decimal for reasons having to do with its mathematical derivation.) After multiplying by that factor repeatedly to get the frequency for each scale step in succession, you should reach the octave, at twice the original frequency. These requirements can be summarized in a formula that yields a value for that factor: Where \( C \) is the constant factor, and the scale is to have \( n \) equal divisions per octave, then \( C = \sqrt[2^n]{2} \). (That is, \( C = \text{the } n \text{th root of } 2 \). Thus, for 12-tone equal temperament, the factor is the 12th root of 2, equal to an irrational number that can be shortened to 1.05946. Knowing this, you can find the starting frequency for each step of 12-equal from a starting tone of, say, A above middle C at 440 Hz, because it is an accepted pitch standard; or, for a lower starting note, start an octave or two down at A-220 or A-110. Alternatively you could choose, say, the low G at 49.0 Hz, or the C at 32.7 Hz, for the tonic. Or, to be practical, you could choose the lowest pitch that sounds well on the instrument that is to play the scale.

For other equal temperaments you can find a similar constant factor, following the same reasoning to arrive at its value. Sidebar 3-1 provides a chart listing the values for a range of equal temperaments.

**Rational Vs. Radical Approaches in Tuning Theory**

With an equal temperament, you can find a similar constant factor following the same reasoning to arrive at its value. Sidebar 3-1 provides a chart listing the values for a range of equal temperaments.

With this information, you can calculate the frequencies for any equal-tempered scale, based upon whatever starting pitch you choose. You need only go through the series of multiplications by the factor for the temperament in question, just as we did for 12-equal above.

**Sidebar 3-1**

Here is a list of the scale factors for equal temperaments of 5 steps per octave through 24, plus 31, 36, 41, 53 and 72 (the last five have been advocated by various theorists because they contain close approximations to just intervals). The factor \( C \) is the constant by which the frequency of each scale degree must be multiplied to obtain the frequency of the next degree. 1/C is the inversion, useful for calculating descending scale degrees, as well as for placement on string instruments and tube lengths for simple cylindrical wind instruments. The values given here are based in this general rule:

\[
C = \sqrt[2^n]{2}
\]

For any m/n-equal temperament, \( C_m = \left( \frac{2^n}{m} \right)^{1/n} \)  

(2 = the mth root of 2)
Mechanics of the Tuning Process

We have been discussing the abstract building blocks for scales. How to apply this information to the construction of particular instruments varies from one instrument type to another. For some instruments, there are calculable correlations between the dimensions of the sounding elements and the resulting frequencies, so that builders can do their advance planning and computation, build the instruments accordingly, and get the desired scales from them. With others, the correlations are not simple and predictable, and builders must work much more by ear and instinct, trial and adjustment. You will find fuller information on these processes in the chapters devoted to the specific instrument types. But there are some aspects of the process which are common to all instruments, and we will look at them now.

If you are tuning by matching pitches, the phenomenon called “beating,” described in the previous chapter, can help. Recall that two close but not identical pitches sounding together produce a continuous wavering of their combined amplitude. The closer in pitch they are, the slower the wavering, until it stops.

To take advantage of this, sound the two tones together, and listen for the wavering of their combined amplitude. The closer in pitch they are, the slower the wavering, until it stops. The beating effect is easiest to hear with instruments of entirely when they match. To take advantage of this, sound the two tones together, and listen for the beating effect.

If, on the other hand, you are following 12-equal or some other prescribed scale pattern of your choosing, then you need some sort of tuning guide — something to help you hear when the sounding element you are tuning is at the desired pitch. There are several approaches to this. One is to use the rather subtle listening techniques developed by piano tuners. These involve specialized applications and we won’t review them here. Another is to buy or make special tuning equipment. In recent years electronic tuners have come on the market that are accurate, easy to use and moderately priced. These and several other tuning aids are discussed in Sidebar 3-2. A third approach — a common and reasonable one for anyone new to the game and lacking special equipment — is to tune by comparing pitches from the new instrument to those of some existing instrument whose tuning you have decided to use as a reference. This can help. Recall that two close but not identical pitches sounding together produce a continuous wavering of their combined amplitude. The closer in pitch they are, the slower the wavering, until it stops entirely when they match. To take advantage of this, sound the two tones together, and listen for the slowing of the beating as you bring the note-to-be-tuned closer to the reference pitch. When you hear the beating stop, you know you have a match. The beating effect is easiest to hear with instruments of simple, sustaining tone quality (not too many noise components or inharmonic partials), and when the tone qualities of the two instruments are similar. Noisy, inharmonic instruments can be torture to tune even for someone with an experienced ear.

Tuning by comparing to a reference pitch is always a good listening exercise. Some people have an inborn knack for hearing whether the note-to-be-tuned is above, below or right on the reference pitch. Others find it difficult. Everyone improves with practice.

**PITCH LAYOUTS, GESTURE, & ERGONOMICS**

Think for a moment about pianos and their keyboards. The standard piano produces 88 different pitches, comprising sombering over seven octaves’ worth of 12-tone equal temperament. The player accesses those 88 notes by means of the keyboard, which has the keys laid out in the familiar two-tiered linear arrangement of white and black keys. This particular keyboard configuration came into being...
MAKING A MONOCHORD

Monochord is the name given to a simple zither designed not primarily for musical performance, but for studying harmonic relationships. Typically there are two identical strings, tuned to the same pitch. The two can be stopped anywhere along their length by small movable bridges, altering the effective string lengths. Beneath the strings is a calibrated ruler, to aid in locating the bridges for specific proportions of the string lengths. Working from the inverse relationship between string length and frequency (if $f$ is proportional to $1/L$), you can determine the frequency ratio between the two strings: it's simply the inverse of the string length ratio. So you can use the monochord to hear any ratio you want, be it a familiar one or something new. Since the time of Pythagoras, monochords have been used for teaching, for research, and as an aid in creating musical scales. Here are a few suggestions for anyone wishing to design and build a monochord.

A common problem with monochords is the movable bridges tilt the strings slightly from their natural positions. This deflection causes changes in tension which throw off the simple relationship between frequency and string length. To avoid this, some monochords use pinching bridges. They are designed to grip the string from above and below, stopping it securely. Some are designed to be placed anywhere along the steel strips; they hold securely yet can be moved easily. For such a design to work well, the clothespins must have strong springs; the magnets must be very strong, and the height of the clothespin-bridge must be just right.

For strings you will need about 10 feet of music wire in the general range of .014" or .018" diameter (designated as sizes #5 to #7). Adjust the open string pitches by means of the tuning pin, tuning both to the same pitch at moderately high tension. The specific pitch is your choice. Frequently you will choose to leave one string open (bridgeless) as a fundamental tone (see Sidebar 3-1). You may also have room for an extra string, either above or below, to give you just a bit more flexibility in choosing pitches.

While accurate intonation is essential for a monochord, great volume and exquisite tone quality are not. With that in mind, you can design your monochord as an easily-assembled rectangular object. For convenience, give it an active string length (bridge to bridge) of one meter. This will allow you to use a meter stick, glued to the surface of the soundboard under the strings, as the string length calibrator, invoking easy ratio calculations based on 100 centimeters. Reasonable overall dimensions for the box might typically be 6" wide, 2" high, and 44" long (this allows for the 1-meter string length). The front and back can be 1/8" plywood. The sides should be moderately thick (about 3/8"), to allow for tacking and gluing of the front and back. The two end pieces should be hardwood at least an inch thick to hold the tuning pins securely. For simple—possible arrangements for tuning pins and end bridges, look back to the harmonica plan in Sidebar 3-1. (For more on string instruments and string instrument bodies, look ahead to Chapters 8 and 9.)

A. A simple monochord, with the magnetic pinching bridges shown. The two strings are anchored with zither pins at one end, and wood screws at the other. Bridges at each end are made from sections of metal rod, glued or held in place by nails.

B. The construction of the box. C. The magnetic-clothespin pinching bridge. For the clothespin to close firmly over the string at the indicated location, it may be necessary to remove a little wood from the usual closure point near the tip.
The fifteenth century, an arrangement much like the present one had become widespread, with the seven below and five above — but still, at that time, in the form of rows of levers. In the course of the sixteenth and seventeenth centuries this evolved into the bed of ivory and ebony that we see today.

Over the years, meanwhile, other layouts were proposed. Most were designed to accommodate the additional pitches required for modulation in just intonation. Like the design shown in Figure A, they often involved subdividing some of the white keys from front to back in the space of one, and finding ways to incorporate additional raised black keys at different levels.

In the present era, performers, builders and theoreticians have continued to propose alternative keyboard designs. Some, like the 19-tone arrangement shown in Figure B, still adhere closely to the standard arrangement. In fact, this 19-tone layout has been promoted for the fact that it fits seamlessly into the existing system, making it a logical next step. Other contemporary systems depart more radically from the existing standard. One important idea has been to use two-dimensional arrays. This brings more keys into a smaller area, allowing the player to reach more tones with less stretch. It also allows a more sophisticated approach to pitch relationships, since one can work with vertical and diagonal spatial parameters as well as horizontal. A pioneer in this area was R.H.M. Bosanquet (1841–1912), whose Enharmonic Harmonium sported a dense geometric forest of protruding levers. Among those working with two-dimensional pitch arrays today is Erv Wilson, whose designs have been incorporated in instruments by several different builders. One of his designs appears in Figure C.

This layout is well suited for its intended musical context. In the usual playing position, the prongs are plucked primarily with the two thumbs, as the hands support the body of the instrument. With the scale ascending left-right-left-right, rapid scalewise passages are easily executed by alternating thumbs. Harmonies in thirds, which play a prominent role in the musical style, are easily realized by simultaneously striking adjacent prongs with the thumb.

A similar arrangement is used on one of the prominent West African instruments, the kora (a many-stringed harp-lute). It works beautifully in this case as well, for many of the same reasons. (And if you think kalimba music is heavenly, then you should listen to some good kora music.)

All this is to introduce the idea that, in designing an instrument, you may find yourself with a choice as to how the instrument's pitches are to be laid out spatially. We have seen that the question is a relevant one for keyboards, kalimbas and koras; it is also important for marimbas, tube drums, zithers, and a host of other instruments with arrays of independent sounding elements. For some other instrument types the choice is not quite so free, being at least partially dictated by physical constraints. In wind instruments, for example, the positioning of the pitches under the player's hands is usually a matter of tonehole placement, an area in which the maker has only limited options. Yet even within these constraints, a carefully planned fingering arrangement can easily make the difference between a friendly, playable wind instrument and an awkward, uncooperative one.

The most important issue here is ergonomics — the degree to which the instrument accords itself to the human body and its natural patterns of movement. And there are other considerations: Pitch configurations often serve not only as a physical interface, but also as a conceptual tool for the player. Keyboard players learn (consciously or unconsciously) to conceive musical relationships in terms of position on the keyboard. Players of other instruments — kalimba, or guitar, for instance — do the same, even when the physical layout of the pitches does not match the keyboard's simple grid. Several contemporary theorists have created alternative pitch arrays designed to reflect their own underlying musical logic. Many of these designs are primarily of theoretical or analytical value, but some have been built into playable instruments. Sidebar 3–4 has examples.

Beyond affecting the ease of playing, the configuration of the pitch elements establishes what kinds of musical patterns will be characteristic to the instrument. Piano music sounds "pianistic," and guitar music is "guitaristic," in large part because of the nature of the physical interface between the player and the instrument. This may seem like an innocent enough observation, but the nature of the playing movements is a key to the character of the instrument as a thing of human musical expression. It is one of the essential elements in musical instrument design.

These ideas can be incorporated into the word gesture. Gesture has its physical aspect in the movements one makes to play an instrument. It has a musical aspect in the characteristic turns of phrase, the sorts of note clusters, or the rhythmic patterns that seem to fit the instrument most naturally. The two aspects are very much intertwined.

Here is an explicit case of the role of gesture in music. In 1946, the American composer, theorist and
Instrument designer Harry Partch built an instrument he called the Diamond Marimba. It was a resonated marimba with the bars laid out in a diamond-shaped configuration, following a theoretical grid Partch had developed to represent important pitch relationships. The layout of the bars naturally gave rise to certain sorts of characteristic playing motions and resulting musical patterns. Writing about this some years later, Partch said, "The inevitable downward arpeggios, or sweeps, of the Diamond Marimba caused me to wish for a twin instrument, one in which the arpeggios would inevitably and automatically sound upward" (Genesis of a Music, 1974). Almost twenty years after creating the Diamond Marimba, to realize his wish, Partch built his Quadrangularis Reversum, with the pitch relationships of the bars inverted.

Finally, there are considerations of kinesthetics and aesthetic effect. Important questions for any instrument are, is the playing position a natural one, a comfortable one, one that lends itself to musical enjoyment and expression? Are the movements involved attractive? Is the visual effect funny, beautiful, dramatic, graceful, odd, boring? Do the stance and movements convey a sense of musicality or a sense of awkwardness?

In recent years our musical culture has suffered an impoverishment in the area of gesture, due to the increasing use of computers and synthesizers. Whatever their other merits, purely electronic instruments have tended (with some notable exceptions) to be gesturally bland. By contrast, many of the new and unusual acoustic instruments described throughout this book are unique in their gestural qualities, both physical and musical. As you design and build instruments, I encourage you to give some thought to these matters. The performer's movements in performance are very much a part of the color and character of any instrument. Playing techniques that may not be facile or that don't lend themselves to the performance of complex music may still produce a rich result when you consider what it feels like to play the instrument, what it is like to see the instrument played, the characteristic musical patterns that the instrument invites, or the directness of contact between the player and the sounding elements.
Chapter Four
IDIOPHONES

And now we move into the investigation of specific instrument types. In order to get a handle on the wide world of possible instruments, we will divide them into broad categories, and study them one at a time. The question of how to categorize musical instruments is a matter of endless debate among people who study such things. For the purposes of this book, we will follow the broad outlines of what has become the most widely used grouping among western scholars, the Sachs-Hornbostel system (described in Sidebar 4-1).

The Sachs-Hornbostel system begins by dividing musical instruments into four fundamental categories, based upon the nature of the primary vibrating body. The largest and most diverse of these groupings is the idiophones. Idiophones are defined as sound sources in which the initial vibrating material is solid, and vibrates by virtue of its own rigidity. The vibrating body is not held taut like a string or a drumhead, nor does the initial vibration take place in the air itself as with wind instruments; rather, an idiophone is just a solid chunk of rigid material that makes a noise when something excites it into vibration. The chair that I am sitting in is an idiophone — strike it, scrape it, squeak it, and it produces an idiophonic sound. So are bells, gongs, triangles, kalimbas, xylophones and innumerable other sound makers.

Many idiophones are played with beaters of some sort, and a few use bows. Beaters and bows are discussed in Chapter 5, "Beaters, Scrapers and Friction Makers," and you can think of that chapter as an important adjunct to this one.

There are many different sorts of idiophones. To bring order to the unruly throng, we will take as our central theme the nature of the vibration pattern within the initial vibrating element in each instrument. Freely vibrating bars such as marimba bars, for instance, have characteristic patterns of vibration. The same patterns appear in freely vibrating rods and tubes, as well as hanging chimes, and so we will group all of these together, and discuss them first. Music box combs, kalimbas, and other instruments with vibrating tongues form another group, along with their various relatives, and we will consider the second. Bells, cymbals and musical glasses form a third group. The list goes on through a few more basic types. Toward the end of the chapter this approach will break down a bit, as we come to an ad hoc, catch-all grouping of instruments whose vibrating patterns are too irregular or idiophonic to fit neatly into the main categories. We begin now with the vibrating bars.

FREE-BAR INSTRUMENTS:
MARIMBAS, CHIMES, AND THEIR RELATIVES

Let us start with an image of a rudimentary free-bar instrument. This will serve as a sort of prototype, allowing us to identify salient features so that we can study those features more closely later. Imagine a xylophone consisting of a series of wooden bars, each one a little shorter than the last. The bars are supported, with their ends slightly overhanging, on two horizontal cross pieces set on legs. The bars don't rest directly on the cross pieces, but on strips of foam rubber padding running along the top of each cross piece. Dabs of hot glue adhesive keep the bars in their places on the foam pads. You play the instrument by striking the bars with percussion mallets.

OK, what are the essential elements here?
1) First, the bars. For this prototype I suggested wooden bars; in fact, almost any reasonably rigid material in an elongated form could have served. Metal bar instruments, for instance, appear in many parts of the world. There are similar instruments which use round metal rods or hollow metal tubing instead of bars, since such forms follow the same vibrational patterns as flat bars. Other possibilities include glass, stone, plastics, bamboo, and ceramics, to name just a few. See Appendix 2 for more on specific materials.
2) The second essential element in the prototype free-bar instrument is a means for getting different pitches from the different bars, allowing for a range of available notes. The prototype achieves this by having the bars cut to different lengths. This is the simplest and probably the most common approach in free-bar instruments. Another alternative would be to vary the bars' thickness, but this requires a bit more sophistication — we will discuss that shortly.

claves
Latin American clavés are free bar instruments too. A set of clavés consists of two cylindrical sticks of heavy hardwood (often eucalyptus), typically a little over an inch in diameter and eight inches long. The player holds one clave loosely cupped in one hand, in a way that allows support roughly at the nodes for the first major mode of vibration. The other clave is used to strike the first, for a very clear, short, high-pitched tone. Clavés are often made in pairs of unmatched pitch, for a choice of exciting pitch. If you can get a 1st down of any heavy hardwood, you have practically got clavés ready made. Just cut the two lengths. Even common, softer woods produce a recognizable clavé sound, but lacking the brilliant ring that percussionists seek.
Here is how to predict the pitch of other bars based upon the pitch of a sample bar. This approach will work as long as all the bars are the same thickness, and are regular in cross sectional shape over their length. If you use bars of different thicknesses, you will either need to cut a new sample for each thickness, or get into more demanding mathematics. The key to the process is this rule: sounding frequency (in the ideal) is inversely proportional to the square of the length. As an example, this means that if you have two otherwise identical bars, one of which is half as long as the other, the short one will vibrate at twice the long one’s frequency, producing a tone two octaves higher. You can derive from this a set of relations that are summarized in the following chart. Generalized formulas (allowing you to vary the fundamental, bringing out the 2nd or 3rd mode as the predominant pitch. The workable range in that case will diminish volume. At the lower end, mere are several ways to enhance the fundamental and de-
Overtone tuning is often done for wooden bars, and it works for solid metal bars as well. It is not
completely inharmonic, since the second partial is at a somewhat sharp seventh above the
fundamental, the third at two octaves and a slightly sharp fourth. That second partial can be
considerably distracting, especially in the lower notes. As a builder, you can respond to this
inharmonicity in one of three ways: 1) Acquaint the bar's natural inharmonicity as part of the sound —
after all, it does have a certain curious appeal. 2) De-emphasize the inharmonicity by striving to
highlight the fundamental (or other desired mode) and suppress other modes as much as possible.
You can do this by using a fairly soft beater to strike the center of the bar, choosing the right
length-to-thickness ratio for a bar of the intended pitch, and using the right sort of resonator (more
on that later). 3) Alter the overtone relationships to bring them into some preferred tuning. This can
do by cutting away some material from the underside of the ends of the bar. This reduces the mass
there without affecting the overtone structure. The disadvantage here is that the cylinder then
retains its characteristic ability to produce the same pitch regardless of the direction of the
impulse.

The overtone relationships of the fundamental and the overtones are

\[
L' = \frac{B}{A} L
\]

Where \( L \) is the length of a given bar, and \( L' \) is the length of the bar one step up in any
inharmonic equal temperament. —

\[
L' = \frac{L}{2}
\]

A similar formula yielding bar length relationships for any just ratio tuning ratio would be:

\[
L' = \frac{L}{2^n}
\]

where \( n \) is the step number (i.e., 1 for the 2nd overtone, 2 for the 3rd overtone, etc.).

Several times now I have spoken about fine tuning bars that were not cut exactly to pitch in the
first place. Here are procedures for doing so. The reasoning will be apparent if you followed the
discussion of the effects of mass and rigidity in Chapter 2, especially Figure 2-1. It will assume that you are tuning for
the bar's first mode of vibration (as is usually the case). If the sounding pitch is slightly below the
desired pitch, you need to reduce the mass of the parts of the bar that move the most. You must do this in a way
that does not reduce the rigidity of the parts of the bar that flex, which would have a contrary effect. If you
look back at Figure 4-1, you can see that there are three regions of generous movement in the bar's
first mode — the center and the two ends. Removing mass by shaving off material at the center would
have the unwanted effect of simultaneously reducing rigidity, so instead remove some material at the
ends of the bar. You can do this by simply shortening the bar. Alternatively, you can shave some material
from the underside of the bar at the center to lower the first mode — fine tune if necessary. Then use the corrected length for the next calculation.

You can proceed through the entire intended range this way, with a minimum of wasted effort and
material.

For truly uniform bars, such as high quality manufactured metal bars or tubes, the numbers generally
come quite close to the mark in actual practice. You can calculate how long the bar should be to produce
a certain pitch, cut the bar precisely to that length, and then get a result requiring no further tuning.
The mathematical predictions are slightly less accurate for lower quality manufactured bars and tubes, and much
more predictable for bars of wood or other natural materials. Still, the calculations will at least
enable you to make an educated guess, cut the bar to that length, and then fine tune as necessary (we
will discuss methods for fine tuning shortly).

With this background, let us describe a simple procedure for making a set of bars for a tuned bar
instrument in (let us say) 12-tone equal temperament. Cut a sample bar to a length that you guess will
give you something close to your intended lowest pitch. If the bar turns out to be too short and
the resulting pitch too high, put that bar aside to use later, and try again. If the bar is long and low, gradually
shorten it, repeatedly testing for pitch as you go on, until it reaches the desired pitch. You have now
established a basis from which to work. Calculate the expected length for the next bar, a semitone higher,
by multiplying the length of that first bar by the “semitone-up” factor of 0.9715 (from the chart above). Cut
the new bar to that length; fine tune if necessary. Then use the corrected length for the next calculation.
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You can proceed through the entire intended range this way, with a minimum of wasted effort and
material.
Resonators & Radiators

The resonator tube, in the most common arrangement, hangs below the bar. You can use any number of hanging or mounting systems, and I will cover some of the options shortly. It is a good idea to make the distance between the tube and the bar adjustable. That distance affects tuning and other resonance characteristics. You will usually find the best resonance with something like a half inch or an inch of space between the two.

Finding the Nodes

For mounting purposes, and often for tuning purposes, you need to be able to find the vibrating bar’s nodes — or at least come reasonably close. If the bar is uniform in shape, rigidity and density over its length, you can use the chart in Figure 4-1 to calculate node locations. For bars of non-uniform materials, the calculated results are less dependable. A deep center scallop, for instance, tends to move the nodes toward the ends of the bar somewhat. In such cases, you can turn to empirical means for determining node and antinode locations for each individual bar.

The most direct methods for locating nodes and antinodes involve varying the points of bar support, striking at different locations, listening, and feeling. Rest the bar on two padded supports and try some exploratory tapping. Placing the supports under nodes for the mode you want to hear will let that mode sing out; supports elsewhere will damp it. Striking the bar at an antinode for the desired mode brings it out most prominently; striking at a node scarcely lets it sound.

If the bar is a flat one, you can try this old-favorite technique for node location: lay the bar on a soft, padded surface. Sprinkle a fine, dry, powdery substance on it, like sawdust, salt, or talcum powder. Repeatedly strike the bar in such a way as to excite the desired mode of vibration. The particles will tend to dance off of the most vibrationally active areas, and gradually collect at areas of less motion, which is to say, at the nodes.

Overtone tuning proceeds according to these rules: To lower the pitch of any one of the bar’s overtones, remove material from the bar at the region of greatest flex for the mode of vibration that causes the overtone. That point of greatest flex will be found at the antinode, midway between the nodes for that mode. Removing material from points progressively farther away from the antinode has less lowering effect on the mode in question, until you get to a node, at which point it has no effect. By removing material at selected locations, you can bring down each overtone in turn by suitable amounts, until you arrive simultaneously at the desired fundamental pitch and overtone pitches.

Sounds simple enough. But in practice it turns out to be a tricky business. The problem is that the effects always overlap. Tuning for one mode always affects other modes at least to some extent. The operation becomes a fine balancing act. Figure 4-3 gives antinode locations for the first three modes, and Figure 4-4 shows the steps of an overtone tuning approach that I have used successfully. Be sure to practice on inexpensive wood (but free of knots), since you can easily destroy a good piece of wood in the process.

Resonators & Radiators

Some free bars can by themselves produce an adequately loud sound. Others require assistance to get their sound out into the world. Radiation is poorest in bars with little surface area, especially at low frequencies. Air chamber resonators below the bars are a good way to provide a needed low frequency boost. The paragraphs that follow provide basic information on air resonators as they relate to free bar instruments. It will also be worth your time as well to read Chapter 6, “Aerophones,” for a fuller understanding of air resonances.

An air resonator may be deliberately tuned to resonate the pitch of an individual bar, or it may be untuned. Untuned air resonators for free bar instruments usually take the form of an open trough below a row of bars. The trough will not have well defined resonance peaks, but it will, ideally, give a broad low-frequency boost. The paragraphs that follow provide basic information on air resonators as they relate to free bar instruments. It will also be worth your time as well to read Chapter 6, “Aerophones,” for a fuller understanding of air resonances.

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They hang vertically, with their tops (which are covered with a metal cap) in an even row, making it play.

For very low-pitched bars, the required lengths for tube resonators become impractically long. And so we turn to Helmholz resonators. Helmholz resonators are vessel-like or globular boxes enclosing a mass of air that is open to the atmosphere through a single relatively narrow opening. They can be tuned either by altering the total volume of the chamber (less volume → higher resonance frequency), or altering the size of the opening (smaller opening → lower resonance frequency). Since altering the overall chamber size usually isn’t practical, the common approach to tuning Helmholz resonators for free-bar instruments is to have some arrangement for altering the opening size.

Some African marimbas use Helmholz resonators in the form of goards throughout the mid and lower range. In western instruments, Helmholz resonators are normally reserved for very low-pitched chimes. In such applications, the resonators cannot be fat all the way around, since a full set of such big round-ish things wouldn’t fit under the bars. Instead, people make big rectangular or tear-drop-shaped flat-sided boxes of about the maximum width to fit under each bar. Such boxes, large in two dimensions and smaller in one, still behave “globularly.” The low-frequency vibrations that occur inside these things are so intense that they can actually flex the side walls if the walls aren’t unusually thick and heavy. Makers have learned to prevent this by placing cross struts within the chamber, in the form of dowels here and there bridging the space between the two walls and preventing their flexing in opposite directions.

With tubular chimes, whether they are suspended vertically like chimes or mounted horizontally like marimba bars, you can try this simple and clever approach to air resonance: let the air within the chime itself serve as a tuned air resonator. The enclosed air column, once properly tuned, will very noticeably improve both volume and tone quality, especially for lower-pitched chimes. There are various ways to tune the column.

The simplest approach was developed and patented by Charles Sawyer. Here’s how it works. For reasonably proportioned chimes, the fundamental resonance frequency of the enclosed air column typically falls well below the fundamental of the chime itself. To bring up the air resonance, a stopper can be inserted into the tube, shortening the air column. In fact, since the desired stopped air column length is normally less than half the tube length, stoppers can be inserted from each end, creating two stopped, or closed, air columns, as shown in Figure 4-6L. The stoppers must be rigid and smooth-surfaced enough to form a solid end-stop for the enclosed air, yet not so heavy or rigid as to significantly damp the chime in its vibrations. Ideal for the purpose is a slightly oversized plug cut out of styrofoam. The tuned air columns don’t do their job, however, if the open ends of the chime have the normal right-angle end-cut. There is no mechanism by which air is forced in and out at the opening, and so no resonance is set up. To create such a mechanism, cut the tube ends at an angle. Then, as the ends of the tube vibrate up and down, the overhanging ends catch the air, creating localized pressure fluctuations at the opening. Those pressure variations are enough to set up the resonance. The procedure, then: Cut and tune the tube, with the angle cuts at the ends. Make stoppers of styrofoam, and force one in from each end. Push them in a bit at a time, intermittently blowing over the ends, and adjusting for resonance.

To improve the tuning, you can try shaping the bar ends to bring out different modes of vibration. There are many ways to accomplish this, from the simple to the complex. One of the simplest ways is to use balloons as in Figure 4-6P. The idea is to attach the balloon at a point far from the node and then adjust the position so that it will be a node for the desired mode. The exact position of the balloon can be adjusted by observation of the mode pattern until the desired node condition is achieved. With practice, this can be done with a balloon and a piece of paper.

Similarly, you can attach various papers or foils to overhang the ends of the bars (as in Figure 4-6N), or you could put the bar in direct contact with something of large surface area, much as a musical string can be coupled to a soundboard. However, it is not advisable to use this method if the bar is very thin or the contact is broadband. Instead, try using a balloon or a piece of paper at one end and then adjust the position until the desired mode is achieved. This method is especially useful for bars that are very thin and have a large surface area.

Well, then, what has the requisite qualities of being extremely light and having relatively large surface area per unit weight? We have already encountered two materials that meet this description: inflatable balloons, and styrofoam. You can rest the bars directly on balloons (as we did with the bar going described in Sidebar 1-2; see also Figure 4-6J) or you can simply tie balloons to the middle of the bars. The balloons not only improve lower frequency radiation; they also provide a mounting with a minimum of damping. With balloon mounting, one needn’t worry about supporting at the nodes. The balloons are so compliant that the vibration is scarcely inhibited no matter what the point of contact.

Styrofoam is even better as a sound radiator. You can lay a steel rod across the open top of a styrofoam ice chest, strike it, and hear its inner vibratory life in full bloom. You can even, within limits, tune the frequency-specific radiation characteristics of the styrofoam by trimming the size of the ice chest: a small ice chest does not project the low frequencies as well as a large one. As long as the bars are fairly heavy, styrofoam gives relatively little damping, even when the support points don’t exactly coincide with the nodal points. (It does not work well, however, for light bars or tubes, or with support points far from the nodes.) Another approach: if you are working with especially heavy metal bars or other high-impedance materials conventionally mounted, by attaching small, light styrofoam pads directly to the ends or center of the bars. Sections of styrofoam egg cartons or styrofoam cups work well for this, or, on a larger scale, by the lid of a small ice chest. But if the styrofoam body is large relative to the bar, you will find that you have purchased greater volume at the cost of increased damping, giving faster decay and a shorter tone.

Similarly, you can attach various papers or foils to overhang the ends of the bars (as in Figure 4-6N), once again increasing radiating surface area with minimal increase in mass. If you experiment a while, you will find you can get some odd and interesting effects this way, due to frequency biases in the paper (which shift according to how you flex it) and rattles that may arise between bar and paper.

For more on these topics, see Chapter 8, “Resonators and Radiators.”
convenient to strike them at the top with a rawhide mallet. This striking at the end brings out all the vibrational modes without favoring the fundamental. The result is a complex blend of non-harmonic partials having a bell-like quality. The ear does not focus on the fundamental as the defining pitch, but instead postulates a different fundamental based upon the relationships between certain prominent overtones.

There is a pitch-control option for hanging metal chimes (as well as bells and gongs) which is not an option for horizontally mounted bars: water dipping. If a vibrating body has sufficient impedance — meaning it is sufficiently massive and rigid to have a vibration which is forceful even if not large in amplitude — it will be able to sustain its vibration even when partly submerged. At the same time, the water adds inertia, slowing down the vibration and lowering pitch. If you slowly dip the lower end of a vibrating chime in water, you will hear the pitch drop. You can use water dipping as a tuning mechanism, or just as an unusual and very pretty textural effect. Dipping can be done by hand, or you can design dipping mechanisms.

Chimes made of metals produce clear pitches with long sustain times. Tubes of various brasses, bronzes or copper are often used; also increasingly common is aluminum, which produces a mellow tone with relatively subdued partials. Chimes made of glass and ceramics are usually less distinct in pitch and have less sustain. Bamboo and other hard, brittle woods may be used for their light, clinky sound; they have almost no sustain in this application.

The degree of sustain makes a big difference in the aesthetic effect. The continuous harmonious wash of large, aluminum tubes is always attractive, while the sparse, delicate clinking of bamboo is equally appealing in quite a different way. If you choose long-sustaining metals, then the pitch relationships between the chimes become an essential element in the aesthetic effect. So does the relative presence or absence of upper partials (which are likely to be non-harmonic). You will want to keep the question of upper partials in mind as you decide how long your longest chime should be relative to its diameter, since long, thin chimes tend to have prominent overtones.

Wind chimes may sound either by hitting each other, or by means of a separate striker. A striker can be a horizontal disk hanging in the center of a set of chimes, with some kind of tail hanging below to be pushed about this way and that by the wind. The advantages of the separate striker are: 1) You can make the separate striker of a chosen mass, hardness and shape to bring out just the tone you want from the chimes. 2) The separate striker allows for the sounding of individual chimes, whereas when two chimes strike one another, both sound with each strike. The sounding of individual chimes is valuable if you seek a more melodic effect, as opposed to a general ongoing textural blend. 3) The separate striker allows for a striking point near the center of each bar, tending to bring out the fundamental — whereas when bars strike one another they're likely to make contact near their ends, making the non-harmonic partials more prominent.

Another consideration is the physical spacing of the chimes and striker. Closely spaced wind chimes tend to sound frequently, while with widely spaced chimes the time intervals between strikes are longer. The mass of the various elements and the degree to which they move in varying winds affect this as well.

The aesthetic question here is, do you want something that continuously tinkles away in the slightest breeze, or do you want something that gives you time to hear each note before the next one comes along?

RODS FIXED AT ONE END:

And now, on to the instruments with tongue-like appendages that can be struck, plucked or bowed to produce a definite pitch. The most prominent representatives of this family are the lamellaphones, known by one or another of their African names including sansa, mbira and kalimba. Other members of the
Kalimbas consist of a set of tuned individual prongs, usually but not always made of metal, mounted on a board of some sort. (As I noted before, such instruments are called by many names: I use "kalimba" as a generic simply because it seems to be the best known in the West among many local African names.) It is usually played by plucking the prong ends, but some makers have created mallet kalimbas as well. The prongs can be made of any material that is rigid enough to sustain the vibration. Hard woods and bamboo have often been used; they lack the sustain of metals and so create a light, percussive effect. African kalimbas are usually made with mild steels (which are relatively soft), for a full, warm sound. Spring-tempered steel, which is very hard, will yield a brighter sound. Flat bar shapes are most common for the prongs, but cylindrical shapes can also be effective. The maker has the option, as well, of hammering round shapes flat on an anvil. A common procedure, following Shona tradition, is to flatten more toward the plucked end, creating an elongated fan shape. See Appendix 2, "Tools and Materials," for ideas on where to get materials for kalimba tines.

## Kalimbas

Kalimbas work well over a very large range. I have made a kalimba-like instrument reaching all the way up to D6 with clear, well-defined tone (although the tone quality is rather different from typical marimba bars). The essential element here is that long protruding thing, variously called a tongue, prong, lamella, or rod. It differs from the bars we have been studying in that it is not free at both ends, but rigidly fixed at one end to the body of the instrument. Plucking or striking the free end causes it to swing back and forth in a vibration whose frequency depends on the mass of the portion that swings, and the rigidity of the portion that flexes. This configuration gives rise to a characteristic set of vibration patterns and overtone relationships unlike those of free bars. The fixed end also plays a very different sort of mountings. They must be rigid, massive, and firm, offering a solid anchor at one end to support the free vibration at the other. Conveniently, the rigid mounting provides the means for the tongue to drive a soundboard. Since the tongues on most of these instruments are much smaller than a typical marimba bar, lacking the surface area to move much air on their own, a soundboard helps radiate their vibrations to the atmosphere.

Figure 4-8 shows the vibration patterns for the first three vibrating tongue modes, along with their resulting frequencies. Notice that the relative frequencies shown here hold only for rods or bars that are uniform over their length and mass. For irregularly shaped prongs, similar vibration patterns hold, but the nodes and antinodes are displaced, yielding different overtone frequencies.

### Overtone Tuning

In the chart in Figure 4-7, notice that the overtones on tuned tongues of uniform dimensions are non-harmonic. This is a serious consideration with kalimba-like instruments, with their relatively long, thin tongues, often of metal, since their tone may be rich in overtones. It is less important for tongue drums of wood, bamboo and most other materials, whose tone tends to be strongly dominated by the fundamental. With any material, you can make the fundamental more prominent and increase sustain by creating a tongue shape with more mass toward the end or, equivalently, thinning it near the base (which also, of course, lowers the pitch). This is analogous to center-scalloping a marimba bar.

And, as with marimba bars, you can take the process further and deliberately retune the overtones on tuned tongues. Some African kalimba makers practice overtone tuning, and a few makers elsewhere have gotten wise to it. The principles are exactly the same as those used in overtone tuning for marimba bars. For each overtone mode, file away material to thin the prong at the points of maximum flex for the mode in question, to lower the mode's pitch. Thankfully, the process is much easier for kalimba tines than for marimba bars. Here is a quick rundown:

1. If you add mass where there is a lot of motion (which means, near the end of the tongue) you lower the frequency. You can do this by lengthening the tongue, or by affixing glue, wax, solder, or anything else that will stick to the end.
2. If you remove mass where there is a lot of motion (again, near the end), you raise the frequency. You can do this by shortening the tongue or thinning the end.
3. If you reduce rigidity in a region where there is a lot of flex (near the base of the tongue), then you lower the frequency. You can do this by thinning the tongue near the base.
4. If you increase rigidity in a region with a lot of flex (again, near the base), then you raise the frequency. You can do this by substituting a thicker tongue. (If the length is unchanged, the effect of the increase in rigidity will outweigh the effect of the increase in mass at the end.)

In the description of the Baschel instruments at the end of the "Friction Rod Instruments" section later in this chapter, you will find information on one more, rather specialized tuning technique.

### Fundamental Tuning

The principles behind the tuning of vibrating tongues were illustrated in Figure 2-1 back in Chapter 2. The basic ideas are these:

1. If you add mass where there is a lot of motion (which means, near the end of the tongue) you lower the frequency. You can do this by lengthening the tongue, or by affixing glue, wax, solder, or anything else that will stick to the end.
2. If you remove mass where there is a lot of motion (again, near the end), you raise the frequency. You can do this by shortening the tongue or thinning the end.
3. If you reduce rigidity in a region where there is a lot of flex (near the base of the tongue), then you lower the frequency. You can do this by thinning the tongue near the base.
4. If you increase rigidity in a region with a lot of flex (again, near the base), then you raise the frequency. You can do this by substituting a thicker tongue. (If the length is unchanged, the effect of the increase in rigidity will outweigh the effect of the increase in mass at the end.)

In the description of the Baschel instruments at the end of the "Friction Rod Instruments" section later in this chapter, you will find information on one more, rather specialized tuning technique.
The natural tree trunk have replaced the log with a rectangular box, and developed forms with many richer sound, with more distinct pitch. In recent years, builders with more access to the lumberyard than to H-shaped cut over the hollow. That shape creates two tongues, and striking the tongues produces a

In this simplest form there is no tongue, but in some more sophisticated versions the slit is replaced by an

log drums take the form of hollowed logs with an open slit cut in the surface. Striking with a

Tongue Drums and Boos

Tongue drums are related to log drums or slit drums found (more rarely, these days) in many parts of the world. Log drums take the form of hollowed logs with an open slit cut in the surface. Striking with a beater near the slit produces an idiophonic sound from the wood, enriched by air resonance from within.

In this simplest form there is no tongue, but in some more sophisticated versions the slit is replaced by an H-shaped cut over the hollow. That shape creates two tongues, and striking the tongues produces a richer sound, with more distinct pitch. In recent years, builders with more access to the lumberyard than to the natural tree trunk have replaced the log with a rectangular box, and developed forms with many

How massive should kalimba prongs be? The very high prong mentioned above is a 1/32" diameter piece of spring-tempered steel rod less than 1/2" long. For the lowest notes on the rumba box just described, I used a similar spring-tempered steel rod of about 1/32" diameter (but thinned at the bass), in lengths ranging up to about 9" (sounding length). For ranges in between, you can select the best prong thicknesses by common sense, instinct and experimentation. You will find, in the process, that this is not simply a question of how massive the prongs are in themselves, but rather how massive they are relative to the soundboard. A prong that is too heavy relative to whatever supports it does not sustain a vibration well; it rocks its mounting with an exaggerated motion and dies. The result, in an extreme case, is a dull thud. At the opposite extreme, a prong that is very light relative to its mountings may set up a nice vibration within itself, but fail to drive the soundboard enough to produce much volume. While a typical kalimba line may not seem very massive, it is far more rigid at the base than, say, a musical string. As a result, it can drive a soundboard more forcefully than you might expect, and so demands a heavier mounting and soundboard than you would find in a string instrument in the same ranges. For more on this, see Chapter 8, "Resonators and Radiators."

Also, remember the common sense rule that the lower the pitches you wish to project, the larger the surface area you need in order to project them. You might get away with a soundboard of less than a square foot for a kalimba in the upper ranges, but for a rumba box to have a good effect you will need a surface of at least, let us say, about 20" x 24" to push those long wavelengths and give it a fat bottom sound. Bigger still is better — think, for comparison, of the size required to project the sound of a string bass. Many kalimbas employ a sound chamber — that is, an enclosure covered with a soundboard having a a soundhole, analogous to the body of a guitar. The air resonance of the enclosure greatly enriches the tone, especially for the lower frequencies. Again, see Chapter 9, "Radiators and Resonators."

With kalimbas, the maker has a great deal of freedom regarding how the pitches are to be laid out. Traditionally kalimbas have used variants of the left-right-left-right pattern, ascending outward from the center, discussed in Chapter 3. Linear scalewise patterns have also been used. For an arrangement reminiscent of western keyboards, you can create a two-tiered mounting system.

Jaw Harps

The instruments commonly called Jew’s harps — another plucked prong instrument — are found in many forms worldwide. Aside from the name they have no special association with Jewish culture, so we will stick with the ethnically neutral alternative term, "jaw harp." The essential element is a prong, usually flat-ish in shape and several inches long, made of wood, metal, or bamboo. It is held in a small, hand-held framework. The player holds the jaw harp in front of his or her mouth, and either plucks the prong, or plucks the body near the base of the prong in a way that excites the prong. The prong excites the air in the oral cavity, and the player can, by changing the positioning of the tongue and lips, bring out a wide range of overtones. A good player can create lively melodies of overtones over the continuing drone of the prong’s fundamental.

Key elements in jaw harp design: The whole assembly should be light and convenient for hand-holding, but the framework must be more massive than the prong, to provide counterpoise. The prong is typically at least two inches long, ranging up to perhaps six inches. It should be fat and wide, rather than round, in order to push the air effectively. It also should be fairly flexible. If it is too strong and rigid, the instrument’s tongue tends to dominate the sound with its fundamental. A more flexible prong, being weaker in the fundamental, allows the overtones to stand out more, as they should. There seems to be an ideal range in which the fundamental is fairly low, and the prong seems a little flimsy, but the overtones resonate well. Some jaw harps have multiple prongs tuned to different fundamentals.

The framework that supports the prong provides a resting point for the player’s teeth or lips, with clearance for the prong in between. The prong should be perfectly parallel to the sides of the frame, with very narrow clearance (see Figure 4.10).

Jaw harps can be made all of a piece, with the prong and the framework cut from the same piece of material. Most bamboo instruments are made this way. Or they can have a separate prong attached to a framework, as with most metal versions. The prong must protrude from the frame far enough to make plucking easy.

Many jaw harp players incorporate blowing and sucking as well as plucking into their technique. Blowing tends to bring out the fundamental, as the vibrating tongue forms a gateway through which the air passes in pulses at a frequency determined by the prong’s vibration. In this mode, the prong functions in a manner similar to the free reeds we will be discussing in Chapter 6, "Aerophones."

Tongue Drums and Boos

Tongue drums are related to log drums or slit drums found (more rarely, these days) in many parts of the world. Log drums take the form of hollowed logs with an open slit cut in the surface. Striking with a beater near the slit produces an idiophonic sound from the wood, enriched by air resonance from within.

In this simplest form there is no tongue, but in some more sophisticated versions the slit is replaced by an H-shaped cut over the hollow. That shape creates two tongues, and striking the tongues produces a richer sound, with more distinct pitch. In recent years, builders with more access to the lumberyard than to the natural tree trunk have replaced the log with a rectangular box, and developed forms with many
tongues. The tone of these instruments, a sort of bubbly “thook,” can be immensely appealing. Typical size for a tongue drum might be 18” by 10” by 6” — but they vary widely. The woods used to make the sides and bottom are not terribly important. Their main function is to provide the structure and define the enclosed air chamber. They also provide mass and counterpoise for the tongues, so it is a good idea to use fairly thick material, like nominal 1" board. The wood for the top is more important. As with marimba bars, you can make a decent-sounding tongue drum with soft woods, but hard woods will give a better result. Denser woods and springier woods, like the expensive tropical tonewoods, are usually assumed to produce the best instruments. But don’t follow the herd on that — see if you can be the one to discover which temperate zone wood will do just as well. Very large diameter bamboo works wonderfully, and has the added convenience that it is its own enclosure — you don’t have to build a box.

As a general rule, the tongues should lie along the grain for strength. Many makers use scroll saws to cut the tongues in their top pieces in fanciful shapes. The reasons for this, one suspects, are visual rather than acoustic. But you will do well with shapes that make the ends of the tongues larger than the bases, putting more mass toward the end and more flex in the base. Lots of tongue drum makers let the tuning of their tongues be random. They simply cut some tongue shapes that appeal to them and then enjoy whatever tones result. Tongue drums are, in fact, tunable, by following the rules given earlier for rods fixed at one end. To facilitate the tuning process, you can attach the top of the drum to the sides, but leave the bottom off until tuning is complete. This allows you to tune by removing material from the undersides of the tongues. Try to remove material by cutting or filing in the direction of the grain, not across the grain. Tongue drum tuning, however, is a problematic process, especially for drums with several tongues. The vibrating tongue drives the whole top of the drum rather forcefully, since the connection between the tongue and the board from which it is cut is quite rigid (compared, for instance, to the flexible junction of a string and soundboard). That vibration is communicated through the top to other tongues. The resulting interaction between tongues can play out many ways depending upon their frequency relationships, but much of the time the interaction has the effect of deadening and/or detuning the individual tongues. A similar problem arises frequently with other monolithic idiophonic instruments as well — for instance, it is a factor in the design of Trinidadian steel drums.

So how to get around the problem? Lowering the pitch by doing some undercutting near the base of each tongue makes the connection between each tongue and the rest of the top less rigid, lessening the problem. Making tongue shapes with large heads and narrow bases has the same effect. You can also place tongues tuned to close intervals far apart on the drum or, better, stick with tunings that don't require tongues tuned to close intervals on the same drum. Since each drum normally only has a few tones anyway, this is not an onerous restriction.

Then again, the ultimate solution would be to make one tongue per drum. You could then make a set of drums to create a complete scale. If you follow through with this very reasonable idea, you arrive at something very much like the family of instruments called boos, which we will discuss shortly.

Air resonance from within the chamber is a factor in tongue drum tone. Tongue drum makers normally do not deliberately tune air resonances, but leave the total amount of opening area small (no large holes in the body of the drum), which ensures that the air resonance will be quite low, hopefully enhancing the bassy sound of the wood. If you make tongue drums with just one tongue, then you can consider tuning the air resonance to the tongue pitch — see Sidebars 4-6 and 4-7 for more on that. Tongue drums need not be made of wood. Several makers have made tongue drums of metals — some of them extraordinarily beautiful to see. Their tone is quite musical, although, in my opinion, it is less distinctive and doesn't have the same appeal as wood. Rigid plastics can work as well.

