The Acoustics of Brass Musical Instruments

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All brasswind instruments have several things in common but being made of brass is not one of them.

The history of brass musical instruments is as long and varied as civilization itself. Although the recorded history of civilization predates the manufacture of brass by several millennia, it is not the material from which the instrument is made that classifies a musical instrument as being a member of the brass family. Rather, it is the fact that the sound originates from vibrations of the player's lips. This sound from the lips, colloquially referred to by some as a raspberry or Bronx cheer, is the driving oscillation for all members of the brass family. During play, the lips open and close periodically and release a train of pulses of air into the instrument similar to the action of the reed of a woodwind instrument, and, indeed, the oscillating lips are usually referred to as a *lip reed* by acousticians.

Technically, these instruments are called labrosones, and it is not clear when they began being referred to as brass instruments or, more correctly, brasswind instruments. To make things more confusing, not all wind instruments made of brass are brasswind instruments. Instruments in the brass family have been made from wood, shell, animal horn, ceramics, tree bark, various metals, plastic, and even human bones. But the saxophone, which is made entirely of brass, is not a brass instrument.

Considering the cultural and geographic diversity of the people who play brasswind instruments, the long list of construction materials is not unexpected. Indeed, the only surprising material in the list may be human bones. It is well-known that animal bones were used in antiquity for flutelike instruments (Zhang et al., 2004; Atema, 2014), and they are still used today as percussion instruments in some cultures. But the use of a human bone for a musical instrument is unusual. In most cultures, human bone is not an acceptable material from which to make musical instruments; however, there are documented cases of trumpets made from human bones in some Amazonian and Himalayan cultures (Baines, 1976). In an interesting note, Baines recounts that after the body of one of the first Europeans to be buried near Darjeeling was interred, it was promptly dug up by members of a local sect so they could use his "trumpet bones." Evidently, the femur makes a serviceable trumpet and the unfortunate victim was a very tall man.

In addition to the wide variety of materials and shapes, brass instruments may have valves, slides, or holes that can be used to play different pitches, or it may have none of these. The large catalog of ancient and modern brass instruments makes it difficult to address the acoustics of the family in much detail. However, by initially limiting the discussion to the most familiar members of the brass family, it is possible to understand much of the underlying physics of all brass instruments. Therefore, for the purpose of investigating the acoustics of the family of brasswind instruments, it is useful to begin by considering a single instrument and then discussing some of the important differences between this instrument and its siblings. To this end, consider the modern trumpet.

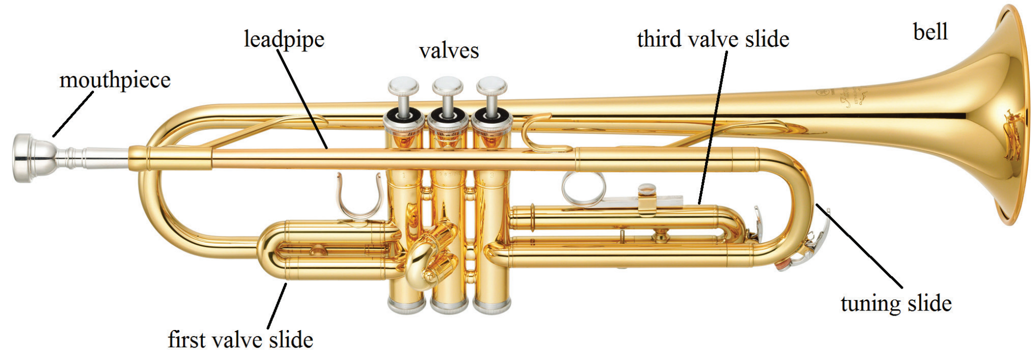

Figure 1. A modern trumpet with the parts labeled. Photograph courtesy of Yamaha Corporation of America.

