Woodwind and Brass Instruments

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The Oxford Handbook of Music Performance, Volume 2
Edited by Gary E. McPherson

Print Publication Date: Apr 2022 Subject: Music, Applied Music
Online Publication Date: Mar 2022 DOI: 10.1093/oxfordhb/9780190058869.013.16

Abstract and Keywords

This chapter briefly reviews the basic science of wind and brass instrument operation and the player-instrument interaction. It begins with how controlled, elevated pressure in the lungs produces air flow is modulated at the instrument input by a vibrating element—an air jet (flutes), a reed (other woodwinds), or the player's lips (brass). This modulation inputs sound waves to the bore (and also back into the vocal tract), where resonances produce standing waves that interact with the vibrating element. Under suitable conditions of embouchure and bore configuration, the standing waves and vibrating element interact to produce sustained oscillations, some energy of which is radiated as output sound. The chapter next explains how the resonances are related to the shapes and configurations of the bore, why some of the resonances are harmonically related, and how these are controlled by the player. In all cases, note production, spectrum, and timbre are related to the musician's control parameters: breath pressure, embouchure forces, tongue, vocal tract and finger gestures. The difficult issue of air speed is discussed, as are the effects of CO_2 humidity, and temperature on playing pitch and techniques including vibrato, altissimo playing, and multiphonics.

Keywords: wind instrument, brass instrument, air speed, reed, sound wave, resonance, embouchure, timbre, harmonics, vibrato

Introduction

KNOWING some of the science concerning the player-instrument interaction can sometimes help a performer solve technical problems, guide experiments to extend his/her technique—and answer questions from students. This chapter introduces some of the basic principles of woodwind and brass instruments and their interactions with players. Further references are provided at the chapter's conclusion and on a website appendix.[1] Unlike with other chapters in this handbook, suggestions for players are integrated throughout the text, rather than as a separate section.

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We concentrate on instruments blown by the player, especially flute, reed, and brass families. For these instruments, the player supplies airflow at raised average pressure (blowing pressure) in the mouth. The next key element is the air jet (for flutes and recorders), the reed (other woodwinds), or the player's lips (brass). This element converts some of the relatively steady flow and pressure of air from the lungs into oscillatory flow and pressure in the mouthpiece of the instrument, producing sound waves.

Sound waves entering the bore are reflected at both ends; this sets up oscillations (technically, standing sound waves) in the bore of the instrument. Those standing waves interact with the jet, reed, or lips to determine the frequency and other properties of the vibration. This interaction also extracts power from the smooth flow from the lungs to drive the oscillatory motion of the jet, reed, or lips.

The player's control is important to performance at all stages, but we begin with the air supply.

(p. 310) Air Pressure, Flow, Power, Losses, and Speed

Producing, controlling, and varying the air pressure in the mouth and the flow into the instrument is fundamental to wind instrument performance. Loud playing in general requires higher pressure and/or higher flow. On many instruments (though not the clarinet), higher pitch ranges require higher pressure for the same loudness. For flutes, pressure is roughly proportional to frequency, and loudness is governed mainly by controlling flow through the lip opening (Fletcher & Rossing, 1998). Blowing pressure often rises in coordination with the tonguing that typically starts a musical phrase and falls during the end of the last note. Pressure and embouchure are varied during the phrase to produce accents and musical "shape." They may also be varied several times per second to produce vibrato (discussed later).

Blowing pressure is usually in the range 1 to 10 kilopascals (kPa), or 1 to 10 percent of atmospheric pressure; ranges for different pitches on different instruments are given by Fletcher & Rossing (1998) and Fuks & Fadle (2002). A pressure of 25 kPa was reported for a trumpet player (Fletcher & Tarnopolsky, 1999). Players (especially trumpeters and perhaps oboists) should be aware that sustained very high pressures can affect circulation in the head and neck, with possible consequences including stroke and eye damage (Banzhoff et al., 2017; Evers et al., 2000).

Muscles in the torso are involved in producing and controlling the blowing pressure as lung volume decreases during a phrase. How the various muscles are used for note production, phrasing, and vibrato varies among instruments and players. It is a topic of strong opinions for some music teachers and is an interesting area of scientific research (e.g., Bouhuys, 1969; Fuks & Sundberg, 1999; Cossette et al., 2008; de la Cuadra et al., 2008; Bianco et al., 2012). When the lung volume is near maximum, the lung and torso's

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elasticity generates a pressure of up to a few kPa; muscle contraction, mainly in the abdomen, can increase this to a higher blowing pressure, when needed. Conversely, torso elasticity generates a small suction at low lung volume; this must be overcome by extra muscular recruitment to produce blowing pressure. In playing, muscles used for inspiration, including the diaphragm, may be used in opposition to expiratory muscles to reduce and to control blowing pressure, as can reduction of the glottal aperture.