Boos are an important variation on tongue drums. Harry Partch gave the name boo to a set of vibrating tongue instruments he made of bamboo; I am taking the liberty here of expanding the term to include a host of similar instruments made from other materials.

A boo consists of a long, narrow, hollow chamber, such as a segment of bamboo, which is open at one end. In the upper wall of the chamber a tongue is made by cutting two slits extending in from the open end, as in Figure 4-12. Boos are usually made in tuned sets, mounted in a row on a framework for ease of playing. The great thing about boos is that, because each tongue has its own air chamber, the tongue and the air resonance can be tuned to one another. The tuned air resonance strengthens and enriches the tone, just as do the tuned tube resonators below a marimba bar. Any rigid tubular material can be used to make boos. The most convenient diameters are between about two and six inches. Bamboo, of course, is great. People have also used metal as well as plastic pipes. (ABS plastic pipe is preferable in this application to PVC. Remember to look to Appendix 1 for notes on where to get what.) Boos of square cross section work well too: some makers have used square metal pipes, and some of the nicest non-bamboo boos have been built in the form of elongated, open-ended wooden boxes.

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Boo tuning

Here is a procedure for tuning boos so that the tongue and air resonance pitches agree. While the specifics differ, the principles apply to adjusting air resonances in other similar instruments as well, but with some modifications — see Sidebar 4-7 for more.

Boos typically take the form of a tube-like enclosure (though the shape may be rectangular), stopped at one end, enclosing what can be thought of as a short air column. The tongue is formed by cutting two parallel slits from the open end. With a very short tongue, the air resonance pitch for the tube-like enclosure will generally be well below the tongue pitch. Lengthening the slits to just the point where the two match — and, hopefully, to arrive at that matching point right at the desired pitch. Begin by selecting, cutting or making a tube, stopped at one end, of the right size to land at about the right pitch in the end. For bamboo, this will be one with a natural air resonance about a 4th or 5th below the desired pitch, since the air resonance usually rises much by the time the bamboo slits are cut to their final length. (You can check the air resonance pitch at any time by blowing over the edge of the tube or tapping it edge-on on a solid surface). Depending on the material and its thickness, coupling will typically be achieved when the tongue is somewhere between 1/3 (for lower tones) and 1/2 (for higher tones) the overall length of the tube. With this in mind, begin by cutting the slits a bit short of 1/3 the length, leaving the tongue pitch a bit high and the air resonance a bit low. Cut the slits farther from there a tiny bit at a time, checking the two pitches frequently. The goal is to get the air resonance right, at a touch below the intended pitch for good coupling. The tongue can then be fine tuned down to the correct pitch by removing material from the underside of the tongue near the base to lower its pitch or near the tip to raise it.

You can lower the pitch of a boo by lengthening the tongue, which is to say, by extending the slits...
You can lower the pitch of a boom by lengthening the tongue, which is to say, by extending the slits alongside the tongue. In the same process, the air resonance pitch rises, as the lengthening of the slits has the effect of opening the tube over part of its length. The process of bringing the two into agreement at the desired pitch is described in Sidebar 4-6.

Once you have created a tuned set of boos, you will need to devise a framework to hold them in playable position. The challenge here, as with many percussion instruments, is to hold them in a manner that is sufficiently firm to withstand repeated blows, but which does not transmit the dull thud of the blow to the framework and floor. Padding in the mounting is in order. You can read more about this at the end of Chapter 5, "Beaters, Scrapers and Friction Makers."

Temple blocks and wood blocks are smaller forms of slit drums. They are similar to the instruments just discussed in that they all involve an air chamber within an enclosure of woody material, producing an idiophonic percussion sound enriched by air resonance.

The easiest slit drum to make involves no more than taking a single joint of moderately large diameter, hard bamboo, stopped at the end by the natural blockages, and cutting a slit in the side, perhaps a quarter or half inch wide, over a portion of the tube length. Strike the slit along its edge with a stick or mallet, for a bright, loud "thock!" You can also make slit drums using hollowed wood instead of bamboo, or build them up box-like. The standard percussionist's wood block takes a slightly different form, as shown in Figure 4-13. The tone is very dry, with less of the richness of air resonance. Temple blocks are similar in principle, but use a hollowed-out rounded shape, as the drawing shows. There is no easy way to hollow out such a cavity, so they are usually made of two or more pieces hollowed separately and then glued together, with the outside carved or otherwise shaped. The tone again is a loud, sharp, but rich, clearly pitched "thock!" sound.

Friction Rod Instruments

Many instrument makers have found bowing to be an effective means for exciting the vibration in a metal rod fixed at one end. You can bow with a normal violin or bass viol bow, or with bows specially made for the purpose. At its best the resulting tone floats forth with an ethereal beauty. It can also be shrill and screechy. Bowed rod instruments have been made with very small rods, as with the 18th century nail violin. More recently, several builders have worked with rods in the range of about 1/8" to 1/4" in diameter, extending in length up to several feet.

Sidebar 4-7

MAKING A TUNED SET OF BAMBOO TONGUE DRUMS

You can use the air-resonance tuning principle described for boos in Sidebar 4-6 to make a lovely sounding tuned set of bamboo tongue drums. Materials: several joints of large bamboo, minimum diameter about 2 1/2". (For sources of materials, see Appendix 1.) For each tongue drum, cut a joint of bamboo so that both ends are stopped by the natural blockages. You will cut a tongue with an opening at the end, as shown in the drawing. After cutting the tongue, bring it down to the desired pitch by gradually lengthening it. Unlike the boos discussed above, the slits created by the cutting of the tongue will not bring the air resonance pitch up sufficiently to agree with the tongue pitch. That's because of the different body form: the bamboo tongue drum has no open end and doesn't behave acoustically like a tube. So you bring the tongue drum air resonance up to the desired pitch by another means: making the enlarged opening at the end of the tongue, as shown. The larger this opening, the higher the air resonance pitch. Gradually enlarge it until it is just below the tongue pitch (and it by blowing over the edge). You should then hear the tongue tone take on greater volume and richness.

Important: As soon as you finish, give the bamboo a couple of coats of polyurethane or other moisture-proof finish, inside and out if possible, to prevent splitting.

The bamboo tongue drum will sound good with a superball mallet or similar moderately soft beater.

Sidebar 4-8

A DESIGN A FOR NAIL VIOLIN

The drawing here shows an exploded view of a nail violin made by the contemporary builder Michael Meadows. He offers this brief description:

The thick side piece is laminated soft maple or sycamore (good nail-holding ability), 1 1/2" high, covered with a veneer of walnut on the outside. A 1/16" strip of walnut was steam-bent for the curvaceous back. The top and bottom are koa wood, 1/8" thick and 10" across, with the edges overhanging the sides 1/2". The bottom is the same shape as the top, but with a hand-hold cut in near the back. I used a variety of finish nail sizes from #10 to #4. Each size has an optimum pitch range of about a major 3rd. Choose these to suit your choice of tunings. With the instrument assembled, drill for each nail hole stopping 1/4" or so short of how deep you've figured each nail should go. The bit used for each nail hole should be slightly underdrilled. If the pitch is sharp on any nail, enlarge the hole in the back in a circumscribing sort of way — will lower the pitch. Too flat? Pound it in some more.
For long metal rods, the fundamental is likely to be subsonic, but quite an array of overtones appear within the hearing range. A typical bow stroke will bring out one or another of these in relative isolation. You can, with luck, select which overtone will sound by stroking the rod at different points along its length, and with different bowing angles or degrees of pressure. This takes a great deal of bow control as well as familiarity with the instrument. With small rods, as on nail violins, upper partials play less of a role. The fundamental is in the hearing range, while the overtones are off in the stratosphere. Yet you still sometimes get unwanted squealing.

Let me give a little more description of specific types, starting with the nail violin. The body of a nail violin is usually a flat, zither-like wooden soundbox perhaps a foot or eighteen inches across, with curved sides, often semicircular in shape. A set of nails, graduated in length, is set into the wood around the curved periphery, near die edge. Due to the relatively high impedance of the rigid nails, they are usually anchored in the heavier side walls of the sound chamber rather than in the soundboard itself. The reason for the curved shape of the chamber walls is the same as for the arching of violin bridges: the straight bow, by playing along a tangent to the curve, can selectively play one nail at a time. There may be a sort of rail along the periphery just outside the row of nails upon which the bow can ride, ensuring that die bow contacts the nails at the right height above the soundboard. The nails can be tuned by driving them in to varying depths, or by filing near the base or top. The tone is whistle-like. See Sidebar 4-8 for more on nail violin making.

Instruments incorporating larger bowed rods need a still heavier and/or more rigid mounting. Perhaps the best known currently of the heavier bowed rod instruments is the Waterphone, first created and patented in 1968 by Richard Waters (Figure 4-14). A middle-sized Waterphone uses bronze rods something over an eighth of an inch in diameter and ranging in length from about four inches to a foot. The rods rise upright from the periphery of a stainless steel, vase-shaped vessel, brazed in place. Individual rods can be bowed tangentially, as with the nail violin. The stainless steel vessel — this is the remarkable thing — contains a small amount of water. It moves about as the instrument is played, causing shifting resonances for an extraordinary, otherworldly tone.

Some of the most ingenious friction rod instruments ever conceived are those of the Parisian brothers, Bernard and Francois Baschet. Let me describe a representative one of their instruments here, the Cristal. (What follows is actually a generalized description of a type that has taken many forms over the years.) The Cristal, in its broadest outline, consists of four functional elements or systems: 1) a friction system for generating a vibration; 2) a tuned vibrating body which imposes its frequency on the vibration; 3) a high-impedance transmission system, which carries the vibration from the tuned vibrator to 4) a sound radiator.

The friction component is a set of upright glass rods, fairly light in weight and typically less than a foot high. The player strokes them with wetted fingers to excite a friction vibration. The tuned elements are lengths of threaded metal rod, mounted horizontally on a heavy metal crossbar so that they protrude to the front of the instrument. As shown in Figure 4-15, the glass friction rods are attached directly to threaded metal rods. The point of attachment is about one third of the rod's length from its mounting, which is near the antinode for the rod's second mode of vibration. It is this second mode that the Cristal is designed to bring out. In addition, there is a tuning weight rising from the threaded metal rod, adjustably located at about two thirds of the its length. This two-thirds point is near the natural location of a node for the desired second mode. The tuning weight further reinforces the rod's inclination to emphasize the second mode. Additionally, adjusting the position of the weight will, within limits, force a shift in the de-facto node location. This allows it to serve as a tuning mechanism: shifting the weight toward the end of the threaded rod lowers the pitch.
The Cristal has one of these assemblies — glass friction rod, metal rod and tuning weight — tuned to
the appropriate pitch for each note in its range. The vibrations in the tuned metal rod go into the heavy
metal support bar. Attached to the bar are additional rigid rods which transmit the vibrations in turn to a
large sheet-metal sound radiator, reminiscent of a giant speaker cone. The radiator moves plenty of air,
and gives us something to listen to.

TUNING FORKS

The vibration patterns that arise in tuning forks can be seen as a special case — a double version —
of the fixed rod patterns we have just been studying. Tuning forks have two matched prongs rising from a
single stem. When the fork is excited, the two prongs vibrate laterally in opposition, moving in toward one
another and then out away from each other. Their patterns of movement, including overtone modes and
the resulting frequencies, are the same as those for rods fixed at one end. The lateral movement of the
tines translates into a low-amplitude, high-impedance longitudinal vibration in the stem (see Figure 4-
16A). When the two prongs are not perfectly matched, the tuning fork will still function, but with some loss
of efficiency, producing a single compromise frequency.

The low-amplitude, high-impedance vibration in the handle of the tuning fork can be used to drive a
soundboard or similar radiating surface. Alternatively, you can design a tuning fork to have lots of surface
area in the prongs, lessening the need for a soundboard. An easy way to do this is make a tuning fork
from a section of metal tubing. Simply slit a metal tube over part of its length, creating two equal halves,
as was done in the Fork Chimes described back in Sidebar 1-3. The longer the slit, the longer the prongs
and the lower the tone.

Other options for tuning fork making:

You can bend a metal bar or rod into a U shape. If you use a good, rigid metal and make a bend with
good uniformity, you may get decent results this way, especially if you give it a strong mounting of some
sort. A better approach is to get metals that have been cast or machined to a bifurcated shape. The
Australian/American composer Warren Burt has obtained excellent, pure-toned, long-sustaining results
by machining blocks of aluminum (Figure 4-19B). Or you can use appropriately shaped pre-existing
metal objects — U-bolts and various other items you find in hardware stores and scrap metal yards. You
can tune a fork either by shortening it to raise the pitch or grinding near the base of each tine to lower it.

Several makers over the years have created instruments using tuning forks mounted on
soundboards and struck with hammers — some keyboard-controlled, and some struck directly.

BELLS, CYMBALS AND GONGS

There is a distinction between bells and gongs: Bells have a node at the center, and an antinode
near the rim. Gongs have a node near the rim and an antinode at the center. You support a bell at the
center, where it is not vibrationally active, and strike it near the rim to excite the vibration. Gongs are
supported near the rim, and are struck at the center. Cymbals, in keeping with this delineation, are a form
of bell. So are musical glasses, whether struck or played by finger friction around the rim, because they
follow the bell's patterns of vibration. Many vibrating bodies can function either way, depending upon how
they are held and where they are struck.

Bells and gongs are by nature inharmonic. Where the overtones actually fall in any given case
depends on the distribution of mass and the curvature of the form.

Bells

There are really two distinct idiophonic forms that are commonly called bells. One is the familiar bell
shape, opening out to the air at one end. The other is an enclosed shape, spherical or roughly so, with
smaller slit-like openings somewhere in the body of the bell. Sleigh bells are a familiar example of the
latter. In what follows we will concern ourselves primarily with the open bell form.

The largest bells, such as some big cathedral bells, may produce over a hundred discernible
overtones. The most prominent tones usually come from the modes shown in Figure 4-17. In small bells,
these lower modes are quite dominant. The one labeled T2 is usually strongest, allowing it be heard as
the fundamental pitch in most small to medium-sized bells. With its complementary equal and opposite
movements, the T2 mode can be seen as analogous to a three-dimensional tuning fork.

Over the centuries bell founders working with very large bells have responded to the inharmonicity of
bells in two ways: First, a bell shape has been developed which brings the pitches of the five most
prominent partials into more manageable, though still not precisely predictable, relationship. By casting
bells in this shape to begin with, the desired overtone relationships are at least approximately approximated. Second, founders have learned to tune those five overtones relative to one another after casting, much as the
Mounting.

Making for a clearer sense of pitch. Of the three, adding a boss is easiest and most controllable, so it is a
at the center, making the gong more convex, and folding the periphery back to form a rim — have the
is quite possible to bring the lowest mode to the fore to provide a defining pitch.

Back to bells of more manageable size: With smaller bells, you can usually tune for T2 as the
defining pitch. Removing mass near the rim — e.g., shortening the bell — raises the pitch. Making the
bell less rigid by removing material near the base, where the flex is greatest, lowers the pitch. Adding
mass near the rim, as, for instance, by attaching bolts near the rim, also lowers pitch, but it should be
done symmetrically all around.

You can also tune a bell to produce two distinct tones in the T2 mode, depending upon where the
bell is struck. (The art of tuning bells for multiple fundamentals was first cultivated in China long ago.)
The trick is to remove material from selected points along the rim as shown in Figure 4-18, rather than
thinning uniformly all around. This creates regions of different degrees of rigidity depending on the
orientation of the T2 vibration. You can achieve the same effect by bending the rim into a non-circular
shape, or by adding substantial weight at four points evenly spaced around the rim.

Bells are usually made of metal, to provide a clear tone and long ring time. The alloy known as bell
metal, used in European cantrons, is a bronze consisting of about four parts copper to one part tin. Other
metals, of course, are used in other sorts of bells. Bells have also been made from wood, clay, stone and
glass. You can find bell forms in all sorts of everyday items, particularly bowls and glasses. A trip to a
scrap metal yard or a well-stocked second-hand store will turn up many bells that didn’t know they were
bells. Several people have found that large old artillery shells, as well as oxygen tanks and similar
compression tanks cut in half, have excellent tone. Clay flower pots, suspended upside down from the
hole in the base, yield an attractive non-metallic bell tone. So do large glass jugs. Cut them in half (easier
said than done) and suspend them upside down from the center, being sure to try both the top and bottom
half for a nice bell tone. Many makers experienced in ceramics have fashioned their own bells from clay.
You can also make metal bells from heavy sheet metal, cut to the appropriate pattern (if you do this, you
can work out your pattern with a paper model), bent to shape and soldered, brazed or riveted along the
seam. If you have the equipment and know-how, you will find that hardening the metal by heating and
quenching improves the tone.

Many traditional cowbells have a rectangular rather than circular rim shapes. This changes the
vibrational pattern and the resulting sound entirely, since the flat sides vibrate quasi-independently. Most
cowbells are made from sheet metal as described above, rather than being cast.

Cymbals are very wide, shallow bells, designed to produce such an array of high overtones that the
sound is all crash andizzle. According to traditional lore, fashioned by commercial interests, cymbal
making is a mysterious art involving ancient family secrets; the uninitiated cannot make a decent cymbal.
Actually you can have a lot of fun experimenting with cymbal sounds in your home workshop. You will
have the best luck with fairly thin sheets of very hard metals. Bell metal is traditional, but I have had good
results with stainless steel. Forget softer steels, aluminum, etc., unless you want more bong than hiss.
You may find that a particular piece of metal sounds good left entirely flat. Otherwise, you will get into the
business of cold-hammering to create the shallow dish shape. This can be done by first creating
some sort of shallow concave mold into which to hammer the metal. Use a heavy ball-peen hammer
directly on the metal, or better, hold the ball-peen head against the metal and strike the flat head with
another hammer. Wear safety goggles, gloves and ear pieces; cover the face of one hammer with an
intermediary material such as a leather covering to prevent metal-against-metal chipping. Incidentally, I
have sometimes found that the best cymbal-like sounds come from the gong modes rather than the bell
modes — in other words, consider hanging a flat-ish sheet of hard metal like a gong from points near the
rim and striking near the center. Also, for lots of extra sizzle, add rattles in the form of loose rivets or small
pieces of wire passing through holes in the cymbal (this is described in Chapter 10, “Special Effects”).

Beaters and clappers: Some bells have internal clappers, in the form of weights hanging within and
striking the sides of the bell when swung. Others use a hand-held external beater. Different sorts of
beaters produce very different tone qualities, and finding the right beater can make all the difference
in bringing out the best in a bell. Experiment.

Musical Glasses and Glass Harmonicas

For centuries people have been making music with wine glasses, as well as with glass and ceramic
bowls. From an acoustical point of view, these are inverted bells vibrating in the normal transverse bell
modes. You can sound them by percussion with light sticks, or the friction of a moistened finger circling
the rim (try this on a wine glass sometime if you never have, listening for a whistle-like tone). The Indian
Jal Tarang is a set of ceramic bowls, played by percussion, and tuned by the addition of water in varying
amounts to the bowls, which lowers the pitch.

Most sets of musical glasses in the European tradition are nothing more than a collection of regular
wine glasses, played by fingertip friction. Some people simply set them on a table. Some find ways of
strapping them down or otherwise fixing them in place. Most sets are water-tuned, but there are also sets
that need no water. For the most part, such pre-tuned sets are found, not ground. Some glass players
audition hundreds of different glasses in search of ones fortuitously producing the desired pitches. Within
limits, however, glasses can be fine-tuned by grinding, removing material from the rim to raise the pitch.
The contemporary glass harmonica maker, Gerhard Finkenbeiner, lowers the pitch of slightly sharp glass
bowls by a process known as acid etching: immersing the bowl in hydrofluoric acid solution for a
specified period of time to etch the “dendrites” of the glass. Thinner walls lead to lower pitch.

Glass harmonicas are mechanized sets of musical glasses developed by Ben Franklin in 1761. He
nested a graduated set of tuned glass bowls in a row on a horizontal spindle operated by a treadle, thus
bringing the rims in closer proximity and making possible the performance of more complex music. In
later years motors have replaced the treadle arrangement; automatic moistening systems have been
added, and a few other improvements have been made. Glass harmonicas use stainless steel glass bowls
which are blown specifically for the purpose, with holes at the center for mounting.

Contemporary makers have created a variety of other forms. Two examples: the German maker
Sascha Reckert's glasses actually are glass tubes, cut to length, mounted vertically at the nodes and
functioning acoustically not as bells but as free bars. Cris Forster's set of tuned wine glasses are
mouted in a two-dimensional array on a vertical board and motorized so that each glass rotates
separately, shimmering in the light.

Miscellaneous additional notes about musical glasses: Inexpensive imported hand-blowed glasses are
the best bet for finding a wide range of pitches, since they are less uniform than mass-produced glasses. A
glass with irregular wall thickness may give two microtonally close notes; sounding together
separately, shimmering in the light.

Bells are usually made of metal, to provide a clear tone and long ring time. The alloy known as bell
metal, used in European cantrons, is a bronze consisting of about four parts copper to one part tin. Other
metals, of course, are used in other sorts of bells. Bells have also been made from wood, clay, stone and
glass. You can find bell forms in all sorts of everyday items, particularly bowls and glasses. A trip to a
scrap metal yard or a well-stocked second-hand store will turn up many bells that didn’t know they were
bells. Several people have found that large old artillery shells, as well as oxygen tanks and similar
compression tanks cut in half, have excellent tone. Clay flower pots, suspended upside down from the
hole in the base, yield an attractive non-metallic bell tone. So do large glass jugs. Cut them in half (easier
said than done) and suspend them upside down from the center, being sure to try both the top and bottom
half for a nice bell tone. Many makers experienced in ceramics have fashioned their own bells from clay.
You can also make metal bells from heavy sheet metal, cut to the appropriate pattern (if you do this, you
can work out your pattern with a paper model), bent to shape and soldered, brazed or riveted along the
seam. If you have the equipment and know-how, you will find that hardening the metal by heating and
quenching improves the tone.

Factors affecting gong pitch: The larger the diameter, the lower the pitch; the thicker (= more rigid)
the material, the higher the pitch. All three of the usual shape modifications — adding or enlarging a boss
at the center, making the gong more convex, and folding the periphery back to form a rim — have the
effect of making the form more rigid, and raising the pitch. They may also help bring the fundamental,
making for a clearer sense of pitch. Of the three, adding a boss is easiest and most controllable, so it is a
good place to start in simple gong making. Look to Slidebar 4-8 for more on gong making, tuning, and
mounting.

Gongs, in their simplest form, take the shape of a flat disk, suspended or otherwise mounted
somewhere near the edge and struck near the center. More elaborate gongs may be slightly convex
rather than perfectly flat. They often have bosses, which are button-like raised portions in the center, and
rims turned back around the periphery.

Like those of bells, gong vibration patterns tend to be complex, having several sets of many modes
that don’t fall in a single linear sequence. Many large, lower-pitched gongs have no single predominant
tone and aren’t perceived as having definite pitch. With smaller gongs and some large gongs, however, it
is quite possible to bring the lowest mode to the fore to provide a defining pitch.

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mounting.

Errors
Gongs have traditionally been made from bronzes similar in make-up to bell metal. After casting, they may be further shaped or cut by cold-hammering or filing. Most readers of this book, not having the wherewithal to do their own metal casting, will find it practical to start with sheet metal, and proceed from there by hammering. With steel or bronze, hammering work-harden's the metal, improving the tone. You can successfully make non-traditional gongs from any number of materials, including most available metals. I have found aluminum, with its characteristically gentle tone and its easy workability, to be especially rewarding. Steels are a bit more clangy, and they are harder to work, but will still yield appealing results. One of the keys to creating a good-sounding gong is to use metal of an appropriate thickness relative to the intended gong's diameter. A too-thin gong will be weak in the fundamental. Just appealing results. One of the keys to creating a good-sounding gong is to use metal of an appropriate thickness relative to the intended gong's diameter. A too-thin gong will be weak in the fundamental. Just

Most gongs sound best with moderately heavy, soft beaters. They can also often be played by friction, using a bow at the edge. Gongs respond very well to water-dipping techniques for pitch bending, as described earlier for chimes. While most gongs are designed for deep tones, you can also use them for cymbal-like sounds with a splash of closely-spaced high frequencies. Best for this purpose are thin sheets of a hard, rigid metal like stainless steel. Cymbal gongs can perfectly well be left flat and un-bossed, and non-circular in shape. Most gongs, especially those that are not designed for deep tones, may benefit from a small boss at the center. A boss can be raised by hammering over some sort of concave mold. A large, flat, thick piece of wood with a cavity carved out in the middle will serve. Use a heavy ball-peen hammer directly on the center of the gong, or, for more control, hold the ball end of the hammer against the gong and strike it with another hammer. Wear gloves, safety goggles and ear muffs; protect the face of the hammerer with an intermediary material such as a leather covering to prevent metal-to-metal contact. When you proceed, check the pitch frequency (since you've already attached the cords, you can hear the pitch by simply holding the gong by the cords and tapping at the center.) You will find that the breadth of the boss is more important for pitch purposes than the depth, and easier to control. Gradually enlarge the boss until you arrive at the desired pitch.

The drawing shows a simple system for hanging gongs; it allows gongs to be added or removed from their framework with minimum effort. Use moderately soft beaters, and strike the gongs at the boss.

A final note: Raising the boss doesn't raise the pitch of all the overtone modes equally. I tend to raise the fundamental more than the others. This means that the overtone relationships within the tone change as the fundamental is tuned, creating changes in timbre. With luck, or perhaps a will born of experience, you can try to bring the two or three most prominent tones into an attractive relationship.

Saws and Wobbleboards

Sheets of metal often show different resonant frequencies depending on how they are flexed. Thus, if you strike or bow a piece of metal and then flex it as it continues to ring, the pitch will bend. The resulting sound may strike listeners as beautiful and mysterious, or comical, depending on the circumstances. Musical saws take advantage of this effect; so do wobbleboards, and so do the flexatones found in many percussionist's trick bags.

Musical Saw

The musical saw may be a regular carpenter's saw, or it may be a modified saw form designed specifically for music. The player sits, holding the handle of the saw between the legs and grasping the far end with one hand (see Figure 4-20A). With the other hand, the player either bows the edge of the blade, or strikes the blade with a medium-soft mallet. The flex of the blade determines the sounding pitch. The player is easier if you attach something like a C-clamp to serve as a handle at the end of the blade. The blade-flexing pitch control system is trickier than it first appears. The blade must be flexed not into a simple arc, but into a double curve, forming a shallow S-shape. The critical area is the region where the direction of curvature reverses — the unique strip with no curvature shown in Figure 4-20B. By altering the flex, the player can shift the location of this strip up and down the blade. The player must bow or strike near that point, even as it moves. Here is what is happening: The saw blade manifests a percussionist's trick bag.

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Instruments with irregular vibration patterns

Imagine a trip to a scrap metal yard in search of sonorous scraps. You will find plenty of rods, bars and tubes, and other regular and symmetrical forms whose acoustic behavior we have discussed. But you will also find irregular shapes — odd configurations made for some forgotten purpose — whose acoustic behavior cannot be predicted based on the simple models we have studied. All I can say about this endless diversity of form is to try each one as it comes along. Try different support and striking points, and try striking with different sorts of beaters. To hear an object without the damping caused by holding it, toss it in the air, if it is small enough, and give it a tap in free fall. Complex shapes may have several regions of vibration and multiple subsidiary vibrating patterns, each with its own node and antinode locations. Some forms turn out to be disappointing in their sonic response. Some turn out to be rewarding. Experiment.

Rasps, Rattles, and a Million Others

There are a number of instruments among the percussionist's standard equipment designed to produce a rush of irregular noise, with not a trace of perceivable pitch. A particularly effective way to do this is with a flurry of separate sounds coming together in a single swell. These include shaken things like maracas, shekerees, and sleigh bells, as well as scraped instruments like guiros and similar things with rough or ridged surfaces. In addition to these, there are a million other small, unpitched idiophones, from slapsticks and coconut shell horse hoofs to springy springs and tin can pop tops, each having its own special flavor. I won't try to list them all here. Just know that they are out there to be found and enjoyed.

Wobbleboards

I have borrowed the term "wobbleboard" from Reinhold Banek and Jon Scoville, who devote several pages to the topic in their book, Sound Designs. A wobbleboard is a rectangular sheet of flexible material that, like saws, produces bending pitches depending on how the material is flexed. The sound has a lovely bubbly quality. Wobbleboards may be made of any flexible sheet material; metals are usually the most fun. They can be played by bowing at the edge, by striking almost anywhere with a fairly soft, medium-heavy mallet (but see the comments below about handles and damping), or by flexing. Flexing works this way: most large, semi-rigid sheets possess at least some small degree of warpage or curvature. If you hold the sheet at the edges and wobble it back and forth so that the center flexes from one side to the other, that little warpage means that the sheet doesn't glide smoothly back and forth. Rather, at the mid point it abruptly pops through. That popping sets up a vibration in the sheet, if by some fluke you end up with a sheet having no natural warpage, you can add some by bending the sheet ever so slightly along the long dimension.

It might seem natural to think that wobbleboards operate on principles similar to musical saws. That turns out to be true only up to a point. The first clue that there are differences lies in the fact that wobbleboards produce saw-like glissando's, yet they don't possess the saw's narrowing toward one end. What causes the pitch to rise and fall? Here is my theory. Wobbleboards are generally much wider than saws, and made of thinner, more flexible metals. A marimba bar-like strip vibrating in saw-like fashion across the wobbleboard would lack sufficient rigidity to vibrate effectively. Flexing the sheet has the effect of increasing rigidity, making for a more sustainable vibration and bringing the natural frequency up into the hearing range. No S-curve is needed for the wobbleboard; a simple curve provides the requisite increase in rigidity, with the degree of curvature controlling the pitch.

Wobbleboards can vary greatly in size and shape. An important consideration is the overall rigidity of the unflexed sheet. Thinner (less rigid) boards sound sloppy and tinny; boards that are too thick are hard to flex and they lack range and volume. Great big boards, such as sheets of 1/8" plywood, produce a low, thudless sound that lacks defined pitch. Go to a scrap metals yard, or anywhere else where you might find lots of sheet materials in a variety of sizes and thicknesses, and experiment.

Sometimes you can improve the sound of a wobbleboard by fixing the right amount of mass at the edges. Convenly, the added mass can take the form of handles. This is especially valuable for percussion playing, since hand-held wobbleboards tend to sound poorly under the mallet due to excessive damping. Just adding handles in the form of C-clamps may help. Too much added mass may have the reverse effect, inhibiting the vibration.

Related to wobbleboards are floppy metal sheets suspended by cords at the corners, sounded by striking or shaking. The sound usually has less defined pitch than a wobbleboard. Very large suspended sheets, known as thundersheets, have been used for theatrical sound effects.

If you find a sheet you like and plan to use it regularly as a wobbleboard or thundersheet, round the corners and/or lap the edges to avoid scratching and cutting.

INSTRUMENTS WITH IRREGULAR VIBRATION PATTERNS

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Chapter Five
BEATERS, SCRAPERS, & FRICITION MAKERS
(Also, Some General Notes on Mounting Systems)

This chapter is devoted to things that you can use to start vibrations. They include mallets, sticks, bows, scrapers, and squeakers. At the end of the chapter are some notes on mounting systems for non-hand-held musical instruments. We start with —

MALLETS AND STICKS

I use mallet to describe percussion instrument beaters with distinct heads, and sticks to describe those that are headless, or nearly so. Mallets and sticks are highly specialized tools. The right beater will bring out an instrument's most satisfying sounds, while many highly musical bodies are completely unmusical under the wrong beaters. To find the best beater for a given application, nothing beats trial and error. But there are some guidelines:

1) Beaters with small striking surfaces excite high frequency vibrations preferentially; larger striking surfaces muffle the high and bring out the low frequencies.
2) Likewise, beaters with hard striking surfaces bring out high frequencies preferentially; softer striking surfaces muffle the high and bring out the low frequencies.
3) Heavier mallets favor low frequencies. More generally, mallet weight should be appropriate to the mass of the vibrating body; heavy mallets will overdrive and possibly damage light or fragile vibrating bodies.
4) Mallets with fuzzy surfaces damp high frequencies.

In addition, the duration of the beater's contact with the vibrating surface is important. In most cases it should be virtually instantaneous, especially if you want to bring out high frequency vibrations. The duration of contact depends in part on playing technique, but also on the degree of bounce in the beater. This is a function of both the bounciness of the head and the resilience of the handle.

Mallet Handles

Mallet handles are typically about 14" long, but that can vary. Their thickness and weight should be proportional to the weight of the mallet head, giving a feeling of control and balance. You can make a handle out of whatever material does the job. With mallets of light or moderate weight, springy materials like thin bamboo do nicely, providing the needed bounce. But the best materials for flex in the shaft are not always the best for sure and comfortable grip. To get around this, you can make mallets with stepped handles, having thicker and more rigid material toward the handle end, leading to something thinner and more flexible toward the head. You might use, for instance, a 1/2" wooden dowel of six or eight inches for the hand grip leading to a 1/8" steel rod of six or eight inches, with the head at the end. For extremely heavy mallets, forget about flex; just look for whatever material is strong enough and has the right weight and thickness to create a controllable and well-balanced mallet.

Mallet Heads

Most mallet heads are spherical, but they can also be disk-shaped, or other shapes. An advantage of disk-shaped mallet heads is that tape, cloth, and other flat coverings sometimes used to wrap the head can conform well to a spherical head. For lightweight mallets, heads of a single solid material will be fine. For heavier mallets it is often good to have multiple layers, with softer, lighter materials toward the outside, and progressively heavier, harder materials toward the center. This makes for a mallet that is massive, yet soft and resilient in its surface characteristics. The resulting tone is, ideally, uniform across the dynamic range — heavy strokes produce a tone quality that is not radically different from that of light strokes. Mallets that are harder on the outside, but compress through a softer layer underneath, produce a lot of surface noise and are inconsistent in tone quality.

Simple mallet heads can be made from a number of readily available materials, such as —

Superballs: For a versatile medium-soft beater, you can hardly do better. Superballs come in small and medium sizes, rarely over 1 1/2". You can affix them to a mallet handle by drilling a slightly undersized hole and inserting the end of the handle with glue. Superballs are also good for drawing out friction sounds, as we will see later. The best adhesive for attaching superballs seems to be superglue.

Other balls: Most other rubbers are softer, lighter, not as resilient, and generally not as effective as superballs. But they come in handy for larger, heavier mallets, since superballs don't seem to exist in large diameters. A rubber imitation softball, for instance, at something over 3" in diameter, has its uses. Other, harder balls, such as real softballs and hardballs, have their uses as well.

Drawer pulls: Spherical wooden drawer pulls can be had in a range of sizes at hardware stores. The make a decent lightweight, hard beater.

Thread spools: These are useful as a core for overwrapping with cloth-like materials that wouldn't conform well to a spherical head (we will talk more about overwraps in a moment).

Inner tube: You can get a medium-soft, medium-light cylinder or disk-shaped head by wrapping several rounds of bicycle inner tube around the end of a wooden or metal stick. Or cut it into long, narrow strips and wrap more randomly for a spherical head. The more wraps, the bigger, heavier and softer the head. Synthetic rubbers: Neoprene rubbers are available from specialized industrial supply outlets. The hardness of the material is indicated by the durometer scale: a rubber with a durometer reading of 50 is good for a soft mallet such as a bass marimba mallet; something closer to 85 is good for a harder mallet such as a xylophone mallet. Synthetic rubbers come in stocks of different forms, such as rods and sheets of varying thicknesses. They are also available in liquid form, for pouring into a mold.

Yarn: Winding a nice, symmetrical ball shape in yarn onto the end of a stick is harder than it looks. The result is a fuzzy, not-too-soft, very lightweight beater. Wrapping a few layers of yarn over a spherical inner core of other material is a bit easier than building up the entire head of yarn. Falts: You can wrap strips of felt or other thick, fluffy fabrics around the end of a stick in a manner similar to the bicycle inner tubes mentioned above. The result depends on the material, but it is similar to yarn.

Nuts and Bolts: On rare occasions where you want a small, hard, heavy beater, you can use a long bolt (the head of the bolt forms the head of the beater), or a large nut screwed onto the end of a wood or metal handle.

Hard rubber and rawhide: the hard rubber or rawhide hammer-shaped mallets used in woodworking shops also serve well as heavy, medium-hard beaters for some applications.

Frequently you will want the density and firmness of one of the harder materials mentioned above, but with a softer surface. Here are some options for creating a softer outer layer:

Rubber coating: There is a product called Plasti-dip, made to give tool handles a non-slip, insulating surface. It is a liquid plastic; you dip the tool handle in it and hang it up to dry. If you take a wooden drawer pull mallet and give it one dip in Plasti-dip, you will have a slightly less edgy mallet. If you give it another dip after drying, you will have softened it a bit more. You can go up to about five dips before the head starts to get misshapen and droopy. For a unique combination of density and hardness, and yet a softened surface, try dipping large bolt heads.
Moleskin: Dr. Scholes' Moleskin is a soft, thin felt on an adhesive rubbery backing, intended as a foot comfort product. It makes a good slightly padded surface for mallet heads. Cloth: For spherical head shapes, simply drape the cloth or leather over the head, and gather and tie it at the neck. The folds that appear in the cloth don't usually cause much problem. The cloth wrap looks nice with a colorful collar tie and the skirt that forms below, and it covers up any rough-looking inner work. For disk-shaped heads, you can wrap the outer surface of the disk with cloth or leather. Adhesive tapes: There is a form of electrical tape made of a softer rubber than the standard PVC electrical tape. You can layer it over the end of a thick dowel or heavier cylindrical mallet end to achieve the desired thickness and softness. Similarly, many layers of duct tape will provide a medium-soft, medium-heavy head. Sheepskin: An overwrap of wool-covered hide provides a soft, fuzzy surface. Weather stripping: A layer of 1/8" adhesive-backed neoprene foam rubber weather stripping makes an effective and convenient soft outer layer for a heavy mallet. For a very big, very dense mallet, you may want many layers of progressively softer materials. The materials I used in creating a successful hockey-puck-shaped gong mallet are shown in Figure 5-1 I. Sticks: There is a standard form for commercially made drumsticks, with a slight taper toward one end culminating in a tiny carved bulb. This shape lets the stick bounce well when it strikes. Drummers take advantage of the bounce in performing rolls and such. Trap set drummers use these sticks all the time, on all the instruments in the kit, primarily because it would be impossible to play with fluidity if one were continually changing beaters for the different instruments. But the sticks are optimized for use on the snare drum. In many special applications, small beaters consisting of a short, light metal rod are ideal. You can use anything from coat-hanger wire to brazing rod. Makers should round off or loop the ends of such beaters to prevent injury. Cymbals, agogo bells, triangles, and other metals display a brilliant clarity at low volume under such beaters. Friction Devices: People tend to think of bows in connection with string instruments, but bowing works well with many idiophones as well. Free bars, rods fixed at one end, cymbals and bells — any of these may respond well to bowing. Bowing devices come in a variety of forms, although for most purposes violin bows and their kin work as well as any of the alternatives. Sidebar 5-1 STICK-SLIP VIBRATIONS: Many of the instruments discussed in this book make use of stick-slip vibrations. Stick-slip vibrations are what make doors squeak, chalkboards squeal, friction drums moan and violins sing. They come about when two objects having sufficient traction rub together. Instead of sliding smoothly past one another, they alternately stick and slip, moving in a rapid series of tiny jumps. If the stick-slip frequency is in the hearing range, then you've got a noise. If one of the components has a pronounced natural frequency, it will often impose that frequency on the stick-slip. With a violin bow and string, for instance, the stick-slip pattern accommodates itself to the string's natural frequency. Conventional Bows: Most bows are made with horsehair running end to end and held more or less taut on an arched stick. Modern orchestral bows are actually arched slightly backward, with spacers at each end to hold the hairs away from the stick, designed this way for reasons having to do with balance and control (Figure 5-2B). Orchestral bows are rather long — a couple of feet and more — allowing for long strokes. Shorter bows are easier to control, and really tiny bows, like six inches to a foot long, perhaps used in pairs (one in each hand) are just the thing for some instruments where longer bows would be too awkward. Despite a lot of tradition about specific types of wood producing the best bows, many different woods and other materials, including plastics, have been made to successful bows. The horsehair (or equivalent) can be affixed at the ends by any form of attachment that works. Each hair has the "bite" needed to excite the string when it pulls in one direction and not the other, so it's necessary, when stringing with horsehair, to reverse every other hair and layer them in opposite directions. Professional violinists rehair their bows frequently as the bite of the hair wears down with extensive use. The ideal degree of tautness in the hair varies from instrument to instrument and playing style to playing style, though it is usually moderately firm but not stressed. Orchestral bows have means for adjusting the tautness. On other bows the tautness is achieved by flexing the bow inward before attaching the hair, and letting the bow's springiness hold the hair taut (Figure 5-2A). Still other bows have the hair deliberately left slack, and leave it to the player to hold it tight as part of the bowing hand's grip. Having the hairs in a flat ribbon arrangement is better than giving them the form of a round cord, because it allows for different playing angles and different amounts of contact. At a sideways tilt, an increase in pressure brings increasing amounts of hair in contact with the vibrating object.
Why horsehair? Because it works well, it is a good length and thickness, and, historically, it has been widely available. Horses don't seem to mind parting with a few tail hairs, I have found. If you have equestrian friends with gentle steeds, you can seek permission to cut or pull a few (but gently). Stand off to one side rather than directly behind! With horsehair, as with all bowing materials, it is necessary to increase the bow's grab by rubbing it before playing with rosin. Rosin packaged especially for bows is sold at music stores.

Other bow-stringing materials are considered less desirable, but they do work. Some cheap bows are stung with strands of fiberglass, or fine strands of nylon monofilament line (sold as thread at fabric stores). In fact, any strong thread will do. Very fine threads are usually preferable, yielding a more even and refined sound. Generous applications of rosin are especially important for synthetics. Plans for a simple folk-instrument bow appear in Sidebar 5-2.

**Unconventional Bows**

Some instruments — especially mechanical string instruments and some oddball historical keyboards — use continuous bows. They take the form either of rossioned wheels or looped bands of some flexible material running between pulleys. In the hungrily (a European chordophone, now rare) a rossioned wheel, usually made of pear wood, sounds several strings continuously and simultaneously. The player operates the wheel by means of a crank protruding from the front of the instrument. The height of the bridges is such that the strings just contact the wheel as it turns. (A veneer of pear wood circling the rim of the wheel is better than a solid disk of pear wood, because that way the grain is consistent against the strings as the wheel turns.) In the Violano Virtuoso, a mechanical violin-playing instrument from the first decades of the 20th century, the strings were played (quite convincingly, believe it or not) by motor-driven, automatically-rossioned cellular disks.

Hard materials like sticks, bamboo and such have also sometimes served as bows. Aided either by rosin or water, occasionally with passable results. To make a tiny, rigid bow, bowed piano composer Stephen Scott has glued horsehair onto the flat sides of popcorn stick, and applied rosin.

**Friction Mallets**

In many applications, direct stroking by moistened or rossioned fingers is adequate to set up a stick-slip vibration. Or special rossioned gloves may be worn. Hand stroking seems to work best when longitudinal vibrations are called for. The Baschet instruments with their glass friction rods (described in the last chapter) work this way; so do most friction drums (see Chapter 7), and so do a number of stroked metal rods instruments, as well as the longitudinally played Long String Instrument mentioned in Chapter 2.

**SCRAPERS**

The most familiar scraped instrument is the Latin American guiro, traditionally made from a gourd with ridges filed into the surface along the side, and scraped with a short stick or switch. But many other scraped instrument forms are possible. Scrape sounds have distinctive character; if I were in charge, there would be more such scraped instruments in the world.

Generally, the most effective scraper is something that gets the thing to be scraped vibrating, without making too much noise itself. Often the best material from this point of view is a simple metal rod, thick or thin, depending on the application. Broad, flat scrapers tend to add too much of their own sound to the mix. A small switch, such as a stick of bamboo or similar material with one end split into several slickets, can produce a distinctive sound in some applications.

Another type of scraper is the strummed bow, in the form of a stick with a series of notches which can be dragged across a string or the edge of a cymbal or other idiophonic sounding body (Figure 5-2D). Combs and similar multi-fingered objects can be used the same way.

**MOUNTING SYSTEMS**

Before ending this chapter I want to address a different topic — one of concern for many different instrument types, including various idiophones, membranophones and percussion aerophones, as well as a few chordophones. Instruments need to be supported somehow when they are played. Some can be hand-held, while some require stands or housings or some other form of external mounting. A good mounting system has these qualities: it holds the sounding elements in a playable position; it possesses the right degree of mass and rigidity; it is sturdy; it is rattle-free; it doesn't inhibit the musical vibration; it doesn't radiate unwanted noise or transmit it to the floor; and (least important or most important?) it looks nice. Meeting these requirements can often be frustratingly difficult, although doing so is primarily a matter of common sense and basic shop skills.

Whenever possible, the best mounting system is the human body. Instruments that can be hand-held, held on the lap, or rested on the knee always seem to do well. The human body is most adaptable; people always seem to find ways to position things to provide the optimal amount of surface contact, flex and rigidity.

The other advantage of human bodies is that they seem to do better than anything else at holding things firmly, while providing insulation. Imagine that you have some vibrating object that you need to hit hard but to bring out its sound. If you set out to build a mounting for this object, you will naturally want to make something strong and firm, to hold the object well. But when you strike hard, the force of the blow is transmitted all through the rigid mounting and radiated from it to the air. Worse, the blow is also transmitted through the mounting to the floor, where it radiates as a heavy thump. This problem rarely arises if the mounting is a human being: you can hold the object firmly in your hand or on your lap, and your body will absorb a good jolt without transmitting unwanted thump to the air, the floor, or the chair you sit upon.

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**A SIMPLE ALL-PURPOSE BOW**

The drawing below shows a small, home-buildable bow using thread or fine monofilament nylon line. I have given specific dimensions here, but you can easily modify the design to suit your purpose.

The ideal wood for the bow is spruce but not prone to splitting; maple is good. For the hair, use fine monofilament nylon thread, cotton thread, or any similar strong thread, available where sewing supplies are sold. For hardware: two eye bolts at 2" and 2½", plus one wing nut and one cap nut to fit. And don't forget the bow rosin.

You can cut the hardwood to the shape shown in the drawing, or assemble a similar shape from smaller pieces very strongly glued together. Drill the two 3/16" holes for the eyebolts: access to the one at the handle end will be difficult; depending on your drill, you may need to use an extra-long bit. Bend the eye of the eyebolt very slightly open as shown in the inset in the drawing, to allow for slipping the thread into the eyes. Put the 2" eye bolt through the hole at the handle end and tighten on the cap nut as shown. Put the 2½" eye bolt through the far end, and thread the wing nut down about 3/8". Tie the thread above and fit one of the eyes, and loop the line back and tight through the eye. Continue looping until you have tied the thread to the handle end. Tie thread to the cap nut as shown. Use 2½" eye bolt through the far end and thread the wing nut. Tie the strips of bow hair (thread) loosely together, ready for playing. Tighten or loosen the wing nut to adjust the bow hair...
The point is, insulation is a central consideration in making instrument mountings. The sounding body must be able to vibrate freely, insulated from unwanted damping effects. And it should also be insulated so as not to transmit unwanted vibration, like a thud from a beater's blow. For low-impedance vibrations, like those originating in strings or in the air itself, these considerations rarely present a problem. Such vibrations require little force to get started — no heavy blows — and once started they lack the strength to drive things they aren't intended to drive. But heavier initial vibrators often need special insulation systems. Struck or bowed rods, for instance, may produce strong enough vibrations to rattle their whole mounting system and whatever it contacts. There are several ways to provide needed insulation.