The Parts of a Modern Trumpet

A photograph of a trumpet with some of the parts labeled is shown in **Figure 1**. (The black lines on the trumpet are an artifact of the lighting and not part of the instrument, which is highly reflective and difficult to photograph.) Although there are several pieces to a modern trumpet, only three of these parts are necessary to identify it as a brasswind instrument. Beginning where the lips introduce the oscillations of the air, the three parts are the mouthpiece, tubing, and bell. The length of the modern trumpet is approximately 1.4 m, most of which is cylindrical tubing. However, valves, which lie along the tubing, are used to change the length of the trumpet during play. The acoustics of the air column inside cylindrical tubing is well understood, so it is logical to begin the discussion there.

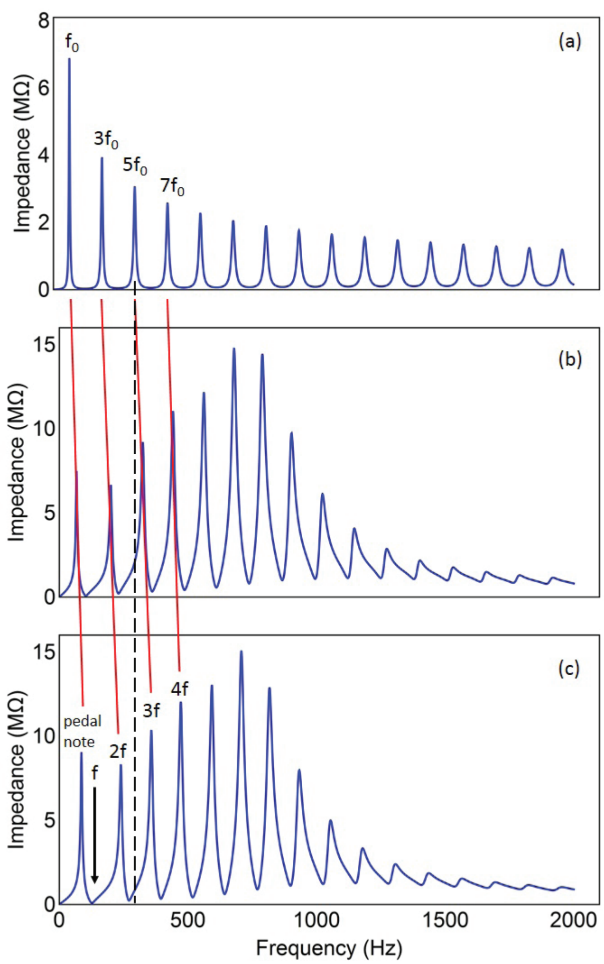

Figure 2. Calculated impedance as a function of frequency for a cylindrical pipe the length of a trumpet (a), a mouthpiece connected to the pipe (b), and a mouthpiece, pipe, and bell (c). The total length has been kept constant in all three cases. f_0 *(a) and f (c), Fundamental frequency of the harmonic series.*

Because the lips impose a pressure antinode at one end of the tube and the other end is open to the atmosphere, the trumpet is an open-closed pipe. Therefore, considering just the cylindrical tubing of the instrument, the wavelength of the fundamental resonance is four times the length of the pipe. The overtones occur at odd multiples of the fundamental resonance frequency as expected. The results of a simulation that calculates the input impedance of the air column of a cylindrical pipe the length of the modern trumpet are shown in **Figure 2a**. The resonances of the air column can be identified by the maxima in the input impedance. The decreasing height of the maxima as the frequency increases is due to a loss of energy to the viscous boundary layer at the wall of the pipe and not to any incidental physical vibration of the pipe.

The input impedance is defined as the ratio of the pressure to the resulting volume flow of the air, so a large input impedance results in a standing pressure wave due to the reflection from the end of the instrument. When the frequency of the vibration of the lips is near one of these resonances, the feedback tends to force the lips to vibrate at that frequency. The feedback of a modern trumpet is so strong that it is extremely difficult to force the lips to oscillate at any frequency other than that of a resonance of the air column. One of the hallmarks of a good brass player is the ability to *bend* a note, that is, to force the lips to vibrate at a frequency that does not correspond to a resonance of the instrument. Although it is logical to ask why anyone would want to play an instrument off-resonance, the importance of this ability will become obvious later.

