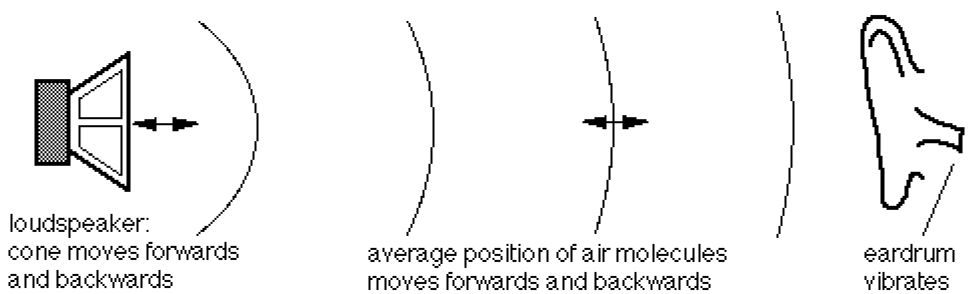
How Do Woodwind Instruments Work?

Overview

A simplified introduction to the woodwind family and how they work. This page describes their different shapes and different types of excitation (air jet or reed) and how these give rise to some of their different behaviours. It gives links to more detailed pages about the acoustics of the individual instruments.

Something about sound

First, a little information about sound. If you put your finger gently on a loudspeaker you will feel it vibrate - if it is playing a low note loudly you can see it moving. When it moves forwards, it compresses the air next to it, which raises its pressure. Some of this air flows outwards, compressing the next layer of air. (More about loudspeakers.) The disturbance in the air spreads out as a travelling sound wave. Ultimately this sound wave causes a very tiny vibration in your eardrum - but that's another story.



Frequency

At any point in the air near the source of sound, the molecules are moving backwards and forwards, and the air pressure varies up and down by very small amounts. The number of vibrations per second is called the frequency (f). It is measured in cycles per second or Hertz (Hz). The pitch of a note is almost entirely determined by the frequency: high frequency for high pitch and low for low. 440 vibrations per second (440 Hz) is heard as the note A in the treble clef, a vibration of 220 Hz is heard as the A one octave below, 110 Hz as the A one octave below that and so on. We can hear sounds from about 15 Hz to 20 kHz (1 kHz = 1000 Hz). A contrabassoon can play Bb0 at 29 Hz. When this note is played loudly, you may be able to hear the individual pulses of high pressure emitted as the reed opens and closes 29 times per second. Human ears are most sensitive to sounds between 1 and 4 kHz - about two to four octaves above middle C. That is why piccolo players don't have to work as hard as tuba players in order to be heard. (This link converts notes, frequencies and MIDI numbers.)

The woodwind family of instruments

Some of the woodwinds are shown in the picture at right. (Click on the piecture for an enlarged version.) A metre rule at left gives the scale. From left to right are bassoon, clarinet, alto saxophone, cor anglais, oboe and flute. They are shown approximately in order of range: the lowest notes are Bb1 (58 Hz) on the bassoon, C#3 (139 Hz) or D3 on the A or Bb clarinet, C#3 on the alto saxophone, E3 (165 Hz) on the cor anglais, Bb3 (233 Hz) on the oboe, B3 or C4 (262 Hz) on the flute. The picture is not complete: to the flute could be added piccolo (one octave higher), alto flute (a fourth lower) and bass flute (one octave lower). Similarly there are the soprano, alto and bass clarinet; the musette, oboe d'amore and bass oboe, the contrabassoon and several saxophones: sopranino, soprano, alto, tenor, baritone, bass and contrabass. (In this picture, the crooks (thin metal tubes joining reed to body) on the bassoon and cor anglais have been rotated 90° to show their shape. With the instruments positioned as shown, the bassoon crook would normally protrude towards the viewer, and the cor anglais crook would bend away.)