One is padding. Padding may be inserted between the initial vibrator and its mounting structure, or between mounting structure and floor, or both. The amount of padding varies with the application. Padding may take the form of rubber washers on the screws or bolts that hold the sounding elements, or sections of soft latex tubing (surgical tubing) placed over nails that secure vibrating bodies. You may need strips cut from a heavy blanket between vibrator and mounting, or imitation fur, or foam rubber in various thicknesses. In some cases the best answer might simply be to rest sounding elements on big pillows on the floor.

Another amazingly effective insulator is one we have seen before: balloons. Nothing allows for freer vibration for the sounding element, and nothing transmits less to other solid bodies. The disadvantages of balloons are 1) they tend to be unstable (they wobble a lot), 2) there's no easy way to attach things to them; and 3) they frequently need to be replaced.

A third approach to insulation is to suspend vibrating bodies by cords or coil springs. Slightly stretchy cords are better than inelastic ones in many applications.

A few quick but important final points: In designing mountings, consider the primary direction of radiation from the sound elements relative to the player and listeners. Remember that some sounding objects need clearances — space around the vibrating surfaces or near aerophonic openings — to sound well. Reflections from flat surfaces near and parallel to a vibrating body sometimes reinforce the tone, but sometimes cause cancellations and weaken the tone. It is often beneficial to design mountings so as to leave room for later adjustment of overall height, important clearances, or any features with close tolerances.
And on we go to the wind instruments. Aerophones are musical instruments in which the initial vibration takes place not in some solid material, but in the air itself. The most familiar aerophones include a body of air in a hollow tube of some sort, as with flutes, clarinets, or trumpets. Among the least common are aerophones having non-tubular air chambers, such as ocarinas, the egg-shaped Chinese Hsun, the clarinets, or trumpets. A little less common are aerophones having non-tubular air chambers, such as ocarinas, the egg-shaped Chinese Hsun, the clarinets, or trumpets.

The principles governing wind instruments are the most subtle of all the instrument types. In this chapter we will start out by describing a simple flute. Then we will talk about the flute's mouthpiece, its resonance, and other aspects of its design.

In one sense, winds are the simplest of all instruments; what could be more straightforward than exciting a sound directly in the air? But the principles governing wind instruments are the most subtle of all the instrument types. In this chapter we will start out by describing a simple flute. Then we will talk about the flute's mouthpiece, its resonance, and other aspects of its design.

EXCITING THE VIBRATION

1) Something to excite the air into vibration. That is what the blowhole is for. The vibrations come from air turbulence arising when the air stream enters the player's mouth and then to the outside. Air column resonances can then coerce the airflow pattern into agreement with the tube's natural frequency.

2) Something to control and enrich the edgetone. This is the job of the tube — or, more accurately, the enclosed column of air with its natural resonance frequencies. Without the air column, the edgetone would be capricious and in poor and in tune quality. The edgetone excites the resonances of the air in the tube, the resonances impose their frequencies on the turbulence at the edge, reducing the capriciousness of pitch. They also help to create a stable tone.

3) Something to allow the player to control the pitch. Here is where the blowhole comes in: it controls the effective length of the air column, altering its resonant frequencies, and so changing the sounding pitches.

Not every wind instrument has a blowhole, a cylindrical air column, and a stop. But most wind instruments do have elements in each of these three functions — something to excite the vibration in the air; something to control it; and something to modify the resonances in order to alter the pitch. Our approach, for the bulk of this chapter, will be to study the possibilities for each of these essential elements.

SIMPLE FLUTES (Part 1)

Here are steps for making a simple sideblown flute like the prototype flute described in the main text. The dimensions and hole spacings are taken from Mark Shepard's excellent booklet, Simple Flutes: Play Them, Make Them. I have used these dimensions and found them to be quite accurate, yielding an instrument with little need for subsequent fine tuning. Notes for making a simple flute of similar tuning and dimensions appear on the following page.

SIMPLE FLUTES (Part 2)

This is the fluted version of the flute appearing on the preceding page.

Materials:

One 3/4" cork (wine bottle size), and 16 7/16" of 3/4" internal diameter tubing, preferably 1/16" - 1/8" thick. Plastic tubing such as PVC or ABS plastics available in hardware store will work well, but see notes in Appendix 1 regarding possible toxicity.

Construction Procedure:

Cut the 3/4" tube to 15 3/4". Tap the cork into one end, to a depth of 1 3/4", as shown in the drawing. To form the blowhole, drill a 3/8" hole in the side of the tube 1/4" from the cutted end. Flatten the hole out slightly so that you end up with an oval shape, about 1/2" in the long dimension, with the long dimension along the line of the tube. Smooth and deburr the edge. Drill the fingerholes, starting with #6 (farthest down the tube). They will be 3/8" holes, spaced as in the following chart. The location values represent the distance from the center of each tonehole to the center of the blowhole.

These hole spacings roughly follow the tube length percentage recommendations for standard pennywhistle fingering given in Figure 6-24. (Read the caption for that figure for information on fingering as well.) Remember that the holes need not be in a straight line down the tube; it makes fingering easier if some are offset to one side or the other to accommodate the natural fall of the fingers.

After the holes are drilled, fine tune if necessary by enlarging a given hole to raise its pitch or reducing it by back-filling with audiosiure filler, epoxy glue or bee's wax to lower its pitch.

The stopper position recommended above is probably optimal. But you can try adjusting its position relative to the blowhole to improve the tone, make it easier to sound the upper octave, or improve the tuning in the upper octave.

SIMPLE FLUTES (Part 3)

This is the fluted version of the flute appearing on the preceding page.

Materials:

One 3/4" cork (wine bottle size), and 16 7/16" of 3/4" internal diameter tubing, preferably 1/16" - 1/8" thick. Plastic tubing such as PVC or ABS plastics available in hardware store will work well, but see notes in Appendix 1 regarding possible toxicity.

Construction Procedure:

Cut the 3/4" tube to 15 3/4". Tap the cork into one end, to a depth of 1 3/4", as shown in the drawing. To form the blowhole, drill a 3/8" hole in the side of the tube 1/4" from the cutted end. Flatten the hole out slightly so that you end up with an oval shape, about 1/2" in the long dimension, with the long dimension along the line of the tube. Smooth and deburr the edge. Drill the fingerholes, starting with #6 (farthest down the tube). They will be 3/8" holes, spaced as in the following chart. The location values represent the distance from the center of each tonehole to the center of the blowhole.

These hole spacings roughly follow the tube length percentage recommendations for standard pennywhistle fingering given in Figure 6-24. (Read the caption for that figure for information on fingering as well.) Remember that the holes need not be in a straight line down the tube; it makes fingering easier if some are offset to one side or the other to accommodate the natural fall of the fingers.

After the holes are drilled, fine tune if necessary by enlarging a given hole to raise its pitch or reducing it by back-filling with audiosiure filler, epoxy glue or bee's wax to lower its pitch.

The stopper position recommended above is probably optimal. But you can try adjusting its position relative to the blowhole to improve the tone, make it easier to sound the upper octave, or improve the tuning in the upper octave.

Materials:

One 1-1/4" long, 3/4" diameter cork (wine bottle size), and 16 9/16" of 3/4" internal diameter tubing — see notes on tubing materials above.

Construction Procedure:

Flatten one side of the cork by cutting and/or sanding, to create a sloped flat surface along one side, as shown in Figure 6-8. Tap the cork into the 3/4" tube to where the end is flush. This will leave a narrow windway between the tube and the flattened part of the cork. Now cut the beveled opening in the cork, to form the aperture and edge. Make the angle cut as in Figure 6-5. To get a range of pitches, you still do six 360° holes along the tube to serve as toneholes. That completes the instrument. To play it, hold it so that just under the lips and blow a fine stream of air across the blowhole, covering and uncovering the toneholes to get different pitches.
To complete the instrument, make the toneholes. The arrangement is the same as that described for the sideblown flute on the preceding page, with all measurements taken from the center of the toneholes to a point in the opening at the end of the windway. 1/8” from the vertical cut.

Another configuration for our simple flute, rather than having the blowhole at the side, would be an end-blowing form (Figure 6-5). In end-blown flutes the player blows directly over the open end of the tube. Sometimes the blown edge is altered in shape — notched, beveled or rounded — to improve tone production. A playing-edge angle of about 30 degrees, some makers have suggested, is optimal. The Japanese shakuhachi, and the Middle Eastern ney, are important examples of endblown flutes. In the West, end-blowing is most often used with tubes stopped at the far end, or with globular chambers such as bottles or jars. End blowing is the standard approach with sets of panpipes, which are almost always made with stopped tubes.

The third common edge-tone arrangement is the fipple. Fipple flutes are those that use a narrow air channel, rather than the player’s lips, to focus the air stream and direct it over the edge (Figures 6-3 and 6-6). Familiar fipple flutes include the recorder family, the referee’s whistle, and most ocarinas. Some of the most beautiful and exotic instruments in the world are the complex fipple flutes of pre-Columbian Central and South America. Fipple-and-edge making is an art, a craft and a science. Sidebar 6-4 has information on fipple and edge design.

Sidebar 6-2

Panpipes are tuned sets of stopped pipes held together in a raft-like row. You play them by end-blowing, sliding the pipes back and forth in front of the mouth in a motion similar to harmonica playing. The sound is a breathy flute sound, but having (in the hands of a good player) a distinctive “chiff” in the attack for each note. The pipes of a typical instrument range from perhaps three to four inches long to ten or twelve. Much longer panpipe sets are used in the Andes, some Pacific islands, and southern Africa. The longer ones are harder to play.

Panpipes are very easy to make. For the tubes, look for an internal diameter in the range of 1/2”. Tube walls should not be too thin — bamboo or various available plastics might be about right. Bevel the blowing ends of the tubes, at a bevel of 45° or more on the side of each tube opposite the lip, where the air stream strikes, usually works well. The tubes should be a little longer than they need to be for the pitches you want, and a stopper inserted and adjusted to give the desired pitch. The stopper can be anything that forms a dependably leak-proof seal — cork, for instance. But I recommend making a spring-fitting adjustable stopper which will allow easy tuning and re-tuning of the pipes. You can make it using a double-headed nail, shortened and wrapped at the head end with a 1/8” layer of closed-cell neoprene foam weather stripping as shown in the drawing. Make the nail long enough so that the unwarped and unwrapped sections are equal in length.

In some traditional panpipes, the pipes are held together in a row by wrapping with cord or leather thongs. Or they are strapped to a board or stick across the back side of the row, usually in scalewise order. Some makers have simply glued the row of pipes together, and some have set the lower end of the pipes in a solid base of some sort. You can also make panpipes from a single piece of solid wood, with the holes drilled to varying depths.
Classical saxophones and clarinets use similar mouthpieces, onto which the reed is strapped. Players of these instruments will tell you that the mouthpiece is the heart of their instrument; the remainder of the tube, with all its fancy keywork, pales in importance by comparison.

**Reeds**

The edgetones just described are one of many possible ways to excite the vibration in our simple flute. Reeds are another. Wind instrument reeds work by converting a steady stream of air into a series of rapid pulses by means of some sort of air-gating mechanism. The steady air stream usually comes from someone's lungs, and the gateway is the reed that alternately blocks and unblocks an opening through which the air must pass. The pulsing generates a vibration in the surrounding air, yielding the audible tone. If the air-gate leads into a wind instrument tube, then the resonances of the air column can come to dominate the reed just as they dominate an edgetone. The need accommodates its pulsing frequency to the tube's preferred frequencies, and you get a controlled tone with all the resonance of the air chamber.

A reed may literally be a piece of cane, or it may be made of other material, such as springy metal. Clarinets, oboes and harmonicas are familiar examples of reed instruments. For analytical purposes, we can regard trumpets and trombones as reed instruments as well, because the trumpeter's buzzed lips likewise form an air-gating system. Let's look at the possibilities one at a time.

**Single and Double Reeds**

Single reeds, sometimes called beating reeds, appear on instruments of the clarinet and saxophone families, and a great many related instruments around the world. The beating reed is positioned over the opening in a mouthpiece as shown in Figure 6-7. When air under pressure tries to flow into the tube, the reed repeatedly slaps shut against the rim of the opening, then swings open again to let more air through, so that the air enters the tube in pulses.

The edgetones just described are one of many possible ways to excite the vibration in our simple flute. Reeds are another. Wind instrument reeds work by converting a steady stream of air into a series of rapid pulses by means of some sort of air-gating mechanism. The steady air stream usually comes from someone's lungs, and the gateway is the reed that alternately blocks and unblocks an opening through which the air must pass. The pulsing generates a vibration in the surrounding air, yielding the audible tone. If the air-gate leads into a wind instrument tube, then the resonances of the air column can come to dominate the reed just as they dominate an edgetone. The need accommodates its pulsing frequency to the tube's preferred frequencies, and you get a controlled tone with all the resonance of the air chamber.

A reed may literally be a piece of cane, or it may be made of other material, such as springy metal. Clarinets, oboes and harmonicas are familiar examples of reed instruments. For analytical purposes, we can regard trumpets and trombones as reed instruments as well, because the trumpeter's buzzed lips likewise form an air-gating system. Let's look at the possibilities one at a time.

**Faktors in Fipple and Edge Design**

Here is a list of factors affecting tone quality in fipple flutes.

1. **Aperture size:** The larger the opening between the windway and the edge (see Figure 6-6), the higher the instrument's overall pitch. Larger apertures also require larger harmonics on the flute body to achieve the same pitch relationships.

2. **Aperture shape:** Short, wide openings (short distance from windway to edge; wide edge) produce a clear, focused tone. With all reeds, pitch tends to rise as the speed of the air stream increases, but the pitch-bending effect is less pronounced with short, wide apertures. Instead, such flutes tend to overblow to the second octave easily. Recorders exemplify this approach, with apertures that are typically over three times as wide as they are long.

3. **Windway size and shape:** The windway must focus the air stream as much as possible, and outflow should be parallel to the tube walls, not heading down from above. Long, narrow apertures produce a breathier tone and require more blowing pressure. The pitch bends broadly in response to variations in wind pressure, but the octave doesn't overblow as readily. Some pre-Columbian flutes were made this way, with apertures a little over twice as long as they are wide.

4. **Angle of incidence:** The windway should be oriented in such a way that it directs the air stream head-on to the edge, centered so that the edge cuts the air stream roughly in half. For most fipple flutes, this means that the windway should be parallel to the tube walls, not heading down from above.

5. **Acuteness of the edge:** Recorders generally use a sharp, narrow edge, at about 20 or 25 degrees. Many ocarinas and clay flutes use blunter edges at about 45 degrees, and you can get a decent tone with still coarser edges, such as the rounded edges of bottles and jugs.

6. **Frames and hoods:** Some of the early Mexican-American flutes have walls built up around the non-edge sides of the aperture, or hoods formed over the top. Frames lower the pitch and make the sound more directional. Hoods alter the overtone content in highly variable ways, creating a reedier tone and making it possible to dramatically shift timbre through changes in wind pressure.

If you wish to delve further into this subject, turn to the literature on organ pipes, in which edgetone mechanics and related topics are studied extensively.

**Sidebar 6-3**

BOTTLE BANDS

There is a solution. Don't tune by adding liquid. Tune by adding sand.

There are probably at some point in your life turned a bottle or jug into an end-blown vessel flute by blowing with pursed lips over the bottle's mouth. You can turn the bottle by adding or removing liquid (adding liquid reduces the size of the chamber, raising the pitch). You can create a tuned set of bottles by adding liquid in varying amounts to a number of bottles. A problem with this approach is that you lose your tuning over a period of days as the liquid evaporates. Worse, leaving an open bottle of standing water for any period of time leads to biological developments better avoided, especially when oral contact is involved.

There is a solution. Don't tune by adding liquid. Tune by adding sand.

The reeds normally used with clarinets and saxes are cut from the stalk of a species of cane called Arundo donax. They are cut to a particular shape, as shown in Figure 6-7, to obtain the desired qualities of lightness and springiness. They're made to different sizes for different instruments, and in different "strengths," meaning thickness and corresponding rigidity or softness. The playing technique for single reeds is rather subtle, and best learned from a teacher.

The steady air stream usually comes from someone's lungs, and the gateway is the reed that alternately blocks and unblocks an opening through which the air must pass. The pulsing generates a vibration in the surrounding air, yielding the audible tone. If the air-gate leads into a wind instrument tube, then the resonances of the air column can come to dominate the reed just as they dominate an edgetone. The need accommodates its pulsing frequency to the tube's preferred frequencies, and you get a controlled tone with all the resonance of the air chamber.

A reed may literally be a piece of cane, or it may be made of other material, such as springy metal. Clarinets, oboes and harmonicas are familiar examples of reed instruments. For analytical purposes, we can regard trumpets and trombones as reed instruments as well, because the trumpeter's buzzed lips likewise form an air-gating system. Let's look at the possibilities one at a time.
Membrane reeds have one troublesome characteristic. You can't predict wavelength based upon tube length. The softness of the membrane covering the tube alters the natural resonance frequency of the tube. Stretching the membrane more tightly raises the pitch. It is a little easier to make all of your double reeds have the same basic shape, or even the same dimensions, than it is to make all of them play the same frequency. Other factors, such as the gap between the lay and the inside of the mouthpiece cut, the twist of the lay, and the curvature of the lay, all affect frequency. Double reeds are made in two halves which are held together. The arrangement of the two reed halves for double reeds is such that they need to be aligned so that the gaps between the halves are such that the gaps between the halves are of the same size.

Membrane reeds, as described in the main text of this chapter, work well over a range of sizes from moderately small to quite large. The plan given here is for a large membrane reed. At this scale, the instrument is rather clumsy and not well suited for metalworking. Membrane reeds tend to be innovation-ally unstable. Yet if the player can gain control over these factors, they allow for a lot of flexibility and some highly expressive effects.

**Sidebar 6-5**

**MAKING SINGLE REED MOUTHPIECES**

There are several ways you can make your own single reed.

1. You can work with a curved strip of metal. Figure A shows an easily made form. It is crude, with a coarse sound, but it works. When I tried this, I used a strip of stainless steel for the reed; other non-corrosive spring materials might do as well. The degree of curvature of the reed (which corresponds to the "lay" of a conventional mouthpiece) is important in the playing response, and with experimenting with. Notice also in this design that the reed does not lie in the bore. You can combine the effectiveness of the bore with the natural frequency of the tube. The arrangement is slightly different for the bassoon. If you are interested in making a double-reed instrument you may find that your best bet is to cut a double-reed mouthpiece made from a music store; or perhaps to use the cane and staple, and then come up with an experienced student to show you the tricks of making reeds. Some historical double-reed instruments have a "wind cap," which is a perforated cap over the reed. The player presses his or her lips onto the cap, and the lips do not touch the reed. Such reeds, which must sound without pressure from the lips, are made flatter than other double reeds, with a narrower opening between the halves. Similar reeds appear in bagpipe chanters.

**Membrane Reeds**

In some of the island of Indonesia, an instrument is made as a child's toy and for sake to tourists. It uses a unique arrangement which I call a membrane reed. The membrane reed is easy to make with common available materials, and it works well.

In keeping with our use of the word "reed," a membrane reed functions as a pulsing air-gate system. The essential element is a small membrane stretched over what would otherwise be the open end of the tube. Figure 6-10 shows one of several forms that such a reed can take.

Classical double reeds are made from the same cane as single reeds, but cut and configured differently, as you can see in Figure 6-10. For the oboe, as shown here, the end of the staple is covered in cork, and it fits snugly into the small end of the conical musical instrument tube. The arrangement is slightly different for the bassoon. If you are interested in making a double-reed instrument you may find that your best bet is to use a ready-made reed from a music store; or perhaps to use the cane and staple, and then come up with an experienced student to show you the tricks of making reeds. Some historical double-reed instruments have a "wind cap," which is a perforated cap over the reed. The player presses his or her lips onto the cap, and the lips do not touch the reed. Such reeds, which must sound without pressure from the lips, are made flatter than other double reeds, with a narrower opening between the halves. Similar reeds appear in bagpipe chanters.

**Membrane Reeds**

For different physical reasons, producing a loud tone by blowing hard usually flattens the pitch. Thus, membrane reeds are sometimes used in children's toys, party noisemakers and such, often you can remove the tiny plastic reed assemblies in order to apply them to your own purposes.

**Double-reeds**

Double reeds are the most used on oboes and their kin. Rather than having a single tongue beating against an opening, double reeds are made in two halves which are held together. The arrangement of the two reed halves for double reeds is such that they need to be aligned so that the gaps between the halves are such that the gaps between the halves are of the same size.

Double-reeds are made in two halves which are held together. The arrangement of the two reed halves for double reeds is such that they need to be aligned so that the gaps between the halves are such that the gaps between the halves are of the same size.

Membrane reeds have one troublesome characteristic. You can't predict wavelength based upon tube length. The softness of the membrane covering the tube alters the natural resonance frequency of the tube. Stretching the membrane more tightly raises the pitch. It is a little easier to make all of your double reeds have the same basic shape, or even the same dimensions, than it is to make all of them play the same frequency. Other factors, such as the gap between the lay and the inside of the mouthpiece cut, the twist of the lay, and the curvature of the lay, all affect frequency. Double reeds are made in two halves which are held together. The arrangement of the two reed halves for double reeds is such that they need to be aligned so that the gaps between the halves are such that the gaps between the halves are of the same size.

Membrane reeds have one troublesome characteristic. You can't predict wavelength based upon tube length. The softness of the membrane covering the tube alters the natural resonance frequency of the tube. Stretching the membrane more tightly raises the pitch. It is a little easier to make all of your double reeds have the same basic shape, or even the same dimensions, than it is to make all of them play the same frequency. Other factors, such as the gap between the lay and the inside of the mouthpiece cut, the twist of the lay, and the curvature of the lay, all affect frequency. Double reeds are made in two halves which are held together. The arrangement of the two reed halves for double reeds is such that they need to be aligned so that the gaps between the halves are such that the gaps between the halves are of the same size.

Membrane reeds, as described in the main text of this chapter, work well over a range of sizes from moderately small to quite large. The plan given here is for a large membrane reed. At this scale, the instrument is rather clumsy and not well suited for metalworking. Membrane reeds tend to be innovation-ally unstable. Yet if the player can gain control over these factors, they allow for a lot of flexibility and some highly expressive effects.

**Sidebar 6-6**

**MAKING A BIG MEMBRANE REED**

(See illustrations on the following page)

Membrane reeds, as described in the main text of this chapter, work well over a range of sizes from moderately small to quite large. The plan given here is for a large membrane reed. At this scale, the instrument is rather clumsy and not well suited for metalworking, but it produces a big, bottomy sound, wonderfully gratifying in a crude sort of way; and it shakes your whole head as you blow. Since these instruments are inexpensive and easy to make, you may want to make several in different sizes.
Materials

4'-diameter tubing. You can use inexpensive thin-walled plastic drain pipe. Length can range from about eighteen inches to five feet or more.

Labial Reeds

Here is an odd one. Labial reeds are air-gating systems that operate by forcing air through a pair of normally closed lip-like diaphragms. In fact, they operate much like the human lip-buzzing described below, but without the human lips. (The term "labial reed," like several others used in this book, is not in standard usage; it is simply what I came up with since no other term seems to exist.) A familiar example of a labial reed would be the squeal of a balloon whose air is allowed to escape slowly through a pinched neck. It should be possible to attach such a system to a tuned air column, so that the column dictates the pitch of the reed and controls the squeal (see Figure 6-11). But I know of no musical instrument that uses a labial reed. I have done just a little experimenting with this system without much success, on one such instrument. But I leave the design of such things to you.

Playing Technique

Take the mouthpiece in your mouth. Holding the ledge of the mouthpiece behind your teeth, you can pull back on the balloon neck, as shown in Figure A. Stretch the neck slightly down and away, so that it does not sag against the tube rim. Now blow.

Stretching the balloon neck tighter raises the pitch; loosening it will cause pitch to drop until the tone drops into nothingness. Placing fingers directly on the membrane close to the edge also raises the pitch. The maximum range depends on tube length; with a long tube, you can get a range of a fourth or fifth; with shorter tubes you can get more.

If you have added a tonehole, hold the tube near the lip with the left hand to control balloon-neck stretching and do any membrane-presessing. Cover and uncover the hole with the right hand.

Acoustic Notes and Further Thoughts

The large balloon-membrane forms a semi-rigid stopped end for the air column within the tube. Stretching the membrane by pulling tighter on the balloon neck makes a tone rigid, which has the effect of raising the tube's resonant frequency. Pressing the membrane with a finger does the same, just as with the balloon tubes described later in this chapter. Stretching, in addition, raises the membrane's own natural frequency — the frequency at which it want to flop up and down like a drumhead — and this too contributes to the pitch-raising effect.

Lip-buzzed Instruments

By placing one's lips against the opening of a tube and buzzing through them — making what without the tube would be a "raspberry" or "Bronx cheer" sound — one can produce a clear, well-defined tone. Bugles, trombones, French horns, shell trumpets, like several others used in this book, is not in standard usage; it is simply what I came up with since no other term seems to exist. Lip-buzzing amounts to using a "lip reed" — namely, an air-gating system similar to that of other reeds, but using the player's lips as the diaphragm. In fact, they operate much like the human lip-buzzing described below, but without the human lips. (The term "labial reed," like several others used in this book, is not in standard usage; it is simply what I came up with since no other term seems to exist.)

Plan for making a big-tube membrane reed — a wonderful sounding instrument — appears in Sidebar 6-6.

Labial Wells

The large balloon-membrane forms a semi-rigid stopped end for the air column within the tube. Stretching the membrane by pulling tighter on the balloon neck makes a tone rigid, which has the effect of raising the tube's resonant frequency. Pressing the membrane with a finger does the same, just as with the balloon tubes described later in this chapter. Stretching, in addition, raises the membrane's own natural frequency — the frequency at which it wants to flop up and down like a drumhead — and this too contributes to the pitch-raising effect.

Construction Procedure

Cut a section of ¼" pipe to your chosen length, with a band and unscrewing cut. These have a reasonable length for an initial effect. Cut a piece of ¼" vinyl tubing long enough to circle the rim of the big tube. With a sharp utility knife, all the vinyl tubing tongue and waste it over the rim of the big tube as shown in Figure 6 (next page). Glue the vinyl tubing in place that glues well, take the point where the tube joins tightly with an electrician's tape to ensure that the ends stay in line with each other.

Cut the end of the balloon and slide the balloon over the top of the big tube, as in C and D. You can hold the balloon in place with rubber bands. (A single rubber band of the very large size designated as 105 works great.) Slip the mouth of the balloon over the mouthpiece (see Figures E and A), and fix it in place with small rubber bands.

What you have now is a simple big membrane instrument of the sort shown in Figure A, which you can play as described below. You can stop here and enjoy the instrument as is, or add a tonehole to increase its range.

Big membrane tube pitch is very flexible, so precise calculation is not needed for tone hole size and placement. For a three-foot tube, try a ⅛" hole centered at ⅞" from the far end — this will give a tone about a minor third above the whole-tone base. After cutting the hole, take about ⅜" of ⅛" x ⅛" dense neoprene rubber weather stripping and cut it in half longways, leaving two ⅛" x ⅛" strips. Using the adhesive backing, create a raised padded rim around the periphery of the hole, with one of these strips, as shown in F. With the weather strip as a gasket, you can now cover the hole leaklessly with your hand.

If you want to add more toneholes, you'll probably have to get into oversized levers and keypads (as I did, with some success, on one such instrument). But I leave the design of such things to you.

Plans for Making a Big-Tube Membrane Reed — a Wonderful Sounding Instrument — Appears in Sidebar 6-6.
Free reeds are used in harmonicas, accordions, the family of Asian mouth organs that includes the Japanese shō, and countless other instruments. Free reeds provide one of the simplest ways there is to make a fairly big musical sound, as the pocket-sized harmonica nicely demonstrates. Free reeds differ from the other reed types we have been seeing in this important respect: they don’t need a coupled air column to tell them what pitch to produce. Each free reed is designed to produce a single specific pitch on its own. For that reason free reeds are used in different ways than other reeds. For instance, it wouldn’t work well to attach a free reed to our prototype flute tube. Instead, instruments using free reeds usually employ an entire bank of reeds — one free reed for each note in the instrument’s range — with, in most cases, no attached air column.

Three variables affect the resonance frequency:

1. The volume of the chamber. The larger the chamber, the lower the pitch.
2. The size of the opening. The smaller the opening, the lower the pitch.
3. The volume of the chamber. The larger the chamber, the lower the pitch.

Helmholtz Resonators

Helmholtz resonators, named for the physicist who first studied their properties, are used in any wind instrument where the instrument is a resonant cavity. Examples are bottles and jugs, the egg-shaped Chinese dominoes used in the question of the volume in antique shop and junk stores, are now becoming rare. Alternatives include the harmonica, the accordion, and the shō, but these are less useful because they usually have entire banks of reeds in a single mounting block, rather than being separately removable.

Alternatively, you can try your hand at making your own free reeds. Here are some suggestions: Use a spring, non-convo metal for the reed itself. Brass is traditional; stainless steel also works well. The reed must not be too massive relative to its mounting; too heavy tends to avoid the mounting flexibly and the reed will then have some initial flow-through to start the tone. This calls for a special form of tube, ringed over its entire length with evenly spaced lateral ridges. This happens to be characteristic of various types of corrugated tubes, such as corrugated tubes by blowing. The most playable of widely available types is 3/8" gas heater hose. No special mouthpiece or embouchure is necessary. The reed needs nothing more than a tongue and a mouth to test the tuning, and...
Acoustic Notes and Other Thoughts

If you make the instrument with longer tubes, you will not get a significantly wider range, but you will have more tones within the range available from each tube. The tube lengths for the suggested tuning were chosen because, given the 0.4" diameter, these lengths would correspond to the 2nd through about the 8th harmonic. If you tune them properly, that yields a scale like the following chart:

... and so forth. I've used do-re-mi-fa in the example above. You could distribute your pitches differently within the tetrachord. An arrangement found particularly attractive in the playing is the Phrygian C - Db - Eb - F.

Acknowledgments

Among the many people who have worked with corrugahorns, Frank Crawford must be acknowledged for developing the idea and researching the underlying acoustics. The idea of using multiple tubes and end-stopping them comes from Richard Waters.

Tubes

The prototype simple flue with which we opened this chapter was a cylindrical tube open at both ends. (One end was stopped with a cork, but the blowhole nearby functions as an opening at that end. For the moment we will ignore the toneholes.) This open-ended cylindrical form is just one among many possible tube shapes. It is easy to imagine others — flaring shapes, narrow cone shapes, lumpy-bumpy shapes, and so forth. But from among the many, only a few are commonly used in wind instruments. The reason is that a typical tube has resonance peaks at several frequencies. For most possible tube shapes, these resonance peaks form an inharmonic series. There are just a few pipes in which the resonances form a harmonic overtone series. The most useful of these are the cylinders and the cones (usually, for wind instruments, very elongated cylinders).

Wind instrument designers generally prefer well-tuned harmonic overtone series in their tubes for two reasons. One is that the series is true, then when the instrument sounds its fundamental tone, the overtones above join in the overall vibration, reinforcing it and creating a tone that is strong, stable and rich. In the absence of this cooperation between the fundamental and overtones, the tone may be weak and unstable. The second reason is that many wind instruments make use of the higher resonances to provide the notes in the upper ranges, and if the resonances are out of tune, so will be those notes.

In actual practice, most existing wind instruments do deviate from the ideal cone and cylinder shapes, for a variety of musical and acoustical reasons. Yet each of the standard wind instruments remains grounded in one or the other bore shape, and each retains certain characteristic patterns of wave motion and vibration. We won't analyze them in detail here, but we will outline the practical results.

Cylindrical tubes open at both ends

Included here are most flutes, including our prototype, since the flute's blow hole acts as an open end. Also included are some percussion aerophones (more on them later), and several other types. Figure 6-14, with the caption that accompanies it, explains the first three vibrational modes for open-ended cylinders, and provides formulas for calculating the approximate resonant frequency for each mode. Two important observations: 1) The cylindrical tube open at both ends resonates a complete harmonic series. 2) In its fundamental mode of vibration, the tube encloses one half of the sounding wavelength (approximately). Thinning this allows you to calculate the frequency for a given tube length, or, conversely, to calculate the length required to produce a given frequency — see the figure caption for details.

Cylindrical Tubes Closed at One End

These include stopped flutes such as whistle whistles, most panpipes and many organ pipes, some percussion aerophones, and many tuned membrane resonator tubes. It also includes those need and lip-buzzed instruments that are cylindrical over most of their length, such as the clarinet family. These latter groups fit the stopped-end description because lips or reed form a barrier at the end of the tube. Figure 6-15 shows the first three modes of vibration for such tubes. Notice that in this case, the overtones series is harmonic, but it is not complete. The vibration patterns support only the odd-numbered tones. The absence of resonances to support the even-numbered harmonics contributes noticeably to the timbre of such instruments. The characteristic sound is sometimes described as dark or hot, and best exemplified in the lower register of the clarinet family.

Conical Tubes

True conical tube instruments are rare, since a complete cone would come to an end at a single point, rather than at, for instance, a mouthpiece-shaped body of air. But many instruments approximate a conical form closely enough to take advantage of some of its acoustic properties. These include need instruments such as oboes, and lip-buzzed instruments such as French horns. As with cylindrical tube instruments, a reed or buzzing lips can take the place of the closed end of a complete cone, and so support wave forms similar to those that would arise in the complete cone. The cone angles of conical musical tube instruments are not large. The largest among standard instruments is found in the saxophones at 3 or 4 degrees, ranging down to about 0.8 degrees for the bassoon.

Although the internal mechanics are different, for our purposes conical forms behave much like cylindrical tubes open at both ends. The resonances cover a complete harmonic series, and wavelength is approximately twice the tube length.

From the information in Figures 6-14 through 6-15 and their captions, you can determine approximate wavelength and resonant frequencies for any given tube length. You can then figure the resulting pitches, by referring to the chart in Appendix 2. In practice, though, various peripheral factors affect the final result; their cumulative effect is usually to make the tube behave as if it were slightly longer than its geometrical length. Appendix 3 provides additional information, should you want to make more precise calculations.

Additional Factors in Air Column Behavior

The end of a wind instrument tube, where the enclosed air meets the outer air, is a critical point. A large opening is good for sound projection, since it creates a lot of "surface area" for radiating the sound. The sound that radiates into the room from a small opening will be restricted, even when the internal wave is quite strong. You can increase the size of the opening, and thus increase radiation efficiency, by adding a flaring bell to the end of the tube. The presence of a bell affects the tuning and relative prominence of the overtones. These instruments have been known to compensate for these effects, but the factors involved are rather subtle. Estimating the effective tube length for a tube with a telltale end is difficult, but is safe to act as if the tube effectively ends at some point mid-bell. On aerophones, open toneholes can also have the effect of increasing radiation efficiency by creating a larger cumulative opening and thus more radiating surface area.
Short, fat air columns are generally poorer in overtones than long skinny ones. At the extremes, excessively fat pipes will not speak at all, and excessively slender ones tend to break up into harmonics rather than produce the fundamental. You can see this effect at work in the ranks of a large organ: the thickest pipes are the ones called "flute pipes," which are characterized by a strong fundamental and little else.

FIGURE 6-14: The first three modes of vibration for a cylindrical tube open at both ends. Stippled areas represent regions of maximum variation in air pressure and minimum air movement, while the double-headed arrows represent areas of maximum movement and minimum variation in pressure. In the following formulas, \( f = \text{frequency} \), \( v = \text{speed of sound} = 343.5 \text{ meters/second or 1127 feet/second} \) is an acceptable value; and \( L = \text{tube length} \). The formulas given here derive from the principle that frequency is inversely proportional to wavelength.

Mode 1 (the fundamental) encloses approximately 1/2 of the sounding wavelength within the tube, to produce an approximate frequency of \( f_1 = \frac{v}{2L} \).

Mode 2 encloses approximately one wavelength, for an approximate frequency of twice the fundamental frequency, or \( f_2 = \frac{v}{L} \). The sounding tone is about an octave above the fundamental.

Mode 3 encloses approximately 1¾ wavelengths, to produce an approximate frequency of three times the fundamental frequency, or \( f_3 = \frac{v}{(2/3) L} \). The sounding tone is about a twelfth above the fundamental.

Mode 4 (not shown) would enclose two full wavelengths for a frequency four times the fundamental, at \( f_4 = \frac{v}{(1/2)L} \). Higher modes continue the pattern, with the generalized frequency formula \( f_n = \frac{nv}{2L} \), where \( n \) is the mode number. The sounding tones proceed up the harmonic series, at two 8ves, two 8ves and a 3rd, two 8ves and a 5th, and so forth above the fundamental.

Mode 1

Mode 2

Mode 3

FIGURE 6-15: The first three modes of vibration for a cylindrical tube closed at one end. Stippled areas represent regions of maximum variation in air pressure and minimum air movement, while the double-headed arrows represent areas of maximum movement and minimum variation in pressure.

Mode 1 (the fundamental) encloses 1/4 of the full wavelength within the tube, to produce an approximate frequency of \( f_1 = \frac{v}{4L} \).

Mode 2 encloses 3/4 of the wavelength, to produce an approximate frequency of three times the fundamental frequency, or \( f_2 = \frac{v}{(4/3)L} \). The sounding tone is about a twelfth above the fundamental.

Mode 3 encloses 1¼ wavelength, to produce an approximate frequency of five times the fundamental frequency, or \( f_3 = \frac{v}{(4/5) L} \). The sounding tone is about two 8ves and a 3rd above the fundamental.

Mode 4 (not shown) would enclose 1¾ wavelengths for a frequency seven times the fundamental, at \( f_4 = \frac{v}{(4/7)L} \). Higher modes continue the pattern, with the generalized frequency formula \( f_n = (2n-1) \frac{v}{4L} \). The sounding tones proceed through the odd-numbered components of the harmonic series, at two 8ves and a very flat 7th, three 8ves and a 9th, and so forth above the fundamental.

Mode 1

Mode 2

Mode 3

Mode 4

FIGURE 6-16: The first three modes of vibration for a conical tube. Stippled areas represent regions of maximum variation in air pressure and minimum air movement, while the double-headed arrows represent areas of maximum movement and minimum variation in pressure.

Although the internal waveforms look different, the frequency and wavelength calculations for conical tubes come out identical to those for cylindrical tubes open at both ends:

Mode 1 (the fundamental) encloses 1/2 of the full wavelength within the tube, to produce an approximate frequency of \( f_1 = \frac{v}{2L} \).

Mode 2 encloses one full wavelength, for an approximate frequency of twice the fundamental frequency, or \( f_2 = \frac{v}{L} \). The sounding tone is about an octave above the fundamental.

Mode 3 encloses 1¾ wavelengths, to produce an approximate frequency of three times the fundamental frequency, or \( f_3 = \frac{v}{(2/3) L} \). The sounding tone is about a twelfth above the fundamental.

Mode 4 (not shown) would enclose two full wavelengths for a frequency four times the fundamental, at \( f_4 = 4\frac{v}{2L} \). Higher modes continue the pattern, with the generalized frequency formula \( f_n = n\frac{v}{2L} \). The sounding tones proceed up the harmonic series, at two 8ves, two 8ves and a 3rd, two 8ves and a 5th, and so forth above the fundamental.
It is also generally assumed that as long as the cross-sectional area remains the intended value, it doesn't matter how the tube may come and come around — a cylindrical pipe will still behave acceptably like a cylindrical pipe even after bending, as long as there are no sharp angles or kinks. This convenient assumption isn’t quite true. A perfectly straight tube has some acoustic advantages. The problems associated with bends should be negligibly small, though, if all bends are reasonably gentle and gradual.

### MATERIALS FOR WIND INSTRUMENT TUBES AND VESSELS

Wind instrument tubing materials that are light and/or yielding will damp air resonances within the tube to some degree, and lower the resonance frequencies slightly. Walls made of rough or porous materials also have noticeable damping effects. Circular cross-section shapes for tubes are good for rigidity, while fan-shaped tubes may show greater damping if the walls are not sufficiently heavy, due to flex in the tube walls. Increased damping leads to poorly defined resonance peaks, especially in the high frequencies, creating a sound that is less bright.

There is a lot of traditional lore about which materials are best for wind instruments. In practice, however, any reasonably heavy, hard, smooth and rigid material will sound much like any other such, and have the same potential for producing a good-sounding instrument. (Different materials, however, will have different qualities in durability, tonal coloration, etc.) Extremely hard reflective materials are not necessarily the ideal; people sometimes prefer the mellower tone of somewhat damped resonances.

Here are suggestions for tubing materials. There are, of course, many possibilities beyond those listed here. For more on these materials and their availability, see Appendix 1, "Tools and Materials."

#### Bamboo and other vegetable stalks

The best natural material for cylindrical tubes is bamboo. The cane reed, Arundo donax, also works well. Some other hollow reeds and vegetable stalks may work, although those that are too soft or absorbent will not make good tubes. All of these materials are naturally cylindrical or nearly so, but you can sometimes find a section of expanding bore near the base of a stalk.

#### Wood

Nonporous hardwoods work best for instrument tubes. There are several ways to make the bore in what would otherwise be a solid piece of wood. Drilling requires a very long bit and a special jig to ensure that it doesn’t wander off to one side. If you have doubts about undertaking such a job yourself, consider getting a well-equipped woodworker to do the job.

Another approach is to carve an open semicircular groove in each of two half-pieces, and then join the pieces to create the bore of the tube. This approach calls for few specialized tools but requires time-consuming precision work. Alternatively, you can assemble a bore-like square-bore tube from four pieces of wood. In either case, use a high grade, marine-quality wood glue to join the parts. While still yielding a cylindrical bore, you can create conical or other bore shapes with the carved-halves and box-building approaches.

A third approach is to have some termite eat a hollow through the core of the wood, as with the Australian didjeridu.

#### Plastic

Plastic tubes are available at hardware stores and plastics outlets in a range of sizes. Many plastics are translucent, and they are generally easy to work. Disadvantages: In mouth-blown wind instruments, they have more problems than other materials with water condensation, meaning necessary for players to stop to wipe their instruments frequently. And, of course, they are unattractive, uneconomical, and difficult to paint or otherwise decorate. As well, some common plastics are considered mildly toxic (see more on this in Appendix 1). The best natural material for cylindrical tubes is bamboo. The cane reed, Arundo donax, also works well. Some other hollow reeds and vegetable stalks may work, although those that are too soft or absorbent will not make good tubes. All of these materials are naturally cylindrical or nearly so, but you can sometimes find a section of expanding bore near the base of a stalk.

#### Metal

For cylindrical bores, a wide variety of prefabricated metal tubings are available. If you have metal-working skills and equipment, you can try making a conical tube out of sheet metal, either by making a sort of spiral wrap or processing as if you were making a very long, narrow funnel with a seam along one side. The tube-shaping techniques used in commercial brasswind manufacturing plants are not do-able in most home workshops.

#### Ceramics

Clay can be molded to any shape, and a few creative builders have made eye-catching wind instruments with it. You can create conical and cylindrical forms as well as globular, not to mention the highly irregular shapes that the material seems to invite. Wind instrument makers have found that an instrument in clay can be played, very gently, when the clay is in the partially dried state sometimes described as "leather hard." After initially shaping the instrument and then setting it aside for a period of time to reach this condition, the maker can let it dry, and make fine adjustments as needed before firing.

#### Kelp

Kelp (macrocystis) is a seaweed found all along the West Coast of the U.S., which dries to form a conical tube of up to six or eight feet long. There is a bulb at the large end that can be cut off at the right point to leave a flared opening. The walls of the dried tube are thin and brittle, but it makes instruments of clearer sound than you might expect, with beautiful form.

#### Animal horn

Horn in the ranks of a large organ: the thickest pipes are the ones called "flute pipes," which are characterized by a strong fundamental and relatively weak higher overtones. The ones called "string pipes" are much more slender, and they show prominent harmonic overtones. Sometimes you may want to add a flaring bell to the end of an otherwise straight-sided cylindrical or conical tube. (Doing so will usually improve volume and tone, but may throw off the overall tuning.) For this purpose you may choose to appropriate the bolt from a commercially manufactured tone instrument, and sometimes attach it to the end of your existing tube. Simply adding a straightened funnel to the end of the tube is less effective acoustically, but it will still improve volume and may brighten the tone quality. Many granery yards have flared sections which can be attached to a tube end to create a bell. You may be able to fashion a cunningly flared bell out of wood or clay or Sculpy™ (a hand-moldable plastic for kids), or to know what. The ideal is to have the flare fan out through a full 90 degrees of curvature.

### Tubing designed specifically for musical instruments

- **Metal**
  - Copper tubing is available in several sizes, from which you can cut smaller tubing by hand. Copper, however, is too soft to make good straight-sided tubes.
  - Brass tubing is generally too soft to make good straight-sided tubes, and it tends to lose its shape easily.
  - Nickel silver tubing is available in several sizes, and it is much harder than brass. Nickel silver, however, is not as hard as brass, and it will tend to lose its shape easily.
  - Stainless steel tubing is available in several sizes, and it is much harder than brass or nickel silver. Stainless steel is also more resistant to corrosion than brass or nickel silver.
  - Titanium tubing is available in several sizes, and it is much harder than brass, nickel silver, or stainless steel. Titanium is also more resistant to corrosion than brass, nickel silver, or stainless steel.

- **Plastic**
  - Polyethylene tubing is available in several sizes, and it is much softer than brass, nickel silver, or stainless steel. Polyethylene is also more resistant to corrosion than brass, nickel silver, or stainless steel.
  - Polypropylene tubing is available in several sizes, and it is much softer than brass, nickel silver, or stainless steel. Polypropylene is also more resistant to corrosion than brass, nickel silver, or stainless steel.
  - Polyvinyl chloride tubing is available in several sizes, and it is much softer than brass, nickel silver, or stainless steel. Polyvinyl chloride is also more resistant to corrosion than brass, nickel silver, or stainless steel.

- **Ceramics**
  - Ceramic tubing is available in several sizes, and it is much harder than brass, nickel silver, or stainless steel. Ceramic is also more resistant to corrosion than brass, nickel silver, or stainless steel.

- **Kelp**
  - Kelp tubing is available in several sizes, and it is much softer than brass, nickel silver, or stainless steel. Kelp is also more resistant to corrosion than brass, nickel silver, or stainless steel.

- **Animal horn**
  - Animal horn tubing is available in several sizes, and it is much harder than brass, nickel silver, or stainless steel. Animal horn is also more resistant to corrosion than brass, nickel silver, or stainless steel.

### Pitch CONTROL FOR WIND INSTRUMENTS

We have spoken about the many ways to excite an aerodynamic vibration, and we have spoken about the resonant air chambers, both tubular and globular, that control and enhance those vibrations. Now it’s time to talk about means for controlling and altering the air chamber resonances in order to get a range of pitches. The prototype flute from the start of this chapter had toneholes to do the job. In the prototype flute, for instance, there are holes on opposite sides of each tonehole, which are to sound your tonic pitch. For a second scale degree at 9/8 the tonic frequency (that’s a major second above in the intervals you want in the scale, then invert those ratios to get air column length ratios. An example: suppose you have a tube one meter in length which is to arc your tonic pitch. For a second scale degree at 9/8 the tonic frequency (that’s a major second above in
available sliding range in the first register the trombone player can jump to the next register a fifth above, re-extending the slide and
than an octave. That's OK for trombones, because trombones overblow the fifth. To achieve an ascending scale, after playing through the
hard material to form the body of the stopper, rim it with a gasket of soft but firm material like dense foam rubber.

A MORE PLAYABLE SLIDE WHISTLE

Slide whistles are difficult to play with good intonation, because the available pitches are not marked in any way and they are not discrete; instead there is an ill-defined continuum of pitch to shift around in. That is true of many other musical instruments, like trombone and violin. But with the violin the player develops a strong tonal sense of the neck and its topography. The trombone is a bit more like the slide whistle in its uncharted sliding, but, because of the size difference, slightly inaccurate slide placement produces a greater deklination on a trombone. Furthermore, professional musicians spend years learning to play the trombone and the violin in tune; nobody does that with a slide whistle.