To actually play the trumpet, it is convenient to have something on which to place the lips other than the sharp edge of the metal pipe. The small bore makes it extremely difficult to buzz the lips into the pipe, but more importantly, the sharp edges of the pipe ensure that without some intermediate interface, trumpet playing would be a short-lived profession. This interface between the player and the instrument is called the mouthpiece.

The mouthpieces of modern brass instruments are typically turned from a solid piece of brass and have three parts: cup, throat, and backbore (**Figure 3**). The outside of the mouthpiece generally follows the bore profile, but the point at which the lip touches the mouthpiece is made much thicker to provide a cushion for the lips.

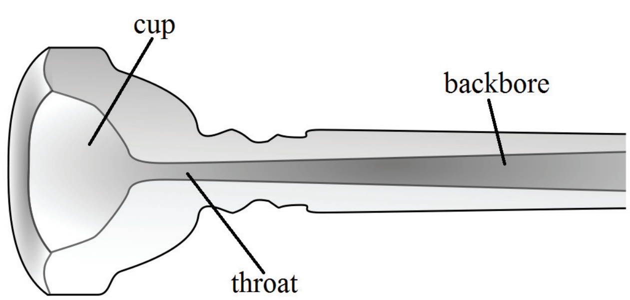

Figure 3. *Drawing of a trumpet mouthpiece with the parts labeled. Drawing by D. Bolton, CC SA-BY 2.0.*

The cup provides a volume of air that acts as a compliance, the throat introduces an inertance, and the backbore acts to gently expand the bore diameter from the narrow throat passage to the wider diameter of the pipe. There is a section of pipe called the leadpipe, which is approximately 25 cm long in a trumpet, that continues this gradual expansion of the bore until it is equal to the diameter of the cylindrical pipe used for the majority of the instrument. However, most of the bore expansion occurs in the mouthpiece.

The inertance (impedance where pressure leads flow by $\pi/2$ radians) and compliance (flow leads pressure by $\pi/2$ radians) together with the resistance to the flow that is inherent in any pipe (flow and pressure in phase) creates a resonance just as an inductor, capacitor, and resistor create a resonant electrical circuit. **Figure 2b** is a graph of the input impedance that occurs when the mouthpiece is connected to the cylindrical piping. In the simulation, the length of the piping has been shortened by the length of the mouthpiece to keep the total length constant. Note that the effect of the mouthpiece is to significantly increase the input impedance between 200 Hz and 1.5 kHz. This frequency range represents the normal playing range of the trumpet. When brass players wish to play above the normal frequency range, they often change the mouthpiece to one with a shallower cup, which raises the resonance frequency of the mouthpiece and makes it easier to play notes that are higher in the musical scale. Professional brass players may have from 3 to 10 different mouthpieces. As a general rule, the better the player is, the fewer the number of mouthpieces used, but most players have at least two or three that are regularly used.

If one were to construct an instrument that consisted only of a mouthpiece and a length of piping, the graph in **Figure 2b** indicates that only the fundamental and the odd harmonics could be sounded. There is a less obvious effect of shifting the resonances slightly in a manner that is not uniform so that they are no longer exactly harmonic, but constructing such an instrument demonstrates that the resonances are still close to the expected relationship. Unfortunately, the radiated sound from this combination is minimal and an audience would hear almost no sound when it is played. To increase the radiation efficiency, the end of the piping is flared into a bell. This flaring increases the radiation into the air so that the audience can hear the instrument, but even with the bell attached, the majority of the sound stays inside the instrument.