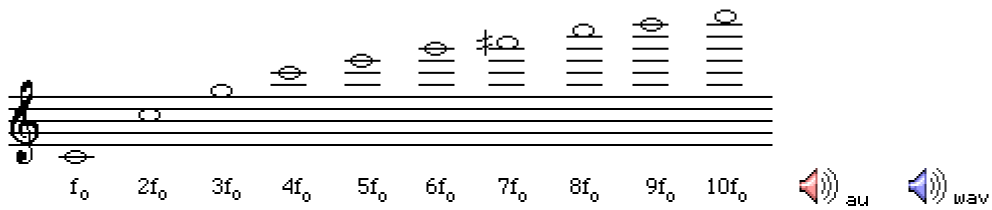
Woodwind instruments have a long, thin column of air. The lowest note is played with all the tone holes closed, when the column is longest. The column is shortened by opening up holes successively, starting from the open end. At the other end there is something that controls air flow: an air jet for the flute family and cane reeds for other woodwinds. We shall look at these elements in turn.

The air column determines the pitch

A sound wave can travel down the tube, reflect at one end and come back. It can then reflect at the other end and start over again. For a note in the lowest register of the flute, the round trip constitutes one cycle of the vibration. (In the lowest register of clarinets, two round trips are required: see Flutes vs clarinets). The longer the tube, the longer the time taken for the round trip, and so the lower the frequency. In woodwind instruments, the effective length is changed by opening and closing finger-holes or keyholes along the side. This is the way pitch is changed within the same register of the instrument: all holes closed gives the lowest note, and opening the holes successively from the bottom end gives a chromatic scale. (The use of simple and cross-fingerings to change the length of the standing wave is discussed in much more detail and with specific examples in Flute acoustics, and the principles are the same for all woodwinds.) Changing the effective length of the pipe is not the only way of changing pitch, however: on any wind instrument, you can usually play more than one note with the same fingering.

The harmonic series

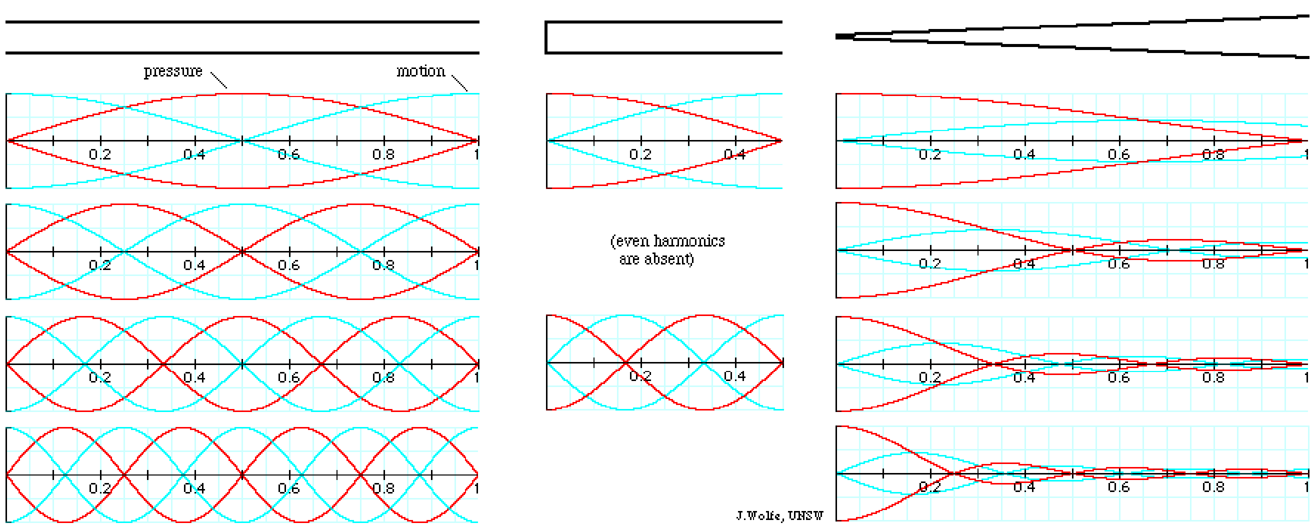
The sound waves going up and down the instrument add up to give a standing wave, a vibration pattern of the air in the instrument. Several different such patterns are possible. On a flute, with all keys down, you can play about seven or eight different notes. Their pitches (approximate) are given below. The frequencies of these sounds are whole number multiples of the frequency of the lowest (f_1). We call them the harmonic series. Try playing the series on any instrument, without changing the fingering. You will notice the half-sharp on the 7th. (For more detail, see Flute acoustics and Clarinet acoustics



Eight harmonics of the lowest note on a flute.