So here is the way to make slide whistles easier to play in tune. You can make these modifications on an existing, store-bought slide whistle, or you can build them into a slide whistle you make from scratch. First, mount the slide whistle on a stick which extends beyond the body of the whistle as far as the farthest extension of the slide (see Figure A). Attach a flexible blow tube of about the length of the slide whistle's mouthpiece. This enables you to lay the slide whistle and attached stick in full view before you are able, while playing through the slide tube. Here you can mark off the slider stopping locations for the pitches you want to hear directly on the stick. Playing by eye and ear together, you will suddenly become a far better slide whistle player.

I did this with a commercially manufactured slide whistle in the alto range, and another whistle of my own construction in the baritone range. For a good store-bought slide whistle I recommend the chromo-plated instrument made under the brand name American Song Whistle (from American Plating Company, Chicago, IL) and sold, at reasonable cost, in many music stores and school music supply catalogs. My baritone whistle is too large by far to play on the lap, so I play it in an upright position, a little like a string bass, with the blow tube running down to the mouth of the instrument near the floor.

Open-tube slides can work where sliding stoppers cannot, in through-blowing winds like reeds and lip-buzzed brass. They have an important practical benefit of the slide whistle, though, the greatest change in length you can achieve from two measuring segments of tubing is something less than a doubling of length, as illustrated in Figure 6-16A. This means that the maximum possible pitch change is less than an octave. This is OK for trombones, because trombones overblow the fifth. To achieve an ascending scale, after playing through the available sliding range in the first register the trombone player can jump to the next register a fifth above, re-extending the slide and

Slide whistles, such as are used on slide whistles; and open-tube slides, such as
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If my opinion is correct, the slide whistle, sometimes called a痕迹 whistle, are one of the great undiscovered instruments of the world. Played well in a melodic style, they possess a haunting beauty. A typical slide design appears in Figure 6-17. The maker's challenge is to

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FIGURE 6-17: Slide whistle components. A: Slide mechanism, in cutaway view (the blue-tinted part of the tube is to the right). The fairly long channel through which the slide passes in the slide to the mouth of the whistle prevents the stopper from passing beyond one side of the tube. B: The slide whistle, showing the position of the slide whistle, and attached stick in full view. C: A side view of the slide whistle, showing the slide in its extended position.

More practical means for altering effective tube length include the toneholes on the prototype flute with which this chapter began, as well as the slides and valves used in brass instruments. We will consider these now, along with a few additional approaches that will probably be new to you.

A MORE PLAYABLE SLIDE WHISTLE

Slide whistles are difficult to play with good intonation, because the available pitches are not marked in any way and they are not discrete; instead there is an ill-defined continuum of pitch to shift around in. That is true of many other musical instruments, like trombone and violin. But with the violin the player develops a strong tonal sense of the neck and its topography. The trombone is a bit more like the slide whistle in its uncharted sliding, but, because of the size difference, slightly inaccurate slide placement produces a greater deklination on a trombone. Furthermore, professional musicians spend years learning to play the trombone and the violin in tune; nobody does that with a slide whistle.

So here is the way to make slide whistles easier to play in tune. You can make these modifications on an existing, store-bought slide whistle, or you can build them into a slide whistle you make from scratch. First, mount the slide whistle on a stick which extends beyond the body of the whistle as far as the farthest extension of the slide (see Figure A). Attach a flexible blow tube of about the length of the slide whistle's mouthpiece. This enables you to lay the slide whistle and attached stick in full view before you are able, while playing through the slide tube. Here you can mark off the slider stopping locations for the pitches you want to hear directly on the stick. Playing by eye and ear together, you will suddenly become a far better slide whistle player.

I did this with a commercially manufactured slide whistle in the alto range, and another whistle of my own construction in the baritone range. For a good store-bought slide whistle I recommend the chromo-plated instrument made under the brand name American Song Whistle (from American Plating Company, Chicago, IL) and sold, at reasonable cost, in many music stores and school music supply catalogs. My baritone whistle is too large by far to play on the lap, so I play it in an upright position, a little like a string bass, with the blow tube running down to the mouth of the instrument near the floor.

Open-tube slides can work where sliding stoppers cannot, in through-blowing winds like reeds and lip-buzzed brass. They have an important practical benefit of the slide whistle, though, the greatest change in length you can achieve from two measuring segments of tubing is something less than a doubling of length, as illustrated in Figure 6-16A. This means that the maximum possible pitch change is less than an octave. This is OK for trombones, because trombones overblow the fifth. To achieve an ascending scale, after playing through the available sliding range in the first register the trombone player can jump to the next register a fifth above, re-extending the slide and

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FIGURE 6-16: Tubular slide. A: The upper two drawings show Patel with two telescoping segments of tubing, the lower one is the telescoping segment of tubing. B: The telescoping section of tubing, the telescoping section of tubing, and the telescoping section of tubing.

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Varying Tube Wall Rigidity

With wind instruments using short and fat, unflared tubes, you can alter the pitch by covering and uncovering the end opening to varying degrees. You can try this experimentally, using the mouthpiece from a recorder (remove the lower sections of the recorder tube), attaching the several bell segments to the outgoing tube opening from each valve.

Practical notes on making workable tube slides: the easy-to-key, leakless sliding is finding or making tubing in sizes that fit perfectly one inside the other. The tubes—in at least, the inner ones—should be as thin-walled as feasible, so that there isn’t a large change in air column diameter at the point where one tube ends and the other continues. Finding well-fitting tubing sets at regular metal outlets may be difficult, but some hobby shops have brass tubing in a range of close-fitting diameters. Alternatively, you can purchase tubing made specifically for trombone slides from one of the band-instrument manufacturers, or you can use the slides from an old trombone. Other non-metallic items may also provide usefully flexible tubing pairs. Peter Schickele, a.k.a. P.D.Q. Bach, has made slide boxes using adjustable music stand uprights. Lubrication between inner and outer tubes is valuable. The grease recommended for sliding stoppers is too viscous for this application—look instead to a lighter oil.

Bentwood and Magrapping

Bentwood is the name I use for another bendable pitch control method I have used with great success. It works equally well on flutes and through-blowing instruments, and even, though more awkwardly, on cornet instruments (impossible with either kind of slide just discussed). And it is fairly easy to make. After I came up with the idea I checked in a patent library to see if I could find anything else like it, and indeed I discovered that several similar mechanisms have been patented at various times, although hardly anyone ever seems to have made much use of them.

The idea is this: You start by making a wind instrument tube with an open slit, a half inch or less wide, running the length of the tube from the air opening forward to a point just past the mouthpiece (see Figure 6-20A). Attach a long strip of stiff but flexible material, extending out over the slit but running even wider, as shown in Figure 6-20B. If you press the strip down, it covers more and more of the slit in the process, the effective tube length increases just as if you were covering up a series of toneholes. You can play melodies or continuous glissando simply by pressing the bentwood down along the slit in varying degrees.

You can play some pretty wild stuff on a bentwood instrument, but the arrangement does not lend itself to crisp articulation and precise pitch.

Roller intrument glissandi are more the norm. So I later developed magraps, an alternative version which, though less dramatic from a visual point of view, allows for more controlled playing. As shown in Figure 6-20C, magraps incorporate a ribbon-like strip of flexible material twirl about the open slit, angling slightly up and away. Using a finger to press this strip down at any point along its length will close the upper part of the tube. The size of that closure would be problematically weak, were it not for the feature: the instrument is made of metal tubing. The flexibility of the slit is made of tubular magnetic material (the same stuff sometimes used for business logos stick to the sides of commercial vehicles). The magnetism is weak, but it is enough to cause the upper part of the strip to stop down over the slit when the finger presses.

Valves

In most of the standard flared-bell instruments, commonly called brass instruments, the sounding pitch is controlled in part by the air column length and a correspondingly lower pitch. A standard valving arrangement and set of tube length relationships has evolved which serves for most members of the brass instruments family. The basic ideas can be seen Figure 6-21, and typical added-tube-length percentages can be found in the figure’s caption.

The valving mechanisms in brass instruments must be made to very close tolerances, and for most mortals it is not possible to make them outside of a metal shop with specialized tools. The best option available for adding valves to a homemade instrument is to borrow the valving mechanism from a commercially manufactured brass instrument which has been junked, or buy a valving mechanism from one of the band instrument manufacturers. The sections of tubing leading into and out of the valve mechanism are usually removable, so you can replace the original tubing with tubing segments made to suit the purposes of your instrument. One limitation in using a pre-existing set of valves is that you are tied to use tubing diameters that match those of the valving.

But why bother with valves in the first place? Why not use toneholes as the wind instruments do, since they are far easier to make? The answer is that flared-bell instruments with side holes yield relatively weak and poorly defined tones as the air column resonance fails to sufficiently dominate and control the buzzing lip. In the past there have been lip-buzzed instruments with side holes, such as the serpent that were used in Europe three or four hundred years ago, as well as some keyed bugles of the last century. Revivals of these instruments have shown that skilled players can coax beautiful sounds from them, particularly from well-made keyed bugles. If you do use toneholes with lip-buzzing, the fewer and the larger the toneholes are, the better the results will be.

Multiple Bells

In some early brass instruments, valving systems were used to send the air from a mouthpiece tube into one or another of several separate horns, each with its own bell. Each horn was a different length, to provide a different wavelength and pitch. Those were wonderful instruments to use, with a bouquet of bells rising from the single stem. From an acoustic point of view, such a design has some advantages over the single bell. Many-keyed brass instruments never became widespread because it entails more work and expense, not to mention more weight and bulk, to provide six bells for a single horn when the job could be done almost as well by one. But for a home builder working with a lightweight, inexpensive and plentiful tubing material, such as dried kelp, the multiple-bell approach might be an attractive option. For such an instrument, you could work with a set of valves appropriated from some existing brass instrument, attaching the several bell segments to the outgoing tube opening from each valve.

Varying the Size of the End Opening

With wind instruments using short and fat, unflared tubes, you can alter the pitch by covering and uncovering the end opening to varying degrees. You can try this experimentally, using the mouthpiece from a recorder (remove the lower sections of the recorder tube), and holding the palm of your hand over the open end. Fully covered, the mouthpiece plate produces the lowest available tone, and with the end wide open you get the highest. The available range between the two depends on the size of the opening. It is difficult to control pitch accurately, so the technique is more useful as a special effect than as the basis for a definite pitch instrument. But it is an attractive effect, with some of the feeling of a hooting owl or bird call.

Varying Tube Wall Rigidity

One of the factors affecting an instrument’s resonant frequencies is the rigidity of the walls and end-stops. The more yielding they
Making toneholes for small wind instruments is a fairly straightforward business. Here are some pointers.

You can make wind instrument tone holes by drilling or burning. Makers working with bamboo often use burning, because bamboo has lesser pitch rises by touching the membrane near the edge with varying degrees of pressure. Maximum range for such instruments is typically about a sixth, although sometimes you can get an octave and more. The standard balloon flute makes use of toneholes near the blow hole set at the center of the tube rather than the usual location near one end. Balloon flute toneholes are fairly large, and usually around 1/16 or 1/8 inch in diameter, with the blow hole set at the center of the tube rather than the usual location near one end. Balloon flute toneholes are typically round and smooth, with a consistent diameter throughout their length.

For many wind instruments, toneholes are the easiest and most practical pitch-control systems. They are especially suited for small instruments. With large instruments, ergonomics difficulties arise; how to stop holes that are too large to cover with a finger, and how to avoid affecting the sound quality of the instrument. Toneholes do what they do by shortening the effective vibrating length of a tube, causing the air within to vibrate at a higher frequency. The tonehole diameter happens to be as large as the tube diameter, the resulting pitch is roughly the same as what the pitch would be if the tube were cut off at the tonehole location. But toneholes aren't usually that large. The effect of a smaller hole is to shorten the wavelength within the tube as compared to a hole-less tube, but not as much as if the tube were cut off at that point (see Figure 6.23). You can raise the pitch at an existing hole by enlarging the hole, or lower it by finding some way to backfill and reduce the size.

Increasing the depth of the hole (by using thicker-walled tubing or building up the rim) is like reducing hole size in its pitch-lowering effect, making the hole shallower raises the pitch just as increasing the size does.

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Increasing the depth of the hole (by using thicker-walled tubing or building up the rim) is like reducing hole size in its pitch-lowering effect, making the hole shallower raises the pitch just as increasing the size does.
To reduce an unrounded hole, a temporary measure is simply to cover it of w. slippery tape. Better yet, as a temporary measure or as a permanent work-around, you can use a wax, which allows adjustment and repositioning. With ceramic instruments you can buff a too-large hole by replacing some clay. In other cases some sort of filler is called for. You can use the non-runny epoxy called as "epoxy gel" or "auto-body filler. Auto-body filler is strong, it bonds very well to most material, and it forms a hard surface which remarkably eases itself out as rapidly dries. For backing substantial areas, bring out the close-fit filling down again. Grease or wax is the closest and slide into the tube, for good measure. Grease or wax is again the portion directly under the hole. Then fit over the. The dowel will support the finger in the hole, and the wax or grease will hold the finger in place. It is likely that it will be easier to remove a small amount of wax or grease than to remove a large amount of wax or grease.

To avoid leaks, the tube surface surrounding the hole must be smooth and free of grit, bumps or irregularities. For finger-covered holes, if the tubing material is thick enough, it sometimes helps to make a small rounded concavity around the hole, the better to accommodate the shape of the fingernail. Alternatively, a raised rim from band instruments repair supply houses or school music supply houses. If you enjoy doing this sort of thing, you can even create a tube with a larger opening at one end than the other, the closed-tube resonance will be lower when it is the large end that is blocked or obstructed. This requires a degree of sophistication in metal working, but whose predominant tone is aerophonic. For a simple example, pick up a piece of rigid tubing, say two feet long and an inch on a half-diameter. If you clamp the path of your hand slightly down on the open end of the tube, you will hear a faint tone at the resonant frequency of the enclosed air. This is the principle of the aerophone. There may be some idiosyncratic sound present as well, coming from the material of the tube itself, but in percussion aerophones, the air resonance tone should dominate. 

Sidebar 5-1


Any piece of approximately sound rigid tubing makes a good end-struck percussion tube, producing a clear tone when you clump your hand over one end or strike it with a soft, flat bat like a rubber beach sandal. Tubes in diameters between about 1” and 2” sound best for playing with the hands, with a larger, flatter bat you can go up to 3” or 4”. Larger diameters give greater volume. The pitch depends primarily on the length of the tube. A set of such tubes can be easily and rewarding instrument to make. Hand-hold tubes always seem to sound best, but you can’t hold them with both hands simultaneously, or you’ll have hands free for striking. For a larger set, leaving enough room free for striking, and to make the right kind of mounting, in designing a mounting, keep these things in mind: 1) The tubes must be spaced 2” or more apart to allow unobstructed strumming of individual tubes. 2) The ends of the tubes must not be blocked or obstructed. 3) If your set includes tubes longer than about three feet, they cannot be mounted upright without making the instrument too tall to play comfortably. Either mount horizontally, or use blocks or a V-joint in an upright mounting. Mounting tubes by themselves. Gradually bend the tube horizontally on themselves. Some tubes may vary in thickness. 5) This is most important and most difficult of all. The mounting must be padded enough that the thump from the blow is not transmitted to the framework or the floor and radiated from there to the air, yet the tubes must be secure and stable enough that they don’t get knocked out of position under the blow. There are many possible approaches here; experiment and let common sense guide you.

FIGURE 5-25: "Percussive" aerophone tube with expanded end to improve tuning. You can achieve a similar effect with a gradually expanding bore — i.e., a tapered conical form.

Percussive aerophones usually involve some kind of enclosed air chamber. The chambers can take globular forms as well as tubular, and they can work well in size ranging from tiny to rather huge. Let’s begin with tubes. Sidebar 5-10 describes the basics for making a simple but surprisingly effective instrument from a graduated set of end-struck tubes. Cylindrical tubes, we saw earlier in this chapter, produce different tones depending on whether both ends are open (forming a half-wave resonator to produce a higher tone) or one end is stopped (forming a quarter-wave resonator, with a tone about an octave lower). Percussive aerophones can be made either way. In fact, the same open tube can function both ways, depending on how it is played. For the closed-tube tone, clump your open hand down on the tube and see to cover the opening completely. Don’t lift your hand immediately, but keep in the plate for the duration of the tone. You will have stopped the tube, and the resulting pitch will be the lower edge. If you strike it in such a way as not to cover the end, lifting your hand immediately after the strike, you will hear the open-tube pitch. You can even create an open-ended tone by striking it as you fully cover the end, but lifting your hand quickly as the tone still sinks slightly into the flesh or key pad that covers the hole. There are many ways to make such a rim; some involve carving into the sides of the hole (to reduce effective hole thickness). Alternatively, you can make a concave seating for the finger on top.

To avoid leaks, the tube surface surrounding the hole must be smooth and free of grit, bumps or irregularities. For finger-covered holes, if the tubing material is thick enough, it sometimes helps to make a small rounded concavity around the hole, the better to accommodate the shape of the fingernail. Alternatively, a raised rim from band instruments repair supply houses or school music supply houses. If you enjoy doing this sort of thing, you can even create a tube with a larger opening at one end than the other, the closed-tube resonance will be lower when it is the large end that is blocked or obstructed. This requires a degree of sophistication in metal working, but whose predominant tone is aerophonic. For a simple example, pick up a piece of rigid tubing, say two feet long and an inch on a half-diameter. If you clamp the path of your hand slightly down on the open end of the tube, you will hear a faint tone at the resonant frequency of the enclosed air. This is the principle of the aerophone. There may be some idiosyncratic sound present as well, coming from the material of the tube itself, but in percussion aerophones, the air resonance tone should dominate.

Sidebar 6-11

MAKING A SCRAPPER FLUTE

You can make an aerophone in which the air enclosed in a tube is excited by scraping the surface of the tube. For this work, the outer surface of the tube must be smoothed. It also helps if the tube is of a somewhat yielding material, so that the tube walls give a little under the scraping and uptake the air within. The sound is coarse, like the raspy singing voice of some hard-living, sentimental protest singer.

You can make either of two approaches with scraper flutes: 1) Make a single tube with toneholes along the side, achieving a range of pitches that way; or 2) Make a set of tubes without toneholes, but graduated in length, and mount them in a row in a framework. The instructions here are for making the single flute.

You will need 15” of 1” polyethylene tubing (flexible black plastic cold water pipe, sometimes called “poly pipe,” usually sold in 100’ coils). In addition, you will need two eyepins in the smallest available size, plus four hex nuts to 9”, and a small bungie cord or equivalent. There is a 12”, 15”-diameter bungie cord that suits the work well.

Cut a section of tubing 14”. Check by blowing over the air, and alter the tone as needed. A. Check by blowing over the edge, and alter to fine-tune for the tuning.

The air tone will swamp under scraping or a little hole in the region that will be stopped. This you can do by scraping the tube in a line (the shaped ellipse is left plain near the cylinder). It is about half the length, which will be the scraping region, leaving the squared end opening in one place, as shown in Figure 8. You can make a swabber exactly like a gouge, or more laboriously with a hand file. Wear goggles and a dust mask.

You will need about 14” apart on center fairly deeply sunk so deep that they catch through the tubing. Cover one face of the squared end with tape or wet newspaper to about 0.0” of the tube length, as shown in the drawing.
successive rings required to achieve this particular set of ratios are 30, 36, 40, 45, 54, 60.)

The holes should not be in a straight line along the top of the tube, but displaced to one side or the other as dictated by the ease and comfort of the fingers that will be covering them in the playing position described below. You will end up with holes #1 - 4 as fingeholes in a curved line off one side of the tube, and #5 as a thumb hole off the other. Fine tuning may be necessary after drilling these holes.

When you operate the scraper with one hand and control the fingeholes with the other, no hands are left to hold the tube securely. For this you strip it to your lip. The usual effect is comical, especially if you get up to walk with the tube still strapped around your thighs, but this mounting works well for playing purposes. One half inch from each end, drill and attach the eyebolts as shown. The small bungee cord will run from eyebolt to eyebolt, around the backs of your thighs, to hold the tube in place as you end play.

You can try different scrapers. I have found that the best of 1/4” diameter or so works well, so I use a medium-large phillips head screw driver, drawing the shaft along the ridges.

Sound the tubes by scraping or striking. Blend the two for a scrape with well-defined attack, by starting the scrape with a bit of percussion. Control pitch by covering and uncovering the toneholes with the free hand.

The maximum number of toneholes is 5, since one hand will be operating the scraper and not available to cover holes. You can space the toneholes to yield the scale of your choice. Here is a hole spacing that will yield a minor hexatonic scale:

<table>
<thead>
<tr>
<th>Hole</th>
<th>Frequency Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3/2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>5/3</td>
</tr>
<tr>
<td>5</td>
<td>3/2</td>
</tr>
</tbody>
</table>

The pitch relationships of the finished instrument — that is, the scale it produces — will depend upon the ratios of the numbers of holes in each ring. For instance, you can make a long tube to produce a tone on an opened-mode drum. Another is to make many holes to produce a carrier frequency ratio of 2:1, corresponding to the interval of an octave. Changing the disk rotation speed will change the actual pitches produced. Such a disk change the carrier frequency, but will not change the pitch relationship. Suppose, then, that you want to create a disk that will allow you to play the pentatonic scale consisting of the minor, a minor third, perfect fourth, perfect fifth and minor seventh. To do this, you create a series of concentric rings whose hole counts correspond to the ratios of that scale. You can use a flexible blow tube and nozzle, hand-held in front of the rotating disk, to direct the air at one or another of the rings and sound the different pitches.

The siren's pitch is determined by the number of holes in each ring. A ring with fewer holes will produce a higher pitch, while a ring with more holes will produce a lower pitch. The siren's pitch can be adjusted by changing the number of holes in each ring. Additionally, the siren's pitch can be controlled by changing the air flow through the rings. By adjusting the air flow, the siren's pitch can be raised or lowered. The siren's pitch can also be controlled by changing the speed of the rotating disk. By increasing the speed of the rotating disk, the siren's pitch will increase. By decreasing the speed of the rotating disk, the siren's pitch will decrease.

The siren's pitch can also be controlled by changing the shape of the rings. Rings with a larger diameter will produce a lower pitch, while rings with a smaller diameter will produce a higher pitch. The siren's pitch can also be controlled by changing the material of the rings. Rings made of a material with a higher density will produce a lower pitch, while rings made of a material with a lower density will produce a higher pitch.

The siren's pitch can also be controlled by changing the air pressure. By increasing the air pressure, the siren's pitch will increase. By decreasing the air pressure, the siren's pitch will decrease.

The siren's pitch can also be controlled by changing the air temperature. By increasing the air temperature, the siren's pitch will increase. By decreasing the air temperature, the siren's pitch will decrease.

The siren's pitch can also be controlled by changing the air humidity. By increasing the air humidity, the siren's pitch will increase. By decreasing the air humidity, the siren's pitch will decrease.

The siren's pitch can also be controlled by changing the air humidity. By increasing the air humidity, the siren's pitch will increase. By decreasing the air humidity, the siren's pitch will decrease.

The siren's pitch can also be controlled by changing the air viscosity. By increasing the air viscosity, the siren's pitch will increase. By decreasing the air viscosity, the siren's pitch will decrease.

The siren's pitch can also be controlled by changing the air compressibility. By increasing the air compressibility, the siren's pitch will increase. By decreasing the air compressibility, the siren's pitch will decrease.
One of the tricks in creating an effective musical siren is to get the air tube nozzle as close as possible to the rotating disk without touching it. This minimizes side spreading and ensures that the bulk of the air passes through the holes in discrete pulses. Even at its best this musical siren design is not loud, and volume drops considerably when the nozzle is not minutely close to the disk. To make it easier to hold the nozzle close to the disk without touching, you can have a “fence” like that on a woodworker’s lathe, crossing in front of the disk. Then make the outer shape of the nozzle such that the player can ride it along the fence much as a worker at a lathe holds the chisel against the fence.

The musical siren calls for a strong but quiet motor, and speed control for the motor is a great help.

**OUTER AIR INSTRUMENTS**

There is another family of aerophones, sometimes called “outer air instruments,” that have no reeds and no air chambers, but simply excite the air in the open atmosphere. The best known of these are bullroarers. A bullroarer consists of a blade, usually of wood, with a string attached at one end and which the player whirls around in the open air. The blade rotates rapidly as it whirls, producing a buzz that varies in pitch and volume with the blade’s speed of rotation. The sound is often compared to a giant insect’s buzz, and it can have, to one who is open to such things, something of a hypnotic effect. The sound is monotonous, but the player’s movement is dramatic.

The blade may be anywhere from 6” to as much as 30” long, and perhaps one sixth or one eighth as wide. It should be thin but not too thin, or it won’t have sufficient weight to overcome wind resistance, making it hard to whirl. A quarter inch thick is usually about right. The silhouette of the blade typically is pointed at both ends but other oblong shapes, including rectangles, can work. It seems to help to have an irregular surface, with carved decorations or saw kerfs or whatever, on one side of the blade (see Figure 6-28A).

You can also make small whirled flutes. (These are not outer air instruments, strictly speaking, but they are similar in concept.) The edgetone is generated in a little canister with an edge-tone hole cut in the side. The canister is whirled on the end of a string like a bullroarer. It rotates as it whirls, exposing the edge to varying air flows and turbulence to create a shifting array of chirping and sighing sounds. Plastic film canisters and pillboxes work well; larger containers can also work. See Figure 6-28B and its caption for details.
And now the drums!

A membranophone is any instrument whose initial sounding element is a vibrating stretched membrane. That includes drums of all sorts, plus a few seemingly rather un-drumlike things. In addition to serving as the primary vibrating element in drums, stretched membranes also serve as secondary sound radiators in an extensive family of stringed instruments. The American banjo is the best-known representative in the West, but the family of membrane-resonated strings includes most African string instruments and many Indian and Middle Eastern ones as well. We will talk more about these instruments in coming chapters, but bear in mind that much of what we learn about membranes in this chapter will also be useful in understanding the banjo and its kin.

One of the great things about membranophones is that they are efficient. Membranes in themselves typically have the generous surface area required to move a lot of air. And most drumheads (though not all) are strong and moderately massive, allowing them to accept a strong impulse and respond with a loud sound, without distortion of sound or damage to the instrument. With their strength and carrying power, drums are wonderful for outdoor music. A special feature of drums is the fact that people rarely attempt to tune them with the sort of mechanistic precision one applies to, say, pianos. Yet listeners are very much affected by the timbre and pitch information inherent in different drums. As a result, drums often serve as a door to a primordial kind of unselfing, relatively free of learned doctrine.

As we did with the aerophones, we will posit a prototype simple drum to help guide our study. For the basic design, we will borrow (not for the first time) from the book Sound Designs, by Reinhold Banek and Jon Scoville, to make something similar to their tube drum. The drum consists of a goatskin head stapled over the top of an extra-heavy over-sized cardboard tube. The head is soaked in water before application; this allows it to shrink as it dries, bringing it up to playable tension. (For fuller instructions on the making of this drum, see Sidebar 7-1.)

Now, what are the essential elements in this simple drum?

1) The drumhead — in this case, the goat skin.
2) The drum body — in this case, the heavy cardboard tube.

The body serves two purposes:

a) It provides a frame over which to stretch the head.

b) It encloses a body of air which adds its resonances to the sound.

3) Means for attaching the head to the body — in this case, the staples.

And there is one more secret ingredient. It is the relationship between the drumhead, with its natural resonances, and the enclosed air below with its natural resonances. A successful drum is one in which drumhead resonances and air cavity resonances work well together. The key element in the interaction between the two is the method of attachment, which, more than anything, governs the tension on the head. It is valuable if the attachment method allows for adjustment of the tension (not possible on our prototype).

This chapter covers the above-mentioned components in this order: 1) the membranes themselves; 2) the structures that support membranes (the drum body); 3) the mechanisms that hold the two together and apply tension; and, 4) the interaction between the elements, along with the question of drum tuning.

Before all that, though, one piece of business: a description of drumhoops is necessary for understanding some of what is to come. Although the head on the tube drum discussed above was held in place by staples, many drums use hoops, which hold the skin securely, distribute tension evenly, and give hold-down mechanisms something to hold on to. Some drums have just one hoop, called a flesh hoop. It is a ring of wood or metal, with an inside diameter slightly larger than the outside diameter of the drum body it is to go on. The edges of the drum membrane are securely wrapped around this hoop, so that the hoop provides a frame to support the membrane. Pressing the flesh hoop down over the rim of the drum stretches the membrane over the opening. It then only takes something to hold the hoop in place — tacks, lacing, tensioning hardware or whatever — and you have a workable drum.

To make the Banek/Scoville tube drum described in the main text, start with a section of very heavy cardboard tubing, let’s say two feet long and 8” in diameter. It must be at least about 3/16” thick. Thicker is better. Industrial-strength cardboard tubing like this is used as forms for pouring concrete pillars, and can be purchased at building supply centers. Paint or otherwise coat the tube to prevent absorption of moisture. Take a 12” goatskin drumhead (see Appendix 2 for supply sources), and soak it in a pan of water for an hour or more. Remove it, wipe off excess moisture, and lay it over the end of the tube with the excess skin running down the sides. Using a heavy-duty stapler, staple the skin to the tube wall all around. Position the staples around the sides in this order: 12 o’clock, 6 o’clock, 3 o’clock, 9 o’clock ... and continue in similar fashion from there to fill in the spaces, making two rounds of closely-spaced staples altogether. Keep the area uniform, putting the skin good and tight as you go. Set the drum aside to dry overnight. The drumhead will tighten as it dries, leaving you with a satisfyingly playable drum the next day.

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A more reliable approach is a double hoop system, used on most modern commercially-made drums. A flesh hoop is held down firmly over the top of the drum by a second hoop, called the counter hoop or the hat. Whatever applies tension — lacing or hardware — doesn’t apply directly to the skin or the flesh hoop, but instead pulls down on the counter hoop. The making and application of drum hoops are discussed in Sidebar 7-3.

**DRUMHEADS**

Most drumheads, like that of our prototype, are circular in shape. Figure 7-1 shows the vibration patterns and resulting overtone frequencies for the first several modes for circular membranes. The
The material and mass of the drumhead itself is an important factor in determining drumhead overtone response. Light, thin, and/or innately rigid membranes tend to bring out high overtones. Heavier, softer ones produce darker tones. Any number of materials can be and have been used for drumheads:

**Animal skin**

This, through most of human history, has been the standard material for drumheads. In this way representatives of many species have found a voice after death. Cow hide gives a rich tone in congas; calf skin is used for a warm tone in orchestral kettle drums. Some makers prefer muleskin, because it has a reputation (whether rightly or wrongly) for being less stretchy. Goatskin is lighter, and is used on middle-sized and smaller drums. For very small drums, pig skin, deer skin, rabbit skin, cat skin, snake skin, and heaven-knows-what else skin have been used. Other animal membranes such as bladder have also served. Many builders and percussionists have great faith in the innate superiority of natural hide over the synthetics that have been offered as substitutes.

Synthetics

In recent decades more and more drums have been given drumheads of plastic or fiberglass. The primary advantages of the synthetics are affordability, uniformity, stability, and durability. Plastic drumheads are available from music suppliers in a great range of sizes and weights. The overtones ring much more than they do with natural hide, and the fundamentals are not as rich. Commercially made synthetic drumheads come with the equivalent of a flesh hoop built in. (but not to metal, to which hide glue will not bond). The self-adhesive property also helps secure the skin to wooden drum hoops. If it has been allowed to dry while stretched over the top of a drum body and pulled down the sides, it will keep the shape and fit for that particular drum.

Natural skin drumheads are soaked in water before being applied to the drum or hoop, and then allowed to dry there. This allows the maker to take advantage of three useful characteristics of skin:

1) It retains the shape in which it dries. Thus, if the edges of the skin have been wrapped around a hoop, they will be inclined to stay wrapped around that hoop; the stiffness of the dried wrapped skin works to hold it in place. If it has been allowed to dry while stretched over the top of a drum body and pulled down the sides, it will keep the shape and fit for that particular drum.

2) The shrinkage after soaking helps to bring the head up to high tension as it dries on the drum.

3) Hide is naturally full of gluey stuff — the basis of old fashioned hide glues — that softens when the skin is soaked, and forms a bond as it dries. For non-tunable drums, like those with tacked-on heads, this helps prevent slippage. The self-adhesive property also helps secure the skin to wooden drum hoops (but not to metal, to which hide glue will not bond).

See Sidebar 7-2 for more on the processes of preparing animal hides for use as drumheads.

**Prepare Animal Hides as Drumheads**

Not so long ago, the skinning of animals and preparation of hides were familiar activities for most people. Now, in the urban world at least, this is not so. Drum makers who work with natural hide but who do not plan to slaughter their own animals have three choices. They can purchase whole hides and do all of their own preparation and cutting; they can purchase sections of hide prepared and pre-cut to circular shapes for drum heads; or they can buy ready-made drumheads, already prepared and attached to a hoop.

**Heads made from animal hides, especially heavy ones like cow skin, are too stiff to work with when dry. To soften them, the skin must be soaked in cold water. Heavier heads soak for several hours or overnight; for lighter heads, an hour or two may be enough. This causes the skin to expand and become malleable, and to take on a doughy texture. After the skin has been soaked, the next step depends upon the sort of drum to be made and the mechanisms used to hold the skin to the drum.**

1) For hoops and drums: The skin can be stretched over the top of the drum, pulled tightly down the sides, fixed there by gluing, gluing, lacing or whatever, trimmed as need be, and allowed to dry. (Some of these options are illustrated in Figure 7-4.)

2) For hand-played drums using hoops, such as congas: You need a skin diameter about six inches greater than the rim diameter. The scaled skin must be formed over the top of the drum, with the edges extending several inches below the rim. The entire hoop is then wrapped in a few layers of cloth soaked in hide glue. The cloth is then wrapped around the hoop and the skin is attached, as described in Sidebar 7-3. Any excess material is carefully trimmed. The hide is allowed to dry, with the head held in place securely but not too tightly to the hoop (undercutting) or some other retaining method. Figure 7-5 shows how the components fit together. (Also, Figure 7-4 shows some alternatives to the traditional lapped hoop approach referred to here.)

Hand-played drums need this special spread-over the top forming process because the drum hoops need to be well below the rim of the drum so that the player can strike the skin near the rim without hitting the hoop. If the drum is to be tunable,
Rubber or stretchy plastics

Balloon rubber and inner tube rubber have both been used for drumheads. Their Stretchiness gives them the advantage of being very easy to mount under tension. The results in typical applications are disappointing, as the soft rubber is too yielding to absorb the energy of the stroke well, and has too much internal damping to sustain a vibration. But the lightness and yield of stretchy rubbers have some value when you need a membrane that is easily dominated by an associated air column. Balloon rubber drumheads set over long, narrow tubes, for instance, will not produce great volume, but the tone is appealing. (Further discussion of tube drums appears later in this chapter.)

Rigid materials

If the material of a membrane is not stretched, but rather is rigid enough to support itself, then the instrument technically does not fit the definition of a membranophone. Be that as it may, many makers have produced drum-like instruments using diaphragms of rigid plastic, thin plywood, metal, ceramic or other materials, and many of the principles of membranophone design apply.

Drumheads are normally made as uniform as possible in consistency and thickness, forming an evenly weighted flat surface on the drum. But it's not unusual to see a trap set drummer offsetting this by taping pieces of gauze or other padding to snare and tom-tom drumheads at selected off-center locations. The purpose is to reduce unwanted ring from various partials in the drum tone. By placing the dampers at selected locations, one can modify different overtones and fine tune the drum tone (albeit, often in a haphazard way). One could bring some sophistication to this process through a study of the vibrational patterns, node locations and frequencies for the several circular membrane modes described in Figure 7-1.

Another way to modify the overtone output of a drumhead is weightening the center of the head. This increases the sustain, brings out the fundamental and diminishes the overtones. One frequently sees this done to a very limited degree by the application of a thin disk of heavier material at the center of commercial synthetic drumheads. Some conga players achieve a similar effect by deliberately thinning their drumheads around the rim by sanding. A fuller application of the same idea can be seen in tabla.

At the center of the tabla drum head is a rounded mound of a special gritty, pasty material applied directly to the skin. It adds mass at the center, diminishing uniformity toward the periphery, but due to its special makeup, it does so without limiting the skin's flexibility. The shai, as this feature is called, is one of the reasons why tabla have such clear, well defined pitch, and such long ring time.

The making of the shai is a sophisticated process and we won't go into it here, but there are ways to apply similar processes to other drum types. Any large, flat, stiff material added to increase weight will inhibit the drumhead's flex. But you can add small weights at the center of the head without such problems. I have found, for instance, that a nut or washer affixed to the center of the head can make a small drum sound deeper and richer. There are many ways one could go about attaching weights. Here is one approach that I have found easy and effective: Drill a small hole at the center of the drumhead. Put a very short machine screw (1/4" or 3/8") through the hole, and secure it with a nut from underneath.

DRUM BODIES

The body of a drum serves, first, as a framework over which to stretch the membrane. For the family of drums called frame drums, that's all there is to it: the body has no more depth than what is needed to provide a sturdy support structure at the rim of the membrane. The best known frame drum in western pop culture is the tambourine (the sort that has a stretched membrane, which not all do; and please ignore the jingles for the moment). A purer example is the Irish bodhran. There are many more the world over.

As a final step, and as an occasional caretaking step as the skin ages, give the head a rubdown with oil. This keeps it supple and, for a skin which has become dry, noticeably improves the sound. Many oils will serve the purpose; I have found mineral oil, being widely available and inexpensive, is a good choice.

Weighting the Drumhead

There are other reasons why tabla have such clear, well defined pitch, and such long ring time. The making of the shai is a sophisticated process and we won't go into it here, but there are ways to apply similar processes to other drum types. Any large, flat, stiff material added to increase weight will inhibit the drumhead's flex. But you can add small weights at the center of the head without such problems. I have found, for instance, that a nut or washer affixed to the center of the head can make a small drum sound deeper and richer. There are many ways one could go about attaching weights. Here is one approach that I have found easy and effective: Drill a small hole at the center of the drumhead. Put a very short machine screw (1/4" or 3/8") through the hole, and secure it with a nut from underneath.

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Drums are often made from hollowed-out tree trunks. I know of no easy way to do the hollowing. One way to make the task more manageable is to first split the trunk in half, then do the hollowing, and finally rejoin the halves. Sometimes, with luck, you can come across a section of trunk that has been naturally hollowed for you by a rolling process that has left the outer wood solid. I have noticed that this seems to happen a lot with ancient apple trees. With hollowed trunks, the upper rim is unlikely to form a true circle, posing problems when it comes to attaching hoops and hardware. In such cases you may choose to be content with tacked-on drumheads. Be aware that some tree species like redwood have softer sapwood near the surface; they don’t make good candidates for hollowing.

Some wide, shallow drums, such as snare drums, are made by building up a strong circular shell of many thin veneers, laminated together using a circular form specifically made for the purpose. For instructions on this process, see Irving Sloans’s Making Musical Instruments. Similarly, there are some lightweight, flexible commercially available plywoods that can be formed into a large drum shape, and instructions on this process, see Irving Sloans’s Making Musical Instruments.

With these principles in mind, we can look at variations in drum body shape and consider the acoustic implications.

Some drums are single-headed, meaning that they have one membrane, and some are double-headed. Single-headed drums are usually left open to the air at the far end. Single-headed drums which are entirely enclosed often produce unsatisfying results (an exception is large drums, such as kettle drums, discussed below). The enclosed air, with no freedom to move, damps the drumhead’s vibration, giving a dull tone; also, the air resonances have no opening through which to radiate into the room. Double-headed drums, however, may be entirely enclosed, because the flexibility of the second head gives the enclosed air the needed freedom of movement. In addition, the sympathetic movement of the second head when the first one is struck contributes to the sound communicated to the surrounding air. Yet even most double-headed drums have a hole in the side somewhere, even if it’s only a quarter or half inch in diameter, to allow some air flow. A larger hole in the side of a double-headed drum, providing a generous direct outlet for the air resonance tone, may also prove effective.

Kettle drums appear to contradict the statement that single-headed drums need an air opening opposite the head to allow the head free vibration. In fact, orchestral kettle drums (timpani) do have a small opening in the base. Opinions differ on how the opening affects the vibration of the head. But it seems reasonable to assume that the relatively large body of air enclosed in a large kettle drum would be more yielding than the air in a smaller enclosed drum, and would inhibit drumhead vibration less. Also, while the enclosed air may restrict the fundamental, it may actually encourage some other modes, such as the one labeled L2 in Figure 7-1.

In single-headed drums with an opening opposite the head, the size of the opening is significant, as are the size and shape of the chamber. When the enclosure is short and fat and the opening wide—as with, say, timbales—then the enclosure is not really much of an enclosure, and lacks well defined air resonances. As with the more extreme case of frame drums, the skin sound will dominate. The head can be tuned to any pitch it can take, while air resonance will have little impact (see Figures 7-3 A and B). At the opposite extreme, if the chamber is long and the opening narrow, as for instance with tube drums, then the enclosed air has well-defined resonances at specific pitches (Figure 7-3E). They will affect the tone very much, and their relation to the drumhead pitches takes on more importance.

Some drums have large internal chambers with relatively small openings. Congas, with their narrow-based barrel-shaped bodies, are an example (7-3 B and C). Such a chamber doesn’t show a set of well-defined resonance frequencies like a barrel tube, but rather is dominated by a single broader resonance peak in the lower frequency ranges. (The word broader here means that there will be resonance response not limited to specific frequencies, but spread out over a wider band of frequencies.) Three primary factors influence the tuning of this broad resonance peak: 1) The larger the chamber overall, the lower the resonance frequency band. 2) The smaller the opening, the lower and narrower the frequency band. 3) The looser and less rigid the drumhead, the lower and broader the frequency band. This last factor means that the air resonance tuning is not fixed, but interacts with the drumhead tuning—a situation which makes the whole business a good deal less cut-and-dried than it would otherwise be. In congas and other long drums with high head tensions, the air resonance peak is typically well below the pitch at which the drumhead rings. That air resonance is the source of the bassy “bottom tone” of a heavy, damped stroke. It affects the quality, responsiveness and richness of the open ringing tone as well, but in a highly variable manner depending on the relative tuning of the skin and the air below. In contrast, with long drums set at lower tensions, such as the cardboard tube goat skin drum described at the start of this chapter, the drumhead fundamental is more likely to be in the same range as the air resonance, and the two will interact more closely.

There are many more possible drum body forms beyond the basic types we’ve just discussed. But the acoustic principles described here are primary guiding principles in drum body design. Later, we will take our level of understanding one step deeper, when we discuss drum tuning.

**Drum Body Materials**

The essential criteria for drum body materials are that they be sufficiently rigid and sturdy, and appropriately massive. Being readily available, affordable, and workable with common tools also helps. Here are notes on some specific materials. Remember to look to Appendix 1 for more information and notes on where to get what.

**Woods**

Hardwoods are more elegant, stronger, and longer lasting than softwoods. They are acoustically superior too, being more massive and reflective, but the difference in the end result between top quality woods and inexpensive softwoods is not as pronounced as you might expect. Also, the larger species of hardwoods can be effective for very small drums or tube drums. The workability of wood helps when it comes to carefully shaping the rim that is the contact surface between skin and body, and attaching hardware (tuning mechanisms and such).

Barrel drums, with staves, are beautiful and make efficient use of valuable woods, but it takes some skill to make seamless, leakless joints between the staves. Some people have made drums by shaving down the sides of actual barrel staves, creating, in effect, a narrower barrel. If instead you start from scratch to make a drum with the traditional bulging shape, you will need either to steam and bend the staves, or cut them in a wide arc on a band saw, to create the outward curvature that is characteristic of barrel drums. Or you can buck tradition by making a straight-sided barrel drum and challenge listeners to scratch to make a drum with the traditional bulging shape, you will need either to steam and bend the staves, or cut them in a wide arc on a band saw, to create the outward curvature that is characteristic of barrel drums. Or you can buck tradition by making a straight-sided barrel drum and challenge listeners to

**Drums are often made from hollowed-out tree trunks. I know of no easy way to do the hollowing. One way to make the task more manageable is to first split the trunk in half, then do the hollowing, and finally rejoin the halves. Sometimes, with luck, you can come across a section of trunk that has been naturally hollowed for you by a rolling process that has left the outer wood solid. I have noticed that this seems to happen a lot with ancient apple trees. With hollowed trunks, the upper rim is unlikely to form a true circle, posing problems when it comes to attaching hoops and hardware. In such cases you may choose to be content with tacked-on drumheads. Be aware that some tree species like redwood have softer sapwood near the surface; they don’t make good candidates for hollowing.**

Some wide, shallow drums, such as snare drums, are made by building up a strong circular shell of many thin veneers, laminated together using a circular form specifically made for the purpose. For instructions on this process, see Irving Sloans’s Making Musical Instruments. Similarly, there are some lightweight, flexible commercially available plywoods that can be formed into a large drum shape, and stiffened by laminating on a second layer of the same material.

**Cardboard**

The heavy cardboard tubes suggested in Sidebar 7-1 are affordable, easy to work with, light in weight, and easy and fun to decorate. Disadvantages are that their strength is borderline—certainly insufficient for cow-hide drum heads kept at high tension—and they turn to mush if they get wet. You can increase their moisture resistance with water resistant finishes such as polyurethane.

**Gourd and Calabash**

Very large gourds can work well for lightweight drums, and they can be found in a wonderful variety of drum shapes, though they are fragile. Calabash are far stronger and in that regard superior, but they lack the diversity of form.
In the book mentioned a moment ago, Irving Sloane gives instructions for making a brass snare drum. He recommends starting with a half-inch 21-gauge (.029") sheet metal stock, and gives full details on working it.

Orchestral timpani are traditionally made of copper, but the demands of their fabrication exceed the capabilities of most home workshops.

For smaller drums intended for light use, you can take advantage of the self-tensioning and self-gluing properties of natural hide to attach lightweight skins using no additional mounting mechanisms. It works best if the area immediately below the rim curves sharply inward, in a shape like those shown in Figure 7-4A. Darrell De Vore makes drums like this using hemispherical sections of large gourds, with an air hole of two inches or so opened in the back. Just soak the skin, then form it over the rim and the receding section of the drum body. It tightens and adheres as it dries, to form a surprisingly full-sounding small drum.

A similar approach — minus the wetting and drying — works with balloon rubber membranes on small tubular drums. Let the body of the balloon form a sort of sleeve to be slid over an appropriately sized opening. Start by cutting off the narrow balloon neck if necessary, then slide the balloon down over the tube until the end stretches over the opening. The traction of the latex is generally enough to hold it in place.

Tacking, Stapling or Pegging

For non-stretchy and/or non-shrinking drumhead materials, tacking is not an effective method. On the other hand, there is an appealing aesthetic to lightly made and lightly played drums that are free of tuning gadgetry. If you are designing a drum for which all the hardware seems a burden to the organic spirit of the drum, then, I say, skip it. Play gently, and accept that the head tuning will not last forever.

Following here are notes on each of several methods of attachment:

MAKING DRUM HOOPS, AND ATTACHING HEADS TO HOOPS

Wooden hoops can be made by lamiating several strips within a circular form, just as wooden drum shells are sometimes made. The individual, thin strips are sufficiently flexible to form the circle, but ten or more of them glued like plywood make a pretty strong hoop. When doing this, make sure that the points at which the ends of the strips meet are located differently in each layer.

To make a hoop out of single thicker piece of wood, you can bend it by means of a special tool called a bending iron, or by boiling or steaming the wood until it is sufficiently pliable, then quickly clamping it over a circular mold to dry.

