Chapter 24
Woodwind Instruments

The family of musical instruments known as the woodwinds includes reed instruments like the clarinet and oboe. It also includes edge-tone instruments like the recorder and flute. Unlike the brass instruments, which are sealed systems of plumbing terminated by a bell where all the sound comes out, the woodwinds have tone holes, and much of the sound is radiated by these tone holes.

24.1 Single-Reed Instruments

A single-reed instrument has a cane reed attached to a mouthpiece. The reed vibrates against the mouthpiece, allowing a puff of air into the rest of the instrument each time the reed opens. If the instrument plays a tone with a fundamental frequency of 440 Hz, the reed opens 440 times per second. Among the well-known single-reed instruments are the clarinets and saxophones.

The Clarinet The clarinet (Fig. 24.1) has a cylindrical bore. Although there is a small bell at the end, the bell is acoustically unimportant except in playing the lowest notes, when most of the tone holes are closed. The clarinet, of all musical instruments, most resembles the cylindrical pipe open at one end and closed at the other. You will recall from Chap. 8 that such a system has only odd-numbered resonances. The low notes of a clarinet reflect that fact. The second and fourth harmonics of tones with low-frequency fundamentals are very weak compared to the third and fifth harmonics. Wow—the physics is working! Contrary to expectation, however, the sixth harmonic can be relatively strong. The wavelength of the sixth harmonic is short enough that small deviations from the cylindrical bore become important—the mouthpiece is tapered, and the bore of the entire instrument is dimpled with closed tone holes.

The low-frequency tones constitute the low "register" of the clarinet. There are 19 notes in this register, and they have the distinctive hollow sound of a complex periodic tone with missing second and fourth harmonics. These notes correspond

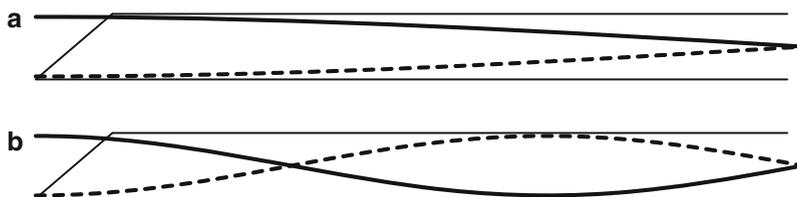**Fig. 24.1** The clarinet resembles a cylindrical pipe, open at one end and closed at the other

Fig. 24.2 (**a**) Schematic clarinet with the first mode of vibration. (**b**) Schematic clarinet with register hole open supporting the second mode of vibration with a frequency that is three times higher than the first

to the first mode of vibration of air in an open–closed pipe, where the open end is approximately at the position of the first open tone hole.

Higher-frequency tones on the clarinet are in the second register, where the standing waves correspond to the second mode of vibration of air in an open–closed pipe. The second mode has one node, and the clarinet is fitted with a register key, which opens a hole to help force a node in the air column at the right place to activate the second mode of vibration. Because the frequency of the second mode is three times the frequency of the first, the clarinet "overblows the twelfth." The musical interval called the "twelfth" is an "octave" and a "fifth," or a factor of three. (See Appendix D.) Still higher notes on the clarinet use the third mode of vibration of air, a mode with two nodes (Fig. 24.2).

The Saxophone Unlike the clarinet, the saxophone (Fig. 24.3) has a conical bore, i.e., the bore is like a truncated (cut-off) cone. While a cylinder open at one end and closed at the other has only odd-numbered resonances, a cone has both odd- and even-numbered resonances. The resonant frequencies of a cone are given by the formula $f = [v/(2L')]n$, where v is the speed of sound in air, and n is an integer, 1, 2, 3, … Length L' is somewhat strange. It is not the length of the truncated cone. Instead, it is the length that the cone would have if it were not truncated (Fig. 24.4).