The explanation of how the trumpet is constructed is now complete, but one issue remains to be resolved. Musicians know that most brasswind instruments can sound an entire harmonic series and not just the odd harmonics, yet it is common knowledge that the resonances of an open-closed pipe constitute only the odd overtones, as is evident from **Figure 2**. So how can a quarter-wavelength pipe have resonances that include the even overtones? The answer is that it cannot, but by judiciously designing the bell, it is possible to shift the resonance frequencies in such a way that when combined with the small shift attributable to the mouthpiece the overtones become a complete harmonic series.

The design of the bells of brass instruments is still more art than science, but we do understand the importance of the profile of the bore created by the bell. Although it is common to consider the acoustical end of a pipe as occurring near the physical end of the pipe, in the flaring bell, longer wavelengths are reflected in the region well before the actual end of the instrument. Furthermore, as the frequency increases, the final pressure node shifts toward the end of the trumpet. Therefore, acoustically, the instrument appears to be shorter than the measured length, but the difference between the actual length and the acoustic length changes with frequency. Near the highest frequencies of the playing range the acoustic length approaches the actual length.

This shortening of the effective length of the instrument caused by the bell flare shifts the resonance frequencies up, but it does not shift them all equally. The bell flare is designed so that the resonance frequencies are shifted in such a way that they become harmonically related in a different way. The odd-numbered overtones are still the only ones that can be produced, but because the frequencies have been shifted by the bell flare in a nonlinear way, they produce a complete harmonic series. The only resonance that is not part of this harmonic series is the fundamental, which in musical parlance is referred to as the *pedal note*. The frequency of the pedal note is much too low to be part of the harmonic series; therefore, the resonances are referred to as being a harmonic series with a detuned fundamental. This can be seen in **Figure 2c** where the calculated impedance of a complete trumpet is plotted. The pedal note is indicated in the figure as is the fundamental frequency associated with the harmonic series.

The bell serves another function that helps create the unique sound of each instrument. It preferentially reflects low-frequency sound. The higher reflection causes the low frequencies to be more prevalent in the air column because they have a greater effect on the lip motion. However, the bell flare also determines the frequency above which the reflection becomes negligible; this frequency is known as the *cutoff frequency.* So although the bell shape is responsible for ensuring that there is more power in the frequencies at the lower resonances than at the higher ones inside the instrument, it is also responsible for ensuring that a greater percentage of the sound is radiated at higher frequencies.

This description of the trumpet can be generally applied to almost all brass instruments. However, there are variations that are unique to each instrument and these variations result in sounds that cover a wide range of timbres. The shapes of the mouthpieces vary between instruments, but they all have a cup, throat, and backbore and they all produce a resonance in the frequency range that encompasses the normal playing range of the instrument. In contrast, the bell flare and bore shape of brass instruments can vary significantly.

Figure 4. *Photograph of a modern cornet. The cornet has sections of conical tubing in contrast to the cylindrical tubing of the trumpet. Photograph from Yamaha Corporation of America.*

The Importance of Bore Shape

The bore shape of any instrument is defined by the shape of the internal walls of the tubing that constrains the air. As noted above, the majority of the tubing in the trumpet is cylindrical as is the bore of the trombone. However, not all members of the brass family have cylindrical bores. Some have conical bores and most have a combination of cylindrical and conical tubing before reaching the bell section. For example, a photograph of a cornet is shown in **Figure 4**. (As in **Figure 1**, the black lines on the tubing in **Figure 4** are artifacts of the lighting and not part of the instrument.) The cornet has a significant length of nearly conical tubing, which is clearly different from the cylindrical tubing in the trumpet shown in **Figure 1.**

Few modern instruments are completely conical or completely cylindrical, so the bore shape may include cylindrical, conical, and flaring sections. Many modern brass instruments start with some cylindrical tubing followed by a conical section that may be a significant part of the length. From a musical standpoint, these conical instruments sound more "mellow" than the cylindrical instruments, and it is not possible to get the classically brassy sound from instruments having a conical bore. Thus the cornet, which has a large section of conical tubing, does not sound like a trumpet, especially when played loudly.