Air flows into the instrument at average rates of typically 0.1 to 1 liter per second (10^{-4} to $10^{-3}\ \mathrm{m^3 s^{-1}}$). Multiplying pressure by flow gives the input power to the instrument: roughly 0.1 to 10 watts for our examples. In practice, the range is smaller because high notes, which usually require higher pressure, usually need lower flow.

Inside the instrument bore, airflow is the sum of the average outwards flow of air going from lungs to instrument to bell and the oscillating component due to the sound waves.

Most of the sound power in the instrument bore is lost as heat to, or viscous drag with, the walls: only several percent or less (typically much less than a watt) is radiated as sound. However, one watt of output sound power produces a sound level of roughly (p. 311) 110 dB at one meter from the source, which is uncomfortably loud. (For comparison, loudspeakers are also typically less than several percent efficient, so a “100 watt” sound system may only output a few watts of sound power.)

Sometimes, the instrument’s wall materials influence losses. Briefly, the energy losses as air oscillates past rough or porous wood weaken the resonances; this effect is reduced by oiling the bore in some instruments. In some woodwinds, sharp corners between drilled tone holes and the bore can produce turbulence, which also weakens resonances. In comparison, losses are smaller with smoothed or undercut tone holes or the smooth corners in metal instruments with drawn tone holes. Vibrations produced in the walls by the sound waves in woodwind bores have at most only very small effects on the output sound. In brass instruments, however, especially thin-walled models, detectable changes are reported, including the coupling of bell vibrations to sound waves in the bore (Moore et al., 2015).

Air speed is discussed by many teachers, sometimes in ways that are not obviously consistent with physical principles. Blowing pressure in the mouth largely determines the average speed of air where it passes the narrow constriction between lips or past reeds. Anywhere between lungs and lips, the average air speed multiplied by the cross-section gives the average volume flow. Air compresses only slightly at the pressures of interest, so, to a fair approximation, the average volume flow between the lips equals that through the mouth, which equals that out of the lungs.

For a quantitative example, suppose you empty 5 liters from your lungs in 5 seconds. The average flow rate is 1 liter per second ($0.001\ \mathrm{m^3 s^{-1}}$) —a very high rate for playing. Divide this flow by a possible cross-section in the vocal tract, say 3 square centimeters ($0.0003\ \mathrm{m^2}$): the air speed at that place is three meters per second. Divide it by 0.1 square centimeters—a small but possible average gap between a trumpet player’s or flautist’s

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lips, or a reed-mouthpiece gap—and the speed is 100 meters per second. For this gesture, the average air speed would be simultaneously $3\ \mathrm{m.\ s^{-1}}$ in the vocal tract and $100\ \mathrm{m.s^{-1}}$ between the lips. (It would also be fast at the larynx if the vocal folds are almost closed, as is reported for some experienced players; Mukai, 1992.)

The speed of air between the lips is especially important for the flute: the time that the air jet takes to travel from the lips to the edge of the embouchure hole is important to the register and intonation (fast jet for high pitch).

From Bernoulli's principle, the blowing pressure in the mouth is (usually) roughly proportional to the square of the speed of the air[2] in the narrow constriction between the lips or past the reed: 1 kPa produces roughly 40 meters per second, but 80 meters per second requires about 4 kPa. Much of the moving air's kinetic energy is then lost downstream in turbulence, so the average pressure in the mouthpiece is usually fairly close to that in the constriction and both are reasonably close to atmospheric. Further, the spatial variation of air speed near lips and reeds implies spatially varying pressures, which (p. 312) are important for lip or reed vibration. While the flow between the lips is reasonably steady for the flute and recorder, it varies strongly for other instruments during each oscillation of the aperture.

The blowing pressure and the air speed past the lips or reed have a more direct effect on instrument performance than do the different air speeds in different parts of the mouth. Because pressure and flow are correlated, it may be that when teachers say "maintain air speed," they mean "maintain blowing pressure" (but without drawing attention to pressure), or they may be encouraging players to adjust their vocal folds or to adopt a vocal tract shape to produce another effect. Air speed is often difficult to sense, and what musicians mean by it is often unclear.

