Lecture 22: Reed instruments

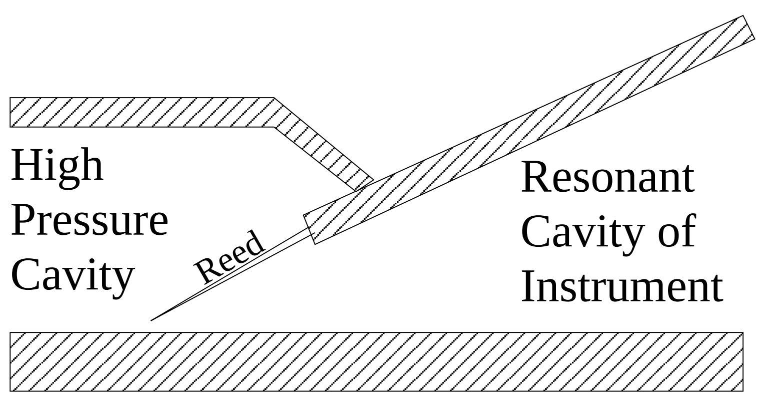
Musical instruments which produce a sustained periodic tone invariably do so by using a resonance to set the frequency of that tone. There remain three problems:

- How is energy to be fed into the resonance?
- How is the resonant frequency to be adjusted so the instrument can play a wide range of notes?
- How is the energy in the resonance to be converted efficiently into sound?

One very nice way to solve the last problem is to use directly a resonance in an air cavity. That way the energy is in sound to begin with. This leaves the problem of tuning the resonant frequency of the cavity, and designing some way for the resonance to be "driven," with energy added every resonant cycle so the resonant phenomenon does not die down.

A reed is a device for putting energy into a resonance, which automatically adds high pressure when the pressure is high and not when it is low. This solves the problem discussed in the last lecture, of making sure "always to push when the swing is going forward." Let us see how it works.

A reed is a thin, stiff piece of material, fixed at one end and free to move back and forth at the other. Since it is thin, it can bend back and forth. Since it is stiff, if it bends, it elastically tries to spring back to its natural position. It is placed at a narrow spot between a source of high pressure air (such as the mouth, the bag of a bagpipe, the compressed air source of an organ, *etc.*) and a resonant cavity or the open air. The design must be such that, if the reed bends one way, it narrows or closes the connection between the high pressure and outside, and if it bends the other way, it opens the connection wider. The cross-section of a reed system might look like this:

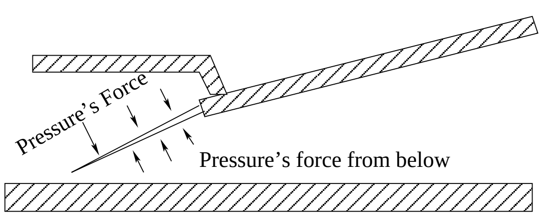


At this point I have to explain something about reeds and distinguish two types. The reed is made out of a stiff, flexible piece of material, sort of like half of a ruler when you clamp the other half against a table with your hand. Because it is flexible, the reed can be bent; because it is stiff and it is attached firmly on one side, it is springy and tries to spring back to its natural position. If you bend the reed and release it, it will vibrate back and forth at a frequency determined by its size, thickness, stiffness, and so forth. This is the resonant frequency of the reed.

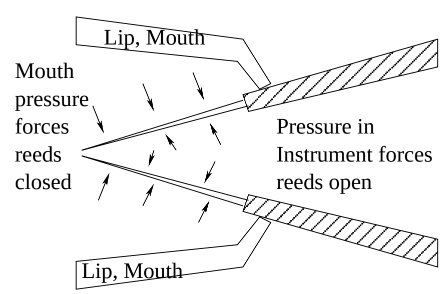
There are two sorts of reeds: free reeds, and reeds coupled to a resonant chamber. The free reeds connect a pressure reservoir and the outside world, and they vibrate at the resonant frequency of the reed. The reeds which make the sound in harmonicas (mouth organs) and accordions are of this sort, as are the party noise makers I will hand out in class. Understanding how the vibration of the reed is amplified by the flow of air through the reed is a little complicated; it involves Bernoulli's principle, and I will avoid talking about it in this lecture. Most musical instruments (such as oboes, clarinets, bagpipes, bassoons, saxophones, and so forth) use the other sort of reed, where the frequency is set by the resonant frequency in a cavity.