A good example of the difference in sound between a cylindrical instrument and a similar conical instrument can be heard in these two recordings by Brian Shook (**Audio 1**, http://acousticstoday.org/tcdemo/). A trumpet was used in the first recording while a cornet was used in the second. Note especially near the end of the recordings where the louder, higher, staccato notes make the differences in timbre most obvious. Although the two instruments are the same length and play the same pitch range, the difference in sound is striking.

It is rare to find a modern instrument with a purely conical bore shape. Campbell et al. (2006) note that the alphorn is an instrument that is almost purely conical, but it appears to be unique in this respect. The bugle comes close to being completely conical, but even here, the bell flares at the end rather than merely ending in a cone. However, several instruments have significant sections of the bore that are not cylindrical. The cornet, flugelhorn, and tuba are good examples of instruments that fall into the conical branch of the brass family but are not completely conical.

The conical shape in the tubing is important for two reasons. As noted, conical instruments are characterized as having a mellow sound and do not sound as brassy as cylindrical instruments when played loudly. The conical instruments such as cornets, flugelhorns, and tubas cannot produce the classic brassy sound found in cylindrical instruments such as the trumpet and trombone because this sound results from nonlinear effects that occur only in long cylindrical sections of tubing (Hirschberg et al., 1996; Myers et al., 2012). Also, in contrast to the cylindrical bore profile that results in only odd harmonic components, a purely conical bore has resonances that incorporate the complete harmonic series. Therefore, the end of a purely conical instrument does not function to shift the resonances into a harmonic relationship. However, brass instruments that are primarily conical still have a flaring bell so the mouthpiece, bell flare, and tubing all must work in concert to keep the overtones harmonically related.

Valves and Slides

The bugle, posthorn, and alphorn are examples of instruments that are played on a single fundamental frequency. These instruments have a length of tubing that cannot be changed, and, therefore, the repertoire is confined to harmonics of the fundamental frequency, which is determined by the length of the horn. However, most instruments are designed so that the player can produce all the notes within the range of the instrument. Naturally, the length determines what notes can actually be played, so for the instrument to encompass the entire musical scale, the length must be changed.

Figure 5. *A serpent made during the early 19th century is an example of a labrosone with finger holes. From the Metropolitan Museum of Art.*

Changing the length is relatively easy, but adding and subtracting lengths of piping quickly is not a trivial process. Much of the history of the development of modern brass instruments involves various attempts to quickly change the length of the instrument. Some early brass instruments such as the serpent shown in **Figure 5** used holes in the instrument that were covered with the fingers much like a modern recorder. Slides, such as found on the trombone, originated in the 15th century as a quick and easy way to change the length of the instrument, but this is only practical if there is a significant length of cylindrical tubing in the instrument. Manually adding and subtracting lengths of tubing was common practice from the 16th through the 18th centuries, but the process is not rapid and in the 19th century, valves evolved as the most economical and practical method for changing the length of brass instruments. Today, the only commonly used brass orchestral instrument that does not have valves to change the length of the air column is the slide trombone, although there are a few uncommon instruments such as the slide trumpet that occasionally appear in concert.

All modern orchestral brass instruments have sliding pieces of pipe that can be adjusted before beginning to play, but these slides are designed to change the pitch slightly and bring the instrument into tune with other instruments. Typically, the extension of the slide is on the order of 2 or 3 cm and once set, the position remains constant, adjusted only occasionally as the temperature changes. These slides, referred to as *tuning slides*, are lubricated with a heavy grease so they can be moved when desired but stay in place during a performance. Slides designed to change the played note, such as those found on trombones, are fundamentally different from tuning slides. Slides used for changing the played note represent a significant portion of the length of the instrument and are lubricated with lightweight oil to enable rapid movement.

