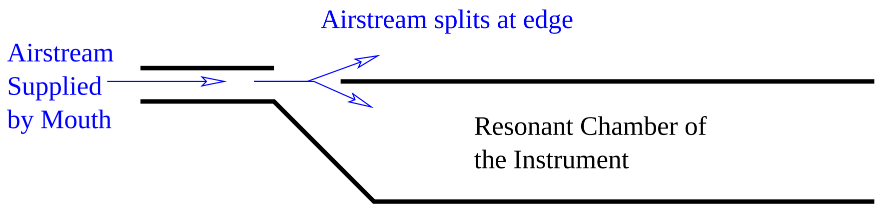
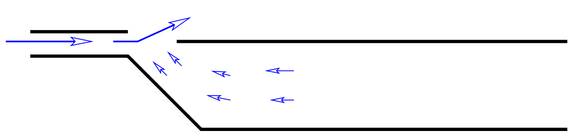
Lecture 23: Flutes and whistles

We saw last lecture that the reed represented one way of solving the problem that the energy in an air resonance damps down with time. The reed presents a technique for pumping energy into the resonance by always adding pressure when the pressure is high and never when the pressure is low. Flutes and whistles operate by the same principle, except instead of playing with the pressure at a velocity node and a pressure antinode, they play with the air flow at a velocity antinode and pressure node, that is, an opening in the instrument.

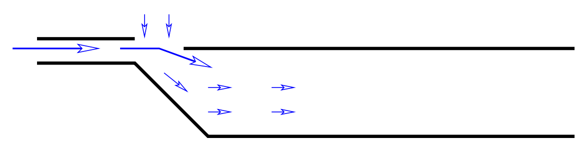
Consider a recorder, which is a kind of whistle. The player blows into a slot or tube, providing a stream of air. (Opposite of the reed instrument, what is important here is that the player is providing air flow, rather than air pressure). The stream of air crosses an opening and is split by an edge. On one side of the edge is the outside, on the other is a resonant chamber:



The air either goes up, into the world, or down, into the resonant chamber. Now suppose there is a resonance going on inside the chamber. The air is crossing an opening, which is one of the places air can get in or out of the resonant chamber. A resonance has a velocity antinode (pressure node) here, meaning it is a spot where there is a maximal airflow during the resonance. When air is flowing out, it will deflect the air stream to go out with it, and when the air is going in, it will deflect the air stream to go in with it:



Behavior when resonance makes air flow out



Behavior when resonance makes air flow in

The airstream you blow therefore joins the air flow, in or out of the resonant chamber, and makes it stronger. That strengthens the resonance, pumping energy into the resonance and making it louder. This is analogous to what a reed does, only it is done by playing with the airflow, rather than with the pressure.

A flute works by exactly the same idea; you blow across a hole (called an **embouchure hole** on a flute) which is an opening in a resonant chamber, and your airstream is split on the other side of the hole, and either goes into or out of the chamber. A resonance in the chamber causes air to flow in or out of the embouchure hole, and that forces your air to accompany it. For the purposes of this class, we will take the distinction between a flute and a whistle or recorder to be, that in a flute, the mouth forms the airstream, while in a whistle or recorder, a length of tube or a slit forms and directs the airstream. Each technique has its advantages, but over time the flute has won out as the more widely used orchestral instrument (though the recorder is enjoying growing popularity).

The problems in designing a flute or recorder are similar to the problems in designing a reed instrument. To play chromatic scales, one must be able to change the resonant frequency of the resonant chamber, which is generally done by making it a cylindrical or nearly cylindrical tube with finger holes. Finger holes means that the far end of the tube must be open, so flutes are almost always open-open instruments. An exception is the pan pipe, where the instrument is made out of a large number of open-closed tubes, often tied together into two rows like the white and black keys on the piano. Each tube plays one note, and the player must move the mouth from place to place to reach different notes.