Air Temperature and Gas Composition: Warming Up and Tuning

Exhaled air entering the instrument is usually hotter and more humid than that in a dry instrument at room temperature. Increased temperature and humidity both lower the density of air, which raises the speed of sound and therefore raises the pitch. (The expansion of the instrument itself is negligible.) Fortunately for woodwind and brass players, the CO_2 in exhaled air raises the density and thus compensates somewhat. The extent of compensation varies with instrument and conditions: from a tuba player breathing deeply and often, the CO_2 concentration should be lower than from an oboist at the end of a long phrase (Young, 1946; Fuks, 1996; Boutin et al., 2020a). Players keep the instrument warm and humid by exhaling through it from time to time during long rests.

The tuning slide can partly compensate for these and other pitch changes, but it has limitations. Extending it a given distance has a larger proportional change in length on a

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"short tube note" (i.e., one in which many woodwind tone holes are open, or few brass valves are depressed) than on long tube notes.

Air Jets, Reeds, and Player's Lips

We first consider features common to these vibrating elements, which are controlled by the blowing pressure and variables collectively known as embouchure. Physicists stress that these elements behave in a non-linear way, meaning that a change in the input and the resultant change in the output are not simply proportional. This contrasts with the nearly linear acoustic behavior of the bore of the instrument and the player's vocal tract. An important result of this non-linear behavior is that, with the rare exceptions of multiphonics, these elements vibrate with a pattern that repeats periodically after a time period T. The inverse of this period is the oscillation frequency ($f_o = 1/T$). Graphed as (p. 313) a function of time, the periodic vibration is usually not a simple sine wave; rather, it has a complicated shape that can be represented as the sum of sine waves in a harmonic series, that is, components at frequencies f_o, $2f_o$, $3f_o$, etc., called the first, second, and third, etc. harmonic. The air jet, reed, or lip vibration determines the air flow input to the instrument, so the sound waves in the instrument also have components at frequencies f_o, $2f_o$, $3f_o$, etc.; in other words, they have a harmonic spectrum. Although the vibration is aided by one or more resonances of the bore (as we'll see), the exact harmonicity of the sound wave derives from the periodic motion of jet, reed, or lips: the sound is already periodic when a clarinettist or trombonist plays just the mouthpiece.[3]

The "shape" of this periodic motion, and thus the proportions of the different harmonics present, depends on the oscillating element itself and on how it interacts with the standing waves in the bore, and thus with the bore's resonances. Flautists can control the length,[4] angle, and cross-sectional shape of the jet with their embouchure, and its speed with the blowing pressure; they also vary the occlusion of the embouchure hole. Reed players can apply controlled forces and mechanical damping at chosen positions on the reed; they can also adjust the mechanics of the reed with a reed knife. Clarinettists and saxophonists can change mouthpiece shape, and double reed players can control the volume inside the reed with lip forces. Brass players control the geometry and tension of the lips and surrounding muscles in ways that are difficult to measure during performance (but see Yoshikawa and Muto, 2003; Newton et al., 2008). Generally, higher lip tensions and stiffer reeds give higher pitch, but the details are subtle and complicated and vary between instruments and between players.

In general, as the blowing pressure increases, the behavior of this element becomes more non-linear, with the result that, while most harmonics increase in amplitude, the higher harmonics have a larger increase. This means that woodwind and brass instruments usually sound brighter when blown at higher pressure. Consequently, one can recognize that an instrument was played loudly even when a recording is replayed softly. *Clipping* is an example of enhancing high harmonics (frequently used by electric guitarists with distortion pedals). At very low amplitudes, the vibration of the jet, reed, or lips may be close to

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sinusoidal. At high amplitudes, however, their vibration amplitude approaches a constant, maximum value: it saturates or clips. Once the reed or the lip completely closes the aperture, flow can decrease no further, although the duration of the closed state can increase. Once the air jet goes nearly completely outside and inside the flute, further deflection would have less further effect on the flow. The spectrum of a sine wave has just a fundamental, but that of a vibration that approaches saturation by one of these saturation processes contains strong higher harmonics.

(p. 314) To play a note, these vibrating elements interact with sound waves in the bore in a way that produces gain or amplification of the sound waves in the bore. In the steady part of the note, this gain provides energy in each cycle to replace the energy lost as heat to the instrument walls and sound radiated outside. In the starting transient, this gain increases the amplitude of the sound wave from one cycle to the next. Let's see how this gain arises in each case.