For double-headed drums, the lacing usually connects the two heads and tightens them by pulling them together. For single-headed drums, the lacing needs something lower on the drum body to attach to, such as pegs driven into the body, or metal hooks looped under the bottom edge. Alternatively, each lace can simply pass under the bottom of the drum and across to the opposite side. For the cord used in lacing, look for something dependably strong and as unstretchy as possible. Avoid nylon cord or rope.

ATTACHING THE HEAD

An essential question in attaching drumheads is whether the method of attachment allows the drum to be tuned and returned after the skin has been applied. With laced drumheads, even if the person who does the tacking does a great job, the skin will inevitably loosen up over time, especially under heavy playing. With natural skin you can re-tighten a bit prior to each playing by holding the drumhead over dry heat (or wetting it, if need be, to loosen it). You can even find a certain pleasure in an untunable drumhead's changeability as you hear it responding to every little change in the weather and communicating the information to you by its tune. But, with drums that are to be heavily played, it is usually worth the effort to find a mounting system that allows adjustment of the tension on the head.

For non-stretchy and/or non-shrinking drumhead materials, tacking is not an effective method.
Natural sisal rope works well.

You can make a decent laced drum without hoops by running the lacing through holes around the periphery of the skin in closely-spaced loops so as to distribute the stress widely and evenly (Figure 7-4C, D, and E). But for better results, hoops are a good idea. A simple single hoop can be used, with the laces running over the hoop and through the skin rather than through the skin alone. In this case you usually need an additional set of lacing loops around and around to hold the skin firmly to the hoop. Double-hoop systems, in which the lacings are attached to the counter hoop, are better yet.

Drum makers have developed many tricks for adjusting tension on laced drums. Several of them are illustrated in Figure 7-4F through I.

Tensioning Hardware

Drum lacing appeals to a natural aesthetic that metal hardware does not. But for strong, long-lasting drums that are to be vigorously played, many makers turn to metal tuning hardware. The principle behind hardware design is the same for most drums: several bolts or heavy threaded hooks are regularly spaced around the counter hoop. Each bolt or hook reaches down from the counter hoop to where the threaded end passes through some sort of anchor attached firmly to the side of the drum. A nut below the anchor allows the whole arrangement to be tightened with a wrench, pulling down on the hoop to tighten the skin. Figure 7-5 shows two typical arrangements. The tuning process is one of tightening or loosening the nuts or bolts, doing just a little at a time, proceeding from one bolt to the next in a star pattern back and forth across the rim, to alter the tension evenly all around.

You can get prefabricated drum tuning hardware from musical instrument supply houses. Or you can recycle from an unused drum. Or you can have it custom made by a metal worker. Or you can make your own from commonly available hardware. If you make your own, let your personal blend of common sense and ingenuity prevail, but be sure to make the system strong. Be sure also — this is important — that it doesn’t get in the way of the player’s stroke and that it doesn’t stick out from the drum body.

DRUM TUNING

The relationship between the drumhead and the air enclosed beneath it is an essential factor in drum tone. If you have a tunable drum (one with lacings or tuning hardware; not with a tacked-on head), then you can work with this relationship by adjusting the tension on the drumhead to bring out the best in the drum. Drumhead tension affects not only the head itself, but also the resonance frequencies within the chamber. That is because the rigidity of the walls is one of the determining factors in air chamber resonance frequency, and the drumhead is one of those walls. As a result of this interdependence, you cannot simply determine the drum’s air resonance pitch and then tune the head to it. You have to go through a process of adjustment to find a region where the two reinforce one another. When you do, the drum will speak with a fuller tone.

The process is not a mechanistic one; it is usually a feel-your-way kind of thing. Rarely is it a simple matter of finding a point where the fundamental resonance of the head matches the fundamental resonance of the body. The head resonances are generally too complex for that, and the air resonances insufficiently well defined. For many drums, with the head at reasonable playing tension, its resonances are too far above the main air resonance to bring the two in line anyway. The process, then, is more a matter of seeking out a tuning at which the head seems most responsive, and one which yields an attractive timbral blend. Remember that in most drums the air resonances enhance a general frequency region rather than specific notes. You can tune the head so that it benefits from enrichment in that general region, without having to tune to a certain pitch.
THOUGHTS ON MAKING A TUNABLE DRUM

Sidebar 7-1 describes a non-tunable drum which is quite easy to make. I have tried to dream up similarly simple approaches to making a tunable drum, but this is easier said than done. Still, this chapter contains information that will allow you to experiment with a wide variety of tunable drum designs. What follows here is an idea for anyone wanting to make a tunable drum that is not excessively difficult to build. No specific plan is given here; I've left the details to the reader. Hopefully you will be able to combine a common sense and creativity to come up with a workable design based upon these notes. This sidebar refers extensively to topics discussed elsewhere in this chapter, so you will want to review the relevant passages in the main text before proceeding.

My favorite design for a home-buildable tunable drum is that described and pictured in Figure 7-4J. The design calls for two rings cut from heavy plywood. The upper ring serves as the drum hoop, with the skin, after soaking, stapled to the underside. If you are making a hand-played drum, remember to start with a skin that is at least four to six inches larger in diameter than the drum body. Form the still-wet skin over the rim of the drum body so that the drum hoop (the plywood ring) will ultimately be positioned well below the rim. Use large staples, and use plenty of them, to secure the skin all the way around. The second plywood ring is located at the base of the drum. The rope lacings anchor to it and, as Figure 7-4J shows, drumhead tension is controlled by twisting the lacings at this lower anchor point. Optionally, with short legs added, the lower ring can also serve as a stand for the drum. Remember to pad the feet; use especially thick, soft pads for low-pitched drums with lightweight skins such as goatskin.

This two-ring approach is solid enough to support high drumhead tensions, with either goatskin or cowhide drumheads. It can be used with any sort of drum body material that is strong enough to support the degree of tension you plan to apply. Whatever you use for the body, remember to make the upper rim of the body, over which the skin passes, as even and uniform as possible. Remember too that the rim should be rounded where the skin passes over. For drum body materials that are too thin to provide a rounded rim, you can add a piece of thicker reinforcing material around the periphery of the body at the rim to allow for rounding.

With wooden drum bodies, the wet skin will likely glue itself to the rim as it dries. You don't want this to happen on a tunable drum. Prevent it by waxing the rim, or even just dusting it generously with talcum powder, before applying the wet skin.

Much of the time, when drummers tune their drums, they don't tune each drum to itself as I have been describing here. They tune to specific pitches that relate to the music being played. A conga drummer recording with an ensemble playing a piece in a particular key will be inclined to tune his drums to pitches that make musical sense in that key. And the results, considering the sound of the ensemble as a whole, justify the practice. But for a real drum lover, the greatest satisfaction comes from tuning a drum so as to bring out its fullest voice, regardless of specific pitch. (Long and narrow tube drums, by the way, are a special case when it comes to tuning — see the discussion under Tube Drums below.)

There is one other possible approach to drum tuning, though it is rarely used. Find a way to make the drum body's air resonances tunable. With tube drums, make the tube length variable. With barrel drums or other types, make the opening size adjustable.

One more word about tuning: an important aspect of tone lies in the balance of tensions within the head itself. Ideally, the head is tightened down in such a way that the pull is uniform all around the rim. Under unequal tension you may get a weak fundamental, or multiple fundamentals, and/or irritating dissonant partials. You can check the uniformity of tension on the head by striking with a series of light strokes just at the rim, progressing around the periphery and listening to hear whether the pitch varies from one point to another. If it does, redistributing the tension may help. On the other hand, the problem may be that the skin itself is not uniform in thickness or consistency.

DRUM MOUNTINGS & DRUM POSITIONING

Drums need to be held in such a way that the drumhead and the openings in the drum body are not blocked by adjacent surfaces. Reflecting surfaces such as floor or walls too little distance away from the open end have variable effects, sometimes enhancing the tone and sometimes detracting, depending on the drum tuning and the distance to the reflective surface. Altering the distance can make a difference in drum tone, as can altering the angle of the drum or the reflective surface. For drums with legs or drums which rest in drum stands, padding the feet where they meet the floor will often improve the tone. Very generous padding such as that described in Sidebar 7-1 may prove especially valuable for drums with lightweight skins (goatskin) set at low or moderate tension. With drums, seemingly more than with other instruments, the surrounding acoustic space can make a substantial difference in sound. The same drum may sound very differently played indoors or outdoors, in a large room or a small room, or at different locations within the same room.

MORE DRUM TYPES, SOUNDING METHODS, ACCESSORIES, ETC.

The remainder of this chapter is a hodgepodge of notes on different drum types, accessories, construction techniques and sounding methods. The last section is devoted to friction drums, which present yet another world of membranophonic possibilities.

Pellet drums

Pellet drums are membranophones sounded by pellets bounced or rolled on the membrane. Most pellet drums are small, say a couple of inches in diameter. Some have pellets within that strike the membrane when the drum is shaken, while others have small objects attached by short lengths of string to the outside of the drum, so that they bounce around and hit the membrane when the drum is twisted or shaken. With larger drums, the player can drop pellets on a drum skin from above. Many things can serve as pellets — pebbles, hard seeds, dry beans, BBs. . . . The key is in choosing something of the right mass for the size of the membrane. The sound often has a kind of gentle thunder or raindrops feeling. You can make a pellet drum of very appealing sound simply by dropping some dry rice grains into a balloon, inflating and tying it, and then shaking it about.
There is a family of West African laced drums in which you can vary the tension on the drumhead as you play (see Figure 7-41). Some types are called talking drums, because the rising and falling pitch of the drums is reminiscent of the inflections of human speech. They usually take the form of double-headed drums, and the key to the design is this: the drum body is waisted, being larger at the two ends where the skins are, and narrow at the center like an hourglass. The lacing runs between the two heads, crossing high over the waist, so that there’s room to squeeze the lacing inward to increase tension on the heads. The drum is normally held under the player’s arm, to be squeezed by bringing the elbow in closer to the body. In this position, the playing angle is awkward unless you use drumsticks having a pronounced curve toward the playing end, and this is indeed what is traditionally done. Strong hoops and a curved, smooth rim are important for such drums.

Snares

The snare from which snare drums get their name is a cord that crosses the bottom (unplayed) membrane of the double-headed snare drum. It is tensioned so that it is not too loose but just loose enough to rattle when the lower head vibrates sympathetically in response to the stroke on the upper head. It changes the sound entirely by adding a mess of sharp, high frequency noise components, yielding sharper definition, reduced ring time and increased perceived volume, and diminishing the sense of defined pitch. Years ago snares were made of gut string, with several strands crossing the head, and some people still prefer the warmer tone and greater sustain of a gut snare. Nowadays they’re more often made with about twelve strands of a kind of wiggly wire, looking a little like a coil spring that’s been over-stretched. Loosening the snare allows it to droop below the head untouched, rendering it inoperative and making the snare drum no longer a snare drum. There are commonly used snare-tensioning hardware nowadays, mounted on the side of the drum, that simply snap the snare on or off. In the old days a screw-tensioning mechanism (of a sort that wouldn’t be too hard to make in a home workshop) was commonly used. The degree of tension on the snare makes a difference in the duration and smoothness of the resulting sound. While the upper head on a snare drum (called the batter head) must be strong, the snare head should be light to make it responsive.

Coffee Can Cuica

Coffee Can Cuica

You can make a remarkably effective cuica-like instrument from a coffee can. The can should be metal, and it should be the sort that comes with a plastic lid for revealing after the top has been removed with a can opener. You’ll also need a bamboo skewer or similar smooth stick about 1/8” in diameter and 8” long, a scap of chamois or cotton rag a few inches square, and some duct tape.

Remove both ends of the coffee can with a can opener. Reinforce the center of the plastic lid by centering a 1/2” square of duct tape on each side. Drill the centerpoint of the plastic lid with a 1/16” bit. Push the skewer through the hole so that about 1/2” protrudes on the outer side of the top. Place the stick there by wrapping several rounds of 1/2” wide duct tape around the stick, snug up against the lid, both inside and out. Put the plastic top on the can, so that the stick extends through the interior of the can and out the opposite end a bit.

To play: wet the scrap of rag, hold the can with one hand. With the other, reach into the can and lightly pinch the stick with the wet rag between thumb and forefinger. The plastic lid groans and bumbles when you rub the rag up and down the stick. Vary the pitch by altering the pressure on your rubbing. Greater pressure causes the stick to push or pull harder on the plastic lid, increasing its tension and raising its natural frequency.

Acknowledgment: I first saw this wonderfully simple instrument in the hands of Mary Buchen.

variable-tension drums

Tube drums differ from other drum types in that they are often made in tuned sets of many drums. (Other drums may come in tuned sets but rarely of more than about six drums — two or three is typical for timpani, conga and tom toms.) Tube drums are suitable for making in multiples for two reasons: they are easy and inexpensive to make, making the manufacture of multiples feasible; and they generally have clearer pitch than other drum types due to the well defined resonances of the tubes. Typical tubing diameters are between two and six inches. Lengths range from perhaps six inches for a narrow drum (anything shorter will not yield well defined air resonances) to several feet. Plastic, metal, and bamboo tubing have been used. The drumheads are best made of fairly light material, such as lightweight plastics or animal skins. Balloon rubber membranes make for an inexpensive and easily-made drum, with a lovely light, bubbly tone. Balloon drums are poor in volume, and they don’t last long. Then again you might be surprised; under modest tension, balloon drumheads can remain playable for a couple months or more.

Tube drums can be tuned to prescribed pitches. The perceived pitch is usually the air resonance pitch. (The air resonance frequencies of the narrow tubes are more strongly defined than the air resonances of bunter drums.) The tiny drumheads, meanwhile, are generally tuned much higher than the air resonances. In the overall mix, the air column resonance stands out in the tone and provides the sense of pitch, while the drumhead tone adds excitement and definition to the stroke, and higher frequency color to the overall timbre. Tube drum tuning is achieved in part by using tubes of varying lengths, and partly by adjusting head tensions. (Head tension, as mentioned before, affects not only the tone of the membrane itself, but the resonance frequency of the air column below.) With skin or plastic heads and adjustable head-tensioning hardware, the tuning operation is a painstaking one, but manageable.

With tube drums having balloon heads, the situation is a little different. They are usually tuned simply by stretching the balloon membranes tighter or looser over the tube opening and letting them stay put by friction. Deliberate tuning is possible within limits, but difficult and frustrating. On the other hand, a randomly tuned array of 10 or 15 balloon-drum pitches can sound unexpectedly lovely. Particularly attractive is the presence of distinct timbres from drum to drum, arising from different relationships between the air column resonances and the membrane resonances.

Tube drums call for specialized mountings, somewhat different from other drums, because of the need to hold a large number of small drums. The drums need to be spaced so that each tube’s lower end has open air around it — otherwise the sides of neighboring drums will interfere acoustically. One way to make such a mounting is to create something like a table with a plywood top, and cut appropriately spaced holes, using a circle cutter, to accommodate the tubes. For this to work you need to have something along the outside wall of each tube near the top to catch on the rim of the hole when the tube is slid in. Whatever holds the drumhead on might do perfectly well for this purpose (with some added padding between mount and board if needed). With balloon drums, it may be that all it takes to catch and hold the tube is the edge of the balloon membrane, partially rolled up along the side of the tube. Alternately, several rounds of rubber bands stretched around each tube at the mounting point may serve the purpose. Such relatively lightweight systems can work because balloon drums sound best played gently, with lightweight beaters.

Frisson Drums

Frisson drums are membranophones in which a stick-slip vibration is communicated, either directly or indirectly, to a drumhead.

Common among friction drums are instruments like the Brazilian cuica, in which the friction is actually against a stick attached to or pressed against a drum membrane. Usually, the player rubs the stick with a small piece of wetted cloth; alternatively, rosined or wetted fingers may be used. Varying the pressure that the stick brings to bear on the membrane varies the tension on the membrane, and thus alters the sounding frequency. Touching the membrane with a finger of the free hand also creates pitch changes and some unusual effects. The very best players can play surprisingly melodically. For most mortals, pitch cannot be controlled with any accuracy, but you can get wonderful groaning, sighing and laughing sounds that are at the same time both bestial and oddly human.

Plans for making a simple but effective cuica appear in Sidebar 7-5. Several systems for affixing the stick to the membrane appear in Figure 7-6.

Variable-tension Drums

Plans for making a simple but effective cuica appear in Sidebar 7-5. Several systems for affixing the stick to the membrane appear in Figure 7-6.

Sidebar 7-5

Coffee Can Cuica

Coffee Can Cuica

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Remove both ends of the coffee can with a can opener. Reinforce the center of the plastic lid by centering a 1/2” square of duct tape on each side. Drill the centerpoint of the plastic lid with a 1/16” bit. Push the skewer through the hole so that about 1/2” protrudes on the outer side of the top. Place the stick there by wrapping several rounds of 1/2” wide duct tape around the stick, snug up against the lid, both inside and out. Put the plastic top on the can, so that the stick extends through the interior of the can and out the opposite end a bit.

To play: wet the scrap of rag, hold the can with one hand. With the other, reach into the can and lightly pinch the stick with the wet rag between thumb and forefinger. The plastic lid groans and bumbles when you rub the rag up and down the stick. Vary the pitch by altering the pressure on your rubbing. Greater pressure causes the stick to push or pull harder on the plastic lid, increasing its tension and raising its natural frequency.

Acknowledgment: I first saw this wonderfully simple instrument in the hands of Mary Buchen.
In some friction drums, a cord passing through a small hole in the center of the membrane and pulled taut serves in place of the stick.

It is also possible, though less common, to produce friction sounds through direct contact of the hand or mallet on the membrane. Some of these sounds are sighs and moans and groans, and some are steady in pitch, though not easily controlled. They lurk in drums everywhere, including the snare drums and tom toms of a normal drummer's kit. The best way to bring them out is through that miracle of modern synthetics, the superball mallet (see Chapter 5 for friction-mallet making). Try drawing a flexible-handled superball mallet across the head of an unsnared snare drum, or a tom tom. Observe the results when you excite different parts of the head, and when you hold the mallet handle with different degrees of firmness. Keep trying: it may take a while to get the knack.
Chapter Eight  
RESONATORS AND RADIATORS

This is a special chapter devoted to systems that help to project the sound of instruments that would otherwise lack volume. The sections on resonance, radiation, phase relationships and impedance in Chapter 2 are also relevant to this topic, and readers may want to review them.

Acoustic sound radiators and resonators are of two main types: radiating surfaces and air resonators. Radiating surfaces include soundboards such as those used on guitars, violins and most Western string instruments, and membranes such as those used on banjos and most African and Eastern string instruments. Their job is to accept vibrational energy from an initial vibrating source like a string or a kalimba line, and spread the vibration over a larger surface area. This allows them to drive the surrounding air more efficiently than the original source could have.

Air resonators include the air resonance tubes or chambers under marimba bars and drumheads, as well as the partially enclosed air chambers of guitars, violins and the like. (Notice that these soundbox instruments benefit from both types of radiation and resonance.) The job of air resonators is to pick up the vibration from the initial source, amplify it and then pass it on to the surrounding air through openings in the body. We covered the principles of air resonance in the aerophones chapter. We also discussed air resonators specifically in connection with marimbas and drums in their respective chapters. The current chapter will further our understanding of air resonance particularly as it relates to instruments with sound boxes.

Before discussing radiators and resonators in more detail, let me make brief note of one more form of acoustic sound reinforcement: sound reflectors. Particularly for unresonated free bar instruments such as marimbas, you can increase the effective volume and create a fuller tone by having a solid flat surface below the bars to reflect the sound. The distance from the bar to the reflecting surface is a key factor here: while a reflecting surface at a suitable distance will be beneficial, you'll find that at the wrong distance it can actually weaken the tone by causing cancellation. See Figure 4-6E for more on this.

We return now to the two main topics of this chapter: radiation and resonance. In practice these two terms overlap to some extent, but let us try to be clear about their separate meanings. Radiation, for our purposes, refers to the ability of a vibrating surface to drive the surrounding air, and thus project a sound. Resonance refers to the enhanced vibratory response of a body to driving frequencies at or near the body's natural frequencies. Thus, a well-tuned resonator can take the input from a driver at the right frequency and respond with an especially generous vibration of its own. Then, if the resonator also happens to be an efficient radiator, it will project the sound with enhanced power.

**SOUBOUNDARDS AND SOUND CHAMBERS — BACKGROUND AND THEORY**

Two qualities are needed if something is to work well as a sound radiating surface: it must be able to move a lot of air when it moves, and it must be able to respond generously to its driver (string, kalimba line, or whatever). The first requirement can be met if the radiator has a lot of surface area. The conditions for the second requirement are more complex — we'll go into more detail later — but in general, the radiator should be light relative to the driver, and not immovably fixed in place. At the same time, in order that the vibrations can spread throughout the radiator rather than simply dissipating locally at the point of input, the radiator must have a degree of rigidity.

You can achieve extensive surface area with minimal mass by giving the driver the form of a thin sheet. But thin materials usually lack rigidity. There are several ways to increase a sheet's rigidity without too much increase in mass. One is to space reinforcing struts along the surface, as is done with piano soundboards. Another is to arch or curve the surface, as is done with violins. Still another is to stretch the material, as is done with banjos. And yet another is to use some innately light, rigid material, such as styrofoam, as is done with a couple of unconventional instruments described in this book.

**Radiating Surface Area Requirements**

How large should the radiating surface area be for a given application? Here are some guidelines.

Small surfaces do not project long wavelengths well. A common rule of thumb is that, for good projection, a radiating surface should be greater in both dimensions than half the wavelength of the lowest frequency it is intended to project. In actual musical situations, however, additional factors come into play, and there can be no hard and fast rule. A soundboard of modest size will reproduce low frequencies, but with poor volume. In some cases the sound may seem loud but, like an undersized loudspeaker, the radiator may be projecting primarily the higher frequencies where the resonant frequency is relatively close. This is especially true for the wider-spreading low frequency. If we want to project the lower frequencies, we need to use a larger radiating surface area.

To achieve better low frequency response at manageable size, most low-frequency instruments, like the string bass, use an enclosed resonating chamber as part of the body that supports the soundboard. This enriches the low end by adding a generous amount of low-frequency air resonance to the mix. The enclosure also helps isolate out-of-phase vibrations from the back of the board. It will talk more about these effects as we go along.

Given that it is impossible to formulate simple rules on the subject, the best advice I can give regarding radiating-surface area size is to study existing instruments and make comparisons. A few selected examples: The lowest note on a string bass has a wavelength of over eight meters, while the soundboard is typically something over a meter high, and a little less wide. That is well short of satisfying the "half-wavelength rule," but the bottom part of the bass tone is aided very substantially by the air resonance coming out of the f-holes. Still, acousticians have suggested that the ideal size for the bass, were it not impractical, would be considerably larger. A grand piano, whose longest wavelengths are half again as long, has a soundboard more than twice as wide, though without the same sort of air resonance enclosure. It does a respectable job on the low notes, although much of the volume derives from upper partials more than a strong fundamental. Meanwhile, upright pianos try to project the same frequency spectrum with a much smaller soundboard — and do a very poor job of it in die bass (an effect also due to the shortened string length). At the opposite extreme, the smaller, lighter soundboard on a mandolin responds well to the high frequencies and projects them without difficulty for a clear, bright tone. The result is a special size for the bass, which is more efficient and resonant with a shorter wavelength.

**Phase Relationships**

We have seen that waves coming from the front and back surfaces of a soundboard are out of phase and likely to cancel to some degree as they spread. This is especially true for the wider-spreading low frequencies. For a simple board of modest dimensions with no enclosure, this effect is quite pronounced, leading, in many cases, to a rather amenic sound. For larger boards the effect is somewhat reduced, as the waves don't reach around as much.

One way to prevent cancellation is to isolate sounds from the back of the board by enclosing the back entirely. Make the whole thing like a sealed box, with the soundboard as one side. Many speaker cabinets are designed this way, to isolate the out-of-phase waves from the back of the speaker. With musical instruments, the trouble is that the restricted air inhibits the vibration of the board. More often than not, you end up losing more than you gain.

An in-between approach is to only partially enclose the box. The violin soundbox, as an example, is almost entirely enclosed but for the f-holes. A great deal of air travels in and out of these holes, effectively communicating the out-of-phase vibration to the front of the violin, like it or not. Violins are overly sensitive to this, because they like the tone quality of the air resonance from within. The resulting cancellation is somewhat mitigated, due to the fact that the air resonance reinforces most strongly different frequencies from those that the soundboard surface projects best. The blend is subjectively richer in timbre than either the direct soundboard surface sound or the air chamber resonance sound alone.

This discussion has focused on the out-of-phase front and back soundwaves. But, as always, the situation is more complex. Soundboards rarely vibrate in a simple back-and-forth motion. They flex in many modes simultaneously, with some parts of the soundboard thrusting forward while others move back. As a result, there are multiple out-of-phase vibrations coming off the front of the soundboard alone, not to mention the back. Acousticians have been developing increasingly sophisticated understanding of these soundboard vibration patterns, but the task of applying the knowledge to soundboard design is daunting. Members of the Catgut Acoustical Society have been in the forefront of studies in this area; see back issues of their journal for more information.

**Mass and Rigidity Impedance**

Impedance relationships are another important element in the operation of sound radiators. The initial vibrator that drives the vibration — the string, kalimba line, or whatever — is typically relatively high in impedance at the point where the driving takes place, concentrating a lot of vibrational energy in a small but strong vibration. The air into which the vibration is ultimately to be directed is a low impedance...
medium, carrying widespread, low-energy vibrations. Soundboards are intermediate in impedance; they serve to make the conversion.

To fulfill its intermediate role, the soundboard must not be so heavy and rigid that the initial vibrator cannot drive it effectively. Nor should it be so light or flimsy that overdriving takes place and the driver's energy is dissipated too rapidly. With especially heavy drivers, it may be hard to find a support system sufficiently strong and heavy to handle the driver, yet responsive enough and with enough surface area to radiate effectively. In this case, it helps to add another intermediate level of transference: the driver can be supported by a massive and rigid mounting system that is in turn attached to a separate radiator made of lighter, thinner material.

There is no clear-cut rule as to the ideal relationship between the mass and rigidity of the driver and that of the radiator. The best suggestion I can make, once again, is to observe and learn from existing instruments. A case study may help:

Kalimba tines are not usually massive, but they are generally quite rigid, and therefore relatively high in impedance, especially at their point of mounting. They demand a fairly rigid and heavy soundboard as a result. Most kalimbas use 1/8” to 1/4” hardwood soundboards, as opposed to the softer, lighter, springier ones used in most string instruments. But notice also that it is not unusual for kalimba players to use a three-tiered system. In this case, the tines are mounted on a rather heavy soundboard — perhaps a single fairly thick board. The heavy board alone provides a good, solid mounting for the tine, but is only so-so as a radiator (too thick and massive to move generously, and not enough surface area). But it in turn is held against the inside of a hemispherical gourd or calabash, so that the vibrations are transmitted to the gourd. The gourd has the requisite thinness, lightness and rigidity of a classic sound radiator, and it does a fine job, amplifying the volume and bringing out the lower frequencies.

To sum up: Light initial vibration sources, like small strings, often do well simply by directing their energy to a lightweight radiating surface. Heavier drivers require heavier mountings and radiators. Substantially heavier drivers benefit from having intermediary stages, such as mounting on a heavy framework attached to or held against a lighter but more extensive sheet radiator.

Transmission of Vibrational Energy

In most musical instruments the sound resonator and radiator mechanisms are attached directly to the drivers. Transmission of the vibration over long distances is not a concern in these cases. But it is actually quite remarkable how easily and efficiently vibrational energy can travel, given a medium without too much damping. Imagine that you create a high-impedance vibration in one location — a vibration which is scarcely audible because it doesn't radiate efficiently to the air — and send it through a network of rigidly connected bars, to where it feeds into an efficient radiating surface at some distant location. A listener will then hear the sound clearly emerging from the distant radiator. (The best examples of intelligent use of mechanical transmission in musical instruments can be found in the instruments of the Baschet Brothers in France, some of which are described in Chapter 4, “Idiophones,” and elsewhere in this chapter.)

Here are guidelines for efficient mechanical transmission of sound vibrations over long distances:

The transmitting medium should have little internal damping, or there will be dissipation along the way. You might be surprised at how well wood does, but hard metals do better, especially over long distances. Wires pulled taut can also do well. All connections and joints must be solid and fast, both for efficient transmission and to prevent rattling. The vibrational energy should be in the form of high-impedance, longitudinal vibrations.

Here is an example of musical mechanical transmission, in the form of a fanciful signaling device. Imagine you have a friend living in the apartment building next to yours, with her window across from yours ten feet away. You find a lightweight, twelve-foot wooden pole, and stick it out your window, reaching across and touching her window with a light pressure (as in Figure 8-2). You take a tuning fork, bonk it on your knee to start it vibrating, and then hold the handle end-on against your end of the pole. The tuning fork is fairly quiet for you, being a poor radiator by itself. But to your friend, the tuning fork tone coming off the inside surface of her window sounds clearly. You can start and stop the tone on her end effortlessly, by touching and un-touching the fork handle to the pole even as the vibration sustains within the fork. This enables you to create a code: long-short-short means "meet me in the foyer," short-short-long means "hide — the landlord is on his way up the stairs to collect your rent;" etc. Alternatively, you could create a sort of remote musical instrument by holding tuning forks of different pitches against the pole to play melodies.
We'll now move from general to specific information about systems and materials for resonators and radiators.

**Wooden Soundboards and Sound Chambers**

For lightweight soundboards such as those used on guitars, the violin family, mandolins and so forth, the traditionally preferred wood is spruce. The quality of commercially sold spruce has deteriorated in recent decades. Spruce of excellent quality, however, can often be found in the form of old piano soundboards, which can often be salvaged from piano repair shops or junk yards. On the other hand, some contemporary makers now swear by cedar or redwood. Pine has sometimes served, but is considered less effective. The best soundboard blanks are quarter-sawn, meaning that the broad surface of the board is roughly perpendicular to the growth rings of the tree. You can identify quarter-sawn wood by the close, straight pattern of the grain. High-quality plywood is sometimes used as soundboards for their durability and workability, especially in applications calling for large, thin boards where splitting would otherwise be a problem.

For sound chamber backs and sides the woods are less critical. Despite a lot of folklore on the subject, any strong, hard wood will do. Maple is often used; so are various tropical woods, favored for their density as well as beauty.

Each of the standard instruments has its traditional sound chamber shape. One could ask, do those instruments have to be shaped that way to work right? It is true that the best instruments represent the culmination of a tradition. No one is likely to make a truly fine instrument without paying attention to lessons from past makers. Yet it is surprisingly easy to make a soundboard and sound chamber that do at least a decent job without following traditionally prescribed shapes. As long as the relationships involving impedance, enclosed air volume and surface area are not too far out of line, most sound chamber shapes are reasonably effective. So, if you wish to make an experimental instrument in an unconventional shape, you can feel free to explore without fear that some immutable law of sound chamber design will doom your efforts. A look at some of the unlikely shapes that have been used in historical instruments will confirm this. With that in mind, here are some general guidelines on sound chamber shape.

The approximate resonant pitch of the air chamber is important to the sound, determining as it does which frequency ranges will be most enriched. That resonance is jointly determined, as with any other vessel, by the volume of the chamber and the size of the openings. This means that even after you have built a sound chamber, you can alter its air resonance with only minor surgery, by enlarging or reducing the size of its sound holes. Just putting a piece of tape over part of the hole of a violin, it has been found, can make a big difference for the better, if a slight lowering of the air resonance happens to be what that particular violin needs.

Traditional sound chamber shapes are often quite elaborate and curvy. The curves help rigidify the sides — an effect which helps to strengthen the box and reduce damping. They may have some value in reducing the likelihood of standing waves and resulting wolf tones in the soundboard. (Wolf tones are tones which are distorted in pitch or tone quality, or disproportionate in volume, resulting from exaggerated resonance at a specific pitch in the instrument body.) But if you can achieve the strength and rigidity you want without adding excessive mass, it remains possible to make decent-sounding instruments with straight sides. Parallel sound chamber walls, in theory, might lead to unwanted standing waves in the enclosed air; in practice, however, the standing waves problem in most instrument-sized rectangular chambers doesn't seem to be serious.

It can help a wooden soundboard to deliberately weaken it around its periphery, near where the board joins the sides. This allows it to flex more readily, as if it were hinged rather than being held rigid at the edges. With violins this is done by cutting a groove near the edge all the way around, and inlaying a decorative strip (which, even if glued in, lacks the structural strength of the natural wood). Lately makers of some other-like instruments have done well with "floating soundboards," which are not permanently attached to the sides at all, but held in place on spaced support blocks around the edges by the pressure of the strings on the bridges.

As part of the process of soundboard design, try to assess where and in what directions the initial vibrator will drive the soundboard. For example, consider the guitar: The bridge is positioned so that strings will drive the lower portion of the soundboard most effectively. Accordingly, the lower portion is large, with lots of surface area, and has a strutting pattern underneath designed to carry those vibrations through the entire region.

Whatever the instrument, thin soundboards generally need reinforcement to increase rigidity and help assure that the vibrations will spread throughout the board rather than being absorbed ineffectually at a too-soft point of input. It is common to place some extra reinforcement directly under the bridge, in the form of wider a strap of wood or larger struts, often extending and carrying the vibration to other parts of the soundboard. Long struts should not attach to the sides of the chamber where they would increase the rigidity of the joint between soundboard and walls; they should stop some distance short of the walls. (Remember, you want something closer to a hinged effect.) There's also the possibility of adding a soundpost, which is an upright support piece wedged snugly between the front and back of the chamber, at a point approximately one side of the bridge. These matters are discussed further in Chapter 9, "Chordophones."

Construction of wooden sound chambers by traditional methods is a rather involved business, especially if you get into bending the sides, and elaborate decorative techniques. But for simpler chambers, you can do well by following the above guidelines and trusting to your basic instrument's instincts.

**Gourd and Calabash**

Many African, Indian and Middle Eastern instruments, including string instruments, kalimbas and drums, use gourd or calabash resonators. Such resonators work very much like wooden resonator chambers. They enclose a resonant body of air, and also provide surface radiation. If possible, the inside of the dried and hollowed gourd should be scoured with steel wool to provide a smoother, harder, more reflective inner surface. Gourds can be finished with wood paints or finishes. Remember that while calabash are surprisingly strong, gourds are fragile; with tensioned elements like strings, it is usually necessary to have other structural elements take the stress.

Some instruments use gourds or calabashes topped with a wooden or membrane sound board. The first step here is to open the gourd with a smooth, flat cut, and sand it perfectly level. This provides a gluing surface for the board, or an even surface for the membrane to pull over. Other instruments use gourds left more nearly whole, with a smaller hole made to remove the seeds and to serve as a soundhole. The gourd can be attached directly to a structural element like a stick or board that carries a set of strings.

Another approach is not to mount the gourd at all. A hand-held gourd pressed directly against a string mounted on a separate carrier will provide a solid stopping point for the strings, so that the length of string between the gourd and the bridge can still vibrate. You can thus use the gourd like a giant slide or bottleneck, as in "bottleneck guitar." At the same time, the gourd serves as a radiator/resonator for the strings.

**Rigid Metal Sound Radiators and Sound Chambers**

We will look at two types of metal radiators and chambers: rigid and flexible. I make the distinction and treat them separately because the two types behave very differently.

It is possible to make metal sound chambers and soundboards very much like the wooden ones just described. Wooden soundboards can be attached to chambers whose backs and sides are metal, with wooden ends. With metal soundboards, the resulting sound is quite different from wood because the metal has much less damping than wood. As a result, it has more pronounced frequency biases, ringing out its own natural frequencies preferentially. Such a sound radiator is likely to have strong wolf tones and dead areas, and may distort the behavior of the initial vibrators by feeding back its own frequency preferences. It also tends to reverberate more than wood after the initial vibrator has stopped — an interesting effect.

More successful have been metal sound radiators designed to function a little like speaker cones. We have encountered these in connection with the Baschet instruments mentioned earlier. A high-impedance vibration is directed to the radiator, usually through metal bars attached to the initial vibrating elements. The radiators are made light yet rigid, so that the entire radiator body moves with the impulses applied to it. A simple cone shape works well (see Figure 8-3). The rod carrying the vibration can join the cone at the end point, which works well for strong vibrations, or along the seam at the side for weaker ones. (Side-mounting makes the cone less rigid in the direction of vibration, allowing for flex and altering the dynamics somewhat.)
Membranes

There is a characteristic membrane-resonator tone quality, often featuring strong partials in a mid-upper range and usually not rich in lower frequencies. This is in part due to the fact that membrane resonators produce a loud sound of relatively brief duration, giving plucked strings something of a percussive effect.

East is membrane, usually in the form of animal skin. Because of their lightness, membrane resonators are not usually very large. Those on some Eastern spike fiddles are only six inches or less across — and still they play quite loudly. Refer back to Chapter 7, “Membranophones,” for information on different membrane types, their preparation, mounting, tensioning and so forth.

Flexible Metal Radiators and Resonators

Freely mounted, flexible sheet-metal sound resonators are in a different world from the radiators we have discussed so far. Rather than simply reproducing only the vibrations fed into them, they add a generous dose of their own personality to the sound.

Such resonators are best made from sheets of stainless steel thick enough to have some body, but thin enough in relation to length and width to be floppy rather than rigid. They should be mounted in such a way that their vibrations are minimally damped, and they remain free to flex. Two effective ways to do this are suspension by cords and by resting on balloons. Sheet metal resonators typically require two or three balloon supports. (Round balloons set in small, bucket-like containers to prevent their rolling work well at feet.) The sheet alone, mounted that way, amounts to an amazing sound source in itself — give it a tap and listen to the resonances and echoes as they go on and on.

Things get a bit more complex when you add an outside vibration source. Figure 8-4 shows an instrument of a type made by Boston builder Robert Fulman, with a string approximately six feet long running corner to corner on a big, hanging stainless steel sheet. When you sound the string (normally by bowing), it starts vibrating at its natural frequency, and delivers that vibrational energy to the sheet metal resonator. The sheet metal picks up the vibration and sends it out into the room. But at the same time, the metal has its own pronounced resonances and, to make matters more interesting, those resonances shift constantly as the metal flexes on its suspension cords. If the string or one of its overtone frequencies matches one of the sheet metal’s resonances, the metal responds hugely. But as the radiator’s resonances shift, it tries to bend the same vibrational impulse off to other frequencies, even as the string tries to sustain the same frequency. To some extent the metal frequencies feed back into the string and alter its behavior, even as the string continues to try to drive the resonator. The effect of all these interactions is a sort of thunderous rainbow of shifting resonances, and an instrument that plays the player as much as the player plays it.

Metal diaphragms (as opposed to free sheets) also lend themselves to shifting resonance sounds.

One of the most wonderful effects, as people who have done a lot of dish washing should know, comes about when there is just a little water covering such a diaphragm (which just might happen to be the bottom of a lightweight cooking pot). As the water shifts and sloshes about, and especially when it only partially covers the diaphragm, the resonances bend wildly about. You can play a saucepan this way, striking the bottom with one free hand as you rock it about with the other, and listening to the bubbly bendy tones. If you were to introduce a steady-frequency vibration from some external source into the pot, you would get an outcome similar to the flexible sheet metal resonator effects described above — similar, that is, but with a lighter, subtler quality. This is the basis of the bowed rod instrument called the Waterphone, made and patented by Richard Waters — an instrument of extraordinarily beautiful sound (described in Chapter 4, “Idiophones”; see Figure 4-14). Richard Waters and others have also used water-modulated metal resonators with strings, metal tongue drums, and other instrument types.

One More Metal Form: Resophonics

Have you ever looked underneath the face plate on a dobro or National steel guitar? These instruments employ a unique system for sound radiation, devised in the 1920s by John Dopera and his brothers. Their primary goal, apparently, was to create a louder guitar in those pre-electric days. Some of their instruments were indeed quite loud, and they also have a distinctive tone quality for which they remain popular to this day.

Dobros and their kin look much like guitars, though the body may be made of either metal or wood. Unseen beneath a decorative cover plate in the middle of the dobro’s face is a shallow cone of thin aluminum (see Figure 8-5). The instrument’s bridge rests on a support piece connected to the apex of the cone, so that the string’s vibrations are transmitted to the cone. The cone is designed to serve as the instrument’s main resonator, functioning, in Dopera’s conception, like a loudspeaker cone. In practice, the wooden or metal body of the guitar, as well as the resonances of the air chambers, contribute significantly as well, and the resulting sound is a composite. The term “resophonic” has been used to describe the system (which, in its entirety, is a bit more complex than the description here implies). In addition to guitars, people have made successful resophonic mandolins, banjos and other instruments.

Membranes

The most common form of string instrument sound radiator in Africa and much of Asia and the Middle East is membrane, usually in the form of animal skin. Because of their lightness, membrane resonators produce a loud sound of relatively brief duration, giving plucked strings something of a percussive effect. There is a characteristic membrane-resonator tone quality, often featuring strong partials in a mid-upper range and usually not rich in lower frequencies. This is in part due to the fact that membrane resonators are not usually very large. Those on some Eastern spike fiddles are only six inches or less across — and still they play quite loudly. Refer back to Chapter 1, “Membranophones,” for information on different membrane types, their preparation, mounting, tensioning and so forth.
The instrument consisted of a stick-like neck and body, with no sound chamber (see Figure 8-6). The vibration at the bridge was transmitted through a mechanical connection to a small diaphragm mounted at the narrow end of a metal horn that opened out toward the side of the instrument. The movement of the diaphragm set the adjacent air in motion, and the vibration was directed out through the horn.

There is another valuable form of membrane sound radiator — one we have touched on several times already but have not described as such. It is inflatable bladders, such as ... balloons. I will add just a few more notes here on this topic.

Balloons make good radiators because — well, what can you think of that has more surface area and less weight? In many instances balloons are the one thing light enough to accept and radiate vibrations from bodies that are too light and weak to drive any other sort of radiator. They are so light and yielding that they can often be attached directly to the most active parts of vibrating bodies without significantly damping the vibration. You can even press a balloon-radiator against a vibrating string without immediately killing the vibration, if you press it fairly near one end where the impedance is relatively high. You get a characteristic balloony tone, short in duration, but not unappealing. The Baschet Brothers have made and concertized with balloon guitars, in which a relatively heavy, durable balloon replaces the entire sound box. A special sort of minimal balloon guitar framework holds the strings under tension and supports a bridge which is pressed directly against the balloon (see Figure 8-7).

Balloons are not the only sort of inflated bladder radiator. Years ago there were crude bowed string instruments made with an inflated pig’s bladder wedged between a single string and a stick that supported it. For a more readily available bladder that is stronger and stiffer than balloons (and tends to damp things more heavily), there are inflatable beach balls.

Styrofoam

It may be inelegant, but it is hard to match styrofoam as a sound-radiating surface. Styrofoam radiators can be amazingly efficient, which is to say, loud, and they seem to reproduce the vibration patterns of the initial vibrator in a fairly unbiased fashion. Styrofoam comes in all kinds of shapes and forms, and for many instrument types you can work with found forms. The throwaway pieces used for shipping electronic equipment often serve musical purposes well. The widely available styrofoam ice chests also work well as radiators. Styrofoam sheets are often available at hobby and crafts shops in various sizes and thicknesses. Closed-cell types (with smooth surface) are preferable for sound radiation to open-cell types. If your purposes call for a specific shape that you cannot find or create from available materials, consider forming your own. Styrofoam-like foams, made primarily for use in home insulation, are available either as a two-part liquid mix or as a fluffy liquid compressed in a spray can. You can squirt the stuff into a mold shaped according to your needs and it will dry rigid and light. See Sidebar 8-1 for additional information on various facets of string instrument design.

A special sort of membrane radiator is that used on the Stroh Violin, invented by Charles Stroh around 1900 and manufactured during the first quarter of this century. (Stroh cellos, guitars, mandolins, and so forth were sold as well. They are now quite rare.) The Stroh Violin was originally conceived for use in gramophone recording, replacing traditional violins which lacked the power to record well in the days of purely mechanical (pre-electrical) sound recording. The advantage of the Stroh Violin lay in its producing a highly directional sound that could be aimed right into the sound-collecting horn of the recording apparatus.

The drawing on the right below shows a styrofoam ice chest as a resonated board zither. There are many possibilities — for instance, I have had good luck with a series of styrofoam guitar-like things in various sizes and pitch ranges, with varying numbers of strings, and some unconventional tuning patterns. The design I favor consists basically of a stick with a styrofoam Joris cooler attached at each end (removable for storage and transport), as shown in the second drawing. These styrofoam radiators provide very little in the way of air chamber resonance, and as a result they don’t have the base fullness that air resonance provides. Partially covering the cooler, as by fastening on the cooler lid with an appropriately slotted sound hole punched in it, will not add a richer air resonance. For the air resonance to take effect, you need a soundboard or something similar flexing in and out relative to the rest of the chamber, creating an air pumping effect through the soundhole. With the styrofoam coolers, the entire box moves as one, and there is no pumping effect. Let this be a design challenge for someone reading this: can you come up with some way to combine the extraordinary radiating properties of styrofoam with the resonance of a well-functioning air chamber?

For anyone who decides to make a styro-guitar or other more complex styro-string projects, Chapter 9 will provide additional information on various facets of string instrument design.
The drawing below shows a string instrument using a tuned air column for added volume and resonance. The instrument has two string segments and two notes, tuned to the air column's fundamental resonance pitch and to its next available overtone, the third harmonic at a 12th above (recall that stopped tubes resonate odd-numbered harmonics only). The two strings are actually one string divided at 3/4 of its length by a center bridge, yielding a string length ratio of 3:1 for the two tones a twelfth apart.

The tuned air resonator is a section of 4" plastic pipe mounted in a hole through the board that serves as the body of the instrument. The end of the tube is covered with a plastic stopper. These stoppers, sometimes called "test caps" or "knock-out plugs," are available at hardware stores.

The trick to making an instrument like this is creating the mechanism that allows the string to drive the air within the tube. This design uses a rocking bridge of hardwood, a little like that of a violin (which you will learn more about in the coming chapter). As shown in part B of the drawing, the bridge drives the plastic stopper, and this drives the air.

The plastic tube, at the suggested length of 18", should have an air resonance fundamental frequency just below F3. You can check it by tapping it or blowing over the edge of the open end. The longer string segment will be tuned to F3. As you use the tuning pin to bring it up to pitch, you will hear the unmistakable increase in power as the string and air column come into coupling. The short string segment should also ring out, at C5. If the interval between the two segments is not an accurate 12th, shift the position of the middle bridge or the small bridges at the ends to correct it.

The tone of the instrument, aside from being more powerful and full-bodied than other strings, will reflect the stopped tube's overtone pattern, with the odd-numbered harmonics prominent and the even ones quieter.

Naturally, you can change the dimensions here to obtain different pitches. But the unglamorous truth is that we have just built a rather large instrument with only two notes. You could increase the range by building a tuned set, but the size problem would be compounded. I have sat down with pencil and paper a few times to see if I could come up with some configuration that would allow me to fit more pitches in a smaller space, but have not come up with anything really satisfactory. Any ideas?

### Tuned Air Resonators in Unusual Applications

Marimba-like instruments, as we have seen, frequently use attached air resonators tuned to enhance specific pitches. Although it is not common, tuned air resonances can serve in many more applications. In the Indonesian bamboo chimes called Angklung, for instance, sections of bamboo are cut to a particular shape that allows the enclosed air column to reinforce the idiophonic pitch. Some bells are tuned for air resonance as well, either using the enclosed air or an attached external chamber. Back in Chapter 4 I described a simple and effective method for making a tubular chime which is its own self-contained air resonator, illustrated in Figure 4-6M. You can even use tuned air resonance chambers in connection with strings. Sidebar 8-2 describes such an instrument.
Chapter Nine

CHORDOPHONES

In this chapter we will cover the many forms that string instruments can take, and the acoustics of strings themselves. We won't have to spend much time on resonators and radiators for strings, having just covered them in the last chapter.