Free Reeds Instruments like the harmonica and accordion also generate musical notes using a single reed. Musical toys played at parties on New Years Eve operate on a similar principle. These instruments might be called woodwinds, but they are not in the same family with the clarinet and saxophone. The clarinet and saxophone have a *beating reed*—the reed opens once per cycle of the tone as it beats against the mouthpiece. The free reed is in a window that allows it to open both in and out of the window. Therefore, the free reed opens twice per cycle of the tone, and the
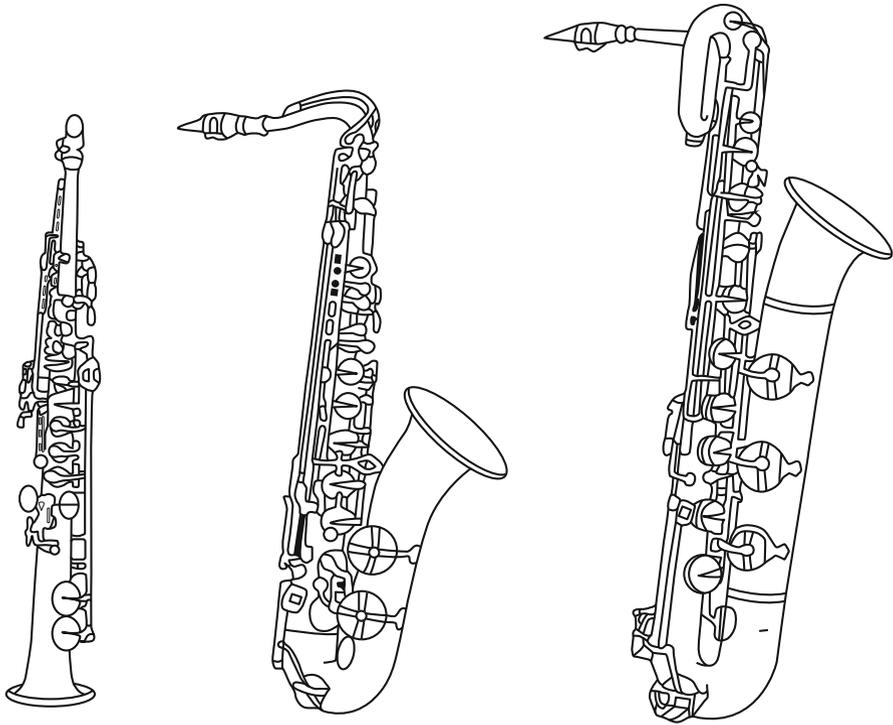
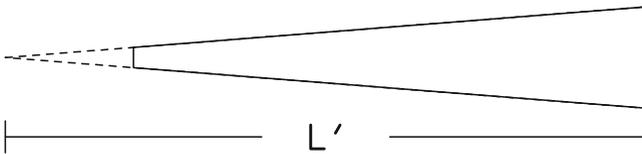**Fig. 24.3** Saxophones from left to right: soprano, tenor, baritone

Fig. 24.4 A saxophone is like a truncated cone, shown by the *solid line*. Its effective length is L' including the *dashed conical extension*

spectrum has a strong second harmonic. Another important difference is that the playing frequency of a free-reed instrument is mainly determined by the reed itself. This frequency is established by a combination of stiffness (numerator) and mass (denominator) that you would expect for a free vibrator. By contrast, the playing frequency of a clarinet or saxophone is determined by the air column. The natural frequency of the reed in these instruments does have an effect, but it does not affect the playing frequency, instead it leads to a formant. Harmonics in the tone that are near the reed resonance tend to be strong.
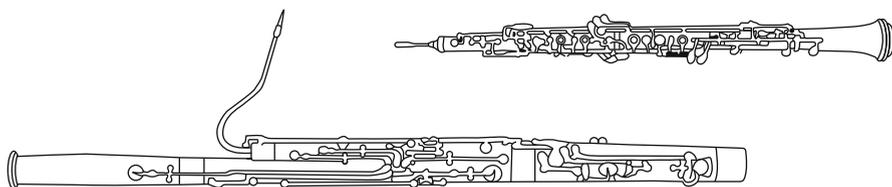
Fig. 24.5 The oboe (*top*) and the bassoon (*bottom*) are the two most important double-reed instruments

24.2   Double Reeds

The best-known double reed instruments are the oboe and the bassoon (Fig. 24.5). In contrast to a single reed instrument, where the reed vibrates against a mouthpiece, the two reeds of a double reed vibrate against one another. At instants in time when there is a gap between the two reeds a puff of air enters the rest of the instrument.

The oboe and bassoon both have conical bores, like the saxophone, but the cone angle is less than in the saxophone and this difference makes the high harmonics of the double reed instruments relatively stronger. Appendix C shows that the frequency range of the oboe is similar to that of the clarinet, though narrower, and the range of the bassoon is similar to the cello. Many of the tones played on these instruments have unusual spectra, with harmonics 3, 4, and 5 as strong or stronger than 1 and 2. Both instruments exhibit formants, near 1,000 and 3,000 Hz for the oboe and near 460 Hz for the bassoon. These formants are probably attributable to reed resonances. As a result, the oboe and bassoon have a very distinctive tone color. Traditionally, the oboe is used to tune the orchestra, possibly because the upper harmonics are strong enough to stand out over the cacophony as other instruments tune up.