Air jets

Consider the jet traveling from the player's lips to the embouchure hole edge in Figure 14.1 (or from the recorder's windway to the labium). If an air jet is disturbed, then a wave-like lateral displacement travels along it[5] and displaces it. Here, it deflects either into or out of the embouchure hole. The speed of this displacement wave on the jet is about half the air speed of the jet itself (roughly 20 to 60 metres per second, depending on blowing pressure). A standing wave in the bore involves air oscillating into and out of the embouchure hole, which can deflect the jet. If its frequency and relative timing are suitable, the oscillating jet can add to this standing wave, thereby sustaining it (Fletcher & Rossing, 1998; Auvray et al., 2014).

Reeds

Figure 14.1d (inset) shows a clarinet mouthpiece. Consider a pulse of high-pressure air traveling up the bore and arriving at the reed. It tends to push the reed away from the mouthpiece. This slightly larger opening allows more high-pressure air from the player's mouth to enter the bore and thus reinforces or amplifies the pressure pulse as it is reflected back down the bore. The double reeds (Figure 14.1e) vibrate in more complicated shapes, with more complicated effects, but a similar explanation applies.

Another way of understanding reed amplification uses the graph (Figure 14.1d) showing how the steady flow U into the clarinet mouthpiece (alone) depends on blowing pressure P. At first, U increases rapidly with increasing P. But sufficiently large P closes the reed against the mouthpiece, so U goes to zero. This occurs at lower P for large lip force (lower curve) than for small. Consider playing with P and U values given by the point marked with a shaded circle. The ratio of pressure to flow for steady or DC flow, P/U (the reciprocal slope of the dashed line), is the DC resistance for this point and, like an electrical resistance, it takes energy out of the system. But now consider the ratio of small *variations* in pressure to the corresponding variations in flow. Near the point[6] marked by the grey

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circle, increased pressure *decreases* the flow, and *vice versa*, so the resistance for a varying or AC flow is negative (reciprocal slope of the solid black (p. 315) line, $\partial P/\partial U$). So, the positive DC resistance of the reed and aperture takes energy out of the steady flow and the negative AC resistance puts some of that energy into the oscillating air flow. (This simple explanation neglects the mass of the reed, which becomes increasingly important at high frequency.)

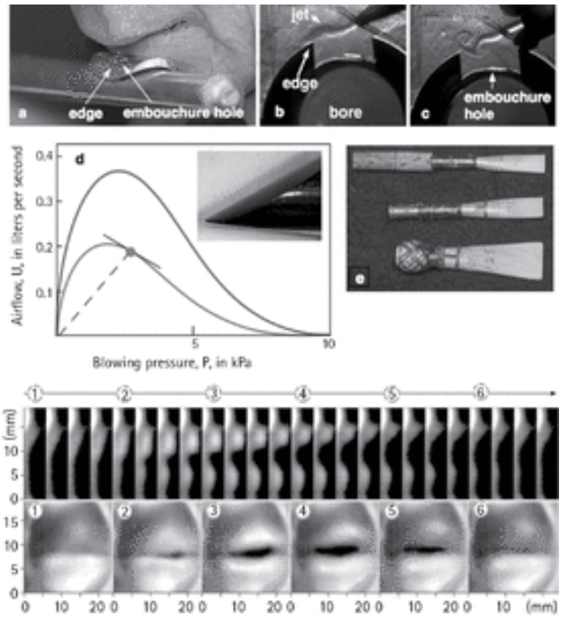

Figure 14.1. (a) shows a flute head joint. (b) and (c) are Schlieren photographs (courtesy Benoit Fabre) showing a comparable model system, with the jet deflecting alternately up and down. (d) shows a calculated flow versus pressure curve for a clarinet mouthpiece without a downstream oscillator, for small (upper curve) and large lip force (lower). (e) shows the double reeds of oboe (top), cor anglais, and bassoon. (f) shows the side and front view of a single oscillation of a trombone player's lips, taken with high-speed video through lenses in the mouthpiece. Boutin et al. (2020).