In most modern brass instruments, valves are inserted into the cylindrical part of the tubing instead of a slide. Valves can quickly change the length of the air column and require much less space when performing. Piston valves, like those usually found on the trumpet and cornet, are the most common kind of valve used in brass instruments, but some instruments, such as the French horn, have rotary valves. Both types of valves have holes through them that correspond to two different pathways for the air to follow. In a piston valve, the piston is depressed directly, whereas rotary valves are turned by depressing a lever that is attached to the valve in a manner to change linear motion into rotary motion. Diagrams of a piston valve in both positions are shown in **Figure 6**, illustrating how depressing the valve results in the addition of a section of tubing to lengthen the bore.

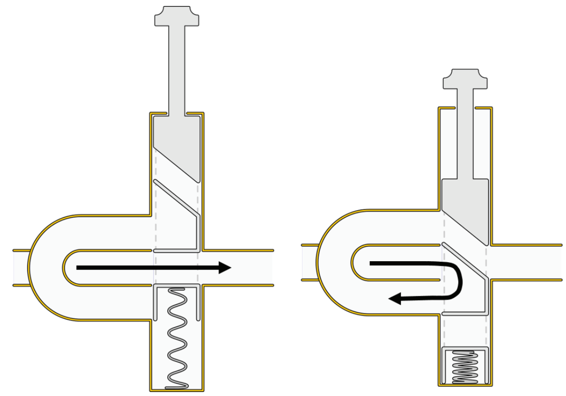

Figure 6. *Diagram of a piston valve in the open (left) and depressed (right) position. When depressed, the air column includes an extra length of tubing. The arrows indicate the direction of airflow. Drawing by A. J. Fijatkowski, CC SA-BY 2.5.*

The choice of valve type is an engineering decision and has only a minimal effect on the acoustics of the instrument, but the placement of the valve has a considerable effect, especially in instruments that are not primarily made of cylindrical tubing. Even if the bore expansion is gradual, interrupting it to insert a section of cylindrical tubing has significant acoustical consequences.

It may not be obvious why one would choose valves over slides, or vice versa, when designing an instrument, but there are advantages and disadvantages to each. For example, slides are not viable in conical instruments and valves can be depressed much more quickly than a slide can be moved. However, in valved instruments, the choice of how much tubing to add to the air column is set by the manufacturer. Slides, on the other hand, are slower to move and take up more space than valves, but they have the ability to change the length in a continuous manner.

It can be argued that it takes a more skilled musician to play a slide instrument than one with valves because there are infinitely many slide positions. Much like a violinist must be conscious of the tuning of each note while the guitarist merely has to press the string between the frets, the trombonist cannot rely on merely pressing the correct valves. This is not a valid assertion, however, because it is impossible to make a perfectly tuned valved instrument.

To understand the problem with adding tubing using valves, it is instructive to return to the example of the trumpet. A typical trumpet has three valves. Ideally, the second valve lowers the playing frequency by approximately a semitone, which is equivalent to moving down one key on a piano (**Audio 2**, http://acousticstoday.org/semi/); the first valve lowers the playing frequency by approximately two semitones (**Audio 3,** http://acousticstoday.org/ws/); and depressing the third valve lowers the frequency by approximately four semitones (**Audio 4,** http://acousticstoday.org/2-steps/). The idea is that by depressing different combinations of these valves, a player can sound any note on the Western scale.

The problem with using valves becomes obvious when you begin to calculate the necessary lengths that each valve must insert into the air column. To lower the pitch by one semitone, you must change the length by 5.95%. A typical trumpet is about 140 cm long, so adding 8.3 cm to the length will lower the pitch precisely where it should be. To lower it two semitones, you need to increase the length by 12.25%, or about 17.2 cm, for the modern trumpet. If you wish to lower the pitch three semitones, it seems logical that you press the second valve to lower the pitch by one semitone and then press the first valve to lower it by two. Unfortunately, pressing the first valve adds about 6% to the length of the trumpet and you need to add 12.25% of the total length to then lower the pitch 2 more semitones. So the necessary length to lower the pitch by one or two semitones will be different depending on what other valves are depressed. In the case of the trumpet, the necessary added length when depressing both the first and second valve together is 26.5 cm rather than the combined value of 25.5 cm. This presents a challenge to both the instrument maker and the musician.