24.3   Reeds in General

Although there is a lot of variety among the single and double reed instruments, it's important to recognize that the basic mechanism of tone production for all of these instruments is similar to the process described for a bugle in the chapter on brass instruments. Just as feedback from the horn entrains the vibration of the brass player's lips, so the feedback from the main body of a reed-woodwind instrument entrains the vibrations of the reed. Both lips and reeds operate as pressure-controlled flow valves. The large pressure variations at the mouthpiece (closed end) caused by the standing waves in the body of the instrument control the entry of puffs of air into the instrument. The importance of the body of the instrument becomes evident if the instrument is disassembled, and the reed and mouthpiece are blown in the usual way. The sound of the mouthpiece and reed alone is a high-frequency squeal. The main

body of the instrument is needed to support a useful playing frequency. Just as in the brass instruments, the resonances of the plumbing determine the harmonics of the tones, but the player's embouchure (position, orientation, and stiffness of the lips) determines whether the playing frequency will be high, low, or in the middle, and thus determines which resonance will be assigned to each harmonic.

24.4   Edge Tone Instruments

When a stream of air impinges on a sharp edge, the pattern of air flow is unstable. If you blow across the width of a pencil, for example, you will hear a rushing noise coming from the air stream chaotically vibrating from one side of the pencil to another. In musical instruments employing a vibrating air stream as the original source of sound, the vibrations can be entrained by attaching a resonator, such as an open pipe. This is the basis of instruments like the recorder or the flute. The edge, where the tone is generated, is in a hole in the wall of the cylindrical tube. As a result, the instrument resembles a pipe with *two open ends*. Therefore, an edge-tone instrument is different from a reed instrument, where the tone is generated at a *closed end*.

Edges with a Fipple   A whistle, like a referee's whistle, is an edge-tone instrument that anybody can play—even without practicing. That's because it has a fipple, an entry duct that guides the stream of air against the edge. With enough blowing pressure, good tone generation is automatic. Recorders (Fig. 24.6) are instruments with fipples, conical bores, and tone holes. They were popular in baroque times and are still used in baroque music ensembles. Recorders are often used for music education in schools because they can be made inexpensively out of plastic and are easy to play because of the fipple.

The Ocarina   The ocarina is another fippled-instrument that is easy to play. The ocarina is rather unique among musical instruments in that its shape can be just about anything that the maker wants. Typical shapes resemble blobs, and the ocarina is sometimes called the "sweet potato."

Unlike the other instruments of this chapter, which use the modes of air columns, the ocarina uses a mode similar to the mode of a soda bottle. It is called the "Helmholtz mode" or the "Helmholtz resonance." In this mode of vibration, the mass of air in the neck of the bottle serves as the vibrating mass, and the
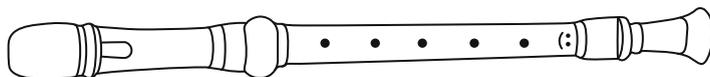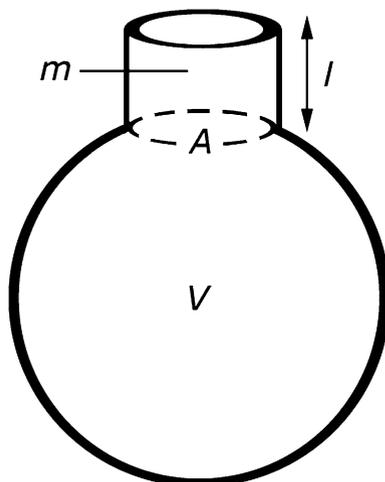

Fig. 24.6   An alto recorder is an ancient instrument

compressibility of air in the rest of the bottle serves as the spring. Of course, for
most bottles the division into mass and spring parts is not clear cut. The bottle tends
to be a continuous system. But just as one could identify mass in the tines of tuning
fork and spring in the shoulders of a tuning fork, one can say that parts of the air in
the bottle play the role of a mass and parts play the role of a spring (Fig. 24.7).