Let us understand how this "normal" sort of reed instrument works. The reed sits in between a resonant cavity and a source of pressure (such as your mouth). Specifically, it is at a pressure antinode and velocity node of the resonant cavity, where the pressure variation within the cavity will be maximal when the resonance is excited. The reed almost closes the connection between the mouth and the cavity. The cavity resonant frequency should be lower than the natural frequency of the reed, which means that the reed will respond quickly to the pressures it feels.

The air pressure pushing on one side of the reed is the high pressure in the air source. The pressure pushing on the other side is the pressure in the resonant cavity. The reed must be mounted such that the pressure in the mouth (or high pressure source) is trying to push the reed closed (that is, to close the path for air to go between cavities). The pressure in the resonant cavity is trying to push the reed open. Here is what it looks like for a single reed (clarinet) or double reed (oboe):



Single Reed

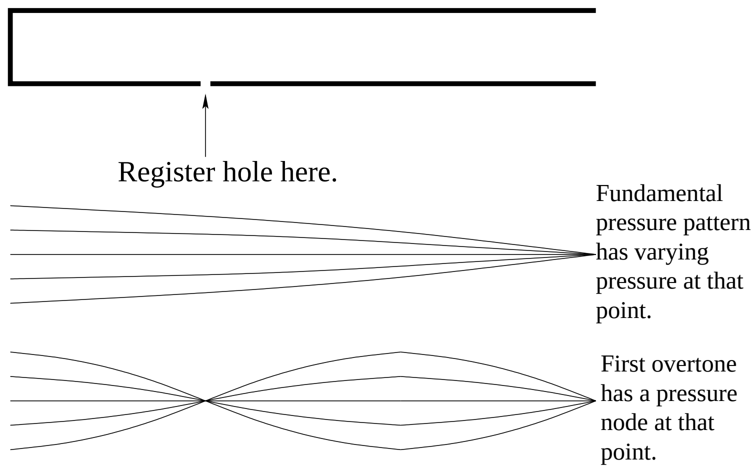


Double Reed

Suppose there is already some sound in the resonant cavity. Then the pressure inside, on the back side of the reed, rises and falls. Since the reed has a high resonant frequency, it moves back and forth as dictated by the pressures on the two sides. When the air pressure in the resonant cavity is high, the reed is forced wider open. That lets through high pressure air from the high pressure source–at just the right time for it to increase the high pressure in the instrument. When the pressure is low in the instrument cavity, that lets the reed fall further shut–at just the right time to keep from spoiling the low pressure in the cavity by adding high pressure from the source. Therefore, the reed *automatically* lets high pressure join the high pressure part of the sound wave, but not the low pressure part, increasing the strength of the resonance in the cavity. If this adds more power than is lost to the finite Q of the cavity, then the size of the sound wave will get bigger.

A few points are in order. First, the resonant frequency of the reed has to be higher than of the cavity. Otherwise, the reed will respond too slowly to the pressures on it, to open and close at the right stage of the oscillation. That is why, when the oboe plays the reed when it is taken off the instrument (in which case it is a free reed, playing at its natural frequency), it makes a high pitched squeak, much higher than the note played by the oboe. To reach the top of the range of a reed instrument, the player often bites down on the reed, which effectively shortens the part of the reed which is free to vibrate, raising its resonant frequency (like moving where the ruler is clamped between your hand and the table, so a shorter stub of the ruler is sticking off the table). Second, the size of the resonance in the instrument body will of course not grow forever. In particular, the peak pressure inside the instrument will never get larger than the pressure supplied by the mouth, since the mouth was only increasing the pressure in the cavity because the mouth pressure was higher. Third, the louder you play, the further the reed moves back and forth. At some loudness, the reed falls all the way shut in the low pressure part of the pattern–it "claps." This makes the pressure pattern very different from a sine wave. Because of the way the reed functions, a reed instrument typically makes something quite far from a sine wave pressure pattern, so reed instruments typically have lots of harmonics in their spectrum. This is especially true if the resonant cavity is designed or chosen such that the harmonics of the note played are also resonant frequencies of the cavity. This is the case for all orchestral reed instruments.