STRING INSTRUMENT FORMS

As with previous chapters, we will start with a look at a simple prototype instrument, in order to derive from it some sense of the essential elements of string instruments. For our model we will use a board zither of a sort that you could make in minutes from a piece of wire and some wood, as shown in Figure 9-1. Start with a 1" by 6" board, 3 feet long. Put a moderately heavy wood screw into the board near each end, leaving the head a quarter inch above the surface, and run a wire, pulled reasonably tight, from screw to screw, attached securely at each end. Now take two 6"-long pieces of wood an inch or so thick — a half-round shape would be ideal — and slide them under the string, pushing one piece firmly toward each end. This raises the wire from the board, and at the same time puts the string under increasing tension as the wood pieces approach the ends. When the string is tight enough, you can play the zither by plucking the string. Bring out a range of pitches by holding a glass bottle against the string at different points to vary its effective vibrating length, while plucking with the free hand.

What are the vital components of this string instrument?

1) The string.
2) A rigid structure to hold the string, which at the same time serves as:
3) A sound-radiating body, since a string in itself is a poor radiator of sound. In the current example, the board provides the structure and also serves as a sound radiator (though not a very powerful one).
4) A string tensioning mechanism. In this case, the process of sliding the wood pieces beneath the string provides the tension. The wood pieces also serve as:
5) Bridges; meaning, something to support the string at the end points of its vibrating length, and to transmit its vibration to the body of the instrument for radiation.
6) Some means for getting a range of pitches out of the instrument. In this case, the bottle in the player's hand serves the purpose.
7) Means to excite the string into vibration. That is provided, once again, by the player who plucks the strings.

These are the basic components of our model string instrument. The same functional elements appear in string instruments in general, but in a variety of other forms. As we proceed through this chapter we will study each of these functions in its own right. But before going to that level of detail, let us look at some of the ways that these components can all be put together. There are several possible configurations for strings and their carriers, and there is an agreed-upon terminology to describe those arrangements.

Zithers

Zithers are string instruments in which the strings are parallel to the sound table, and there is no separate neck. ("Sound table" can denote either a soundboard or the equivalent in a membrane.) In addition to our board zither prototype, hammer dulcimers are zithers; autoharps are zithers; mountain dulcimers are zithers; qanun are zithers. By this definition, pianos and harpsichords are zithers too. With some exceptions, zithers are not designed to yield more than one pitch from each string, and so, in order to provide many notes, most have many strings. With the strings running right across the soundboard, it is normal to have the strings anchored to hitch pins or tuning pins set in heavier wood near the periphery of the board. Then, to communicate their vibration to the board, the strings pass over a low bridge near each end, crossing the board some distance in from the edge. There may be additional taller bridges mid-string as well, dividing each string into two or more vibrating segments. A few zithers, like Appalachian mountain dulcimers, are fretted or otherwise allow for varying the sounding lengths of the strings.

Lutes

Lutes too have strings running parallel to the sound table, but with a separate neck. The strings cross or are attached to a bridge that communicates the vibrations to the soundboard. Guitars, violins, shamisens, mandolins, and ouds, among many, many others, are lutes — not to mention the specific European instrument that claims the name "lute" as its own. The separate neck means that the strings' vibrating lengths can easily be altered by pressing them against the neck, pinching them, or simply exerting finger pressure against them in mid-air. Each string thus yields many notes, and so, unlike on most zithers, a few strings can produce a wide range.

Harp

Harpers are instruments in which the strings rise at an angle from the sound table. This means that the strings pass through an open space to some sort of beam or bowed neck above. In the most basic forms there is no means for altering vibrating length, so, like zithers, harps usually have many strings capable of one note each. Where the strings attach to the sound table, extra reinforcement is needed, so there usually is a narrow board running on the inner and/or outer side of the sound table, along the line where the strings join.

Several African instruments, often labeled as harp-lutes, have lute-like necks — some even have multiple lute-like necks — but strings that join the soundboard with a harp-like angle of incidence.

Lyres
Lyres have strings parallel to the sound table, but rising, harp-like, through an open space to a yoke or cross bar above.

**Basics of String Vibration and String Scaling**

We turn now to the individual components in string instruments, starting with the primary element, the strings. A common sense definition of a musical string might go something like this: a musical string is a long, thin strand of material which is stretched taut between two fixed points. It should be non-rigid, yet string enough so that it can be stretched fairly tightly without breaking or permanently distorting. Ideally it should be cylindrical in shape — that is, circular in cross section, and uniform in diameter over its length.

1) Strings that are too long and thin produce a weak fundamental; they also may not be sufficiently massive to drive a soundboard well.

2) Strings which are too short and fat tend to be rigid, making their overtones inharmonic.

There are several possible modes of vibration for strings, but the transverse modes are the ones of primary musical significance. The first several transverse modes are diagrammed in Figure 9-6, and their frequencies given. Notice that the overtone series is harmonic. The harmonic relationships actually hold only for a theoretically ideal string, but with modern commercial strings set to reasonably high tensions, the actual results usually come out very near to the ideal.

Three factors in interaction are primarily responsible for determining a string’s vibrational frequencies. They are vibrating length (L), tension (T), and linear density (D). Linear density is the mass of the string per unit of length (ML), and for most practical purposes you can think of it as a function of string diameter. The three variables are related to frequency as follows:

\[
 f = \sqrt{\frac{T}{\mu L}}
\]

\[
 f = \frac{1}{4L}
\]

\[
 f = \frac{1}{2D}
\]

(The symbol \( \propto \) indicates proportionality and can be read as "is proportional to.")

In other words: 1) greater string length yields lower pitch; 2) greater linear density yields lower pitch; and 3) greater tension on the string yields higher pitch. Sidebar 9-1 discusses further the physical properties of strings.

String Scaling

The term “string scaling” refers to the art of deciding just what sort of strings will bring out the best in an instrument. Pianos, harpsichords and harps, for instance, have a great many strings covering a wide range. They demand careful planning regarding string diameters, materials and overwindings. Good string scaling is equally important for small fretted instruments, even though they have fewer strings. People who work in string scaling and design have developed highly refined approaches, using precise formulas, and in recent years looking to computer programs. (One such program, which is commercially available, is listed in Appendix 1.) We will attain no such refinement here, but I will try to indicate some of the variables involved. What follows here is concerned primarily with string lengths, tensions and weights; more on choice of stringing material can be found in Sidebar 9-2.

The most important variables in scaling for a given string are linear density, length, and intended pitch. (Linear density is defined as the string’s mass per unit length. It depends upon diameter as well as the material and makeup of the string.) The idea is to find the best values for length and linear density for the string to have appropriately high tension, at the string’s intended pitch. The question of string tension may seem a bit abstract — most string instrument makers and players never actually measure their string tensions. (There are ways to do so, but they’re not very convenient.) But string tension affects both tone quality and playing “feel” (perceived response under the fingers) in ways that are very much observable, even without measuring in pounds or kilos. In addition to being optimized for individual strings, it is important that the tension be uniform, or nearly so, across all of an instrument’s strings. This helps ensure that the strings will be in agreement in timbre and “feel,” or at least reflect gradual transitions in these areas. In practice, it’s not always feasible to have equal tension all across, as doing so would require either excessive lengths or excessive diameters in the bass. Some decrease in tension toward the bass is a common compromise.

**Sidebar 9-1**

**Physical Properties of Strings**

The “Basics of String Vibration” section of the main text describes string vibration patterns in a general way. Here now are some of the subtle factors affecting string tone for different stringing materials.

- **Internal damping** refers to the degree to which vibrational energy is dissipated as heat in the material of the string itself. A high degree of internal damping leads to poor sustain and dullness of tone. Strings made of softer materials tend to have greater internal damping.

- **Rigidity** is the measure of how much stress a string of a given diameter can withstand without breaking. A related concern is elasticity, the measure of a material’s ability to endure stress short of the breaking point without stretching permanently out of shape. These two factors determine how high you can set the tension for a given string without it breaking or permanently out of shape.

- **Tensile strength** is the measure of how much stress a string of a given diameter can withstand without breaking. A related concern is elasticity, the measure of a material’s ability to endure stress short of the breaking point without stretching permanently out of shape. These two factors determine how high you can set the tension for a given string without it breaking or permanently out of shape.

- **Stretchability** is another important consideration. Strings made of easily stretched materials do not drive soundboards as forcefully as unyielding ones. They also tend to be high in internal damping. Stretchable strings have one advantage: strings set at low tension, when plucked forcefully, start out at a higher pitch initially and then stabilize at a lower pitch. (This same happens at higher tensions, but so slightly as to be negligible.) Stretchy strings, however, are less subject to this effect and so can be used at lower tensions. This was once an important consideration, but has become less so since the invention of overwound strings.

Standard stringing materials are available in closely graduated sizes. (See Sidebar 9-2, part 2.) This allows the builder to find just the right diameter to yield the right tension at the desired length and pitch. Extremes to be avoided in string scaling:

1) Strings that are too long and thin produce a weak fundamental; they also may not be sufficiently massive to drive a soundboard well.

2) Strings which are too short and fat tend to be rigid, making their overtones inharmonic.

3) Strings set at too high a tension break easily; and

4) Strings set at too low a tension suffer pitch drop after plucking and don’t drive the soundboard strongly.

While high tensions are generally preferable, as a practical matter, some safety margin is needed between the string’s intended pitch and the string’s breaking point. A rule of thumb is that the breaking point of the string should be at least a whole tone or three semitones higher than the intended pitch of the string. But this recommendation can be taken with a grain of salt. Much lower tensions can be acceptable, and are actually desirable for string materials such as nylon which stretch and distort at

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**Sidebar 9-2**

**String Scaling**

The term “string scaling” refers to the art of deciding just what sort of strings will bring out the best in an instrument. Pianos, harpsichords and harps, for instance, have a great many strings covering a wide range. They demand careful planning regarding string diameters, materials and overwindings. Good string scaling is equally important for small fretted instruments, even though they have fewer strings. People who work in string scaling and design have developed highly refined approaches, using precise formulas, and in recent years looking to computer programs. (One such program, which is commercially available, is listed in Appendix 1.) We will attain no such refinement here, but I will try to indicate some of the variables involved. What follows here is concerned primarily with string lengths, tensions and weights; more on choice of stringing material can be found in Sidebar 9-2.

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How many different ways are there to excite a string? Many. But first, some basic principles:

1) The point at which you inject the energy into the string makes a big difference in the resulting tone. Plucking, striking or bowing near one end tends to excite lots of high harmonics; doing it nearer the middle tends to excite more of the lower harmonics. The core provides die tensile strength. The overwinding provides a great deal more mass, but adds relatively little rigidity. The lowest strings for piano and some bass strings actually have multiple layers of overwindings. In planning how to string a new instrument, you can get a good start by looking at existing instruments of similar size and range. This will give you a general sense of what to expect in terms of suitable materials, lengths, diameters and tensions. You can proceed from there by trial and error, simply by trying out different string sizes on the instrument you're working with. To do this you will need the following items in good supply: 1) strings of the desired material in finely graduated diameters; 2) common sense plus some familiarity with string instruments; and 3) patience.

For those who prefer more advance planning, here are some further guidelines. With many-stringed instruments like piano and harp, the ideal is to have both diameter and length gradually increase from string to string. To keep tension and tone quality more or less constant across the range. There's no accepted standard rate of change for the two variables; different instrument designers over the years have used different formulas. But as a very rough guideline, an increase in string length by a factor of 1.77 per descending octave, coupled with an increase in diameter by a factor of 1.13 should produce good-sounding results. These rates of change will yield a slight decrease in tension toward the bass end. (The foregoing numbers are based on the way, on measurements from the upper middle ranges of a well made harpsichord.) In practice, a 1.77 increase in length per octave is impractical for many instruments, and so a lesser length increase offset by a greater diameter increase might be in order, especially in the bass range.

Other Materials

A partial list of less common materials that have been used for musical strings includes horsetail, leather thongs, animal intestine, one of the oldest string materials, is now rarely used, having been to a large extent superseded by nylon. The exception is in early instruments for which historical authenticity is important. There is a popular, often-debunked notion that gut strings are made of catgut. Actually, all gut seems to be most common, white or fawn-colored, a product of the intestines of various species of sheep, goat, and deer. There is a tradition of processing, drying and preparing the gut which is too repulsive to detail here. Individual strands of gut are very thin, and gut strings of various thicknesses are made by binding different numbers of strands together. The traditional mandolin string might be just two strands, while the largest bass string would use something over a hundred. In time, gut strings are weak in the partials and strong in the fundamental, giving them a darker, more subdued sound than metal strings. Steel strings hold tunings poorly, because they are sensitive to changes in humidity. But they stretch and distort under tension less than nylon. Some people prefer the tone of gut to nylon, especially in the upper registers.

Nylon

Nylon strings sound fairly similar to gut, and are now used almost everywhere that gut once was. Nylon possesses both flexibility and high tensile strength; it is subject to stretching and distortion over time. There are several types of nylon, and a particular variety chosen for its strength is used for musical strings. Multifilament nylon wire is most common, but some overwinding installations use an aggregation of music wire for the core. Other Materials

A partial list of less common materials that have been used for musical strings includes horsetail, leather thongs, animal intestine, and natural vegetable fiber from various vine-like plants.
Plucking amounts to displacing a string to one side and releasing it. It can be done with fingers or finger nails, or various sorts of plectra, or picks. The best plectra for most purposes are moderately hard, but not too rigid (as always, there are exceptions: some instruments traditionally are played with fairly hard, rigid plectra). In the past, hand-held plectra were made of tortoise shell, which has the right blend of hardness and flex.プラスジクス are more common now. You often can make a passable plectrum from common throwingaway plastic items. The shape of the end of the plectrum (the plucking part) is important, since it determines the width of the plucking surface. The plectra in harpsichords traditionally have been quite narrow — quite nanow — and this partly explains the harpsichord's rather bright sound.

Bowing

Bowing involves sounding a string by friction, exciting a stick-slip vibration. Violin-type bows are not the only things that can induce a string to join in this particular dance, and so bows take a variety of forms — some of them rather un-bow-like. Bows and their construction were discussed in Chapter 5, "Beaters, Scrapers and Fretted Makers."

Stirring

Most people are familiar with the hammers that strike piano strings, so there's no need to describe them here. Smaller hammersed instruments, like hammer dulcimers, generally use a smaller, lighter, harder hammer, producing a light, bright tone (see Figure 5-1H). You can produce attractive hammer tones on strings with other sorts of light, hard beaters or sticks as well. One of the nice things about hammering by hand is the effect of bouncing the hammer on the string, producing a rapid tremolo.

Hammering-On and Stirring with Targets

The clavichord is an early keyboard zither with a different sort of hammering action. The arm that strikes the string is fronted with a small metal blade, called the tangent. It does not bounce off and leave the string to vibrate freely, instead it remains in contact with the string, and so in doing defines one end point of the string's vibrating length. The energy of the tangent's blow is enough to set the string into vibration (though not very strongly) — clavichords are quiet instruments. The action is described later in this chapter in the section on keyboards.

A string-sounding technique very much like this can also be used in hand-played fretted instruments. The player brings down one of the left hand fingers (normally used for fretting, not for plucking) rapidly and forcefully on the string, hammering it against the nearest fret. The fretted instrument player's jargon for this technique is "hammer-on." With acoustic instruments like electric guitar, it is possible to develop a playing style entirely around hammering on. Since you don't need the right hand for plucking, you can devote all ten fingers to hammering on, and the fretted instrument suddenly takes on a keyboard-like quality, both in terms of physical gesture and, in the hands of an experienced player, in the nature of the music as well.

The Chapman Stick is an instrument designed by Southern California builder Emmet Chapman specifically for a two-handed hammer-on technique. It looks like little more than an extra-wide fretted guitar neck, with no separate body. It has ten strings, with electric-guitar-style pickups, and is played with a neck strap in a position similar to a guitar. Another hammer-on instrument has been designed by John Stewart, to take the hammer-on idea closer to its logical, keyboard-like connections. The Starboard, a 32-string zither with pickups, rests on a table in front of the player, showing a checkerboard grid with the strings running toward the player and 24 frets running crosswise. John Stewart has also developed an acoustic version of the instrument, quiet in tone but playable.

Serrated Scrapers

Rarely, strings have been played using serrated sticks or large combs. Although the motion is similar to bowing, the sounding principles are not — there is no stick-slip, just the percussing-plucking effect of the serrations. You can get a variety of tones this way, generally pretty noisy, but sometimes noisy in interesting ways.

Wind

Aolian harps are string instruments sounded by wind blowing over the strings. Traditionally, they take the form of a simple zither that can be set out on a window sill on a breezy day. Any string instrument, in fact, will sing if a strong enough wind crosses it at the right angle. The sound is eerie and beautiful, as the air currents excite a shifting array of harmonics. The tones tend to be sustained, gently rising and falling, sometimes hovering at a single pitch and sometimes sweeping rapidly across a range of harmonics. Sidebar 6-3 contains aolian harp design information.

Makers have experimented with aelien harps in diverse configurations. Many recent efforts, for reasons I have never understood, involve really huge constructions with extraordinarily long string lengths. The result is a subsonic fundamental and, in the hearing range, a general wash of indistinguishable microtonally close overtones. With strings of more conventional length, you get overtones within the hearing range bearing meaningful harmonic relationships, and the effect is more musical.

Aolian harps remain mute if the winds are not strong enough or the wind direction is not right. You can make a more responsive, but coarser-sounding wind harp by using ribbon-stings (strings in the form of flat bands). Bands of metal can be amazingly loud, but harsh in timbre.

There were some piano-like instruments made in the 18th and 19th centuries, with strings sounded by jets of compressed air, the most famous being the aereoncarde made by Johann Schnell in 1786. At least one modern re-creation of the idea has been attempted, with, according to the builder (Japanese engineer Ako Abuchi), promising enough results to merit continued effort.

A very few chunophones use breath-blown strings, notably the gora and the lesboa, both originating in southern Africa. The blown portion of the instrument in this case is an attached segment of flattened quill, which is more responsive to the air stream. You can also make wind-driven chunophones which depend not upon the movement of surrounding air, but rather upon the movement of the instrument through the air. Such instruments must be small and light enough to be swaying or waving about. Once again, flat strings produce more sound than round ones. Large, flat rubber bands do the job quite nicely. They can be stretched over a minimal framework such as a cross shape, which can then be whirled or waved through the air.

Resonators

One more way to set musical strings into vibration is through electromagnetism, using an arrangement which is basically an electromagnetc pickup operating in reverse. Electric guitar pickups respond to the movement of a steel string across the magnetic field of the coil contained in the pickup. This generates an alternating current in the coil that is analogous to the string's pattern of movement, and electromagnetism is basically an electromagnetic pickup operating in reverse. Electric guitar pickups respond to the movement of a steel string across the magnetic field of the coil contained in the pickup. This generates an alternating current in the coil that is analogous to the string's pattern of movement, and that electronic signal is sent to an amplifier and speaker. You can reverse the process by sending a heavily amplified alternating current pattern to a pickup, speaker driver, or other device which will serve as an electromagnet. When the electromagnet is held close to a steel string, it will drive the string. If the frequency of the signal sent to the electromagnet doesn't approximate any of the string's natural frequencies, the string doesn't respond much, but if there is a match, the string shows a generous resonance response, with gradually increasing amplitude.

You can work with this idea in several ways. One is to set up an electromagnet over each of a set of tuned steel strings, and use frequency generators to send the appropriate frequency to the electromagnet for each string. This is what Stephen Scott and Alex Stahl did with their "Blowed Pianos" in the mid 1980s. Another is to use a pickup in the conventional manner to pick up a string's frequency, send it to an amplifier, and then back to another electromagnet held near the string, to perpetuate the sound. This is the idea behind the electric guitarist's sustain-enhancing device called the E-Bow.
All of the string instrument body types described earlier call for some means to hold the strings at high tension, and to adjust that tension for tuning purposes. This calls for a strong, dependable, and minutely adjustable mechanism. The bridges wedged under the strings appearing on the prototype board zither from the start of this chapter comprise one of the simplest possible approaches. Many other approaches can be and have been used, including various kinds of adjustable tie downs, turnbuckles, and so forth. The three most widely used and dependable methods are tuning pins, tuning pegs, and tuning machines. The hardware or materials for all three are readily available; see Appendix 1 for sources. Alternatively, you can make your own tuning pegs of hardwood, especially if you have a lathe.

**Miscellaneous notes:**
- Tuning pegs, turned from hardwood stock, usually appear on lutes, such as violins. They are the least dependable of the three preferred methods. They slip easily, and they wear, and when they wear they slip even more. Peg dope, a resin made to increase their grabbing power, helps. Tuning pegs are made with a slight taper, so that they become more snug as you push them in further. The holes they go in must be shaped accordingly. While violin headstocks may look delicate, it is important that the wooden body in which the peg sits be strong and solid hardwood.
- Tuning pins are most often used in many-stringed instruments, such as pianos and other keyboard instruments, harps and zithers. They likewise must be set in a substantial hardwood body and carefully sized holes. The lower part of the body of the pin has tiny threads of very slight pitch, which ensure that the pin doesn’t pull out. Standard piano pins are designed to fit a 3/8” pre-drilled hole. They are actually slightly larger in diameter, ensuring a snug fit; in fact, they are made in a range of very slightly increasing sizes, so that a pin can be found to fit tight even in a worn hole. Smaller pins, sold as zither pins, are usually made for a 3/16” hole, with actual diameter just slightly larger. Tuning pins can be turned with any adjustable wrench, but tuning wrenches made specifically for the purpose are not expensive, and are much preferable.
- Tuning machines, such as appear on guitars, are the surest of tuning mechanisms, and also the most expensive. Their worm-gear mechanism prevents slippage, and, by setting a low gearing ratio, makes fine adjustments easy. Some tuning machines are individually mounted; others come in sets of three, four or six on a mounting bracket designed for use on particular instruments.

While the three methods just mentioned are most common, other string tensioning systems are possible. Figure 9-7 shows a simple system that I recently came up with (simple enough that I won’t take inventor’s credit, since I’m sure someone must have thought of it before). For this tuning mechanism, the instrument’s strings are comprised not of a single strand of musical string, but of a double strand twisted together. (The idea of using multiple strands twisted together has been in use for centuries, since it has other advantages independent of the current discussion.) It’s easy to make the two-strand twist by forming the string as a loop, pulled tight, anchored at the ends, and twisted by rotating one of the end-anchors, as the figure shows. To increase tension on the string, and thus adjust the tuning, one simply increases the amount of twist by turning the anchor. The resulting tunability is as dependable and as finely adjustable as the worm gears on a tuning machine, but you can create this mechanism out of common components at negligible cost. Because of its configuration, the twist-tune system is best suited to harps and lyres.
method. (Once again, the word harp is a misnomer; the instrument is a zither.) The earliest wall harps, also called diddley bows, were the work of sharecroppers in the southern United States in the decades following emancipation. They were one-string instruments, played with a slide, sometimes plucked and sometimes struck with a stick beater. Similar instruments, but portable, were also sometimes made using a single board in place of a wall.

To make a wall harp you'll need a large area on the side of a building with wooden siding, some moderately heavy galvanized wire, such as bailing wire, some heavy nails, and short wooden blocks — several 3" pieces of 2x2 will do. Cut several lengths of wire between 2 and 4 feet long. Drive nails into the side of the building to anchor the wire segments at each end, and attach the wires in a vertical orientation, pulling them taut. Slide two blocks underneath each wire, one near each end. Tie the wires from the wall and bring them up to tension. Tune by forcing the blocks closer to the ends to increase tension and raise pitch.

A few more notes on the wedged-bridge string tuning method discussed earlier. The farther you push the wedges toward the string ends, the more they stretch the string, and the higher the pitch (the increase in tension outweighs the effect of increased string length). To make wedged bridges or any similar approach more fine-tunable, consider adding a tension-adjusting screw or turn-buckle somewhere between one of the bridges and the string end-point (see Figure 9-8).

BRIDGES

For most string instruments, the strings need some means to communicate their vibrations to a sound table, as did the wedged bridges on the prototype zither. To fulfill its function well, a bridge must deliver the vibration in a way that really gets the sound table going. Bridges serve a second essential function by providing a hard, defined end-point for the string’s vibrating length. The form of the top of the bridge, where the strings make contact as they pass over it, is important in this connection. The shape should not allow buzzing. Narrow rounded shapes work well; they also reduce wear on the string. Flat or angular shapes at the string crossing create problems. A slight notch at the crossing point can provide a seating to keep the string from moving laterally on the bridge as it vibrates.

There are several different types of bridges, with distinct physical and acoustic characteristics. Let’s look at some examples.

Tall Bridges

With the term tall bridge, I refer to bridges like those used in members of the violin family; those ornately carved things rising high above the arched soundboard. I start with them because their action illustrates some important ideas. Figure 9-9 shows the arrangement of the bridge, strings, and elements of the body in a violin.

The bow moves perpendicular to the string, creating a transverse motion (right and left in the orientation of the picture). The left foot of the bridge rests directly over the sound-post, an upright pillar wedged firmly between the front and back of the instrument. This prevents the left foot from moving much, except to pivot. The right foot, meanwhile, is directly over the bass-bar. The bass bar stiffens the soundboard at this critical point and, extending across most of the length of the board, spreads any input far and wide. But it does not immobilize the board as the sound-post does. Thus, when in the course of vibration the string makes a rightward movement, the bridge pivots on the solidly anchored left foot, and pushes down on the right foot, forcing a whole portion of the soundboard downward. This makes for strong surface radiation from the right half of the front face of the soundboard, with minimal out-of-phase motion from the left half of the front face. It also compresses the air within the chamber, driving the air resonance and effectively pumping a pulse of air out through the violin’s f-holes, again without much out-of-phase movement from the other half of the board. When the string swings back the other way, the reverse actions follow. The surface radiation off the soundboard and the air resonances coming through the violin’s f-holes emphasize different frequency ranges, and the two combine for an attractive composite tone.

The height of the bridge provides leverage for its rocking action. A little more subtle is the effect of the elaborately carved shape of the bridge. The shaping modifies how the bridge delivers different frequencies to the soundboard. The standard design somewhat diminishes the transmission of high frequencies. People with expertise in these matters can modify an existing bridge, or carve a new bridge, to alter the tone of a violin in deliberate ways.

Low Bridges

Low bridges are used in most plucked lutes and zithers. They lack the sophisticated mechanics of the violin family, but they do the job. With hammer dulcimers, pianos, and harpsichords, the direction of impulse to the string is not lateral, as it was with the bowed strings, but vertical — directly toward or away from the soundboard (Figure 9-10). This is the ideal direction for driving the soundboard, so no pivoting action is called for.
With plucked lutes, the plucking impulse is usually more at an angle, somewhat off perfectly lateral, but nowhere near perpendicular to the soundboard, as shown in Figure 9-11. This makes for less efficient transmission. It is one of the reasons why plucked lutes tend to be quiet, but the slow transmission may also allow them a bit more sustain. It is tempting to try to get better volume out of a plucked instrument like a guitar by plucking in the perpendicular direction. You can do this with very small amplitudes, but at large amplitudes — obtained by pulling the string straight out from the guitar and releasing — the string bangs into the frets and fingerboard. There is not enough room to vibrate in that direction. So by this: loosen the lowest string of a guitar enough to slide a block of wood between the string and fingerboard beside the nut, raising the string an inch or so above the fingerboard. Retighten it. Now you can pluck perpendicular to the soundboard without snapping against the frets. You may be surprised at the difference this makes. The string sound is louder than it is in the normal configuration, and the tone richer in the bottom. Now pluck the same string laterally. What an anemic sound, by comparison! Designing a guitar or other plucked lute for vibration perpendicular to the soundboard, however, would be easier said than done, especially since guitar playing typically involves several different strokes with different plucking directions.

Buzzing Bridges

That guitar experiment illustrates at least part of the reason why harps are efficient sound-producing instruments. Unlike a guitar, the natural direction of pluck in the harp's normal playing position sets the string vibrating nearly perpendicular to the soundboard (Figure 9-12). Harps, for this reason, can be made louder than guitar-like instruments, though with the rapid delivery of energy, they tend to have more rapid decay.

Vertical Bridges

The kora, and a lessor-known instrument from west central Africa called mvet, use upright bridges designed to hold the strings in a vertical line above the soundboard or string carrier. Such a design works for instruments which will be plucked, harp-like, in the direction perpendicular to the soundboard or carrier, and it has many of the acoustic as well as ergonomic advantages of harp-like arrangements.

Horizontal Bridges

Some bridges are designed not simply to transmit vibrations faithfully from string to soundboard, but to add distinctive new elements to the sound in the process. The best known of these are the extraordinary buzzing bridges found on several lutes from the Indian subcontinent, including rudra vina, tamboura, and sitar. Instead of providing a discrete edge to define the end of the string's vibrating length, these bridges have a very slightly raised stopping point, with a gently curving plateau of ivory, antler or bone in front, typically about an inch wide (Figure 9-14A). The string buzzes gently against the surface as it vibrates, producing the characteristic shifting blend of very prominent high harmonics. Sometimes a thread is introduced between the string and bridge to fine tune the harmonic buzz. In addition to its striking sound quality, the effect increases the string's perceived volume and sustain. The gentle slope is called jawai, and shaping it to just the right contour for the desired tone is a subtle business. If you don’t have an experienced maker to guide you through the process, you can still make some progress by trial and error. Some people have managed to create an effect like that of the jawai using slightly re-shaped sections cut from metal conduit. Alternatively, consider purchasing a bridge ready-made for one of the Indian instruments. Incidentally, it is easier to get good results with this sort of bridge on longer strings.
ACTION

Some bridges are glued in place on the soundboard, with the strings actually tied to them, so that the bridge serves as a bridge and a string anchor. Classical guitar bridges are made this way. With most other string instruments, the strings pass over the bridge and are anchored somewhere farther down the line. The bridge is then held in place against the soundboard by the pressure of the strings. With non-glued bridges you can adjust the position of the bridge for optimal sound or for international purposes. The mechanics of transmission are somewhat different in the two cases. Glued-on bridges serving also as string anchors undergo a lot of stress, and sometimes pull up. To reduce that likelihood, they must have a large surface of contact with the soundboard and be very strongly glued.

Some bridges, like violin bridges, are shaped to stand on two feet. Footed bridges are most common on arch-topped instruments, in part because having feet eliminates the need for a large undersurface fitted to the contour of the soundboard. Glued-on bridges should be flat-bottomed rather than footed, to provide the maximum adhesive surface.

Many zithers have one or two middle bridges in addition to those at the string end, dividing each string into shorter, independently vibrating segments. Middle bridges must be higher than the end bridges, so that the string presses down on the middle bridge as it passes over. A single additional bridge at the string’s center point yields two equal string segments having the same pitch. Whichever side is initially sounded, sympathetic vibration between the two half-strings will enrich the tone. A bridge at the 2/3 point gives a string length ratio of 2:1 for tones an octave apart, providing an increased pitch range as well as some sympathetic resonances. There are many other options, multiplied further if one adds two middle bridges. On some oriental zithers, each string has its own small, separate center bridge, allowing for different bridge spacings from one string to the next. These movable bridges often take a two-footed A-frame shape. If the bridges are not glued down, but held in place by string pressure, they can be moved about to achieve different tunings.

The positioning of the bridge on the soundboard is important to the efficiency of vibration transmission. Locations at or very near the edge of the soundboard may be too rigid for the bridge to drive effectively. Some potential bridge locations, on the other hand, may be too weak to support the pressure of the strings. The positioning of struts on the underside of the soundboard affect strength at any given location, as well as the effectiveness with which vibrations introduced at that location are dispersed through me board. Another factor to consider: many soundboard shapes (guitar and violin are good examples) have recognizable vibrating regions within the overall shape. Different bridge locations will drive different regions more or less effectively. If a particular region of the soundboard, such as the large lower portion of a guitar, is essential to a good sound, then be sure to locate the bridge so as to drive that region most effectively.

PITCH CONTROL MECHANISMS FOR CHORDOPHONES: MULTIPLE STRINGS

It is time now to talk about the methods available for getting a range of notes from string instruments. The prototype board zither from the start of this chapter used a slide, like a Hawaiian guitar. That is but one of many options; here are more.

The most direct way to obtain many pitches from a string instrument is to have many strings, to choose from, tuned to different pitches. This works well for plucked or hammered instruments like harps, harpsichords, pianos, and most zithers. Problems arise for bowed instruments, if all the strings lie flat in a plane. Then the bow can’t get at them individually (unless you use a very small, rotating-wheel-type bow). To get around the problem, many-stringed bowed instruments usually have the strings arranged in a “curved plane” to allow for tangential bowing of individual strings (see Figure 9-16). Some builders have mounted strings all the way around the perimeter of a cylinder-shaped resonator to allow bowing all around and maximize the space available for strings. Some have even put the cylinder on a rotating bearing.

Figure 9-17 shows another approach that allows a player to selectively bow individual strings on a many-stringed zither. Instruments of this sort, commonly called bowed psalteries, have the strings arranged so that each extends slightly beyond its neighbor, leaving a small portion of its length accessible to the bow. To make this work, you need small, unobtrusive individual bridges for each string at its exposed end. The little bridge usually takes the form of a metal pin shaped much like a tuning pin, but with the string passing in a groove over the top. It can be made from a standard tuning pin by cutting a bit off the top to shorten the pin, and using a hacksaw to cut a groove across the top to hold the string in place.

Un-fingered bowed instruments have a lovely, light and fine tone, because the absence of the damping finger allows the upper harmonics to ring out and allows the string to continue ringing with each note after the bow has left it. The fine edge to the tone is especially prominent with bowed psalteries due to the necessity of bowing near the end of the string, preferentially exciting the upper partials.

Historical note: despite the ancient-sounding name, the idea for the bowed psaltery seems to be a modern one, first appearing in Germany in the 1930s.

Another approach to sounding-string selection for many stringed instruments is the keyboard. We discussed keyboard layouts in Chapter 3, but we did not talk about keyboard mechanisms. Keyboards can be made to control hammering mechanisms, as with pianos, or plucking mechanisms, as with harpsichords, or hammer-on mechanisms, as with clavichords, and even bowing, aeolian and electromagnetic mechanisms, as with a number of intriguing but lesser-known instruments. Keyboard-controlled hammer mechanisms (pianos) have two important advantages: unlike plucking mechanisms (harpischords), they allow for wide variation in dynamics, and unlike hammer-on mechanisms (clavichords) they can be loud. But the mechanisms involved in creating an effective piano action are extremely complex, with about fifteen moving parts per key in modern piano actions. There are
The problem with fingers is that they are soft, and with direct contact they damp a string's vibration. The approach of using a plectrum instead is one way to overcome this limitation. The advantage of plectrums is that they are made of hard materials that do not damp or touch the string, allowing for a cleaner sound. However, this also means that the player must carefully control the pressure and direction of the plectrum to achieve the desired sound. 

Fingering, Fretlessly

To produce the intended pitch, the tangent must dependably strike at the right point along the string. As shown in Figure 9-19, the back sides of the key lever may need to be offset at an angle, rather than extending straight back from the front of the key, to land the tangent in the right place. The angling makes it more difficult to create a smoothly operating lever. Most clavichords have guides at the far end of the key lever, as shown in Figure 9-18, to keep the tangent in line. The situation is less exacting in un-fretted clavichords, because with them you can use the tuning pins to tune each string to the desired pitches even if the tangent's strikinglocations are not ideal.

How about a bowed-piano keyboard mechanism? In the approach most often suggested, there is continuous bowing, in the form of a band of bowing material running between two pulleys like tractor treads. Pressing a key lifts one end support for an individual string, to bring the string into contact with the bow. This attractively simple mechanism allows for some control of timbre and dynamics, even some vibrato, through key pressure. But despite several attempts over a period of centuries — the first known suggestion of the idea is in the notebooks of Leonardo da Vinci — the notion has never caught on.

Autoharpude

Finally, one last rather clever and, to my mind, understated sounding-string-selection method. The autoharp is a zither incorporating a selective string damper mechanism, apparently invented in Germany and first patented in the U.S. in 1882 by a German immigrant named Zimmermann. A set of anywhere from three to nine or more bars crosses over a soundboard with two or three dozen strings. Each bar is spring-mounted so that it can be pressed down onto the strings. On the underside of the bars are several damper pads, spaced out in such a way that when a given bar is pressed down, the damper stops all the strings except those required to sound a particular chord. Each bar has its pads arranged to allow a different chord to sound. You play the zither by strumming across all the strings, while pressing different bars to bring out the desired chords. While the instrument is seemingly designed very narrowly for accompaniment in the form of block chords, good players have shown that it has a distinctive sound and a great deal more potential than the basic concept would imply. Some fancy versions have mechanisms for changing the damper positions, or modular extra bars to increase the range of chords available.

MORE PITCH CONTROL MECHANISMS:
STRING LENGTH & TENSION

We have been looking at ways to select the string that sounds from among the set of strings on a multiple-string instrument. Now we turn to ways to get different pitches from a single string. The primary factors controlling string pitch, as we saw earlier, are length, tension and linear density. You can't very well change a string's density for each note of a melody, so that leaves tension and length as the two manipulable factors. Of these, string length is the more manageable and by far the more common method, so we will start with it.

You can shorten the effective vibrating length of a string, causing it to vibrate at a higher frequency, by "stopping" it somewhere along its length — that is, pressing it directly with a finger or plucking it, or holding a slide or bottle-neck against it. With unfretted instruments like violins, it is the player's job to know where to stop the string — where to place the finger, which is to say, how much to shorten the vibrating string length — in order to get any desired pitch. With fretted instruments like the guitar, it is the maker's job to place the frets in the right locations along the neck. Sidebar 9-5 contains the information you need to calculate string stopping points and fret placements. Alternatively, you can work out your stopping points by experimentation/earwork/trial and error, or by copying the string stopping points (e.g., the fret placements) from an existing instrument of the same type.

By fingering, I refer to any method for shortening a string's effective vibrating length by pressing it with a finger. The problem with fingers is that they are soft, and with direct contact they damp a string's vibration considerably. That is why most plucked string instruments have frets: the frets form a hard, well-defined barrier to the string's vibrating length, so that the finger does not touch the active part of the string. Most fingered string instruments that don't have frets are not played by plucking. Instead, they inject an ongoing stream of mechanical energy into the string to ensure its continued vibration. In other words, they are (for the most part) bowed instruments.

This is not to say that fretless fingered instruments are never played by plucking. With the violin the plucking technique (called pizzicato) yields a brief tone of very rapid decay — an attractive effect, but one
That is why fretted instruments are more amenable to equal temperaments than unequal tunings. The same set of available pitches and pitch relationships on any string tuned to any of the scale degrees can be used for a certain string tuned to a certain note. Those same fret spacings under adjacent strings tuned to other notes make intonation in fretted instruments a complex one. Imagine that you make an instrument with the frets placed to get the desired pitches at the fret locations. The locations of the frets on an instrument neck determine what the available string-stopping points will be and, as a result, what pitch relationships will be available. Very nearly all the commercially made and all the fretted instruments in the West are set to 12-tone equal temperament. But as an individual maker, you can set your frets to whatever scale relationships suit your fancy, or you can use movable frets. Sidebar 9-5 tells how to plan your fret placements.

Frets are the small metal ridges that cross the necks of most plucked stringed instruments, and some bowed instruments. The player presses the string against the fretboard just behind the desired fret, so that the string presses against the fret to provide a hard string-stopping point. Fretted bowed instruments usually have a brighter tone than their unfretted relatives, and longer ring time after the bowing stops (an attractive effect almost entirely absent on unfretted bowed instruments), but they offer less freedom for subtle pitch inflections. The notes on fingerboard action from the preceding paragraph apply to fretted instruments as well as unfretted, with these additional notes: while many fretted instruments have straight fingerboards, in other cases, including many guitars, the fingerboard is given a very slight curvature over its length, as if the tension of the strings had caused it to bow. This allows for slightly closer action at the highest frets. Aside from such deliberate curvature, any warpage, valleys or humps will lead to buzzing and difficulty in playing. Most steel string and electric guitar fingerboards are made with a slight lateral arching as well, to facilitate barring (a certain type of guitar fingering). The locations of the frets on an instrument neck determine what the available string-stopping points will be and, as a result, what pitch relationships will be available. Very nearly all the commercially made and all the fretted instruments in the West are set to 12-tone equal temperament. But as an individual maker, you can set your frets to whatever scale relationships suit your fancy, or you can use movable frets. Sidebar 9-5 tells how to plan your fret placements.

Frets have been made of glued-on strips of metal, wood, bone, or ivory. Cord has also been used, such as the same gut used for strings, tied in one or two loops around the neck. The standard modern metal frets are cut from commercially available fret wire, which has a special cross-section shape for the purpose (see Figure 9-20) and is available in a range of sizes. Western instruments use low frets, so that the player can press the string over the fret and hard against the fingerboard without undue string stretching and pitch distortion. On many Eastern instruments the frets are made high, for the opposite effect with room to press the string farther in toward the neck behind the fret (or greater ease in bending it sideways, as is more common), the player can realize more varied intonational inflections. Sitar frets, for instance, take the form of high, curved bars arching over me neck. Sitar frets also have the great advantage of being movable, so that the instrument is not locked into a single intonation system. Moveable frets can also be made using cords tied around the neck, and a variety of other movable fret mechanisms have been designed.

There is a lot to be said for the freedom that fret movability affords. But the matter of non-standard intonation in fretted instruments is a complex one. Imagine that you make an instrument with the frets spaced out along the neck so as to produce a particular scale — one with unequal intervallic spacings — for a certain string tuned to a certain note. Those same fret spacings under adjacent strings tuned to other notes will yield a transposition of the scale. In effect, each string will be fretted so as to play in a different key. This problem doesn’t arise for equal temperaments. With the fret spacings even and equal, you get the same set of available pitches and pitch relationships on any string tuned to any of the scale degrees. That is why fretted instruments are more amenable to equal temperaments than unequal tunings.

### Sidebar 9-5 LOCATING STRING STOPPING POINTS

This sidebar outlines principles for determining locations for string instrument frets to obtain particular intervals. Essentially the same principles can be applied in determining string stopping points for non-fretted instruments as well — e.g., fingering points along the neck of a violin for particular pitches, or tangent striking points for a fretted clavichord.

The basic rule is that, other things being equal, vibrating frequency is inversely proportional to string length. This means that the ratios between the active string lengths determined by the fret locations should correspond to the inverses of the desired frequency ratios. To see how this works, imagine that you want to place frets under a string, spaced so as to produce a basic just major scale at frequency ratios 1:1, 9/8, 5/4, 3/2, 5/3, 13/8, 21/16. For simplicity’s sake, assume an open string length of one meter; with the open string pitch serving as the tonic and first degree of the scale. Where then should you place the fret to get the second degree at 9/8 times the fundamental frequency? Following the inversion rule, the calculation is: first fret location = 8/9 x 1 meter = 88.9 cm. Place the fret so that this is the distance from the fret to the far bridge. The location for the second degree scale, at 5/4 the open string frequency, is at a point 4/5 of the open string length, or 80 cm from the bridge. You can calculate the remaining fret locations in a similar manner. (But — important! — see the comments at the end of this section for offsetting factors.)

Notice that I haven’t said anything about specific frequencies here. The actual sounding pitches will be determined by the tuning of the open string. But the pitch relationships established by the fret placements will remain true regardless of the tension (within reasonable limits).

In practice, fretted instruments are not often set to just tunings, in part because of problems associated with unequal fret spacings described in the main text. Most contemporary fretted instruments are set to the standard 12-tone equal temperament. Other equal temperaments can work too, as long as the number of tones per octave isn’t too large. With equal temperaments, as discussed in Chapter 3, the frequency increases with each scale step by a constant factor. (Sidebar 3-1 gives values for the constant factors for a range of equal temperaments.) In keeping with the inverse proportion rule, the frets must be placed so that each successive fret shortens the active string length by the inverse of that factor. Thus, to locate the frets for 12-tone equal temperament on a 1-meter string, you proceed as follows:

The 12-tone scale factor (from Sidebar 3-1) is 1.05946; its inverse is 1/1.05946 = 0.9438. Starting with the open string at 100 cm —

1st fret located: 0.9438 x 100.0 cm = 94.38 cm from the bridge.
2nd fret located: 0.9438 x 94.38 cm = 89.08 cm from the bridge.
3rd fret located: 0.9438 x 89.08 cm = 84.08 cm from the bridge.

And so forth, through as many frets as you wish. This will yield the familiar pattern of progressively closer frets going up the neck one sees on guitars and mandolins and such. Similar patterns will appear when you apply the inverted factors for other equal temperaments, but the actual spacings will be different.

Important: These fret locations represent a theoretical ideal. In practice one must take into account an increase in tension due to the slight stretching of the string when it is pressed down to the fret, pulling the pitch slightly sharp. Correct for this by offsetting the fret to allow a slightly longer vibrating length. If the string is already in place, you can incorporate the correction into the original calculation by this method: Find the stopping location at which the string produces a true octave when pressed down to the fingerboard. (You can determine when the octave is true by comparing the fingered pitch to the harmonic tone generated by lightly touching the string at its midpoint and plucking.) The fingered true octave location will be a little short of the actual string length midpoint. Double the active string length at this true-octave stopping point to get a slightly long "corrected" total string length, and use the corrected string length in place of the actual string midpoint. Double the active string length at this true-octave stopping point to get a slightly long "corrected" total string length, and use the corrected string length in place of the actual string midpoint.
Another approach some makers have used — simple and convenient if a little less precise — is "the rule of 18." Place the frets so that each successive fret shortens the sounding string length by 1/18th relative to the previous fret. This gives a result very close to the twelve-equal factor with a small correction built in.

Finally, if the bridge on the finished instrument is not glued in place, but is movable, then you can easily compensate for fretting tension effects by adjusting the bridge location after the instrument is completed. If, for instance, the pitch is a bit sharp at what should be the octave fret, move the bridge a bit farther away, thus increasing the overall string length. Fine tune the bridge location as necessary to bring the frets in tune.

One more possibility is to give up the idea of unequal tunings and work instead with higher-order equal temperaments. This approach is ideal as long as the number of tones per octave isn't too high. 19-equal, 21-equal, and 23-equal, many of which have been made, have proven to be quite musical. Above about 24-equal, for guitar-sized instruments, the fret spacing begins to get too small and the instruments become unplayable.

Pedal steel guitar is perhaps the most highly developed tension chordophone. Several in the family of string instruments are made to play exclusively in harmonics. One such is the trumpet marine, the Hawaiian guitar, and some dobros, are made specifically to be played with slides. Just as often slides are used as a special effect on instruments that are normally fretted. In fact you can use a slide on virtually any musical string. A serious limitation is that you can’t very well use the slide to stop adjacent strings at different stopping points. It is awkward to make the slide cross one string at, say, the equivalent of the 7th fret, and simultaneously cross another string at the 5th. If you wish to play two strings in harmony, you are limited to pre-tuned intervals between the strings. Pedal steel guitars, widely used in country and western music, get around the problem by means of a tension-control mechanism that allows the player to change the intervals between the strings on the fly. (That’s what the pedals are for.)

A lot of builders with an interest in alternative tunings use slides with their string instruments because of the freedom of pitch slides offer. A common approach is to make an instrument with the neck marked off beneath the strings to show the stopping locations for various intervals and scales. You can get quite elaborate with this, indicating different scale patterns and interval types in different colors, and creating in the cumulative effect quite a work of art. The late Ivor Darreg, a San Diego builder and international theorist, specialized in multi-sided board zithers (electrically amplified) with banks of strings on each side, all colorfully marked off for different scale types.