(p. 316) Lips

The motion of a brass player's lips Figure 14.1f combines an outwards swinging motion with a transverse (roughly vertical) contraction and stretching. These motions are not in phase: as the figure shows, the axial motion leads the transverse: the lips begin to travel forwards closed, then they open, then retract opened, then close. Opening and closing the aperture modulates the air flow from mouth to mouthpiece. The axial motion of tissue into and out of the mouthpiece adds a further oscillatory flow component into the mouthpiece. Both motions, but especially the axial, are smaller at high frequency.

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In a sustained note, the oscillatory flow entering the instrument provides energy to the sound wave in the bore which replaces energy lost in the bore and output sound. But the lip oscillation is also powered by the pressure and flow of air. The details are complicated: the fact that players can play either above or below a resonant frequency of the instrument, or even without an instrument at all, poses challenges for simple explanations and models. A widely used model considers the oscillating pressure fields in the mouth and mouthpiece interacting directly with a simple (one degree of freedom) swinging lip. Another effect is due to the different phase of axial and transverse components of the two-dimensional sweeping motion noted above and in Figure 14.1; this can extract oscillatory power from the steady blowing pressure and sweeping flow. Also, differences in phase between the transverse motions of the front and back of the lip channel may change the channel's shape during a cycle from diverging to converging and back. The resulting changes in the distribution of pressure within the channel could power oscillatory motion. The relative importance of these effects varies for different pitch ranges and conditions and possibly among players (see, e.g., Elliot & Bowsher, 1982; Copley & Strong, 1995; Adachi and Sato, 1996; Newton et al., 2008; Bianco et al., 2012; Boutin et al., 2020b). See Campbell et al. (2020) for a review.

Contrasting Instrument Families

A brass player or clarinettist[7] can easily produce a note with just the mouthpiece. In normal playing, however, the player's lips, reed, or air jet collaborate with one or more resonances in the bore to produce a note with stable pitch at a frequency near that of a bore resonance. For flutes and brass, the playing frequency also lies reasonably close to the natural frequency of vibration of the jet and the player's lips, respectively, and the player controls these over a wide range. To move to a higher register, the flautist increases blowing pressure to increase the jet speed and may reduce the jet length. The (p. 317) brass player adjusts the lip tension and geometry and the blowing pressure. In contrast, the natural frequency of a woodwind reed usually lies above the playing range. When changing registers, the reed player may adjust the reed's natural frequency a little with the embouchure but need not usually tune it near the frequency of the desired note.

The Bore and Its Resonances

The body of a wind instrument is the wall of an acoustic duct, with the mouthpiece attached at one end. Flutes, oboes, and soprano clarinets are straight, but the ducts of lower-pitched woodwinds and nearly all brass are bent to make them more compact—this bending has a subtle but only modest acoustic effect.[8] For the trombone, the length of this duct is adjusted continuously with a slide; for the other brass, three or more valves insert extra lengths of tubing. For woodwinds, tone holes in the wall are variably covered by keys or the player's fingers to change the effective length.

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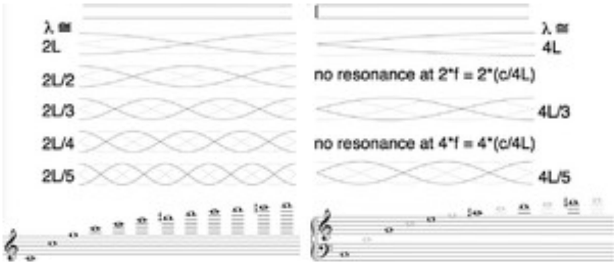

Figure 14.2. Acoustic pressure (grey) and acoustic flow (black) for the resonant modes of cylindrical pipes. For the open-open pipe (sketch top left) there are pressure nodes and flow antinodes at each end. With one end closed (top right), this end has a flow node but allows an antinode in pressure. At left, the stave shows the complete harmonic series on C4; at right the odd series on C3. These would be produced by pipes of ~65 cm length, roughly the lengths of a flute or clarinet.

To understand resonances, we define acoustic pressure as the amount by which pressure in a sound wave varies above or below atmospheric. Acoustic pressure varies along the bore. For the simplest case, consider sound waves in a completely cylindrical bore (Figure 14.2), a case roughly approximated[9] by a flute or clarinet with all tone holes (p. 318) closed. (We will return for roughly conical bores and brass instruments later.) In all orchestral instruments, the far end is open so the acoustic pressure there is small (total pressure is close to atmospheric).

For a flute, the embouchure hole is open to the atmosphere, so it has little acoustic pressure there—we say it has a pressure node at both ends. Schematic diagrams representing the resonances (oscillation mode diagrams) of a tube open at both ends are shown at left in Figure 14.2.