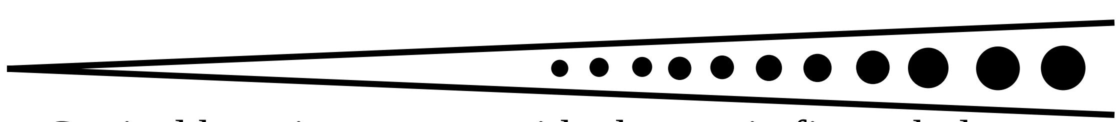
How is a reed instrument to play a wide range of frequencies? Part of the answer is, by playing not just the fundamental frequency of the resonant chamber, but the resonant frequencies of its overtone series as well. This requires some way for the performer to favor the buildup of sound in an overtone of the cavity without building up in the fundamental resonant pattern of the instrument. One way to do this is with a **register hole.** This is a small hole which can be opened in the instrument at the spot where the fundamental resonant pattern has a high pressure, but some higher overtone has a pressure node. For instance, on an open-closed cylinder (the clarinet), a hole one-third of the way along the instrument,



is at a spot where the resonance of frequency $3v_{\mathrm{sound}}/4L$ has a pressure node, but the fundamental $v_{\mathrm{sound}}/4L$ does not. When the fundamental plays, the high pressure at that spot will force air to leak out of this little hole. That means that energy is lost from the resonance; the fundamental has a low Q. However, since the overtone has no pressure variation at that spot, no air is forced out, and the Q is unchanged. A low Q resonance requires a large strengthening of the resonance pattern each period, while a high Q resonance will build up even if only a little energy is added each period. Therefore the high Q resonance will win out. Most reed instruments use such holes to help the player force the instrument to play on a particular overtone (which is called playing in a particular register).

This is obviously not good enough, since it only lets the instrumentalist play the overtone series of the instrument. To get all the notes inbetween, it has to be possible to change the resonant frequency of the resonance. Since most instruments are built around tubes, this means changing the effective length of the tube. This is done by opening larger holes, called **finger holes**, placed along the tube of the instrument.

If the finger hole were as big around as the diameter of the instrument, then opening a hole would effectively end the instrument's tube there. Since the air is free to leak out at the finger hole, it has to be a pressure node; the condition which determines the frequency played by the instrument is the distance from the closed end of the instrument (at the reed) to the pressure node at the end of the instrument, which has now moved to the finger hole. To play a chromatic scale on a conical bore instrument, one would need 11 such holes, spaced further apart at the end of the instrument and closer together at the middle:



Conical bore instrument with chromatic finger holes

In practice it is a better idea to use holes which are quite a bit smaller than the diameter of the instrument. (For one thing, it is easier to cover them with your fingers!) Since such a hole lets out less air than a big hole, the pressure does not have to be quite at a node at a smaller hole; the resonance pattern extends a little ways further up the bore of the instrument, which means that you can change the frequency a little by opening or closing the holes further down than the first opened hole. This reduces the number of holes needed to play a chromatic scale. Since some instruments are quite long and many have holes too big for fingers to cover accurately, an elaborate system of levers, wires, and spring mounted hole covers is required. The fingering technique is complicated, varies between instruments, and beyond the scope of this lecture.

Two final remarks are in order. First, the timbre of the sound inside the instrument is not the same as the timbre of the sound emerging from the instrument. This is because of the way that the sound radiates out from the holes in the instrument. We saw in lecture that, when a tube opens from area A_1 to a much larger area A_2, only a fraction $4A_1/A_2$ of the sound intensity escapes. What should we use for A_2 to understand sound escaping into the world? The answer turns out to be, roughly $A = (\lambda/\pi)^2$ with λ the wave length of the sound. The higher the frequency, the smaller λ is, and the bigger $A_{\rm tube}/\lambda^2$ is. Therefore, the high frequencies more efficiently escape the instrument, and the sound you hear is richer in harmonics than the sound inside the instrument. Since it involves the square of the wavelength, the effect is a factor of 4, or 6 dB, per octave.

Second, the way the sound radiates from a series of open finger holes, each much smaller in diameter than the tube, and the way sound radiates from the end of the tube, are quite different. That means that if a reed instrument really used a strictly conical or cylindrical bore, the notes with all finger holes closed would have a very different timbre from the notes played with several open holes. The bell (a flaring opening at the end of the instrument) was designed by trial and error as a way of changing the radiation pattern of the notes with all closed fingerholes so it more closely resembles the timbre of a note radiated out from the finger holes.