The frequency of the Helmholtz resonance is given by

$$f_H = \frac{v}{2\pi}\sqrt{\frac{A}{Vl}} \qquad (24.1)$$

where v is the speed of sound in air, V is the volume of the bottle, A is the cross-
sectional area of the neck, and l is the length of the neck. The dependence on the
volume of the bottle indicates that the details of the shape are unimportant.

By blowing very hard, a player can excite a second mode of vibration of air in an
ocarina—more easily in some instruments than in others. Modes of vibration higher
than the Helmholtz resonance are called "cavity modes." In general their frequencies
are much higher than f_H and not at all harmonically related to f_H. The shape of a
cavity mode, its frequency, and the ease with which it can be excited depend on the
shape of the instrument.

A case can be made that the ocarina is a more successful instrument than the
recorder. The problem with the recorder is that it is difficult to play low-frequency
notes loudly. When the player increases the blowing pressure, there is a great risk
that the oscillation of air will jump from the low-frequency mode to a second mode,
with a frequency that is an octave higher. The ocarina suffers less from this problem
because the second mode of vibration is so far removed in frequency and so different
in mode shape. For the same reason the ocarina does not have a rich spectrum. It's
waveform is mostly a sine tone.

24.5 Boatswain's Pipe

From old movies of ancient naval warfare, you will recall the high-pitched sound of the boatswain's pipe. The pipe, or whistle, of the boatswain (pronounced "bosun") had to be audible in a gale everywhere on the ship. It is tuned to about 3,000 Hz, right where the auditory system is most sensitive and well above the spectral range of most wind and waves. The boatswain's pipe uses the resonance of a small, hollow metal sphere with a hole. Because it is metal, the wall of this spherical cavity is thin and one can hardly imagine a neck length. Thoughts like this raise the concept of the Helmholtz resonator without a neck.

The theory of the neckless Helmholtz resonator supposes that the mass of the oscillator corresponds to the air just outside the tone hole. It is essentially the same concept as led to the end correction for the open ends of pipes. The resonance frequency of such a cavity is given by

$$f_H = \frac{v}{2\pi}\sqrt{\frac{1.85a}{V}}, \tag{24.2}$$

where a is the radius of the tone hole.

24.6 The Flute

The flute (Fig. 24.8) is an edge-tone instrument resembling a pipe open at both ends like the recorder. However, the flute does not have a fipple. Instead, the player is responsible for directing the stream of air optimally against the edge to make a tone. Therefore, the flute is more difficult to play than the recorder. Nevertheless, the flute has now replaced the recorder as an important instrument in orchestras and bands. The reason is that the flute player can redirect the air stream so as to avoid the octave jump at high stream velocities. Therefore, the flute player can play low-frequency tones at higher levels of intensity. Actually, loud, low-register tones on the flute tend to have a very strong second harmonic. But even though the second harmonic is strong, the flute player is able to keep the oscillations going in the first mode of vibration so that the fundamental of the tone is still in the spectrum, and the pitch stays in the lower octave.

Because it has a cylindrical bore for most of its length, the flute overblows the octave. "Overblowing the octave" means that if a player is playing a

Fig. 24.8 The flute looks complicated, but it is basically a cylindrical pipe with holes in the wall

low-frequency tone, and blows harder without making a compensating correction in the embouchure, then the frequency will jump up by an octave. Tones in this second register (one node) and tones in the third register (two nodes) are rather like sine tones if played softly. No other instrument in the orchestra makes a tone that is more sinusoidal.

The flute is about 60 cm long. That is such a long piece of pipe that if tone holes are placed optimally, the tone holes are too far apart for a player's fingers to reach. As for the reed woodwinds, an elaborate system of keys, rings, and pads has been worked out so that the instrument can be played with ordinary human hands. The present design was invented by Theobald Boehm in 1871. The world still awaits the genius who will invent such a system for the ocarina. When this happens, the sweet potato will be boss.

The piccolo operates according to the same principles as the flute. It is about half as long, and, as expected, plays about an octave higher.

Exercises

Exercise 1, Clarinet resonances and clarinet tones
The clarinet is approximately a cylindrical tube, open at one end and closed at the other. (a) Show why you expect the clarinet tone to have only odd-numbered harmonics. (b) Appendix C says that the lowest note on a clarinet has a frequency of 147 Hz. Given a first mode frequency of 147 Hz, calculate the expected length of a clarinet.

Exercise 2, Clarinet register key
The clarinet has a register key to aid in playing the second mode of vibration of air in the column. Why would you expect the register key to be at a position that is 1/3 of the way from the mouthpiece to the end of the horn?