For the flute with keys closed, each end has a pressure node, but allows large flows in and out: a flow antinode. This permits a lowest mode whose wavelength λ is roughly twice the pipe length: say $\lambda_1 \cong 2L$. As the left of Figure 14.2 shows, the next few modes satisfying these end conditions have wavelengths $2L/2$, $2L/3$, $2L/4$, etc. Using speed of sound $v_s = f\lambda$, the first frequency is $f_1 = v_s/\lambda_1 \cong v_s/2L$, and the others are $2f_1$, $3f_1$,

$4f_1$, etc. Frequencies in the ratio 1:2:3:4 make up the harmonic series, shown on the left in Figure 14.2. A flautist can "bugle" the first several of these modes by closing all keys and blowing successively harder to sound notes with f_1 (C4), $2f_1$ (C5), $3f_1$ (G5), $4f_1$ (C6), $5f_1$ (E6), $6f_1$ (G6), and a note ($7f_1$) between A6 and A#6, etc., as illustrated. When playing C4, all of the modes contribute to the harmonics of the note; for C5, only those near the harmonics of C5 (i.e., C5, C6, G6, …) contribute, and so on.[10]

Unlike a flute, a clarinet is nearly closed at one end by the reed, which allows large acoustic pressure for small acoustic flow. It is approximated by the closed-open cylinder sketched at right. For this pipe, the figure shows that the asymmetric end conditions al-

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low wavelengths of approximately $4L$, $4L/3$, $4L/5$, etc. Here, f_1 is $c/4L$, which is half that of the previous case, and the other resonant frequencies are $3f_1$, $5f_1$, etc. So, a player of a completely cylindrical clarinet with effective length equal to that of the flute could bugle the odd harmonics starting on C3 as shown at right, starting an octave below the flute. (In practice, because of the bell, the clarinet's lowest note is not C3, but C#3 or D3 and written E3 on this transposing instrument.) When playing C3, the odd harmonics (G4, E5, etc.) are enhanced by these resonances. The relatively weak even harmonics contribute to the characteristic timbre of the low (chalumeau) range of the clarinet.

Clarinettists pay for the extra, lower range, however. Starting on the lowest note, flautists can play about an octave using the first mode and opening tone holes successively for each note. Because $f_2 = 2f_1$, they can then play notes in the next octave using mainly the same fingerings but blowing a faster jet. Clarinettists' second mode has (p. 319) $f_2 = 3f_1$, so clarinettists cannot repeat fingerings until they reach the twelfth note of a diatonic scale: this complicates fingerings near the "break" between registers.

The bores of oboe, bassoon, and saxophone are mainly conical, with the apex of the cone truncated and its volume replaced by the volume of the mouthpiece plus a small effective volume for the reed. Brass instruments have a combination of cylindrical pipe (which accommodates slides and valves), flared sections, a bell, and a mouthpiece. Their mode diagrams are more complicated.

Frequency Response: Impedance Spectra of Instruments

To discuss the resonances of real instruments quantitatively, we introduce acoustic impedance Z, which is the ratio of the acoustic or oscillatory pressure at the mouthpiece to the acoustic flow into the mouthpiece at a given frequency. The magnitude of Z varies strongly with frequency: it typically varies by a factor of roughly a thousand over the playing frequency range. At frequencies where Z is large, the same acoustic flow will exert much greater forces on a reed or a lip. So reed and brass instruments play near frequencies of the maxima in Z, and for those instruments, taller peaks are "stronger" resonances. For flutes, in contrast, a *minimum* in Z gives the frequency where flow into and out of the embouchure is easiest, so that's where the flute plays. The phase of Z is also important, because the pressure oscillation can be ahead or behind the flow oscillation. Caution: when a player refers to "resistance," this more closely relates to the ratio of (steady) blowing pressure to average flow. This DC resistance is not simply related to acoustic impedance, which is more closely related to what a player might call "resonance."

Figures 14.3–14.5 plot impedance spectra for some woodwind and brass instruments. For brass, saxophones, and double reeds, the combined effects of the mouthpiece and a bore diameter that increases along its length have the surprising but useful result that several of the resonances fall in a complete harmonic series, even though these instruments have

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a pressure antinode at the mouthpiece and a node near the bell. (This takes some explanation: see Music Acoustics, 2019.)