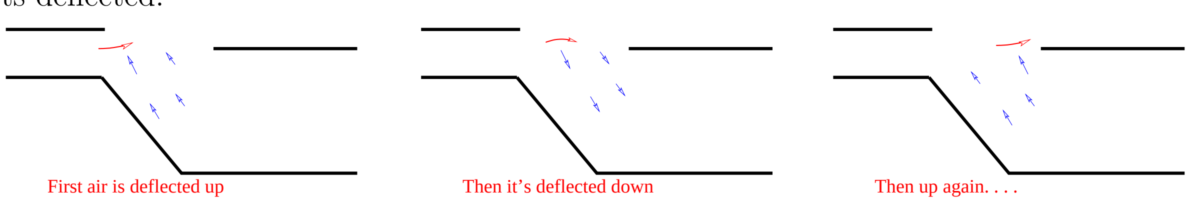
How does a flute or recorder player force the instrument to play overtones of the resonant chamber? A recorder often has a register hole (your thumb covers it on the cheap grade school recorders), but register holes are actually not necessary for flutes and recorders to hit overtones. It can be done instead with the speed of the airflow across the embouchure hole (and in the flute, the placement of the mouth too).

The explanation given above, of how the resonance and the air flow interact, would be true of any resonant frequency of the chamber. However, not all resonances are enhanced by the same amount. It turns out that the airstream crossing the embouchure hole has a natural frequency which it enhances the most efficiently–the frequency where the time for the airstream to cross the embouchure hole is about half of the period of the resonance:

$$f_{\text{most enhanced}} \sim \frac{2v_{\text{airstream}}}{d}$$

with $v_{\text{airstream}}$ the velocity of the airstream blowing over the opening, and d the distance for the airstream to cross the opening. Let us see why.

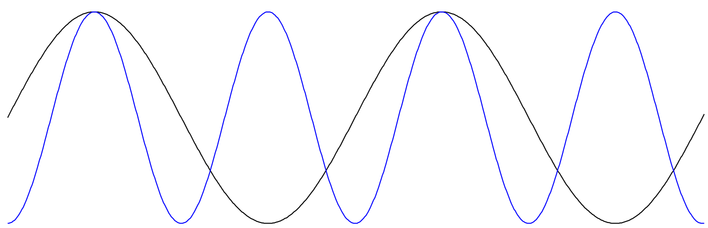
First, consider a resonant frequency in the body of the instrument which has a shorter period than the time it takes for the air to cross the opening. In this case, the airstream is first pushed in, then pushed out, then pushed in, . . . on its way across the opening. To see this, imagine following one bit of air from the airstream, on its way across the gap where it gets deflected:



The different deflections do not add up, and do not help make the airstream more or less likely to deflect the right way at the edge on the other side of the embouchure hole.

That means that high frequency oscillations do not self-reinforce. For this reason, flute and whistle instruments tend not to be very rich in harmonics (though they have some, if the resonant cavity has harmonically related overtones). We saw this during instrument days when we sampled flutes and/or recorders.

What about a resonance at a frequency lower than the time for the air to cross the opening? This does push in the right direction consistently as the air crosses the opening. However, if more than one resonance has a frequency below $f_{\text{most enhanced}}$, only one of them is typically amplified. To see why, imagine that both the fundamental and a first overtone at twice the frequency were oscillating inside the body of the instrument. They alternate between pushing in the same direction, and in opposite directions, because the two waves we are adding look like this:



When they push the same direction, they will make the airstream move with them, which enhances *both* waves. When they push in opposite directions, the airstream will move with whichever is larger. That enhances the resonance with the larger amplitude, and diminishes the resonance with the smaller amplitude. If the resonant chamber happens to start with mostly the low frequency resonance present, it will be strengthened and will remain. If neither is present, or if the high frequency one is present with a larger amplitude, the high frequency one tends to build up and the low frequency one does not. That means that, once you get the instrument to start making one of the available frequencies, it tends to stick with that frequency. However, it is easier to get the higher frequency started. Tricks flutists know, like using the tongue to briefly stop the airflow, can help the instrument "find" the higher frequency. Also, depending on how fast you blow, the higher frequency harmonic can take over even if the lower frequency one was present first.

In other words, when the flutist controls which overtone of the resonant cavity they play, mostly by varying the way they form the air stream. To play the fundamental register, the musician pulls the lips back so that the whole embouchure hole is exposed, blows slowly, and shapes the airstream with the lips so that it will not be narrow and fast. This leads to a slow airstream crossing a large opening, which can drive the fundamental but not the higher overtones. To skip up an octave, the flutist narrows the lips, speeds the airflow, and moves the lips forward somewhat, shortening the distance the air travels to cross the embouchure hole. This means that it takes less time for air to cross the hole, so higher frequencies can be enhanced. There are also tricks with fingerings which can help the resonance in the chamber find a higher overtone.