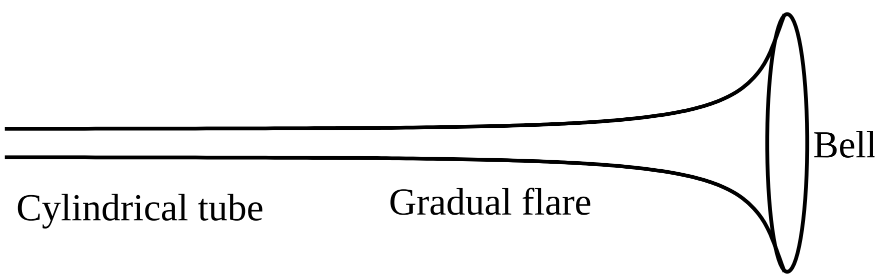
Lecture 24: Brass instruments

There are two key ideas behind brass instruments. The first is to use the lips as a reed. It is quite easy (and annoying) to play your lips as a free reed. You tighten them and bring them almost together, and then blow. By varying how tight you make your lip muscles, you can change the pitch your lips produce. Tightening the muscles makes the lips both thinner and stiffer, and raises the frequency.

As reeds, your lips have two properties which distinguish them from the single and double reeds used by orchestral reed instruments. First, they are heavier. That makes it more difficult for them to move at frequencies far from their resonant frequency. Therefore, the brass instruments will generally play notes quite close to the frequency the lips would make if you moved the brass instrument away. Second, the resonant frequency of the lips is much easier to control, since they are part of you. This makes it practical to have a reed with a highly and rapidly variable vibration frequency.

The other key idea of a brass instrument is that the sound emerges from a wide opening, called the **bell** of the instrument. The bore of the instrument is cylindrical for much of its length, but then it flares out wider, gradually at first and more rapidly at the end:

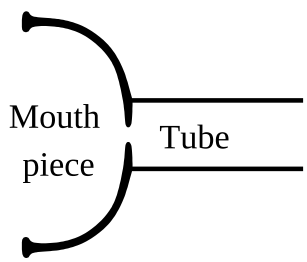


The gradual flare is an impedance matcher which lets the sound move from the narrow to the wide part of the tube with little reflection. By widening the bore before the sound reaches the outside world, the efficiency of the radiation of the sound is improved. Recall that, when a sound goes from being in a pipe of cross-section A_1 to a pipe of cross-section A_2, the fraction which is transmitted is

$$\frac{I_{\rm transmitted}}{I_{\rm incident}} = \frac{4A_1A_2}{(A_1+A_2)^2} \, .$$

To understand the flaring of the instrument, remember that this expression is for a *sudden* change in the diameter. If the tube changes gradually, one should roughly use this formula repeatedly for the amount of flaring which happens every 1/4 wavelength of the sound in question. When A_2 is close to A_1, almost all sound is transmitted; for instance, even for $A_2 = 2A_1$, 8/9 of the sound is transmitted. Therefore, if the flaring of the instrument is by only a factor of 2 every 1/4 wavelength, the sound intensity continues without reflection. At the opening of the instrument, we should use this expression again, with A_1 the area of the opening and $A_2 = \lambda^2/\pi$ as the "effective area of opening into the outside world."[1]

Now think about a high frequency overtone. It has a short wavelength, and will make it almost unreflected through the flaring of the instrument. It therefore radiates into the world using the full area of the instrument's bell, making for efficient radiation of the sound in the instrument out into the world. For a low frequency tone, on the other hand, the sound makes it unreflected out to where the bore starts to change diameter rapidly. Then most of it is reflected back in, and only a fraction makes it to the bell, which again gives an inefficient radiation because the area is much less than λ^2. Therefore the brass instruments are especially efficient at radiating high frequencies, compared to low frequencies. This is both what makes them loud and what makes them "brassy" (which is the timbre of something with a lot of power in overtones).