Figure 14.3 shows $Z(f)$ measured for five ducts, all with the same *effective* length of about 33 cm. The bottom graph shows $Z(f)$ for a simple cylinder. Here, the minima in Z (low impedance, so large flow for given acoustic pressure) correspond to the resonances of the open-open pipe (left of Figure 14.2), and they lie in a complete harmonic series with f_1 near 520 Hz (about C5). The maxima in Z correspond to the resonances of a closed-open pipe (right of Figure 14.2) and form a series comprising f_1 near 260 Hz (C4) and its (p. 320) (p. 321) odd multiples. The resonances decrease in strength with increasing frequency because wall losses and fraction of sound power radiated both increase with increasing frequency.

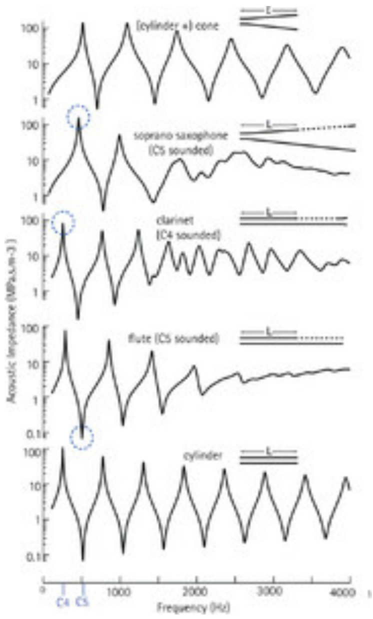

Figure 14.3. Measured magnitude impedance spectra $Z(f)$ (after Wolfe et al., 2010). Top, a truncated cone. Next a soprano saxophone fingered for (sounding) C5, then a clarinet fingered for C4, a flute fingered for C5, and a cylinder. All have multiple tone holes open, giving an effective length, L, equal to that of the cylinder and cone: about 33 cm. Units are acoustic megohms: 1 $MPa.s.m^{-3}$= 1 kilopascal/(1 litre per second).

Above the cylinder is the $Z(f)$ for a flute fingered to play C5: the relevant minimum is circled. (The flute is open at the embouchure, so a pressure node, so low Z.) This is an octave above its lowest note and nearly all the tone holes in the downstream half of the instrument are open. So, its effective length—at least for low frequencies—roughly equals its closed upstream half, as the schematic suggests. The second and third minima assist the second and third harmonics of the sound of the note played at the lowest minimum.

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The flutist can also overblow to C6 and G6, using the second and third minima, with the same fingering.

At low frequencies, both flute and clarinet have a $Z(f)$ that resembles that of the simple cylinder: at low frequencies, the bore is effectively terminated near the first open holes. The clarinet, however, has a nearly closed mouthpiece and operates near a maximum in $Z(f)$. Here, with tone holes open in the instrument's bottom half, it plays C4 (circled)—an octave lower than the flute with the same effective length (here about 33 cm). Using the same fingering, the clarinettist can overblow to the second maximum, which has three times the frequency and plays G5, but no notes in between.

The top measurement is of a truncated cone, with a cylinder of equal volume replacing the truncation. Immediately below is the $Z(f)$ of a soprano saxophone, fingered to play C5 concert (trill fingering using the first palm key). As for the clarinet, the reed is driven at a pressure antinode, so it plays near a maximum in $Z(f)$ (circled). Note the different frequencies of the first peak in the different graphs. With the same effective length of bore, but with this nearly conical geometry, the saxophone, like the oboe or bassoon, plays roughly an octave higher than a hypothetical clarinet with the same effective length.

The bore is acoustically in parallel with the volume of air inside the mouthpiece, plus an effective volume for the (flexible) reed: a larger volume or a softer reed lowers the resonance and usually plays flatter. However, a soft reed is more easily closed by the same blowing pressure or lip force, which on its own raises pitch. Double reed players can increase the reed volume with inwards lateral lip force or by adjusting the wire, but this shape change also makes the reed blades stiffer.

Tone Holes and Register Holes in Woodwinds

Modern woodwinds have a tone hole (closed by a finger or a key) for each semitone in the first register. An open tone hole connects the bore to the atmosphere, so the effective end of the air column is not far beyond the first of the open tone holes—at least for low frequency, where the bore behaves acoustically like a simple pipe truncated near the first open hole (Figure 14.3). However, the small, oscillating volume of air in and near (p. 322) an open tone hole has mass and must be accelerated backwards and forwards by the sound wave.