Exercise 3, Clarinet and flute
A flute is a pipe open at both ends. It is about as long as a clarinet, but it sounds an octave higher. Why?

Exercise 4, Clarinet and oboe
The oboe has a conical bore. It is not cylindrical like the clarinet but flares on the inside. The oboe also has a double reed and not a single reed. The double reed of the oboe snaps shut for an appreciable fraction of a normal playing cycle. The single reed of the clarinet does not normally close so much except at very high playing levels. Explain why you expect the oboe to have a brighter tone color.

Exercise 5, Reeds and singing
(a) In what way are the behaviors of vocal folds and vocal tracts in singing similar to a free-reed instrument . . . and not similar to a saxophone? (b) In what way are the vocal folds more like an oboe than like a clarinet.

Exercise 6, The flute

From the embouchure hole to the open end, the flute is about 60 cm long. What do you expect the frequency to be for the lowest possible note on the flute?

Exercise 7, Platinum flutes and metal clarinets

The sound of a woodwind instrument comes from the vibrations of a column of air inside the instrument. The walls of the instrument only serve to confine the air column. The walls do not vibrate much, they do not radiate appreciably. Therefore, the scientific evidence supports the notion that the wall material is ... well ... immaterial to the playing of the instrument or the quality of the tone. Musicians on the other hand often disagree. What do you think?

Exercise 8, The bosun's pipe

On a boatswain's pipe, the radius of the tone hole is about half the radius of the spherical cavity. Show that the frequency of the pipe is given by

$$f_H = 5146/D \qquad\qquad (24.3)$$

where D is the diameter of the sphere in cm. Therefore, to make the pipe have a frequency of 3,000 Hz requires a sphere with a diameter of about 1.7 cm.

Exercise 9, Tuning up to the oboe

The text says that the oboe may be used to tune the orchestra because its upper harmonics are strong enough to be heard against the rest of the orchestra. What good would that be? What good would it be to hear only the upper harmonics?

Exercise 10, Harmonica spectrum

Figure 24.9 shows the power spectrum of the lowest note on a Hohner Blues Harp. (a) What is the fundamental frequency, and what musical note would that be? (See Appendix E.) (b) How many harmonics can you find over the range of the spectrum? (c) Do you expect the harmonica tone to be periodic in time? (d) Compare the levels of the fundamental and the second harmonic. (e) Compare the levels of the fundamental and the 12th harmonic.
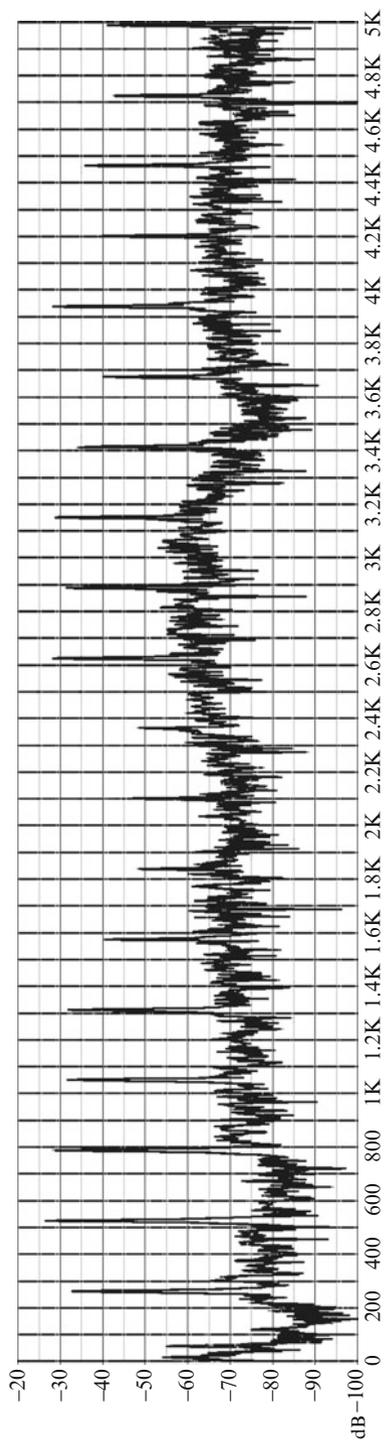
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Fig. 24.9 Spectrum of the lowest note on a small harmonica for Exercise 10