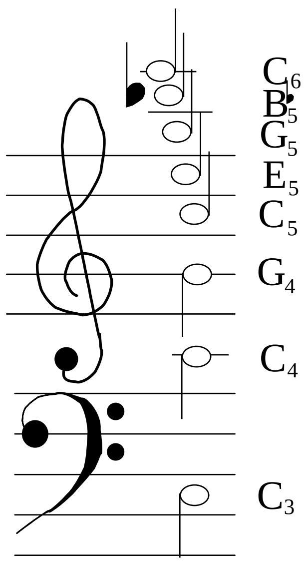
On the other end of the instrument, the lips to not attach to the cylindrical tube of the instrument directly. It is easier to play the instrument if there is a **mouthpiece**, a roughly hemispherical piece of metal which provides a larger ring for the mouth to touch and a narrow opening into the tube of the instrument, as pictured to the left. The mouthpiece is a separate piece of metal and can be taken on and off.

In designing an instrument, one must choose either to have the sound radiated from finger holes, or from a bell. Modern orchestral instruments always use finger holes for reed, flute, and whistle instruments, and bells for lipped instruments. There is no reason in principle that an instrument with a reed and a bell cannot exist, or an instrument played with lips and finger holes. In fact, brass and wind musicians often try this before and after rehearsals, putting their mouthpieces on fingered instruments or reed bocals onto brass instruments in place of the mouthpiece. It works, and PDQ bach wrote a piece for the "tromboon," a trombone played with a bassoon bocal. However, the history of instrument design has dismissed this idea and preferred brass instruments with a bell played with the lips, and fingered instruments played with a reed or as a flute or whistle.

There was a good reason for finger holes, though; it allowed the length of the bore of the instrument to be varied. How is the brass player to play any note without finger holes? One solution, used for the bugle, is that you don't; only the overtone series of the instrument can be played. This is good enough for the army, but not for orchestral use.

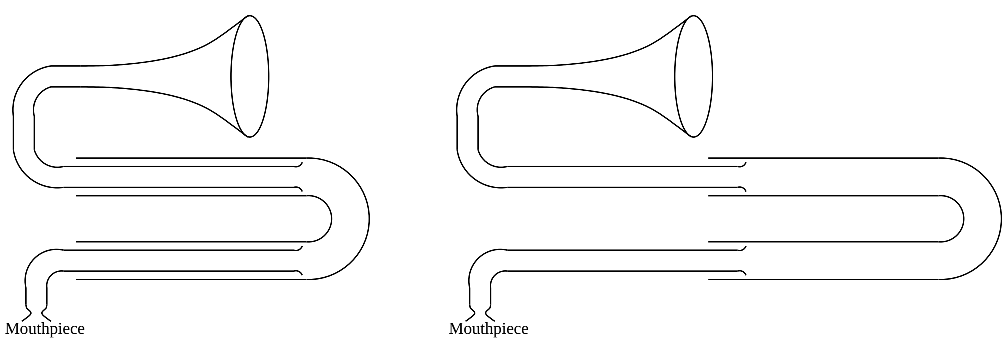
To see the problem, let us look at the notes which a trumpet in C can play, without varying the length of the instrument.

[1]This is the result of a tricky calculation which you don't want to see.



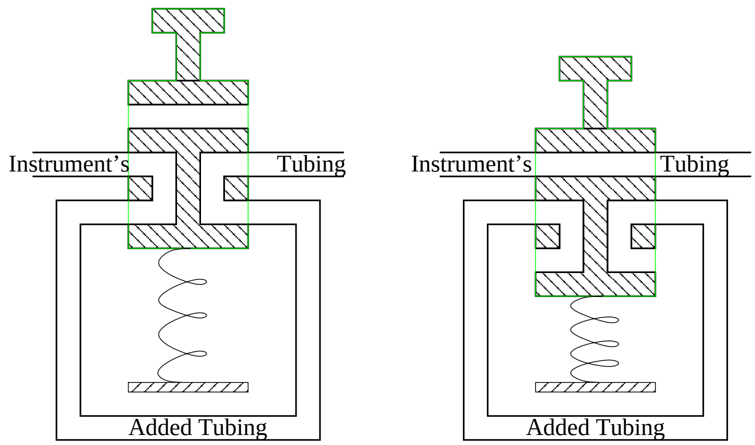
The fundamental is C_3. As we will see below, this is hard to play and rarely used. The harmonics are in the $1, 2, 3, 4, \ldots$ progression, so the next is C_4, followed by G_4, C_5, E_5 (14 cents flat), G_5, $B^\flat_5$ (31 cents flat), C_6, and so forth.
Abandoning playing C_3, the largest interval is from G_4 to C_4, 7 half-steps. One needs to be able to play the 6 notes between these ($F^\#_4$ to $C^\#_4$) in order to play any chromatic note. To do so, it must be possible to make the instrument longer by amounts varying from a factor of 1.06 (adding 6% of the instrument's length) to 1.41 (adding 41% of the instrument's length). That way, the instrument can play down from G_4 to $C^\#_4$. This also allows the instrument to play below C_4, down to $F^\#_3$. (Most trumpets are in $B^\flat$, which means that all notes are a whole step lower than the notes I just named.)