Harmonics and the different instrument bores

Why can the air in the flute vibrate in these different ways? Well, the tube is open to the air at both ends, so the pressure is pretty close to atmospheric, but the air is free to move in and out. Inside the tube the pressure can be higher or lower, but the air is less free to move. The diagram on the left shows the different vibration patterns or modes that satisfy the condition of the flute: zero pressure and maximum vibration at both ends. The top graph is the pattern of a wave whose length is twice that of the flute (2L, say), the second has wavelength 2L/2, the third 2L/3, and so on. The frequency is the speed of sound divided by this wavelength, and that gives the harmonic series f_1, $2f_1$, $3f_1$ etc. (This is a slight simplification: the pressure node is a little distance outside the pipe, and so L, the effective length of the tube that should be used in such calculations, is a little longer than the physical length of the tube. The end effect is about 0.6 times the radius at an open end.)



These graphs show the wave patterns in the three simplest air columns: open cylinder, closed cylinder and cone. The red line represents sound pressure and the blue line represents the amount of air vibration. These pipes all have the same lowest note or fundamental. Note that the longest wavelength is twice the length of the open cyclinder (eg flute), twice the length of the cone (eg oboe), but four times the open length of the closed cylinder (eg clarinet). Thus a flutist or oboist plays C4 using (almost) the whole length of the instrument, whereas a clarinetist can play approximately C4 (written D4) using only half the instrument (ie removing the lower joint and bell). **Important**: in all three diagrams, the frequency and wavelength are the same for the figures in each row. When you look at the diagrams for the cone, this may seem surprising, because the shapes look rather different. This distortion of the simple sinusoidal shape is due to the variation in cross section along the tube. See Pipes and harmonics, where this point is discussed in detail.

There is a more detailed discussion of standing waves in pipes in the introduction to flute acoustics, introduction to clarinet acoustics and introduction to saxophone acoustics, which also have a discussion of the use of register holes to produce harmonics. The effects of different bores are discussed in more detail in Pipes and harmonics.

Flutes *vs* reed Instruments

Reed instruments are different: the end in the player's mouth is not open to the outside air, so the air is not maximally free to move in and out. The pressure is not fixed at atmospheric - in fact it can have its maximum value at this closed end. Consider the clarinet: it is mainly cylindrical and is open to the outside air at the bell end, but closed at the end in the mouth.

The vibration patterns that the clarinet can play are shown in the diagram in the middle. The lowest wave is four times as long as the tube (4L'), the next is 4L'/3, the next 4L'/5 etc. So it only produces the odd members of the harmonic series (see above). Two consequences: first, that a clarinet can play nearly an octave lower (twice the wavelength) than a flute of the same length. Second, it "overblows a twelfth" - you have to go up 12 scale steps (3 times the frequency) before you can restart the same fingering. This is explained in more detail in the introduction to clarinet acoustics.

The bores of woodwind instruments. The diameters are exaggerated. The flute (top) and clarinet (middle) are nearly cylinders. The oboe, saxophone and bassoon are nearly conical (right). (See also Pipes and harmonics and Flutes vs clarinets.)

Conical bores: oboes, bassoons and saxophones

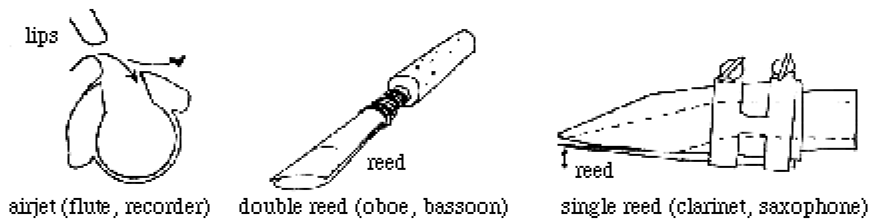
What about oboes, bassoons and saxophones? Like the clarinet, they are closed at one end and open at the other, but the difference is that their air columns are in the shape of a cone. The resulting pressure and air motion vibrations are shown in the right hand diagram. When these waves get out into the outside world, they have the same frequencies as those from an open pipe of the same length. So an oboe, which is about the same length as the flute or the clarinet, has a lowest note close to that of the flute and, like the flute, it plays all of the harmonic series. To say more requires mathematics. Flute players can control which vibration pattern or mode they produce by the way they blow. In reed instruments, there is an octave hole or register hole which helps obtain the higher notes. Its purpose is to open up the tube to the outside air at or near one of the points where the air pressure should be atmospheric for the high vibrations.