You can also draw different pitches from a single string by selectively bringing out different overtones. Since strings behave harmonically, this yields a coherent set of scale relationships as you move up on the series. But how can you get one overtone to sound without all the others? The trick, well known to string players, is to pluck or bow the string while using the other hand to touch it lightly at a nodal point for the overtone that you wish to bring out. This immobilizes the lower modes of vibration that would normally be active at that point, while still allowing the higher mode having a node there to come through almost like a new fundamental. You can enhance the effect by plucking at or near an antinode for the same mode (Figure 9-21).

Harmonic tones are often used as a special effect on conventional instruments. There are relatively few string instruments made to play exclusively in harmonics. One such is the trumpet marine, the unlike string instrument mentioned earlier for its unusual buzzing bridge. While trumpet marines had but one or two strings, some contemporary harmonic instruments have many. They fill the gaps in the lower part of the series where the pitches are widely spaced, and also invite attractive sweeping effects across the strings. One of the most extraordinary harmonic instruments — both in conception and in sound — is the harmonics guitar with center bridge described in Sidebar 2-1.

Overtones Selection

In the traditional system of temperaments, each degree of a key has a fixed ratio. In order to accommodate every desired note for every string, that quality becomes a problem as the frets get too close together to play properly — it turns out that help closer than about 1/4" is more or less unplayable — and, furthermore, playing such an even-tensioned instrument gets confusing. Another approach is the use of Helmholtz — short frets that don’t cross the entire neck, but lie under only one or two strings. They allow for different fret spacings under different strings. This is a more drivable approach, but it, too, can be confusing and difficult to play.

What to do, then, if you want to realize an unequal tuning on a fretted instrument? One solution is to add more and more frets to accommodate every desired note for every string. That quickly becomes a problem as the frets get too close together to play properly — it turns out that help closer than about 1/4" is more or less unplayable — and, furthermore, playing such an even-tensioned instrument gets confusing. Another approach is the use of Helmholtz — short frets that don’t cross the entire neck, but lie under only one or two strings. They allow for different fret spacings under different strings. This is a more drivable approach, but it, too, can be confusing and difficult to play.

You can get cleaner, more accurately tuned harmonics and a more complete range (extending farther up into the series) working with relatively long, thin strings.
Imagine a string which, instead of having both ends attached to fixed anchors, has one end attached to the mid-point of another stretched string. What would this configuration sound like when plucked? How would the tuning configuration that you choose go a long way toward establishing what sort of music comes most naturally to the instrument.

On harps and zithers, it seems unlikely that the strings should ever be arrayed in any pattern other than an ascending scale, but as we saw earlier with the kora, more imaginative patterns can be musically fruitful. It has long been a fantasy of mine to make a big zither with many, many strings, laid out in separate sub-groups with varying numbers of strings. There would be movable bridges available to shove under the strings, making it possible to alter lengths to make all kinds of tunings feasible within the different groups. I would set some string groups to choral sets, and others to scale or melodic sets, none of them necessarily in ascending order. There would be melodic sequences to be effortlessly brushed at any time, and some quasi-melodic, perhaps highly dissonant clusters. I would expect to move the bridges around and alter the tunings frequently, either for exploratory purposes or to provide the vocabulary for a particular piece or musical style. Why am I telling you this particular fantasy? To convey, in fancy tale form, a certain sense of the effect of tuning and layout in many-stringed instruments, and the role these factors have in creating an instrument's musical vocabulary.

To close this chapter, let me describe a few musically interesting unorthodox string types.

**Collected Strings**

Most people are familiar with some of the acoustic properties of springs, because most people have at one time or another sprung a stretched spring and enjoyed the highly reverberant sound. A long, not-too-thick coiled spring can be set up to function much like any other musical string. Spring-strings concentrate high mass in a short length with relatively little rigidity. Their volume tends to be low, because their stretchiness prevents them from driving soundboards forcefully. But, being made of steel, they are free to vibrate. But, for various reasons, inharmonic overtones and dual fundamentals sometimes appear, especially with shorter lengths of rigid materials like metal banding.

Ribbon strings with their wide flat surface have greater wind resistance. How much this inhibits vibration is difficult to estimate. But it has the positive effect of allowing the vibrating string to move more air by itself, making it possible to have a soundboard-less string instrument, albeit a quiet one. And, conversely, ribbon strings are also far more responsive to air currents, making all kinds of wind-activated string instruments more feasible.

**Idiochords**

An idiochord is an instrument in which the string is actually part of the body of the instrument, as with, for example, a strip of fabric from the surface of a length of bamboo or raffia stalk, but left attached at the two ends (Figure 9-22). Two small slivers of wood or bamboo are wedged under the lifted fibers and shoved toward the ends, in this way both raising the strip of fiber and tightening it. The end of the bamboo section may be wrapped with twine or wire to prevent the raised strip from running to the end and disconnecting entirely. The strip of fiber thus raised and tensioned functions as a string, while the hollow body of the stalk serves as a resonator.

Instruments built upon this principle exist in many parts of the world. A common elaboration is to bind several small idiochord zithers together to form what is called a raft zither. The tone of a well made instrument, while never very loud, can be clear and string-like, with well defined pitch. The thickness and shape of the fiber string are important determinants of tone quality. Thick strings, being more rigid, will produce a more inharmonic, percussive and short-sustaining tone. Thin strings will produce something sounding clear and unified in pitch with little sense that this is in reality several different tones. Darreg's Megalyra instruments, with similar registrations but in strings, possess the same grandeur.

**Scordatura**

Scordatura is the term used for unorthodox tunings of the intervals between the strings, and the fun comes because unorthodox tunings lead to new musical patterns that would be unlikely to arise in the standard tuning. These conventions make a lot of sense, but you can also have fun with scordatura. Scordatura is the term used for unorthodox tunings of the intervals between the strings, and the fun comes because unorthodox tunings lead to new musical patterns that would be unlikely to arise in the standard tuning.

The tuning configuration that you choose goes a long way toward establishing what sort of music comes most naturally to the instrument.

A related matter: many string instruments use pairs of strings, or groupings of three, spaced so closely that they are naturally played together as one. The idea is to increase volume and enrich the tone emanating from a single pluck. Frequently with double or triple courses (as such multiple-string arrangements are called) all the strings of each course are tuned to the same pitch, as in pianos and mandolins. Sometimes one is tuned an octave above another, as with the lower four double courses of 12-string guitars.

A more potent approach was advanced by the impresario Ivor Darreg. He set as many as six or eight strings in a single course, tuned to relationships derived from traditional organ registrations. For certain stops on a big church organ, when you press down a single key, you get many pipes sounding not only the pitch normally associated with the key, but a number of additional pitches based in the main tone's overtone series. The result, with a well-designed registration, is a terrifically grand composite tone, sounding clear and unified in pitch with little sense that this is in reality several different tones. Darreg's Megalyra instruments, with similar registrations but in strings, possess the same grandeur.

**UNORTHODOXIES**

To close this chapter, let me describe a few musically interesting unorthodox string types.

**Coiled Strings**

Another unorthodox string type is flat, ribbon-shaped strings. Metal strapping material, magnetic recording tape, flat rubber bands and many other ribbon-like materials will behave as musical strings when stretched taut between two points. Their shape alters vibrating behavior in that they are not uniformly free to flex in all directions. It would appear that they should vibrate harmonically in the direction they are free to vibrate. But, for various reasons, inharmonic overtones and dual fundamentals sometimes appear, especially with shorter lengths of rigid materials like metal banding.

Ribbon strings with their wide flat surface have greater wind resistance. How much this inhibits vibration is difficult to estimate. But it has the positive effect of allowing the vibrating string to move more air by itself, making it possible to have a soundboard-less string instrument, albeit a quiet one. And, conversely, ribbon strings are also far more responsive to air currents, making all kinds of wind-activated string instruments more feasible.

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Instruments built upon this principle exist in many parts of the world. A common elaboration is to bind several small idiochord zithers together to form what is called a raft zither. The tone of a well made instrument, while never very loud, can be clear and string-like, with well defined pitch. The thickness and shape of the fiber string are important determinants of tone quality. Thick strings, being more rigid, will produce a more inharmonic, percussive and short-sustaining tone. Thin strings will produce something sounding clear and unified in pitch with little sense that this is in reality several different tones. Darreg's Megalyra instruments, with similar registrations but in strings, possess the same grandeur.

**Scordatura**

Scordatura is the term used for unorthodox tunings of the intervals between the strings, and the fun comes because unorthodox tunings lead to new musical patterns that would be unlikely to arise in the standard tuning. These conventions make a lot of sense, but you can also have fun with scordatura. Scordatura is the term used for unorthodox tunings of the intervals between the strings, and the fun comes because unorthodox tunings lead to new musical patterns that would be unlikely to arise in the standard tuning.
would the strings affect one another's patterns of vibration; how would the two behave together acoustically? Taking the question further, how would a complex system of several conjoined strings behave?

The results turn out to be quite interesting — unwieldy in may ways, but intriguing, and sometimes quite beautiful. The plucked tone is generally a blend of many discernible pitches arrayed in nonharmonic relationships, a little like a large bell or gong. But unlike metal percussion, conjoined string systems are manipulable. By altering string lengths and tensions you can modulate the sound both timbrally and melodically.

The system described above, with the end of one string tied to the mid-point of another, functions as a system of three strings joined at the middle. The end-tied string pulls the other into an angle at the connection point, and the two resulting half-strings become quasi-independent (see Figure 9-23). This is the simplest of the many possible multiple-string configurations.

Conjoined string systems are hard to tune, because altering either the length or tension of any one segment affects some, but not others, among the several pitches that make up the composite tone. The interactions are multifaceted and complex. Yet a bit of noodling around is sure to yield any number of chance tunings of beauty or interest. You can create extraordinary effects by using a slide to play melodically on one of the string segments. This creates a mix of drone tones and changing harmonies of a sort no composer would ever dream up.

The peculiar tonal relationships of a single set of conjoined strings, present to some degree in every note played, grow tiresome before long. So it is worthwhile to create instruments having several differently tuned conjoined string sets.

Sidebar 9-6

INTONARUMORI

Luigi Russolo, an artist and thinker identified with the Italian Futurist movement, conceived and built a number of remarkable instruments in the years between 1913 and 1921. The instruments were designed to realise Russolo’s ideas concerning the creation of an art of noise, which he outlined in his work L’arte dei rumori. His conception of noise instruments incorporated the possibility of recognisable pitch within the context of highly irregular, inharmonic — in short, noisy — sounds. One recording of his instruments survives, but none of the instruments themselves survive. Information on their construction is available, with varying degrees of detail for different instruments, and reconstructions of some have been done in Europe and the U.S.

Most of them followed similar principles. A single main string was fixed at one end, and attached at the other to the middle of a membrane radiator mounted on a drum. The drum led directly to a large speaker horn, thus creating a membrane & horn arrangement not unlike a giant version of the Stroh Violin described in Chapter 8. Apparently the membranes on different instruments were treated with different substances to bring out different timbral qualities. The string was sounded by a rotating wheel, hurdy-gurdy-style. In some cases the wheel was rosined, for a stick-slip vibration, and in others it was notched or toothed, with the particular notching patterns eliciting different sounds. String pitch was controlled either by a tension lever or by a lever which controlled a heavy movable tangent. This entire arrangement was enclosed in a box, with only the large horn, the pitch lever, and the wheel-turning crank protruding outside and giving viewers something to wonder about.
We now have studied the four primary acoustic instrument types. In this chapter we will look at tricks you can use to modify the sound of an instrument to create a special effect or tone quality. We will talk about ways to take simple sounds and make them more complex, in order to make them subjectively richer, or warmer, or spicier, or edgier, or more rhythmic and impulsive. This chapter is not oriented to any particular instrument type; many of the ideas presented here apply across the board to several types. We begin with —

**CHORUSING AND BEATING EFFECTS**

In Chapter 2 I discussed how, when two tones of close but not identical frequency sound together, interference patterns arise which the listener hears as a wavering of amplitude, called beating. You can hear this effect in piano notes for which the three strings are not exactly in tune, or in imperfectly tuned 12-string guitars or mandolins, with their double string courses. Some slight detuning is not necessarily bad with these instruments, as it does subjectively create a slightly fuller sound. But it is not part of the accepted style, and the intent of the person who does the tuning is usually to get the strings precisely in tune. On the other hand, in gamelan orchestras in the island of Bali, the makers create the effect deliberately, building the metallophones in detuned pairs, to be played in unison. The result has been described as a “shimmering” effect. Chorusing effects are especially effective with sustaining wind instruments. Many old-time harmoniums have stops, such as the one lovingly called “Vox Humana,” that bring two banks of reeds into play. Two separate reeds, nominally tuned to the same note, sound for each key that is depressed. The two are never really in tune, and the resulting slow beating is quite pronounced. Accordionists, all but the smallest and humblest of them, do the same. One of my favorite sounds in the world is the highly irregular beating of a single melody line played on an old, poorly tuned accordion.

You can create the same effect in any instrument by using pairs of sounding elements. The closer the two tones are in pitch, the slower will be their beating. This means that you can control their beat rate by their relative tuning. It also means that you can create a sound with a continually varying beat rate by having their pitch differential vary slightly through time. This creates an attractive effect, one that is subjectively more natural sounding than beating at a steady rate. Electronic “chorusing” effects work this way, mixing the original sound with a warblingly detuned version of itself.

Double wind instruments, such as double oboes or double ocarinas, have arisen in many parts of the world (see Figure 10-1). There is always a temptation to play polyphonic music with these instruments, but the loveliest sounds from them may come when you play the pair in unison, creating a single melody enriched by the two voices. Given the sensitive nature of woodwinds, the two voices are never quite precisely in tune, and the degree of detuning inevitably varies from note to note. The shifting beat patterns can be beautiful, especially with ocarinas in the lower ranges. I have made a double slide whistle in which both whistles are played as one, in near but imperfect unison, for a very distinctive sound.

You can get the same effect with strings (though it is less pronounced) by plucking while holding a steel slide at the mid-point of the vibrating length, and moving the slide slightly back and forth along the string. This causes the vibrating string segment on one side to wobble up and down in pitch as the opposite segment wobbles down and up. If you try this with something like a guitar, be sure to pluck on the side of the string away from the soundboard. (If you pluck on the soundboard side, the tone from the non-soundboard side will be too quiet to contribute to the effect.)

**REVERBERATION & SYMPATHETIC VIBRATION**

“Reverberation” refers to the lingering of a sound in the room after its original driving source has ceased sounding. Similar effects can be built into musical instruments themselves, independent of room characteristics. Many instruments are inherently reverberant. For instance, a harp’s strings tend to pick up vibrations from one another, ring along with one another, and often continue to sound even after the original vibrating string has ceased. Other instruments have reverberant qualities due to the nature of their radiators and resonators.

For some instruments you may want to introduce more reverberation. The trick in doing this is to find some vibrating medium that will readily pick up the sound from the initial vibrator and vibrate in sympathy at the same frequencies. Several materials do this reasonably well.

**Strings**

Strings are an old favorite. Many instrument types, both Western and Eastern, employ extra strings intended only for sympathetic vibration. Sympathetic strings can work with instruments whose primary vibrating elements are strings, as well as idiophones of many sorts.

The most common approach has been to attach a relatively small number of strings, deliberately tuned for reverberation at specific pitches. This is done on the sitar, the European Viola d’Amour, and many others. Alternatively, you can attach a large number of strings which are not carefully tuned, under the assumption (justified by experience) that with enough randomly tuned strings, virtually any note you play will find a resonance in one or more of the strings. This latter approach is more work initially (more strings to be put on) and less work later (no careful tuning needed). It yields a satisfying wash of reverberance, with particularly fine, well defined high frequencies. The instrument called Prongs and Echoes, described in Sidebar 10-1, illustrates the idea in practice.

People sometimes use a piano with the dampers lifted for the same effect. Someone once told me how he had sat in a practice room playing trumpet, completely mystified when he seemed to hear someone in another nearby practice room also playing trumpet, and echoing his every note with uncanny accuracy. He was mystified, that is, until he realized that he had his foot on the damper pedal of the practice room’s piano, and the ghost trumpeter was in fact the strings of the instrument right in front of him.

**Springs**

Coil springs make excellent reverberation devices, because a single spring can pick up and resonate a broad range of frequencies (in contrast to an individual string, which is quite specific in what frequencies it will resonate). This means that you can use one, two, or three springs, without any special tuning, for reverberation over the entire sounding range, where you would have had to use many strings. Their tone quality is not as good as strings, though. Their frequency biases tend to make for a recognizably “springy” sound.

The ideal spring is a long, thin, lightweight coil spring. It can be attached to the sounding body much like a string, under light tension. Like sympathetic strings, the spring may also provide an additional sound source in its own right.
SHIFTING RESONANCE EFFECTS

We discussed shifting resonance effects in Chapter 8, "Resonators and Radiators," but because they create such unusual results, I want at least to mention them here. You can produce these effects only on instruments for which the driver and resonator/radiator are separate elements, such as strings and certain idiophones.

The idea is this: Many sound resonators and radiators have distinct frequency preferences, meaning that they respond to a greater or lesser degree depending on the frequency of the input from the driver. If these preferences are not fixed, but shift as the instrument is played, the sound takes on an iridescent quality, as different overtones within the original signal are emphasized from moment to moment. There are several ways to create shifting resonance effects, including the use of water-filled resonators and flexible sheet metal resonators. Both of these are discussed in Chapter 8.

You can also devise shifting resonance effects with air-chamber resonators. The best-known example of this is in vibraphones. Below each vibraphone bar is a tuned air-resonator tube. Between the bar and tube is a rotating baffle, driven on a spindle by a quiet motor. When the baffle is in a horizontal position it blocks any coupling between the bar and tube, and eliminates any resonance response from the tube. When it is in a vertical position, there is no blocking and full resonance is restored. The result is that as the baffle rotates, the tube resonance comes and goes, creating an oscillation in volume and tone quality.

In a related effect, many organs, including both pipe organs and small reed organs (harmoniums), use variable baffles, alternately blocking the soundwaves near the source or letting them pass freely into the room. The baffles are intended primarily as volume-control mechanisms, and on some of instruments the baffle position is controlled by a spring-loaded knee lever. Inevitably, the position of the baffle affects tone quality as well as volume. In addition to the intended crescendos and swells, the baffle mechanism can, if the baffle is not too large and unwieldy, be used to create wavering tremolos and similar effects.

RATTLES

By "rattles" I refer to any small thing that is loosely attached to a vibrating part of an instrument, so that it bounces against the vibrating body and adds its contact sounds to the instrument's overall sound. But "rattles" may not really be the right word here, since it makes one think of rattly sounds. Well designed rattles can actually add a wonderfully light, delicate edge to an instrument's tone.

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You can attach a rattle to any solid vibrating body, including strings, bars, tines, bells, and gongs, as well as secondary vibrators like soundboards. The effect of a well made rattle at its best sounds as an integral part of the overall timbre, perhaps highlighting selected upper partials. The effect can also add to the impression of loudness.

A well functioning rattle’s contribution to an instrument’s timbral mix ideally takes the form of harmonic overtones, even in cases where the initial vibrator’s mix is itself non-harmonic. The reason this is possible has to do with the restricted nature of rattling motions. The rattle’s own vibrating pattern at the initial vibrator’s fundamental frequency is “clipped” due to its confined movement, producing not a sine wave, but something closer to a square-wave pattern of vibration. The ear interprets this vibrating pattern as possessing harmonics.

Rattles on Strings

For a rattle to work well, there should be an appropriate balance between the mass of the rattling object and the strength and amplitude of the vibration of the initial vibrator at the point where the rattle is attached. A string, as an initial vibrator, is very light. The rattling object must be considerably lighter if its mass rests on the string. The ideal place for a string rattle is at a point near enough one end that the impedance is sufficiently high to drive the rattle, but not so near that the amplitude is too small to do the job. Typically (depending on the weight of the rattle relative to that of the string), you can find a good point at about 2% - 4% of the total string length — for a guitar string, for instance, between about 6/8” and 1” from the end.

There are probably many ways to attach a string rattle that will stay put near that ideal location; one practical approach appears in Figure 10-2A. The rattle shown here, made of very light gauge metal wire, adds a glittery effect to the string tone. Try attaching it to just the one or two highest strings of a many-stringsed fretted instrument, to let melodies played on those strings stand out finely limned against the accompanying strings.

Another way to add a harmonic-enhancing rattle to string tone is through the use of buzzing bridges. Look back to the section on bridges in Chapter 9, “Chordophones,” for details on these.

Rattles on Kalimba Tines

Some kalimbas have shells or bottle caps loosely tacked or tied to their sides or bodies. I have also found it to be effective to attach lightweight rattles directly to the tines themselves. As with strings, rattles on tines add a delicate silver lining to the tone. Kalimba tines are generally higher in impedance than strings, so they drive the rattles more effectively. This makes the business of positioning and fine tuning of relative masses less exacting. A kalimba tine rattle design, very similar to that suggested for strings, appears in Figure 10-2B.

Rattles on Free Bars

As with strings and tines, a rattle attached directly to a marimba bar can add a harmonic edge to the tone. (This is despite the fact that the bars and tines themselves have non-harmonic overtones, as discussed above.) Free-bar rattles also create an impression of greater loudness. They work well on both wooden and metal bars. Vibrating bars are generally massive enough that the weight of any reasonably small rattle will not noticeably affect their vibration, so the rattle can be attached wherever the amplitude is sufficient. Attaching directly to the surface of the bar near one end usually works well. Figure 10-2C shows a free-bar rattle design.
DAMPERS

Deliberately damped tones from sound sources that are normally allowed to ring can be appealing. The nicest effects seem to come about in connection with plucked strings. With just the right amount of damping the sound acquires a persuasive quality, yet retains its sense of pitch. Some guitarists learn to achieve the effect by lightly brushing the strings near the bridge with the fleshy side of the hand even as they pluck. An easier way is with a piece of foam rubber wedged between or beneath an instrument’s strings. Normally the foam should be adjacent to the bridge — if it is closer to mid-string, the damping will be too much, and the tone reduces to a dull thud. On the other hand, a very light damper at selected mid-string regions can have the interesting effect of inhibiting lower harmonics more than higher harmonics — a node in the vicinity of the damper. This alters the relative prominence of the components in the overtone make-up, altering the tone quality in interesting ways. When the mid-string damper is very light and somewhat spread out, it may allow for fretting the strings within a limited range while losing the effect.

MOVING SOUND SOURCES AND DIRECTIONAL EFFECTS

The ears' directional sense, which allows one to recognize where sounds are coming from, is highly developed. Yet it is not often exploited in sound arts, even though the directional dimension within a sound composition adds depth and clarity. Near the end of Chapter 1, "Musical Sound Perception," I discussed some of the factors affecting directional perception. There are several ways you can bring directionality into play as part of the aesthetic effect of instruments you design. One is simply to play in a highly reverberant room, where wall reflections envelop the listener from all sides. Another is to spread point-sound sources, each carrying different sounds, far apart. This is fairly easy to do with electronics where you can simply run wires to remote speakers. Some performers and composers have done wonderful work along these lines. Another use of
Directionality is to place several performers, each with their own instruments, at diverse points around a listening space. Hocketing is the technique, used by bell choirs, vocal groups, panpipe ensembles and others in diverse parts of the world, in which several players, each responsible for certain pitches and not others, work together in series to create melody. It is a great pleasure in its melodic-spatial effect as well as in its sense of social interlocking.

The German-American builder Trimpin has created extraordinary pieces involving computer-controlled, electromechanically played sound sources around the periphery of a room. The sound sources may be conventional instruments, new instruments of Trimpin's devising, or everyday noise objects, played by various mechanisms driven by solenoids under the command of a remote computer. The compositions often involve rapid, exquisitely timed sequences of events from the different points in the room, and the effect is unparalleled.

Within limits it is possible to build acoustic instruments with wide-ranging sound sources. Cathedral organs, with their banks of pipes spread across entire walls, are an example. One could also create remote playing mechanisms, or use the kind of highly efficient mechanical sound transmission to remote sound radiators described in Chapter 8, to spread far and wide the points from which an instrument's sounds emerge.

You can also create moving sound sources. Make a swinging trumpet by buzzing your lips into the end of a flexible hose and swinging the hose around your head as you play. Add a mouthpiece and some sort of flared bell at the end for improved tone and playability. You can also make a swinging harp (or bell harp, as it was once called), an instrument that actually achieved some popularity in the late 19th century. It was a zither, typically having sixteen courses of diatonically tuned strings, designed to be played while swinging at arms length. Or use hummers and bullroarers, described in earlier chapters, played by swinging on a cord around the head. And the list goes on.

With moving sound sources, listeners can experience the Doppler effect. The Doppler effect occurs when a sound source moves toward a listener, and the wave fronts coming off its surface are in effect crowded together, resulting in a shorter wavelength and a higher frequency. With a retreating sound source the reverse occurs. A whirled instrument will thus have a slight rise and fall in pitch for most observers as it alternately approaches and retreats.

A couple of other effects come about when sound sources spin rapidly on an axis. Picture a flat disk gong suspended from a single cord and made to spin rapidly as it sounds. The gong radiates its sound most strongly in the directions perpendicular to its flat surface; it does not radiate well to the side. For a listener in a given location, it is louder when it faces the listener; softer when it has turned edge-on at 90 degrees; louder again at 180 degrees, and so on. The listener hears a tremolo. The listener also experiences recurring phase reversals: the vibration coming from the front of the gong is precisely out of phase with that coming from the back. As the gong spins, the listener hears first one then the other. The sounds are identical, but reversed in phase, creating a subtle shifting effect.
Chapter Eleven

A FEW MORE THOUGHTS

I have filled this last chapter with ruminations touching broadly on musical instrument design. These reflections are concerned not so much with how one actually builds instruments as with how one thinks about instruments and their design. Some of these thoughts are practical and prosaic, and others are of no practical value whatsoever, unless you happen to work better against a backdrop of ideas.

First, some considerations of a utilitarian nature for anyone with an instrument-making habit.

There are big instruments, and there are small instruments. Big instruments take up a lot of space. If you persist in making big instruments, you will have storage problems. The closet fills up; the living room fills up; the kitchen fills up; etc. There is no cure for this, but there are a few things you can do for symptomatic relief: 1) Try very hard to build small instruments only. 2) If you have yard space, build instruments of weather-proof materials and keep them outdoors. 3) Make instruments that can be dismantled into storable parts, and reassembled. 4) Rent a warehouse.

One design concept is particularly helpful in making instruments smaller and at the same time more versatile. It is modularity (the term used by an advocate of the idea, Bob Phillips). Modular instruments are made with interchangeable components, so that an instrument can be configured for one musical purpose today and, by the removal of some parts and the addition of others kept on hand, configured for another musical purpose tomorrow. Most often this means that the instrument has a generous stock of sounding elements tuned to different pitches, but the instrument is only large enough to hold a subset of them at one time. Modularity has proven especially practical for marimba-type instruments, chimes and the like.

Adjustability is another valuable idea. Musical instruments are delicate devices requiring manufacture to fine tolerances. Because it is not always possible to know in advance the ideal settings for all the interacting parts on a given instrument, it is helpful to be able to adjust crucial settings after the instrument has been assembled, and throughout its playing life. This applies to many, many facets of instrument design, from the location and height of a string instrument's bridge, to the orientation of the edge in a fipple pipe, to the distance of travel of a clavichord key, to the positioning of a flute pad, and so on indefinitely.

Unfortunately, it usually makes for more work in the construction process to build in adjustability at every turn. Further, adjustable components tend to be inelegant. And in many instances the addition of adjustable mechanisms is simply impractical. The common-sense approach is to try to assess, in an instrument's early design stages, where the tolerances are most sensitive for the proper functioning of the instrument, and then to consider in each case whether it is feasible to build adjustability in there.

A lot of musical instrument design, for those who are not simply reproducing standard instrument types, is imagination work. At the earliest stages in the conceptualization of a new instrument, try not to let yourself get locked into a particular way of thinking about the design. It is not unusual to persist in envisioning the finished instrument in a particular form, all the while remaining inexplicably blind to some slightly different approach which would yield better results. The simpler the better is a good rule, and when the simpler and better approach does come to you, you will find yourself saying, "but it's so obvious — why didn't I think of that before?"

In creative instrument making, you must expect to depart from the original plan now and then. Through the process of construction and that you learn what works and what does not for a particular sound-making mechanism. For that reason, it is valuable to work initially towards the creation of a rough but functional prototype. From the prototype you can work toward more refined realizations of the idea. The best instruments come from makers whose results improve as they work through an idea, and then work through it again, and then work through it again. You can learn things from prototyping and modeling that you cannot learn any other way.

Does it matter what an instrument looks like as long as it sounds good? There is no right or wrong answer to that question, of course, but I will say this: Musical instruments are interesting to look at. People are attracted to them visually. The requirements of acoustic design give rise to intriguing forms, whether or not the maker deliberately makes design choices based upon a visual aesthetic. An instrument which looks beautiful, or even one which looks bizarre, has an appeal that makes people more inclined to listen with open ears. Makers do well to know this, and to cultivate and enjoy the visual aspect of their instruments.

What about names for newly created instruments? It turns out that, for whatever reason, people respond strongly to instrument names, and a good name may play a significant role in drawing interest to a particular instrument. Harry Partch came up with some wonderful ones, and it's worth noting that some of his best-remembered instruments are those with the most memorable names, and not necessarily those that were most important to his music. His Spools of War, Mammy Elnoce, and Quadrangulairs Reversum come to mind.

And finally, a word on the question of control in musical instruments and musical sound. Musical instruments are designed to produce sound, and to do so in a fashion that can be controlled by the player. Typically this means that the player decides which pitches should sound when, and for how long. As a secondary matter, the player may also govern volume and, to some degree, timbre. Need this priority be accepted as given? Or could one have musical instruments in which timbre is primary, while pitch selection is secondary? Or, how about instruments in which microtonal pitch modifications are primary, while traditional scale degrees fall by the wayside? For that matter, how about a different concept of control, such that the ideal of the player's mastery over the instrument is replaced by one of creative interaction with the instrument?

The answer of course is that all these things are possible and are sometimes practiced, and sometimes yield beautiful and exciting music. Such music may call for a different sort of listening than the listening that goes with familiar musical styles.

I encourage you to keep a flexible attitude regarding control as you work with the wide variety of possible sources of musical sound. It will be tempting to turn each sound-generating system into a pitch-selection and rhythm-control device — after all, that is what most musical instruments are, and what most instrumental music is composed for. But it may be that to do so is to impoverish the sound. Try to let the instrument and its sound suggest their own music.

Now we have come to the end (but for the appendices that follow). I hope that these pages have been valuable to you, and will continue to be. To all who put the information in this book to use, may your efforts be fruitful, and may they bring more music to the world.
Appendix One
TOOLS AND MATERIALS

This appendix contains information on tools and materials that are useful in musical instrument making. A list of supply sources is at the end.

TOOLS
Tools and equipment for instrument making, or any other sort of shop work, may sometimes seem more a barrier than a door-opener. So, let me stress from the start that there is a great deal you can do using a minimum of tools. One of my favorite builders, whose instruments strike me as endlessly creative and enjoyable, works entirely with commonplace materials and just a few simple hand tools. Even for those who later learn to use special materials and advanced shop equipment, the early experience of working with hand tools is a vital one.

Professional makers of particular types of musical instruments use many specialized tools. We will leave those tools to professionals, and won't discuss them here. You can learn more about them from books and periodicals devoted to construction of specific instrument types. For most purposes, the tools most broadly useful in acoustic musical instrument making are the same tools that are standard in general wood and metalworking. They include various sorts of hand saws and/or power saws, sanders, drills and bits, vises, measuring devices, squares, clamps, wrenches, screwdrivers, files and rasps, planes, knives, snips, a radio for distraction, and so forth. Those more serious about metal work may get into welding and soldering equipment. Among special-purpose tools that might come in handy are tubing cutters. These come in various sizes, and allow quicker and cleaner work than hack saws. Very large, powerful bolt cutters can save hack sawing and filing time, and a motorized grinding wheel is also a time saver for certain jobs. Quartz tuners or other tuning equipment (discussed in Sidebar 3-2) and leaklights for wind instruments (discussed in Chapter 6) have a special place in some instrument building shops. For fuller discussions of shop tools, look to any of the widely available books devoted to the topic.

Please use your tools and materials wisely. Follow safety instructions on tools and product labels; wear face or eye protection even in borderline cases where it doesn't really seem necessary; use a breather mask when doing dusty work or anything involving toxic fumes; and don't use power tools if you are tired or agitated.

Certain materials commonly used in musical instruments are toxic. Experimental instrument builders often use PVC plastic as an inexpensive tubing material. PVC fumes are toxic and carcinogenic, so any operations involving heating, sanding or cutting require a mask and good ventilation. Metal filing, grinding and soldering operations require similar precautions. The dusts from brass and aluminum are poisonous, and stainless steel yields hazardous gases when heated. Soldier contains lead. Dusts from many tropical woods are either allergenic or to some degree toxic, as are those of some temperate softwoods such as redwood and cedar.

MATERIALS
This is an overview of some of the most useful among the many materials that can be employed in the making of musical instruments. I will start with a rundown of uses and properties of important new materials, followed by a review of manufactured items or materials made specifically for musical instruments. Following that is information on a few particularly useful secondary materials. Toward the end of this appendix you will find notes on where to get what, including a list of suppliers for many of the materials discussed.

Woods
Hardwoods work well for marimba bars and tongue drum tops, sound chamber backs and sides, and any application calling for strength, density and durability. Traditionally, various tropical hardwoods, such as rosewood and ebony, have been considered the best woods for musical applications. The preferred tropical woods have greater density than most temperate hardwoods, not to mention richer colors. But with the increasing scarcity of tropical woods, it becomes imperative to consider the alternatives. Temperate hardwoods commonly used in instruments include maple, walnut, and cherry. Osage orange and black locust are two temperate woods comparing well to rosewood in strength and density.

Softwoods work well for soundboards and applications where strength and durability are less essential. The universal standard for soundboards is spruce, prized for its lightness and resilience, although top-quality spruce is getting rare. Some makers are partial to cedar or California redwood. Pine is an inexpensive alternative. Redwood, incidentally, makes surprisingly clear-toned xylophone bars. Plywood musical instruments have a bad reputation, but plywood has a place in musical instrument making, given their strength and versatility (not to mention availability and inexpensiveness), especially since musical instrument design so often calls for strong, thin surfaces. I have always enjoyed working with non-commercial local woods. In my part of the United States we have baya, sometimes called laurel or pepperwood, a beautiful aromatic hardwood, but subject to pest infestation; madrone, a very hard whitish wood that is murder to season up without checking (splitting); tanbark oak, which finishes up very different from other oaks in grain and color; and the list goes on. In your region the list will differ, but is likely to be comparably extensive. Many non-commercial woods are non-commercial not because of problems with the wood itself, but for reasons having to do with the economics of availability, distribution, and demand. If you have the opportunity, it can be fun, rewarding, and sometimes frustrating, to work with such wood. Along the same lines, always keep an eye out for salvageable used wood. The quality of stock cut when the world was younger often exceeds that of anything commercially available today.

Metals
Steel
Steels are blends of iron with small amounts of carbon. They come in several grades, differentiated primarily by their carbon content and degree of work-hardening. For many musical applications, such as music wire, the highest grades of high-carbon, spring-tempered steel yield are often preferred. These are the hardest and strongest steels, with the least internal damping: they generally produce a very bright tone. For a rounder tone and less sustain, use a softer steel or use one of the other metals. Those softer steels are more commonly available — they're the stuff of steel reinforcement rods, metal conduits, threaded rods and household wires you see in hardware stores. For many musical purposes their warmer tone is more preferable. Stainless steel — a steel alloy containing chromium — can be made quite hard and is corrosion resistant, and so is good for outdoor purposes. For corrosion resistance in a softer, less expensive steel, use the commonly available galvanized steel, which is conventional steel with a coating of zinc.

Spring-tempered steel may be hard to find. You can get coils of music wire in a wide range of thicknesses from piano supply houses and some lumber suppliers. (See Sidebar 9-2 in Chapter 9 for a chart of standard music wire sizes.) You can get 3-foot rods in thicknesses ranging up to a quarter inch, still sold under the name "music wire," at many hobby and crafts shops. You can also look to industrial metals suppliers for further options. As well, you can salvage spring-tempered steel, or only slightly softer tool steels, from a variety of sources: clock springs, Victrola drive springs, spatulas, putty knives, the teeth of long-toothed rakes, hack saw or coping saw blades, hand saw blades and circular saw blades.

Brasses, Bronzes and Copper
Brasses are alloys primarily of copper and zinc; bronzes are copper and tin. They are slightly softer than the hardened steels, with a slightly warmer tone. These metals serve for strings on some instruments, and they are the metals most often used for bells, chimes, and gongs, as well as metal- phone bars in many parts of the world. Copper tubing is available in hardware stores; for other forms of copper, and for brasses and bronzes in general, look to metals suppliers and scrap yards. Find telescoping tubing for slides at some hobby shops.

Aluminum
Aluminum is softer still, and so produces the mellowest tone of the metals described here. Yet it can have excellent ring time. Thus it makes lovely chimes or free bars with relatively little clanginess. Look to metals suppliers and scrap yards.

Plastics, Synthetic Rubbers, Synthetics
As a rule, plastics do not have especially desirable acoustic qualities, but they prove useful now and then. Some of the very dense, highly rigid new synthetics have been favored for making the bodies of electric guitar-type instruments. Plastics can also serve as wind instrument tubes and the like, where the shape, mass and reflectiveness of the material matters, but internal acoustic properties do not. Hard plastics are commonly used for respectably playable but inexpensive student models in woodwind instruments.

Lots of experimental and homemade wind instruments are made of PVC (polyvinyl chloride), for the simple reasons that PVC tubing is functional, inexpensive, fairly workable, and widely available in a
range of diameters at hardware stores. On the downside, it is unattractive, doesn't clean up or take finishes well, becomes brittle if exposed to sunlight for long periods, and has toxic qualities mentioned earlier. ABS (acrylonitrile-butadiene-styrene) plastic, available in tubes and other forms at many hardware stores, is superior to PVC in its internal acoustic properties (greater resilience, workability and appearance).

You will find a few other plastic tubings at the hardware store as well, some of which are softer and more flexible than ABS or PVC. Plexiglass and related plastics are more attractive, but quite a bit more expensive. Plexiglass is available in rods, sheets, blocks and tubing shapes from retail plastics outlets like Taps Plastics, as well as industrial suppliers.

For plastics in shapes not commercially available, consider clear epoxy resins in a two-part liquid form that you can cast in a mold.

Synthetic rubbers are useful as mallet heads and occasionally for other purposes such as padding or damping. They have already spoken of rubber balls, as well as various foam rubbers, and the liquid rubber coating called Flexal-dip, all commonly available. In addition, specialized industrial supply outlets may have liquid rubbers in a two-part mix, made to be poured into molds, or ready-formed in sheets or rods. They come in a graduated range of hardnesses.

Styrofoam is an extraordinarily effective sound-radiation surface material. Styrofoam can be cut with a hack saw or a styrofoam cutter, or you can shape it by sanding. (A styrofoam cutter is nothing more than a heated wire which easily swims through the material. You can purchase one at low cost, or make one using batteries and a stainless steel wire.)

Similar rigid foams are used for insulation in building construction and are available at hardware stores in spray cans or in two-part mixes. With these, you can make molds to fabricate your own styrofoam shapes.

Glass, Ceramics and Stone

Glass is especially effective used as an initial vibrator in friction instruments. It also makes a nice-sounding marimba bar. Being rigid and brittle, glass tubes work well for wind instruments. It is not particularly effective as a soundboard material. It is fragile and not easily workable, but it can be cut (in straight lines) and, within limits, ground. The most resonant glasses seem to be the high quality quartz glasses, often called crystal, followed by lead glass, then soda-lime glass (the most common type), and, least resonant, Pyrex.

In contrast, the clay from which ceramics are made is infinitely shapable, making it especially valuable for oddly shaped wind instruments. As an initial vibrator, as with marimba bars, chimes, bells and the like, the tone of ceramic is somewhat damped but still appealing. Ceramics have been used for string instrument bodies and even soundboards with acceptable, though not spectacular, results — but this calls for exceptional skills on the part of the maker. There are many different clay formulas and firing techniques which affect the material's resonant qualities.

Instruments using stone as the initial vibrating element are called lithophones. Many different sorts of stone marimbas and chimes have been made, as well as some stone whistles. The resonant qualities of stone vary substantially from one sort to another; most are extremely dull, while some, like travertine marble, and some slates and volcanic rocks, produce a fairly bright tone quality.

Natural Materials

Bamboo and Other Hollow Stalks

Bamboo is an instrument maker's delight. The wood of a good bamboo is hard and strong, yet springy, and the tubular shape suits many musical applications. The tone quality of the wood itself tends to be bright, with clear pitch.

There are several species of bamboo. Of the main families, those of the Phyllostachys family produce fine, strong, hard woods in large sizes; the Arundinaria family produces good woods in smaller sizes; and the Bambusa family generally produces inferior woods. The largest varieties are Phyllostachys pubescens, commonly called "Moso," and Phyllostachys bambusoides, with stalks reaching maximum diameters of 6 inches or 7 inches.

Bamboo is very much liable to splitting with changes in humidity. Coat bamboo instruments inside and out with liquid rubber, or some other moisture-proof finish to retard moisture loss and prevent splitting.

Arundo donax, the same cane reed that is used for making woodwind reeds, is also useful for flute making. There are many other light vegetable stalks that are hollow and suitable for making a variety of flutes and whistles.

You can order cut bamboo in large and small diameters from suppliers listed under "Natural Materials" at the end of this appendix. Smaller diameters are often available at garden supply outlets.

Gourd and Calabash

The word "gourd" refers to a whole family of vine-growing plants, but it is the hard-shelled fruit of certain species that interests instrument makers. Gourds have been bred to grow in an endless variety of sizes and shapes, though dried gourds are light and somewhat fragile. The word "calabash" is sometimes used to refer to the same hard-shelled fruits, but more properly it refers to the fruit of the calabash tree. Calabashes are roundish in shape, heavier than gourds when dry, and incredibly hard and strong. Gourds and calabashes are ideal for producing sound chambers and radiating surfaces for instruments like strings, kalimbas, and drums. The incredible variety of gourd shapes means that they can also be useful as wind instrument tubes or ocarina bodies.

Calabash trees do not grow in temperate zones, but gourds grow well through most of the world, and it is a great pleasure to grow your own if you have a little earth. To prepare a gourd for musical use, the green gourd must, after harvesting, be hung up to dry for several months. If you are drying several, make sure they do not touch one another. Then it can be cut open (where you cut depends upon the final form you want) and the seeds and loose fiber removed. The inside should then be scoured with steel wool to prevent splitting.

Kelp can be found in great quantities washed up on the ocean beaches of the West Coast of North America, especially after a storm. Sometimes usable horns dry nicely on the beach, in exotic twisty shapes. You can order cut bamboo in large and small diameters from suppliers listed under Natural Materials at the end of this appendix, or from various sources advertising in the American Gourd Society's Newsletter.

Kelp

The seaweed known as giant bull kelp (mero cystis or macro cystis) is one of the few materials in which you will find a natural conical bore for wind instruments. The weed, which grows to astonishing lengths in the ocean, dries to form a hollow tube of uniformly expanding diameter, and even obliges wind instrument makers by providing a bulb at the larger end which can be cut off midway to leave a small bell. The dried kelp tube is light and fragile, but fairly rigid. It is easy to cut and drill, but not strong enough in itself for the attachment of key levers and such. Even so, for those who live where they can get their hands on it, it is a delightful resource for an experimental wind maker.

Kelp can be found in great quantities washed up on the ocean beaches of the West Coast of North America, especially after a storm. Sometimes usable horns dry nicely on the beach, in exotic twisty shapes, and you can just collect them. Alternatively, you can harvest fresh kelp and sun-dry it yourself. The key to doing this is to keep the entire plant intact, from the bulb to the root, until dry. If cut or punctured, it will collapse upon itself, and rot, and stink. Dried kelp is very much inclined to re-absorb water, so as soon as the kelp is dry, give it several coats of a moisture-resistant finish like polyurethane.

Hom, Bone, Shell and Hide

These various animal materials are available from suppliers in the list at the end of this appendix, or you may be able to scrounge them from butchers, slaughterhouses, zoos, or ranchers.

Horns from the main species of domesticated livestock — cattle and sheep — have been used for wind instruments since before the start of recorded history. They possess a natural conical bore; they are both strong and workable; and they can be polished to great beauty. Cow horns range roughly from 12 inches to about 20 inches, with a gently curved shape. Sheep horns cover a roughly similar range, but are curvy. Some other animal horns, such as antelope and gazelle, have also been used.

Many animal bones are long and hollow, and can be used for flutes. Some makers have also made bone marimbas, which are more interesting for their concept than for their sound. Leg bones from domestic livestock can be had without contributing to the demise of wildlife species. Hollowed tusks from elephants and other species have served for conical wind instruments, but severe trade restrictions, with good justification, have made it almost impossible to obtain usable tusks.

Eggshells from larger birds can make good ocarinas and whistles. Ostrich eggs are especially good for egg craft of all sorts. A typical ostrich egg is perhaps five inches in diameter and as thick and strong as fine china, with a lovely dimpled surface. The shell can be drilled or ground without fracturing. Ostriches are widely domesticated; their eggs are available and are not under trade restrictions.

Tortoise shell and armadillo shell have been used for sound chamber bodies, though tortoise shell is most useful.
Adhesives, Fillers, Finishes: The usual epoxies, wood glues and such serve their accustomed purposes in musical instrument making. Flexible glues, water-soluble glues, and glues that will yield to heat are favored for certain purposes, because they are undone later for repairs; they may be less prone to change when subjected to vibration; and they may allow free vibration. A couple of special products worth highlighting: 1) Autobody filler, sold at autoshops everywhere, has a thousand uses. 2) Non-ew-nyope epoxies are available; their ability to stay put while drying is valuable in some applications. 3) Hot glue is not very strong and makes an inlaid joint, but it is quick and convenient for casual or temporary purposes. The glue is a plastic that comes in the form of sticks that are loaded into a hot glue gun. The cost of the gun is not prohibitive. 4) For wind instruments made of wood, dependably water-resistant glues are called for. Marine-grade adhesives such as Weldwood Resorcinol™ will serve. But avoid toxic adhesives where there will be oral contact.

Regarding varnishes and other finishes for musical instruments — there is a lot of folklore on this subject, much of it pretty silly in my view, especially regarding violin varnishes. I will avoid the controversy and simply say that conventional and widely available finishes work just fine in most musical instrument applications. One special case: mouthpieces for wind instruments must be left unfinished or else finished with something non-toxic. Options for wood include mineral oil, walnut oil, and mixtures of such oils with paraffin or beeswax. Such mixtures are sometimes sold at housewares stores as salad bowl finish.

Balloons: Useful in a million ways, as described in earlier chapters. Variety stores only often have balloons in small sizes, made with thin latex. Go to a party store or a toy store for a wider selection. Sometimes you can get giant weather balloons in surplus, made of a similar latex, but in sizes up to six feet in diameter.

Corrugated Tubing: Essential for corrugated tubing. The stuff sold as hot water flex pipe doesn’t work well. (The corrugations are too shallow.) Use the more deeply ridged gas-heater hose, available at hardware stores. Various plastic flextubes also work as well or better, except that they tend to turn up in diameters too large for blowing. Corrugated plastic tubing is often available through surplus outlets.