There are two ways to vary the length of tubing making up the instrument: with a slide, and with valves. The idea of a **slide** is to have two long, straight cylindrical pieces of pipe at some point in the instrument's tubing. Another pair of pipes, of slightly larger diameter, fit around these pipes. The inner pipe comes to an end, and the air flows into the outer pipe; it has a 180° bend, taking the air to the other straight section of tubing. The outer tube can be pulled back and forth, like so:



which varies the total length of the instrument. It is difficult to design an instrument where the slide makes up more than about half the length of tubing, but it does not have to; it only needs to make up about 40% of the total length of tubing, as we saw. The advantage of this method is that it is possible to tune the instrument to any note in the range allowed by the slide. It also allows certain effects; a glissando (a note sliding in pitch smoothly rather than jumping from one note to another) is easy to achieve using a slide. The trombone is the most common brass instrument using a slide as the main tuning device.

The other way of varying the length of tubing in a brass instrument is by using valves. The general meaning of "valve" is a device which can open or shut a pipe, like the handle you use to turn on or off water at a sink. For a brass instrument, a valve is something which can reroute the air in the instrument so that it either goes through a very short tube (usually, just across the valve) or it goes through a longer section of tube. A cartoon of how this could work is,



One Valve Position:
Tubing Added

Other Valve Position:
No Tubing Added

The thing in the green box is the valve; the top is a button for a finger to press, on the bottom is a spring. When you push down (on the right in the figure), the tubing of the instrument is routed through the short piece of tubing across the valve. When you let it up (left in the figure), the tubing of the instrument is routed to attach to an extra piece of tubing, thereby increasing the effective length of the instrument's tube. In this cartoon, pushing down the valve button makes the tube shorter, but in practice it is generally done the other way, so pushing down the valve button adds the extra piece of tubing and makes the instrument's tube longer. By having 3 or 4 valves, each attaching a different length of tubing, enough combinations are possible to achieve any desired length of tubing to reach the notes in a 6 half-step range. On a trumpet, this is achieved by having a valve which adds enough tubing to go down a half-step, one valve with enough tubing to go down 2 half-steps, and a valve which adds enough tubing to go down 3 half-steps. This does not work perfectly; each added half-step requires more tubing than the half-step before it (since pitch goes as the log of the period and therefore the log of the instrument's length). To some extent this is solved by the performer "pulling" the pitch a little by varying the lip tension and shape, called "lipping a pitch up or down." On some instruments (depending on the manufacturer), a very small slide is added to adjust the note by a fraction of a half-step. On the deeper brass instruments with longer tubes, such as the tuba, a fourth valve is added, to allow more possible combinations of length, which makes it easier to design the instrument so that some combination is close to the right tuning for each note.

Different instruments use different kinds of valves, *eg*, piston versus rotary valves. The distinction is important to the musicians and manufacturers, but their role in the instrument is the same.

The key problem in the design of a brass instrument is getting the overtones of the instrument's cavity to lie in the right harmonic series. The problem is, that the instrument is not an open-open cylinder, or an open-closed cylinder, or tapered in a cone. The instrument should be closed or nearly closed on one end (the end with the mouthpiece), so it will have a pressure antinode where it is being played as a reed. It must have a long cylindrical section, and it is chosen to have a flaring section at the end. The tricky thing is that the long cylindrical section will *vary in length* as the slide is moved in and out or as valves are depressed or lifted.

