The Physics of Music: Brass Instruments

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As a first approximation, brass instruments can be modeled as **closed cylindrical pipes**, where *closed* means closed at one end, open at the other.

Here are some sounds from blowing into a simple PVC pipe, from the text.

The lips have their own natural vibrating frequency, controlled by the *lip tension*.

The pipe has its own natural resonance frequencies (the possible frequencies of standing waves).
The animation in the section **The lip reed instrument is a ‘closed’ pipe** illustrates how resonance occurs

Note in particular that (as we learned in lab) some of the wave is emitted at the open end (which makes the sound that is heard) and some reflects back into the instrument (to help make a standing wave)
For more detail, let’s look at the diagrams in the Pipes and Harmonics page of the text.

The main points of these diagrams:

- Pressure and displacement (motion) are $90^\circ$ out of phase in a sine wave.
- The resonant frequencies of open pipes and conical pipes are the set of all harmonics of the fundamental frequency.
- The resonant frequencies of closed pipes are the set of odd-numbered harmonics of the fundamental frequency.
- For open pipes and conical pipes, the longest wavelength is $2L$, but for closed pipes it is $4L$; this means that the fundamental frequency of a closed pipe is $1/2$ that of an open or conical pipe of the same length.

Together, these imply that the resonant frequencies of an open or conical pipe are higher and more closely spaced (interval-wise) than those of a cylindrical pipe.
Our PVC pipe is a closed pipe, since the player’s lips close one end, so only odd numbered harmonic frequencies can give rise to standing waves

Note: this model for the resonant frequencies in pipes is simplified and idealized; in actuality, as the pipe diameter increases, the higher resonances are successively flatter

Two difficulties with using this PVC pipe as a brass instrument:

▶ The notes are too far apart
▶ It’s not very loud

This is where a flare and a bell can help...
A *flare* is a gradual widening of the instrument’s sound tube; a *bell* is a rapid (although continuous) widening at the end of the instrument’s sound tube.

Adding a flare and a bell now make the PVC pipe approximately conical, which raises the fundamental frequency by (about) an octave and allows for resonance at all harmonics, not just odd-numbered harmonics.

To compare these two, listen to a 110 cm long cylindrical pipe with no flare or bell and one of the same length with flare and bell (both from our textbook).

The flare and bell raises the fundamental and brings the first three resonances closer together.
Other effects of the bell:

- Long waves (low frequencies) are least able to follow the curve of the bell and so are effectively reflected earlier than shorter waves (higher frequencies).

- The further short waves (high frequencies) go into the bell, the more easily they escape to the outside air, so they are radiated as sound more efficiently.

- Correspondingly, brass instruments have a “brassy” sound, meaning with prominent higher harmonics — the amplitude of the harmonics does not decrease as rapidly with frequency as it does for woodwind instruments.

- High transmission means low reflection, which means weak standing waves, weak resonances, and rather flexible notes.

- The high frequency radiation from brass instruments is rather directional (ask the bassoonists).
Now we can add a mouthpiece to our instrument, consisting of a *constriction* and *taper* around an *enclosed volume*, as in the text.

You can think of this as a tiny bottle, which is a Helmholz resonator, whose frequency depends on the enclosed volume and the geometry of the constriction (or “neck” of the bottle).

You can excite the mouthpiece’s resonance by slapping the wide end of it with your hand, giving a “pop tone”.

The mouthpiece allows you to connect the pipe to a comfortably large section of lips.

The enclosed volume and constriction lower the frequency of the highest resonances (approximately those above the pop tone), which is the opposite of the flare and bell effect.

The mouthpiece also strengthens some of the resonances, again countering the flare and bell effect.
Let’s look at sound production specifically in a trumpet, as a model for brass instruments in general.

A diagram of the trumpet is available at Mole Valley Music, and further description of its parts are at the ThinkQuest trumpet site.

The path of the sound is:

- The player blows into the instrument at the mouthpiece.
- The lips act as a vibrating valve.
- The air in the instrument vibrates at frequencies determined primarily by its resonances.
- As the air in the instrument vibrates, part of it escapes and is radiated as sound; part of it is reflected and returns to reinforce the vibrations.
- Without valves, lip tension will determine which note is played.
- The length of the instrument’s tube can be changed with the valves (or with the slide for a trombone), allowing for more notes.
Brass players can make musical sounds just with their lips, from a low-pitched “raspberry” to a high-pitched musical note, depending on lip tension.

A sound sample of this can be found in the text, along with a useful diagram of the lip motion.

Lip motion works as follows:

- Making a high air pressure in your mouth by blowing forces the lips open
- This lets the air rush out, which lowers the pressure in the mouth
- Lip tension and this lower pressure draw the lips closed
- Because the lips are closed, the air pressure builds in the mouth and the cycle repeats

All else being equal, high lip tension means a large “restoring force” to the lips, which gives a high frequency of vibration and so a high pitch.
Playing softly, especially a low note softly, the lips don’t move fast enough and so don’t close completely, giving an approximately sinusoidal vibration

Playing loudly, the lips do close, possibly abruptly, which gives “clipping”

Clipping brightens the timbre by bringing out higher harmonics, as it does when applying distortion to an electric guitar

Correspondingly, the tone brightens as the instrument is played more loudly, as this [trombone sound sample] in the text indicates
Without the valves, lip tension determines which of the trumpet tubing’s resonances will be played.

The trumpet is shaped so that its resonances will be close to the complete harmonic series except the fundamental frequency, which is not a resonance of the instrument.

With sound samples from our text, we can hear (many of) these for a C trumpet, a guitar, and a flute.

Early brass instruments were valveless, such as the Baroque trumpet in this sound sample from our text demonstrates.

Good trumpet players can use higher resonances to help the lips establish a nonlinear vibration at the frequency of the missing fundamental.
Mutes lower the volume and alter the timbre of the sound from a trumpet.

The three most common types of trumpet mutes are:

- straight mute
- cup mute
- Harmon mute

These are shown (along with sound samples) at David Summer’s website.
Straight mutes act basically as high-pass filters, allowing frequencies of more than about 1800 Hz through

Cup mutes are similar to band-pass filters, allowing frequencies of about 800 Hz to 1200 Hz through

Harmon mutes have open pipes in the center with resonances at around 1500 Hz, 3000 Hz, and 4500 Hz

Partially closing the end of a Harmon mute changes the sound from more like an “ah” sound to more like an “ooh” sound, which is why Harmon mutes are also known as *wah-wah* mutes
The two main types of valves used on brass instruments are *piston* (as on the trumpet) and *rotary* (as on the French horn).

Our text has some good pictures showing how *valves* work.

The first valve on a trumpet lowers the pitch by a whole step; the second by a half step; the third by three half steps.

A tuning difficulty arises when we use more than one valve at a time: the total percent increase in tube length isn’t the sum of the individual percent increases.

To help compensate for this, trumpets have a slide on the added pipe.