Elastics: Latex rubber bands age badly, especially if stretched for a prolonged period of time. For long term applications, use elastic straps purchased from fabric stores, or bungee chords. They, too, do poorly under continuous stretching, but they outlast rubber bands. Surgical latex rubber tubing, available from medical supply stores, serves well in many applications. Where rubber bands are what you want, they can be obtained (sometimes on special order) in a great range of sizes from office supply outlets and from surplus outlets. Whatever the elastic material, many wraps of loosely stretched bands will perform better and outlast a few wraps of tightly stretched bands.

Foam Rubber: Useful for many applications in padding, sealing and insulating. Hardware stores and auto parts stores have adhesive-backed weatherstripping in a variety of densities, widths and thicknesses. For most applications in musical instruments, the dense, closed-cell neoprene weather stripping foams are much more preferable to the softer open-cell foams that don’t spring back after squashing. Larger foam pieces, like those used in mattresses and pillows, are available in various densities from various places you can find in the phone book. Industrial surplus places may have a variety of foams or solid rubbers in sheets of various thicknesses, often adhesive-backed.

Grease: Useful for lubricating and improving the seal on all sorts of sliding stoppers. Don’t use margarine; use lithium grease, available as bearing grease from auto supply stores.

Inner Tubes: Useful either for latex or as padding material. You can get used inner tubes from garages and bike shops.

Monofilament Nylon Line: Useful as musical instrument strings, imitation bow hair, and for other purposes. Use nylon intended for musical instrument stringing where possible; it is stronger and less stretchy. Otherwise, go to nylon fishing line. For large-diameter nylon, similar to the unwound gut bass strings of old, try weedwacker line, sold at hardware stores and sometimes available as surplus. For very fine nylon, as for bow hairs, use nylon thread, available at fabric stores and sewing centers.

Surgical Rubber Tubing: Soft latex tubing, useful for various padding, insulation and elastic stripping purposes; available from medical supply centers.

Velcro: A thousand and one uses. Available from fabric stores at high prices, or from industrial surplus places in quantity for much less.

**Sources**

Here are some ideas on where to get what. Send a large, self-addressed, stamped envelope when you write for catalogs or information from any of the vendors listed; that saves work for the vendor, and will get you a quicker response.

**Local Sources**

Neighborhood Retail Outlets: Hardware stores, fabric stores, auto supply stores, hobby and crafts shops, toy stores, music stores, and variety stores (K-mart) have many of the things instrument builders seek, at great convenience. Prices may be higher than what you’d pay via second-hand scrounging or discount mail order.

Lumberyards, Metals Suppliers, Plastics Outlets: These are basic sources for raw materials, but they don’t always stock the specialty items that instrument builders crave.

*Scrap Yards:* Here you will find all kinds of metals. If you are searching for something in particular, it is a matter of luck whether you will find it. If you go there looking to be sonically inspired, you will be inspired.

Flea Markets, Pawn Shops, Junk Yards: Important sources for used and junked instruments which you will get you a quicker response.

**Specialty Stores**

There are several stores specializing in unusual and hard-to-find instruments and accessories, and that do much of their business by mail order. Here are some of them:

- All Music College of Music Stores, 215 West End Ave., San Rafael, CA 94901
- Andy’s Records, P.O. Box 307, Voorheesville, NY 12186
- Anyone Can Whistle, A Catalog of Musical Discovery, Box 4407, Kingston, NY 12401
- Earthshaking Percussion, 900 Moreland Ave., Atlanta, GA 30316
- Elderly Instruments, 1100 N. Washington, P.O. Box 14210, Lansing MI 48901
- The Folk Music Center, 220 Yale Ave, Claremont, CA 91711
- The Lark in the Morning, P.O. Box 1176, Mendocino, CA 95460
- Luthier’s Mercantile, P.O. Box 774, 412 Moore Lane, Healdsburg, CA 95448
- Musicmen Kits, PO Box 2117, Stillwater, MN 55082 (specializing in buildable kits for unusual instruments)
- Musicmakers Kits, PO Box 1176, Mendocino, CA 95460
- Anyone Can Whistle, A Catalog of Musical Discovery, Box 4407, Kingston, NY 12401
- Andy’s Front Hall, P.O. Box 307, Voorheesville, NY 12186
- Interstate Music Supply, P.O. Box 315, 13819 West National Ave., New Berlin, WI 53151
- Lark in the Morning, P.O. Box 1176, Mendocino, CA 95460
- Luthier’s Mercantile, P.O. Box 774, 412 Moore Lane, Healdsburg, CA 95448
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- Luthier’s Mercantile, P.O. Box 774, 412 Moore Lane, Healdsburg, CA 95448
- Musicmen Kits, PO Box 2117, Stillwater, MN 55082 (specializing in buildable kits for unusual instruments)
For natural drumheads, pre-cut to various sizes, with or without hoops —
United Rawhide Mfg. Co., 1644 N. Ada St., Chicago, IL 60622

Natural Materials

Here are some sources for shell, bone, gourd and the like:
Boone Trading Company, 562 Coyote Road, Brinnon, WA 98320 (tusk, bone, shell, ostrich egg, horn, turtle shell, etc.)
Teddy Leather Company has stores in cities across the U.S. and will also sell by mail. One store location is 116 W. 25th Ave., San Mateo, CA 94403 (long horn and steer horn)
Eastern Star Trading Company, 624 Davis St., Evanston, IL 60201 (with additional outlets in California, Florida & Washington) (bamboo)
The Gourd Factory, P.O. Box 9, Linden, CA 95236 (dried gourds)

Industrial Supply and Surplus

This company, which sells primarily to industry, has the most complete inventory of hardware items and raw materials you will find anywhere:
McMaster-Carr & Company, P.O. Box 4355, Chicago, IL 60680-4355

If you haven't browsed through the American Science & Surplus catalog, you're missing all the fun. An incredible potpourri of useless junk, much of which turns out to be just what you didn't know you needed.
American Science & Surplus (formerly Jerryco), 601 Linden Place, Evanston, IL 60202

Another surplus catalog, with more emphasis on electronics:
Herbst and Rademan, 16 Canal St., P.O. Box 122, Bristol, PA 19007-0122

Software

Stringmaster, available from Mark Bolles, 1405 Little Leaf, San Antonio, TX 78247. This is a string scaling package, allowing you to calculate suitable string lengths, diameters, materials and tensions for different applications. For IBM compatible computers.
Just Intonation Calculator, available from Sound Scape Productions, 1071 Main St., Suite 1, Cambria CA 93428. Performs a wide variety of calculations for composers and theorists in connection with just intonation, with internal sound for tuning reference and ear training. Also sends MIDI tuning dumps to many different types of synthesizers. For Macintosh computers.
Microtonal MIDI Terminal, available from The Southeast Just Intonation Center, P.O. Box 15464, Gainesville, FL 32604. Just intonation calculations with MIDI synthesizer re-tuning capability. For IBM compatible computers.
Appendix Two
FREQUENCY AND TUNINGS CHARTS

This appendix contains two charts designed to map out the territory of the audible sound spectrum. It supplements information in Chapter 3, “Tuning Systems and Pitch Layouts.”

FREQUENCY CHART

The chart on the following two pages shows the pitch name, frequency, wavelength, and musical staff notation for frequencies within the hearing range. It uses several standards and conventions addressed in the following paragraphs.

Pitch Names

There is substantial agreement in western musical practice as to how to name the pitches within the octave, using the familiar note names C, C#, D and so forth. But distinguishing between like-named pitches in different octaves remains confusing. Quite a few systems have been used to give each pitch a unique label. The one given in the left hand column of this chart, using capital letters with subscripted numerals to denote octaves, has become the most commonly used among acousticians; it has been accepted by the American Standards Association; and it is the one we have used throughout this book. In the adjacent column the chart gives note names according to the Helmholtz system, since this system appears in widely used musical sources such as Grove’s Dictionary of Music and Musicians.

Pitch Standards

The frequency of A above middle C is normally used as a benchmark for fixing musical pitches to a standard. Over the centuries the frequency of that A has ranged from below 400Hz to 455Hz and higher. The International Organization for Standardization has set the modern pitch standard at A=440Hz (1955; reaffirmed in 1975), and this chart is predicated upon that standard.

Just vs. Tempered Tunings

The chart presents frequencies for pitches in 12-tone equal temperament, despite calls from many thoughtful musicians to lessen the dominance of 12-equal. The reason for using 12-equal here is that it presents a familiar frame of reference, while the just systems in use are too diverse to allow for standardized presentation. (The scales chart following this one presents a better picture of just relationships.)

Sharps and Flats

To keep the chart to a manageable size, only the “natural” notes are given. Instructions for finding frequencies and wavelengths for the sharps and flats appear at the end of the chart.

Air Temperature

The wavelengths are accurate for typical room temperature conditions. Instructions for estimating wavelengths at other temperatures, including the slightly elevated temperatures typical in breath-blown wind instrument tubes, appear at the end of the chart.

COMPARATIVE TUNINGS CHART

Following the frequency chart is a comparative chart of tuning systems, showing how various musical scales compare to the most basic just intervals, to the familiar intervals of 12-tone equal temperament, and to one another. It contains the historical European quarter-comma meantone scale system; three raga tunings and blues intonations as representatives of tunings outside the European tradition; Harry Partch’s “monophonic fabric” as a model of the work of a 20th-century theorist; plus a couple of higher-order equal temperaments.

The chart presents pitch relationships only. Intervals between pitches are shown, but actual frequencies are not specified. For comparative purposes, all the tuning systems are built over a common, unspecified root tone.

Each tuning appears on the chart as a ladder, with the pitches laid out in ascending order, spaced vertically according to interval size. Each tuning is given over a range of one octave. (The one-octave range is adequate if you assume that the same set of intervals are to be duplicated in other octaves. That is true of most tuning systems, though not all.) To help demarcate the tonal territory, horizontal reference lines cross the entire chart at heights corresponding to certain basic just intervals: the major second 9:8, the major third 5:4, the perfect fourth 4:3, the perfect fifth 3:2, and the major sixth 5:3. The pitch locations are marked by a short, bold horizontal line across the ladder. In cases where the scale degrees are flexible or ambiguous, the stippling within the ladder indicates the relevant pitch regions. The notations surrounding each scale degree are as follows:

1) For tunings based in just intonation, ratios appear to the left of each scale degree mark. The ratio represents the frequency of the given scale degree over the frequency of the scale’s first degree. It is the number by which the frequency of the first scale degree must be multiplied to obtain the frequency of the higher degree in question.

<table>
<thead>
<tr>
<th>Scale Degree</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>1:1</td>
</tr>
<tr>
<td>C#3</td>
<td>9/8</td>
</tr>
<tr>
<td>D3</td>
<td>5/4</td>
</tr>
<tr>
<td>E3</td>
<td>4/3</td>
</tr>
<tr>
<td>F3</td>
<td>3/2</td>
</tr>
<tr>
<td>G3</td>
<td>5/3</td>
</tr>
</tbody>
</table>

FREQUENCY, PITCH, AND WAVELENGTH
Ragas are more than scale systems. Each raga has diverse musical and extra-musical associations, which of course are not reflected on the chart.

The pitch set associated with a particular raga may have five, six or seven tones. Frequently, however, the tones are not discreet, but rather very subtle, so much so that an entire region may be one of sliding pitch, with no recognizable resting point at all. As with the blues, the flexible tones within the raga are indicated on the chart as gradations rather than fixed points.
There is much to be said for letting quiet instruments be quiet, and simply learning to listen. Still, there are occasions when quiet instruments need amplification if they are to be heard. There are three steps in the electronic amplification of acoustic sound instruments. 1) As raw material, you have the sound of the instrument — vibrations in the body of the instrument or the air it encloses, which are radiated into the atmosphere. The first step is to take the movement patterns of these vibrations and convert them into analogous patterns of alternating voltage. That is the job of the transducer — the microphone or pickup. 2) Step two is to take the patterns of alternating voltage, called the signal, and make them stronger — amplify them — without distorting the pattern. This is the job of the amplifier. 3) Finally, the amplified electronic signal must be converted back into sound in the air. This is the job of the loudspeaker. Through the electromagnetic effect associated with the movement of current in a wire, the amplified signal drives the speaker cone in a pattern of movement that, ideally, replicates the original vibration. The speaker, in turn, drives the surrounding air.

**Stages and Three** — the amplifier and speaker — are generally the province of commercial electronics manufacturers. In most cases all the instrument maker does is to try to get hold of decent equipment. But in stage one — converting the physical sound into an electronic signal — the instrument maker has some real choices. Let us consider the options. Discounting some exotic technologies that remain on the horizon, there are three practical possibilities.

**Air Microphones**

By “air microphone” I refer to the standard microphone, which you place in front of a sound source to pick up the sound. The mic responds to the same vibrations in the atmosphere that the ear does, converting them into minute fluctuations of voltage. There are several types of microphones with different mechanisms for picking up and converting atmospheric vibrations, the two most widely used being condenser microphones and dynamic microphones. Condenser microphones tend to have a brilliant tone with well-defined transients, working particularly well on plucked string instruments, percussion, and other sounds that benefit from precision, clarity and definition. Dynamic microphones tend to give a warmer feeling and do well with voices, many wind instruments, and other sounds that benefit from a sense of fullness or richness of tone. Dynamic microphones as a rule are also less expensive and more rugged than condenser mics.

Some microphones, called omnidirectional mics, respond equally to sound from all directions. Others, called cardioid mics, are designed to pick up preferentially sounds from sources located in front of the mic. All mics, but especially omnidirectional mics, are prone to feedback. Feedback occurs in any amplification system when the output finds its way back into the input and cycles through again, only to be picked up by the input again. With microphones, for instance, the sound from the speakers is picked up by the mic, re-amplified and sent to the speaker again, only to be picked up by the mic once more, creating a vicious circle that results in unwanted squealing or whistling from the speaker. Cardioid mics can be aimed away from the speakers, mitigating the feedback problem to some degree.

**Advantages of Air Microphones**

Air microphones can be used with any audible sound source.

- **Air mics aren’t very selective:** they pick up whatever extraneous sounds are present in the surrounding air along with the sounds of the intended instrument.
- **It is difficult to build an air mic into an instrument:** For the best sound they usually need to be held on a separate stand in front of the instrument (more on mic placement in a moment).

Air mics, as mentioned before, are prone to feedback. Mic placement and orientation can help control the problem, but this can inhibit the player’s positioning and movement.

**Tips for using air mics:**

- **Microphone placement is an art and a science:** sound technicians make a lifetime study of it. But as the maker of an instrument, you have the advantage of having a good sense of which aspects of the instrument’s sound you wish to emphasize or balance, and where along the body those sounds emanate most strongly. For instance, on a plucked string instrument with a soundbox, you have the air resonance from within the soundhole, the plucking noise coming directly from the strings, and the tone coming off the front of the soundboard. All play a part in a full, yet bright and well defined composite tone. Don’t tape a small air mic inside the soundhole (as is sometimes done); you will get too much air resonance for a boomy, muddy tone. Place the mic in front of the face where it can pick up all the components, angling it slightly this way or that to emphasize different components according to your taste. Alternatively, in some cases you will find that a more natural sound comes not from a close mic, but a more distant mic positioned to pick up a natural blend of the instrument’s sound components, along with some room reverberation. (Distant miking has the disadvantages, however, of picking up more extraneous noise and producing a weaker signal.) If circumstances allow, do both: use a close mic for clarity and a distant mic for balance and added room resonance.

Feedback is not a big problem in the recording studio, because it is not necessary to boost the volume to high levels in the recording chamber. It is more of a problem in performance situations demanding high volume. To minimize feedback problems, avoid positioning mics too close to speakers, and aim directional (cardioid) mics away from them. Watch out for solid walls that will reflect speaker sound directly back at the mics. Use equalization (electronically filtering selected frequency ranges) to reduce the effects of disproportionately strong resonances at specific frequencies in the room or in the instrument itself.

**Contact Microphones**

Contact microphones take advantage of the piezo-electric effect. Piezo-electric crystals are chemical structures which respond to changes in pressure by producing a tiny fluctuation in electric voltage. Subjected to a vibratory movement, they produce an alternating voltage which is, ideally, analogous to the vibratory pattern. This signal can be sent to an amplifier and speakers just like the signal from a microphone. The piezo-electric contact mic is attached directly to the body of an instrument so that it can respond to the vibratory movement. It can be attached permanently or stuck on temporarily.

Notice that acoustic sound in the atmosphere, such as a listener in the room would hear from the unamplified instrument, is not the part of the equation here. What gets amplified is the vibration pattern at some specific location in the solid material of the instrument, not the sound in the air. In instruments for which air resonance has a role to play, the air resonance tone is lost on the contact mic. So is the blend of sound radiating from different parts of the instrument’s surface. As a result, contact mics tend to have a sound which, speaking subjectively, is unnatural and (to this critic’s ear) not especially appealing. Various tricks have been used to compensate. These include placing multiple contact mics at carefully selected locations, using compensatory electronic equalization or other electronic signal processing to recreate a more natural sound, and using contact mics in conjunction with air mics.

**Advantages of Contact Microphones**

Contact mics are convenient and unobtrusive, since they can be attached directly to an instrument, or simply built in. They are conveniently compact, too.

Contacts mics are far less subject to feedback than air mics. They can feed back, however, especially when attached to soundboards, as they often are. (The sound from the speaker drives the soundboard, where the contact mic picks it up once again to complete the feedback loop.) The problem lessened considerably when the contact mic is attached to something heavier than a soundboard. They can be used for instruments having strong vibrations in the body, but which don’t radiate well to the surrounding air. In fact, they can be used in place of soundboards or other sound-radiating mechanisms, simplifying the instrument design and construction process considerably. Designing an instrument this way — e.g., designing a string instrument with a rigid body but no soundboard — can allow for longer sustain in sounds such as plucked strings, since energy need not be dissipated in radiation to the air.

**Disadvantages of Contact Microphones**

They can’t be used very well with aerophones, since they need some solid vibrating body to attach to. In instruments with solid vibrating bodies but air resonance as well, they pick up the body sound but miss the air resonance entirely.

They tend to yield an unnatural and often unattractive sound.
While contact mics pick up relatively little unwanted room sound, they may produce an exaggerated and disconcerting response to any unintentional knocking or scraping on the body of the instrument. Tips for using contact mics:

The key question for any given instrument is where to attach the contact mic. It should not be attached where it will inhibit the initial vibration. This generally means that it must be attached where impedance is high enough that the vibration will not be significantly affected by the added weight. Thus, for string instruments it cannot be attached directly to the string, but may be attached or built into the bridge, or somewhere on the soundboard, or even at the headstock or along the neck. For heavier initial vibrating bodies such as chimes or marimba bars, where the impedance is high to begin with, it may be acceptable to attach the contact mic directly to the initial vibrator. In special cases where you wish to bring out a particular mode of vibration or de-emphasize another, and you can locate the nodes and antinodes on the vibrating body, then you should attach the contact mic as near as possible to an antinode (point of maximum vibration) for the desired modes, and as near as possible to nodes for the unwanted ones. In most cases, however, the situation is not so clear cut, and then experimentation is the key. Apply the contact mic at different points, play, and listen. Consider using two or more at different locations and mixing their signal. This leads to varying degrees of cancellation between out-of-phase signals, but you may get lucky and find just the blend you want.

**ELECTROMAGNETIC PICKUPS**

Electromagnetic pickups are the sort used on electric guitars. More generally, they can be used in any application where the vibrating body is of a ferrous metal, which is to say, any metal that is responsive to magnetism. In addition to steel strings, electromagnetic pickups have been used with the steel tines of kalimbas, various sorts of chimes or forks in electric pianos, and so forth. They work on the principle of magnetic induction. Movement of a magnet near to a loop of conducting wire will induce a tiny current in the wire. Electromagnetic pickups contain windings of a great many loops of fine copper wire wrapped over a bar magnet, so that the movement of magnetic materials in the vicinity alters the magnetic field and induces a current in the coils. If the movement is, say, that of a vibrating string, the induced current will be an alternating current in a pattern analogous to the vibratory movement. This signal can then be sent to an amplifier and speaker for a sound corresponding to the initial vibration.

As with contact mikes, what one ultimately hears from the pickup is not a reproduction of a sound in the air. It is a direct transduction of the string's movement. Radiation from the instrument to the atmosphere plays no significant role; air resonance plays no significant role; and the acoustic properties of the body of the instrument play a relatively small role.

Electromagnetic pickups are subject to electromagnetic interference from outside sources, which adds an unwanted hum to the tone. The hum can be greatly reduced by using two coils wired together in a particular way. These dual-coil pickups are called "humbucking" pickups. Their tone tends to be fuller and darker, while single-coil pickups are clearer and brighter in sound.

Advantages of electromagnetic pickups:

- While their tone quality is quite different from that radiated to the air by an acoustic instrument, electromagnetic pickups give a relatively undiluted transmission of the initial vibratory movement, often resulting in a subjectively pure sound that can be appealing.
- Feedback problems with electromagnetic pickups are minor. At the same time, in some applications electromagnetic pickups allow for a relatively controlled form of feedback that can be cultivated to good effect.
- Electromagnetic pickups pick up almost no unwanted sound, responding exclusively to the movement of the instrument's intended initial vibrating elements.
- Electromagnetic pickups can be conveniently and unobtrusively mounted on the instrument.

By positioning the pickup at different locations relative to the vibrating body, you can emphasize different modes of vibration, and obtain a variety of tone qualities. By using multiple pickups in different locations, you can make these different timbres available at the flick of a switch.

As with contact mics, electromagnetic pickups can be used with instruments which radiate poorly to the air, and can make radiation systems such as soundboards unnecessary. Without the need to dissipate energy through radiation, such instruments can be designed for longer sustain in sounds that would otherwise decay rapidly (e.g., plucked strings).

Disadvantages of electromagnetic pickups:

- They work only with initial vibrators of steel or other ferrous metals.
- They do not reproduce the instrument's natural sound as radiated into the room. Acoustic qualities of the body of the instrument and air resonances are largely lost.

**ADDITIONAL NOTES**

All three of the transduction methods described here produce a very weak output signal commonly called "mic level." (One exception: some electromagnetic pickups may produce a signal substantially stronger than typical mic level.) Mic level signals must initially be sent to a pre-amp, which boosts them to a higher level of signal strength referred to as "line level." The line level signal is then sent to the main power amp. Most amplifiers have pre-amps built in. An amplifier's input jacks labeled "mic" will route the signal through the pre-amp. Those labeled "line" or "tape" (along with a few other designations) are intended for signals already at line level and are wired to bypass the pre-amp.

Very few home builders attempt to make their own contact mics or air microphones; they buy them from electronics manufacturers. Some electric instrument builders do like to make their own electromagnetic pickups, particularly in cases where the size and shape of commercially available pickups isn't suitable for the intended instrument. Pickup winding by hand is a time-consuming task, and it is difficult to produce results as good as even modestly priced commercially made pickups. For more on pickup winding, look to one of the books on the subject, such as Donald Brosnac's Guitar Electronics for Musicians.
**Appendix Four**

MORE ON AIR COLUMNS, TONEHOLES AND WOODWIND KEYING MECHANISMS

This appendix contains technical information on wind instruments and their construction, with an emphasis on calculation of air column lengths and their frequencies, tonehole sizing and placement, and tonehole keying mechanisms for woodwinds.

**Calculating Effective Air Column Lengths & Frequencies**

To a first approximation, the wavelength for the fundamental resonance in a conical tube or an open cylindrical tube is twice the tube length. For a cylindrical tube stopped at one end, it is four times the tube length. (See Figures 6-14 through 6-16.) You can determine the frequencies and sounding pitches for these wavelengths by referring to the wavelength chart in Appendix 2. However, in practice, wind instrument tubes consistently behave as if they were slightly longer than they actually are. Some of the factors involved vary from player to player and cannot be quantified, while others are more predictable. The following paragraphs will help you to estimate actual effective lengths, given these secondary effects.

**End Corrections**

One reason wind instrument tubes behave as if they were longer than they actually are is that the standing wave within extends a bit beyond the open end. The amount of the extension varies with frequency and with the diameter of the opening. For practical purposes, this end correction factor can be approximated in a simplified fashion as \( e = 0.3d \), where \( I \) is the end correction and \( d \) is the tube-opening diameter. Thus, the approximate effective length of a tube open at one end is

\[
L_e = L + 0.3d
\]

where \( L \) is the actual tube length and \( L_e \) is the effective length. For a tube open at both ends, you need to apply the correction twice, which comes to:

\[
L_e = L + 0.6d
\]

**Effects of Mouthpiece Cavities**

On many wind instruments, the shape of the mouthpiece causes the overall tube shape to deviate from the ideal conical or cylindrical form. For instance, on conical brass instruments, where the apex of the cone should be, there is instead a definitely un-conicalike appendage (the mouthpiece). You can minimize the ill effects of distortion of tube shape at the mouthpiece by thinking in terms of equivalent volumes as shown in Figure 12-1, if the mouthpiece encloses the same total volume of air that the cutoff portion of the cone would have, then the overall air column will show resonance peaks at frequencies close to those that the complete cone would have. The desired tunings and overtone relationships will be roughly preserved. An imperfect missing-apex volume match can lead to serious mistuning in the upper frequencies.

To apply the same reasoning to cylindrical instruments, think of the length of additional cylindrical tubing that would have the same volume as the actual mouthpiece. The resonance of the overall air column will correspond roughly to the volume of the basic tube with this equivalent-volume length added in place of the mouthpiece.

These equivalent volume calculations are most accurate at lower frequencies. At higher frequencies, where upper partials come into play, the situation is more complex.

In determining the mouthpiece volume to be used in finding these equivalences, you may also need to take into account the fact that the elasticity of a reed or lips applied to the mouthpiece can cause the mouthpiece to behave as if it is longer than it is—in other words, the effective mouthpiece volume may be greater than the measured physical volume. The softer the reed or lips, and the greater their surface area over the mouthpiece, the greater is this effect.

Aside from equivalent volume considerations, a mouthpiece may still have its own independent higher frequency resonances, as the peculiarities of its shape enhance or inhibit specific frequencies. Small differences in mouthpiece shape make a big difference in overall instrument sound.

**Irrregularities in Air Column Shape, and a Remedy for Flat Upper Registers**

Bulges or constrictions along an air column affect its resonance frequencies. The effects depend upon the size, shape and location of the irregularities. Figuring these effects out in detail is a rather subtle business, but we can make a couple of useful observations. First, let us note that a common perturbation is caused by the small cavities along a tube's length within closed toneholes (for instance, the little bit of extra space along the side of a clarinet tube under a closed key pad). While the specific effects on different resonances vary, the presence of closed toneholes above the first open hole will usually tend to lower the sounding pitch slightly.

Second, let's highlight one particularly useful air column irregularity effect. For various reasons, wind instruments have a tendency to be flat in the upper registers. You can counteract this problem by modifying the tube shape in a way that has a slight lowering effect on higher frequencies, and progressively less effect on lower frequencies. This can be achieved through a slight taper toward the blowhole end. For example, an effective taper for a simple flute might be a gradual reduction in tube diameter starting at a point about 1/5 of the total tube length from the blowhole end and reaching a total reduction of about 10% by the time it gets to the stopper just beyond the blowhole (Figure 12-2).

**Tonehole Location and Sizing for Wind Instruments**

It is difficult to use prescriptive mathematical methods to determine precisely the correct tonehole sizes and locations to produce particular pitches for tubular wind instruments. (Mathematical models do exist, but they aren't easy to apply.) But it is possible to arrive at acceptable approximate locations for desired pitches, and then to fine tune by adjusting the tonehole size.

Chapter 6, "Aerophones," describes the process of fine tuning through hole-size adjustment. Here are guidelines for tonehole location, followed by guidelines for register holes.

**Toneholes**

Imagine that you want to know where to place a tonehole so as to produce a particular pitch in a tubular wind instrument. You can begin by making a preliminary location assessment based upon the simplifying assumption that hole diameter is to be as large as the tube diameter. Were this assumption true, it would mean that the hole could be located at the same point where the tube would be cut off to produce the same pitch. You can figure out where this point would be by either of the two ways described in Chapter 6: 1) if you know what absolute pitch you want, then you can calculate the tube length needed to produce the wavelength for that frequency. 2) if you are more concerned about relative pitch within the instrument than absolute pitch, you can figure it based upon the frequency ratio of the desired tone to the
Principles for Wind Instrument Design

One final note: Formulas designed to yield exact hole sizes and location for specific pitches in wind instruments have been created by researchers including Douglas Keefe, John Coltman, and the late Arthur H. Benade. The best of these formulas yield good results in many situations, and better-than-nothing results in difficult situations, such as those with serious mouthpiece biases. The formulas are too complex for inclusion in this text. For more information see the booklet "Air Columns and Toneholes: Principles for Wind Instrument Design" by Bart Hopkin (distributed by Tai Hei Shakuhachi, PO Box 294, by Bart Hopkin (distributed by Tai Hei Shakuhachi, PO Box 294,}

If your initial hole location estimates are good, you will end up with holes of roughly the same size on cylindrical tube instruments, or holes that uniformly increase in size for conical tubes. Instruments in which hole sizes vary in an irregular manner will be uneven in tone quality from one note to the next.

End correction effects play a role here as well, making the air act as if the hole were slightly deeper than it actually is. To compensate, move the theoretical hole location up the tube by an amount slightly more than the hole depth.

Many large closed-tonehole cavities above the first open hole → slightly larger tonehole correction.

This effect is somewhat variable but, on balance, closed toneholes located above the tonehole in question tend to lower the sounding pitch slightly if those closed holes are large and deep. Compensate by shifting the theoretical location up the tube slightly for those holes that will have closed toneholes above.

4) Additional open toneholes below the first open one → smaller tonehole correction.

When there is another open tonehole below the primary tonehole, the additional opening has an effect similar to making the primary hole larger. This counteracts the pitch-lowering effects of factors 1 - 3 above, so: where there will be additional open tone holes below the one in consideration, accommodate by reducing the upward displacement suggested by the other factors.

Where the primary hole is quite large — say over 75% of the tube diameter — the presence of additional lower open tone holes makes relatively little difference. But when the primary hole is small, the additional opening afforded by one or more open toneholes below is significant. This can be summarized in the following subsidiary rules:

a) The smaller the primary hole, the greater the reduction of the tonehole correction factor due to additional open holes below.

b) The larger and/or nearer the additional open tone holes, the greater the reduction of the tonehole correction factor.

A useful sidelight: While there are many advantages to large toneholes, small holes have the advantage that they make cross fingerings possible. Cross fingerings are fingerings which leave one open hole but cover the next, in order to obtain a slightly lower pitch. As indicated above, covering the next hole below the primary open hole doesn’t have the required pitch-lowering effect if the holes are very large. Cross fingerings may seem awkward in a way, but they do allow a greater number of pitches with fewer holes than would be the case if each pitch demanded its own separate hole.

Even with the help of these rules, trial and error will continue to play a substantial role for most builders, along with a generous dose of after-the-fact fine tuning through hole-size adjustment. Especially difficult are instruments in which strong biases at the mouthpiece distort the expected air column resonances. In such cases, end results often turn out to be very different from even the best predictions.  

1) Smaller hole → larger correction.

This is the most significant factor. A smaller hole lowers the pitch. To compensate, shift the theoretical location up the tube (toward the mouthpiece). How much to shift depends upon how much smaller than the main tube diameter the hole is to be. The smaller the ratio of the hole diameter to the tube’s internal diameter at the hole location, the greater the hole’s displacement toward the mouthpiece.

2) Thicker hole → larger correction.

The tube wall has some thickness, and the hole correspondingly has some depth. In addition, you might intend to build up the tube wall a bit to make a good seating for finger or key pad, making the hole deeper. That hole depth functions like a bit of additional tube length, lowering the pitch relative to the predicted value. End correction effects play a role here as well, making the air act as if the hole were slightly deeper than it actually is. To compensate, move the theoretical hole location up the tube by an amount slightly more than the hole depth.

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Register Holes

A register hole usually takes the form of a small hole rather closer to the mouthpiece than the far end, which remains open the entire time the instrument plays in the upper register. There may be one all-purpose register hole on an instrument, or two or three on a single instrument, designed for different registers or different portions of different registers. Or, as is the case with flutes and recorders, one of the regular tone holes may double as a register hole.

Register holes work by inhibiting the lower mode of vibration that would normally dominate in the tube, allowing an upper mode to sing out as the predominant tone. Here’s how: the register hole is located at a point of substantial pressure variation for the lower mode. When the hole is closed, the air column vibrates normally, with that lower mode predominating. But when the hole is open, it creates a leak at a point where the periodic pressure build-up is essential to maintain the lower mode oscillation. The leak undermines the pressure build-up and inhibits the lower mode from sounding. Yet it has no such effect on any mode that happens to have a pressure node (point of minimum pressure variation) at that point. Higher modes meeting that description remain free to sound. The trick, then, is to locate the register hole at a point of substantial pressure variation for the lower mode(s) you wish to eliminate, yet near to a pressure variation minimum (a node) for the mode you want to bring out. Figure 12-4 shows the ideal locations for a register hole designed to throw the instrument into the second register for the three most common basic tube types.

Notice that the locations indicated in Figure 12-4 are ideal for a tube with no other open tone holes. If you open toneholes along the tube, you shorten the effective wavelength, moving all the nodes and antinodes farther up the tube. The register holes will then be misplaced. It seems to follow that you need a new, precisely located register hole for every note of the lower register. That would indeed be ideal, but real-world musical instruments get by with much less. When the register hole is slightly removed (but not too far) from the ideal location, it still has the effect of inhibiting the lower mode a good deal more than it inhibits the upper, and the air column remains more inclined to set up a strong vibration in the upper mode than the lower. And so a compromise position for the register hole can usually be found which will be OK, though perhaps not great, over a substantial part of the range. Misplaced register holes cause a small amount of detuning; that’s part of the compromise.

For a reasonable compromise location, place the register hole near the ideal location for some representative pitch near the middle of the range over which the register hole is to apply. This means moving the hole some distance up the tube (toward the mouthpiece) from the ideal whole-tube location suggested by the diagrams in Figure 12-4.

TONEHOLE KEYING SYSTEMS

When toneholes are too big or too far apart to be covered by fingers, keys are needed. Elements of a typical tonehole key are: 1) the head of the key, usually flat and round and slightly larger than the hole, made to close down over the hole; 2) the pad, covering the underside of the head and allowing the head to seal silently and leaklessly over the hole; 3) some sort of arm or lever, with the head at the end, which may incorporate a pivoting or fulcrum arrangement; 4) some kind of spring to keep the key open or closed (as the case may be) when not activated by the player.

The key must dependably come down squarely over the hole. Any tilting or misalignment virtually assures that there will be leakage. For this reason, the components of the key must be sturdy, well designed, and made to close tolerances. Tonehole key making in all but the most rudimentary applications is a difficult and exacting business; that is why casual home builders don't often get into it. But a casual builder may be able to equip an instrument with one or two simple lever-operated keys for out-of-reach toneholes. Some simple, home-buildable approaches to key-making appear in Figure 12-5, and the following notes provide further information.

About tonehole key pads: The softer the pad, the more readily it accommodates irregularities in the hole rim, and compensates for any misalignment in the angle at which the pad comes down over the rim, making for a leakless seal. But the surface of a soft pad also contributes to damping, and many soft pads of large surface area covering the holes undermine tone quality. You can purchase keypads ready-made in a range of sizes from woodwind manufacturers and band instrument repair places. Alternatively, you can make your own pads from leather, thin sheets of soft rubber or foam, or whatever else seems to serve the purpose.

Normally open vs. normally closed: You can make tonehole keys that automatically remain closed down over the hole until the player lifts them through the key action, or keys that remain open until the player presses them down. Choose whichever approach makes for easier fingerings. For remote keys, normally closed keys are generally easier to make, through a simple fulcrum-and-lever action. For keys designed to cover large holes falling directly under the fingers, it’s easier to make normally open keys having no fulcrum as in Figures 12-5 A and B, which the player simply presses down to close.

Springs: Whether normally open or closed, some sort of spring must be in place to return the key to default position when it is released. Very stiff springs improve the seal on default-closed holes, but they make the playing action stiffer. The ideal is to use a moderately soft spring with perfect key alignment for a leakless seal. Commercial woodwinds often use needle springs — straight sections of spring-tempered stainless steel wire — typically about an inch long, rigidly mounted at one end, with the other end pressing against a catch somewhere on the key lever to push it in the desired direction (see Figure 12-5C). Or they may use flat springs, as in Figure 12-5H. You may come up with a design in which coil springs do the trick, or one which uses clothespin-style springs (Figure 12-5C). For normally open keys, you may be able to have the arm which holds the key serve also as the spring, as in Figure 12-5A. An ingenious but workable approach is to use some sort of elastic banding to pull the key lever back one way or the other, as in Figure 12-5 E and F. If you do this, do not use rubber bands. Left under tension, they deteriorate rapidly. Use elastic cord or straps such as are sold at fabric stores, with many rounds of elastic under light tension rather than a few rounds under high tension.

Fulcrums and Pivoting Mechanisms: Many key designs use some sort of lever arrangement.
Commercially manufactured woodwinds make extensive use of long pivoting rods, similar in concept to that shown in Figure 12-5G. This and other arrangements are not hard to work out on paper, but to make such tiny yet strong metal components with the required degree of precision is a daunting task for most people. So is the attachment of such mechanisms to the instrument tube as firmly as is necessary. Figure 12-5A through F show possible key lever designs in a rougher, more homemade sort of style. If you're a tinkerer and junk collector you may be able to scrounge workable key lever hardware components from old instruments or other small mechanical items.

Compound Actions: On many commercially manufactured woodwinds, the keying actions are mind-bogglingly complex. They are designed so that a single action of the player's finger results in multiple tonehole actions up and down the instrument — press down one key, and several different holes open or close. Long pivoting rod actions like that shown in Figure 12-5G work well in applications like this, because you can arrange for arms extending out from different points along the pivot rod to fulfill various functions. Once again, the job of building such an action from scratch is a lot to ask of anyone but a skilled machinist in a well-equipped shop. One must admire the manufacturers who produce such fine mechanisms.
Relative pitch

Instrument into an upper register.

Antinode A point in a vibrating object which undergoes maximum movement or pressure variation for a given standing wave vibrating pattern.

Attack The manner in which a sound begins.

Beating A steady rise and fall in loudness that results when two tones of close but not identical frequency sound together.

Cancellation When two out-of-phase vibrations counteract one another's effects so as to reduce the cumulative signal strength, they are said to cancel.

Chordophone Siting instrument.

Chorusing effect The subjectively richer effect of two or more vibration sources sounding together at approximately, but not precisely, the same frequencies.

Contact microphone A microphone which responds not to vibrations in the atmosphere, but to vibration in a solid object to which the microphone is attached.

Damping The diminishing of sound energy in a vibrating medium, through radiation or frictional losses.

Decay The manner in which a sound diminishes after reaching maximum volume.

Displacement The distance of a vibrating object at any given moment from its rest point or equilibrium position.

Driver Any vibrating object which drives a vibration in another object or substance, as, for instance, a vibrating string drives its soundboard.

Edgetone A vibration in the atmosphere created when a narrow air stream strikes an edge, as with flutes.

End correction Sound waves in air column tubes behave as if the tube were slightly longer than it actually is. The end correction represents the difference between a tube's physical length and the slightly longer effective length of the air column.

Envelope Usually, the characteristic pattern of rise and fall in a sound's volume over time. (May also refer to other sorts of patterns that can be represented on a graph.)

Equal temperament A tuning system in which the scale degrees are equally (logarithmically) spaced. (Each successive step of the scale is the same interval above the preceding one.)

Ergonomic Comfortable to use and well suited to the natural motions of the human body.

Fipple flute A flute in which a narrow duct directs an air stream against an edge, as with recorders.

Formant A frequency region that is favored in a resonating system. When different frequencies are fed into the resonator, any input frequencies which happen to fall in the range of a formant are resonated particularly strongly.

Frequency The number of complete vibratory cycles per second in a given vibration. A sound's pitch is a function of its frequency — the more cycles per second, the higher the perceived pitch.

Frequency ratio The ratio between two vibrational frequencies. This corresponds to the perceived musical interval between the pitches for the two frequencies, e.g., a frequency ratio of 2:1 corresponds to the interval of an octave.

Fundamental Most musical sounds contain a blend of many frequencies. The lowest of these is me called the fundamental. Its pitch is usually perceived as the defining pitch for the sound.

Harmonic A tone whose frequency is an integral multiple of a given fundamental frequency. Most musical sounds contain a blend of many frequencies including a fundamental and additional overtones; when the overtones are integral multiples of the fundamental's frequency, they are called harmonics. The fundamental itself is considered to be the first harmonic.

Harmonic series A series of pitches whose frequencies bear the relationship $f, 2f, 3f, 4f, ...$

Helmholtz resonator An air chamber which is not long and thin like an air column, but extensive in two or three dimensions (i.e., short and fat, or globular), open to the outside air through a relatively small opening.

Hertz Term used to designate frequency as measured in cycles per second, often abbreviated as Hz, e.g., 440 cycles per second = 440Hz.

Hocketing The practice of distributing a melody line among two or more players or singers, each of whom is responsible for some, but not all, of the pitches of the melody.

Idiophone Musical instrument in which the initial vibrating body is a solid, unstretched material.

Impedance Roughly, a measure of a vibration's concentration of energy, as manifest by how much force must be applied to achieve a certain amount of movement in the medium.

Inertia The tendency of any moving object to continue its motion in the same direction with constant speed.

Interval The musical relationship between two any pitches. Between a very high and a very low pitch, there is a large interval. Between two nearly identical pitches, there is a small interval.

Just intonation Any tuning system in which the intervals are based on frequency ratios.

Kalimba A lamellaphone, or plucked-prong instrument, of eastern, central and south-western Africa. In this book, the name is used generically to refer to hand-played plucked prong instruments of all sorts.

Longitudinal vibration Vibration in which the direction of displacement is along the same axis as the direction of wave travel.

Marimba Strictly speaking, certain types of kalimbas and certain African and Latin American xylophones, usually with resonators. More generally, it is often used to refer generically to free-end bar instruments of all sorts, and that is how it is used in this book.

Membranophone Musical instrument in which the primary vibrating body is a stretched membrane — i.e., a drum.

Mirliton A small membrane covering a hole in the side of an air column or air chamber, which adds a prominent buzz to the sound.

Mode of vibration Pattern of vibratory movement for a standing wave in an object or substance. Most vibrating objects are capable of many modes of vibration and manifest them simultaneously.

Natural frequency Frequency at which a body vibrates if left alone after initial excitation, as, for instance, a string vibrates at its natural frequency after plucking.

Node A point in a vibrating object which undergoes no movement, or no pressure variation, for a given mode of vibration or standing wave vibrating pattern.

Organology The study of musical instruments, particularly from a historical and cultural perspective.

Overtone Most musical sounds contain a blend of many frequencies. The lowest of these is normally called the fundamental; the additional tones above it can be called overtones or partials. Overtones may or may not be harmonic, depending on their frequency relationship to the fundamental.

Partial Most musical sounds contain a blend of many frequencies. The individual frequencies can be called partials.

Phase In a steady-state vibrating pattern, phase refers to where in its vibratory cycle the vibrating body is at any instant. Given two vibrations of the same frequency, the two are said to be "out of phase" when at a given instant one experiences displacement in the opposite direction from the other. They are "in phase" when they experience displacement in the same direction at the same time.

Pitch The listener's sense of how "high" or "low" a musical sound is. It corresponds to vibrational frequency, with higher frequencies corresponding to higher pitches.

Radiation The transmission of sound energy from a vibrating medium to the surrounding atmosphere.

Register In wind instruments, the range of tones available when the instrument tube operates in a particular mode of vibration. Most tubular wind instruments have a fundamental register in which the air column's fundamental mode dominates the tone, a second register in which a higher mode comes to the fore acting as a surrogate fundamental over a higher range and, in some cases, a still higher third register. "Register" can also refer to a rank of organ pipes.

Register hole In wind instruments, a small hole relatively near the mouthpiece which aids in throwing the instrument into an upper register.

Relative pitch Pitch, in a context where absolute pitches as identified by their rates of vibration are not
important, but the relationships or intervals between pitches are.

Resonance The especially strong response of any vibrating system to driver frequencies at or near the preferred natural frequencies of the system.

Resonance response curve A graph showing how the intensity of vibratory response varies over a range of frequencies for a given vibrating object or medium. The resonance response curve of a soundboard, for example, indicates how strongly the soundboard vibrates in response to different input frequencies from its driver.

Restoring force A force that works to return an object which has been displaced to its equilibrium position.

Reverberation The continued ringing of a sound in a room after the original source of the sound has ceased. It may also refer to a continued ringing in other vibrating elements such as attached springs or sympathetic strings.

Standing wave A wave in a medium of finite length which repeatedly reflects back on itself, developing seemingly stationary patterns as the cumulative result of the multiple reflected traveling waves. Standing waves are contrasted with traveling waves, in which the wave progresses through the medium, carrying wave energy to a distant location rather than repeatedly reflecting back on itself.

Stick-slip The mechanism by which vibrations are generated in bowed instruments, as well as other friction instruments and non-musical squeaks.

String scaling The science of selecting the best string lengths, diameters and materials for a given application.

Sympathetic vibration Vibration in a string or other vibrating element which comes not from being played directly, but rather from picking up vibrations from other vibrating elements at or near one of the sympathetic vibrator's natural frequencies.

Temperament A tuning system in which some of the ideal just intervals are deliberately detuned slightly in order to achieve more regular intervals between the pitches of the tuning.

Timbre Tone quality.

Transducer Something which converts a sound vibration from one medium to another; most often used in connection with microphones and pickups which convert vibrations in the air or solid media into patterns of changing voltage in an electric circuit.

Transverse vibration Vibration in which the direction of displacement is perpendicular to the direction of wave travel.

Traveling wave A progressive wave, which moves through its medium. All waves are in fact traveling waves, but traveling waves are often contrasted with standing waves, in which seemingly stationary patterns develop as the cumulative result of multiple reflected traveling waves.

Twelve-tone equal temperament The standard tuning system in Western music today, employing twelve equally spaced scale steps per octave.

Wave The cumulative effect of a series of small movements in a medium such as the air or a solid object, in which slight displacement of one particle causes a similar displacement of adjacent particles, giving rise to a series of displacements traveling rapidly through the medium. Sound, as perceived by the ears, is the result of a rapid series of waves in the atmosphere impinging on the eardrum.

Waveform The characteristic repeating pattern of change, either in pressure variation or in displacement, for a vibratory movement. Waveform is usually represented as a wavy line on a graph, plotting displacement or pressure change against time for a representative point in the vibrating medium.

Wavelength The distance between one wave front and the next. The longer the wavelength, the lower the frequency and the lower the perceived pitch.
This bibliography includes selected English language works on general organology, texts on acoustics and intonation theory, and collections of instrument-making plans. It is not exhaustive in any of these areas.

This bibliography does not list works devoted to specific standard instruments, since the number of different instrument types and books would be unmanageably large. If you have an interest in a particular instrument, begin by looking it up in the New Grove Dictionary of Musical Instruments (available at large libraries), which is organized like an encyclopedia. Most of its articles contain bibliographies that can help guide your further research.

This bibliography also does not list books on the instruments of specific cultures. The world is too big, the books too many, and the field too rapidly changing to do a good job of that here. Once again you can begin with general sources such as the New Grove, and follow the bibliographies.

In searching for further information on topics relating to musical instruments, keep in mind the periodical literature. There are newsletters or journals devoted to most standard instrument types, as well as many obscure types (jaw harp and musical saw, for example). You can find periodicals devoted to particular instruments by perusing the music section of Ulrich's International Periodicals Directory or similar sources to be found in the reference section of the local library. The only periodical devoted to new and unusual instruments of all sorts is Experimental Musical Instruments, edited by the author of this book, available from PO Box 784, Nicasi, CA 94946 ($24/year ($34 outside the North America) at the time of this writing).

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Collections of Instrument Plans and Descriptions


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