To solve this problem, most brass instruments are designed so that the tubing inserted by depressing either of the first two valves is slightly longer than it should be if it were the only valve being depressed. In this way, the length is slightly longer than it should be when the valves are used independently and slightly shorter than it should be when the valves are used in combination. It is incumbent on the player to play the instrument slightly off the resonance to achieve the correct pitch. As noted above, this is not easy because the feedback to the lips forces them to oscillate at the resonance frequency defined by the air column.

It takes skill, but when using the first two valves, a good player learns to bend notes and playing the correct pitch is not an unreasonable expectation. Unfortunately, when you add the third valve to the mix, it becomes unreasonable to expect even the best trumpet player to bend the notes enough to play in tune. Therefore, the length of tubing added by depressing the third valve is chosen to be approximately what is required to lower the open-valve configuration three semitones (**Audio 5,** http://acousticstoday.org/three/) and a slide capable of rapid movement is added to the tubing associated with this valve. On the trumpet, the slide is moved with the ring finger, but on larger instruments like the tuba, the player usually just grasps the slide with his/her free hand and moves it as required. Many trumpets, such as the one shown in **Figure 1**, also include a slide for the first valve, which is operated with the thumb.

Figure 7. *A six-valve trombone made by Adolphe Sax ca. 1863. The instrument does not suffer from the intonation problems of other valved instruments because the valves are never used in combination. From the Metropolitan Museum of Art.*

Over the years, there have been several attempts to deal with the problem of mistuned valves, with only limited success. Adolphe Sax invented a brass instrument with six valves that does not merely add tubing to the instrument but rather replaces almost the entire length when the valve is depressed. This arrangement, shown in **Figure 7**, is like having seven different instruments available to the player and therefore eliminates the problem of mistuning by never having more than one valve depressed at a time. For better or worse, the idea never caught on.

Some Closing Thoughts

The acoustics of brasswind instruments has been studied for almost two centuries, and many of the interesting details have not been discussed here. They are truly fascinating instruments. But while much of the physics of brass instruments is well understood, it would be misleading to leave the impression that there are no open questions. One important area that is still ripe for investigation concerns the motion of the lips during play and how the instrument interacts with them. There has been significant work in this area, but there is still much we do not understand (e.g., Yoshikawa, 1995; Stevenson et al., 2009; Boutin et al., 2015). Similarly, almost all brass players firmly believe that the effects of the vibrations of the instrument have a significant effect on the sound. This has been shown to be true in the case of bell vibrations (Moore et al., 2005) and a theory has been proposed to explain the effect (Kausel et al., 2015; Moore et al., 2015), but it is not clear that vibrations of other parts of the instrument affect the sound.

There are many things that musicians think are important but about which many scientists are skeptical. For example, a short discussion with almost any skilled brass player will quickly elicit an opinion on the importance of the dc air flow. Air must pass through the instrument during play, but this is just a by-product of the buzzing lips. By placing a rubber diaphragm between the mouthpiece and tubing, it can be shown that the airflow is not needed to produce the sound. All that is required is for the pressure oscillations to be propagated down the tube. However, almost all musicians believe the flow of the air is critical to the sound. Many scientists are less certain.

We understand the basic physics of how brass instruments produce sound and recognize that there are still interesting questions to pursue; however, it is important to remember that brasswind instruments are not scientific instruments. They are played by artists and their value lies in their ability to help a human make music. The ability of these instruments to make music motivates the research, but those of us who study the physics of musical instruments agree that music should be enjoyed without thought to the complicated acoustics that produces the sound. We save those thoughts for after the concert.

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Biosketch

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