Yet somehow, the overtones need to be in an integer progression ($1, 2, 3, 4, \ldots$ times a fundamental). This is important to make it easy to play the instrument in tune, since a major way the player goes from note to note is by going from overtone to overtone. It is also important to the timbre of the instrument; if the musician is playing C_4, and the overtones of the cavity are $C_5^{\#}$ and A_5 instead of C_5 and G_5, then the harmonics of the C_4 note will not resonate. That makes the tone too nearly sinusoidal, which sounds hollow, and it turns out to make it harder to hold the note in tune.

If there were no flare in the instrument, and the mouth end were really closed, the overtones would be in the progression,

$$\frac{v_{\rm sound}}{2L} \times \left(\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}, \ldots \right)$$

rather than the desired progression,

$$\frac{v_{\rm sound}}{2L} \times \Big(1 \, , \, 2 \, , \, 3 \, , \, 4 \, , \, \ldots \Big)$$

Each note is too low, and the early ones are too low by more. What the flaring of the tube does, is to make the low frequency (long wavelength) modes reflect before reaching the bell, which makes the instrument effectively shorter for them. This lifts the frequency of the low overtones more than for the high ones, which is just what we want. A gradual widening reflects only long wavelength modes. A rapid widening reflects shorter wavelength (higher frequency) modes. To make the instrument shorter for the longer wavelength modes, it should flare gradually at first and more rapidly at the end. The mouthpiece also modifies the resonant frequencies somewhat.

The best way to make the instrument's bore flare is a hard design problem, which had to be solved with the most powerful design technique known: trial and error. Over the years, for each instrument, instrument makers have learned how to make the flare of the instrument just right so that the overtone series is very nearly in harmonic progression. The exception is the fundamental; there is no way to design the instrument so it is in tune. In practice it is well flat of the ideal tone, typically around 0.8 times the desired pitch (which is a major third). This makes it very hard to play, and generally it is not played. The note at the missing fundamental (half the frequency of the first overtone, C_3 for the C_4 trumpet discussed above) *can* be played, even though there is no resonance in the instrument there! The presence of resonances at all the overtones makes this possible. This note is called the **pedal tone**. It is difficult to play and is separated by a gap from the rest of the instrument's register (the trumpet in C discussed above can play $F_3^{\#}$ and a pedal tone at C_3, but nothing between these notes), so it is only used infrequently.

We end with two amusing remarks about wind instruments.

The first is about the pressure required to play. The reed and brass (lip) instruments require a high pressure and a low airflow. The flutes and whistles take a fast airflow but not much pressure. Flute players may get out of breath; reed and brass players get red faces.

Why red faces? The arteries and veins which serve the head pass very close to the pharynx in the throat. The pressure of the air in the pharynx (between the back of the mouth and the larynx) pushes against the arteries and veins. Typical blood pressure is "120/80" in *torr*, or millimeters of mercury. In real units, this is about 16 000 Pascal and 10 500 Pascal, or 16% and 10.5% of an atmosphere. The higher number is the pressure of the blood being pumped *into* the body from the heart, the lower pressure is the pressure of the blood *returning* to the heart. The higher the pressure a reed player puts up, the higher the pressure inside the instrument can be; so you must push hard to get a loud sound. Reed and brass players, playing at maximum dynamic, can use air pressures in excess of 10% of an atmosphere. This is enough pressure to close the veins draining the head. As blood fills into the head without leaving, the face turns red. This is more amusing than harmful.

Very skilled trumpet players can reach even higher pressures, sometimes in excess of 16% of an atmosphere, in very loud playing. This is enough pressure to close off the *arteries* bringing blood *into* the head. The blood in the head then becomes anoxic and turns blue, giving a bluish white complexion. *This is bad for you* and will catch up with you eventually. This gives some trumpet players have health problems late in life.

The second remark is about circular breathing. Skilled reed players and extremely skilled flute and recorder players can sustain a note *indefinitely*. The trick is to use the mouth as an air reservoir. Just before running out of breath, the musician fills up the mouth and cheeks with air. Then he/she closes the mouth off from the throat, and expels the air in the mouth to keep the instrument playing, while breathing in through the nose as fast as they can. This requires coordination and is easier on an instrument which requires a low airflow (reed and brass) than on an instrument which needs a fast airflow (flute and recorder). A musician who is adept in doing this can sustain a note without interruption until they get bored and decide there is something else they could be doing instead.