Flutes

I expect that most of us have played a note by blowing over the top of a bottle. The air in the bottle is springy and can vibrate, rather like a spring with a mass on it. When you blow across the top of the bottle, the stream of air from your lips can be deflected up or down by the expanding and contracting air in the bottle. When the stream is deflected down, some of it goes into the bottle, increasing the vibration. Thus the power in the stream of air can sustain the vibration in the bottle. (For an analysis of the sound made blowing across the top of a bottle, see Helmholtz Resonance).

The mouthpiece of the flute (diagram below) works on the same principle - a jet of air passes a volume of air (the air in the tube of the instrument) which can vibrate. This is an oversimplified account, so go follow this link for a more detailed introduction to flute acoustics.

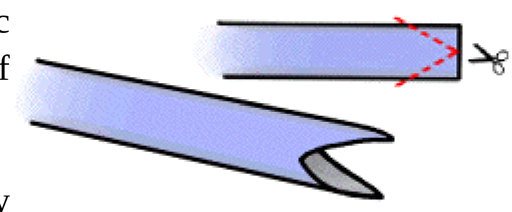
Air jet or reed excites the vibration



Reeds

Reeds are made of springy cane and can vibrate on their own. Attached to the instrument, they are (usually!) forced to vibrate at the natural frequency of the air in the tube. When the pressure falls, the reed tends to close and to let less air in, when the pressure goes up the reed opens a little and lets more air in. Once again the power in the air stream from the player's lungs is used to sustain the vibration in the in the air in the instrument. (This is explained in more detail in the introduction to clarinet acoustics.)

You can make a double reed out of a plastic drinking straw. Cut a V shaped point on the end of the straw as shown in the diagram at right.



Put the cut end in your mouth, squeeze slightly with you lips and blow. The sound probably resembles that of a beginning oboist! You can "tune" it by cutting pieces off the other end, and with fast scissor work you can even play a little tune - provided that the notes go only upwards!

The Clarinet

The clarinet has a single reed which swings in and out, cutting off and opening the stream of air as the pressure in the tube goes up and down, so in principle the operation is much like that of the double reeds. Clarinets come in a range of sizes, from sopranos that are 3/4 the size of the normal one, to contrabass clarinets which look like a plumber's nightmare. We saw above that the clarinet has only the odd numbered members of the harmonic series, so the gap between the first register and the second is a frequency ratio of three (a musical twelfth, or 19 semitones). All other woodwind players can play a scale of one octave and then use (nearly) the same fingerings again for the next register. A clarinetist must ascend twelve scale steps to repeat the fingerings. Because this exceeds the number of fingers on standard players, clarinets have four or five keys for the little fingers and extra keys for the knuckles of the index fingers. (See also the Introduction to clarinet acoustics.)

The Saxophone

The saxophone has a mouthpiece and reed much like that of a clarinet, but it is approximately a conical tube (like the oboe and bassoon) rather than a cylinder (like the clarinet). So it plays all the harmonics and has an octave between first and second registers. See the Introduction to saxophone acoustics. (See also Pipes and harmonics for some explanations about the importance of the conical bore and how it changes the harmonics.)

The saxophone has a larger bore angle (and so a wider diameter at the bell) than any of the other woodwinds and this makes it possible to play rather louder. Like clarinets, saxophones come in a large family from tiny sopraninos to huge contrabasses. We have just posted a data base on saxophone acoustics. See this French saxophone site for a great series of pics on the fabrication of saxophones.

Double reeds: Oboes and bassoons

In the oboe and bassoon the sound is produced by a double reed (see the diagram and photographs above). (We players of double reeds have been accused of spending half our lives making reeds and the other half complaining about them.) The bassoon is the bass of the woodwind family - a long, folded conical tube reamed and mandrilled into four pieces of maple. Both have conical bores, like the saxophone, but their smaller angle makes them less loud than the saxophone.

Source: http://www.phys.unsw.edu.au/jw/woodwind.html