Consequently, the standing wave in the bore extends some distance past the first open tone hole. The accelerating force for oscillatory flow of given amplitude is proportional to frequency, so this effect increases with increasing frequency. It is this that allows cross-fingering to work in the high registers of modern instruments—and all registers for Baroque instruments. (Also, players can adjust the extent of key opening to adjust the tuning of individual notes.)

Higher registers are played more easily by opening a small register hole, usually at a position between mouthpiece and first open tone hole. At low frequency, this hole acts as a

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leak that weakens and detunes the first resonance, so notes in the first register do not usually play. At higher frequencies, the inertia of air in the register hole is almost enough to seal the bore, so higher registers are less affected. Ideally, a register hole would be at (p. 323) the position of a pressure node for the desired note, but because of the inertia of air, they work at some distance from this position, and so can serve several pitches.

At still higher frequencies, the inertia of air tends to seal the tone holes. So, above a value called the cut-off frequency, f_c, the standing wave is little affected by open tone holes. (For flutes, oboes, clarinets and bassoons, f_c ~2000 Hz, 1500 Hz, 1500 Hz, and 600 Hz, respectively.) In the examples of Figure 14.3, the maxima and minima in Z for flute and clarinet have frequency spacings roughly half as large above f_c as below. This is because, above f_c, the effective length is the entire bore, despite the open tone holes. Frequency components below f_c radiate largely from open tone holes, those above f_c radiate mainly from the bell.

Complicated cross-fingerings on woodwind instruments often produce impedance spectra with two strong maxima (or two minima for a flute) whose frequencies are not part of a simple harmonic series. Sometimes, these can be played to produce simultaneous notes at both frequencies. These are called multiphonics and are sometimes requested in modern repertoire (see Figure 14.4).

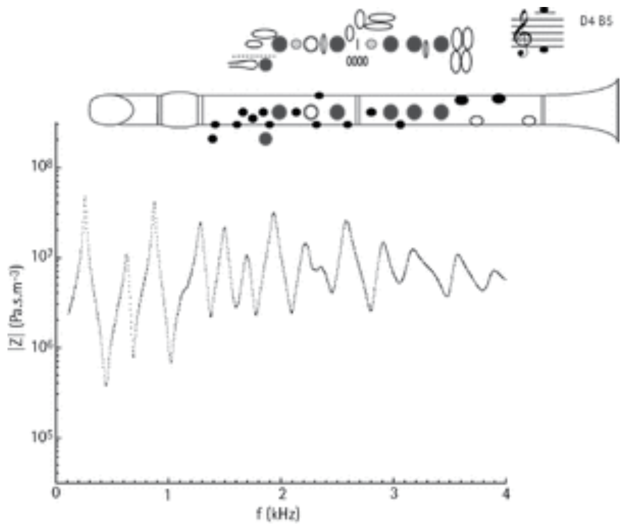

Figure 14.4. Input impedance spectrum of a B♭ clarinet cross-fingered to play the multiphonic D4&B5 at the first and third maxima, which are not harmonically related. Compare with the more regular curves in Figure 14.3 (Music Acoustics, 2019).

Brass Instrument Bores

The impedance spectrum of the cone in Figure 14.3 has maxima forming a complete harmonic series. Brass instruments have more complicated bore shapes. Their impedance

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spectra (Figure 14.5) look a little similar, and the second and higher peaks fall close to a complete harmonic series—2*f*, 3*f*, 4*f*, etc. However, the first peak falls at a frequency well below the implied fundamental, *f*, of this series. In spite of the absence of an impedance peak at *f*, players can usually play a rarely used note, called the pedal note, at this frequency. In this case, the higher resonances are collaborating to drive the higher harmonics of the lip's vibration, so the system oscillates without the help of a resonance at its fundamental. *Z*(*f*) for the trumpet and trombone are plotted on different frequency scales, to show that, acoustically speaking, they are almost scale models—as their names suggest.

The overall peak in the envelope of *Z*(*f*) (around 700 Hz for trumpet and lower frequencies for the other brass) is related to a resonance in the mouthpiece.[11] This resonance produces the mouthpiece's "popping" frequency: the frequency you hear if you slap the palm of your hand to close the mouth end of a mouthpiece (without the instrument). This resonance is due to the mass of air in the mouthpiece constriction and the springiness of the air in the cup. Manufacturers offer many different mouthpiece (p. 324) (p. 325) geometries and players choose for ease of playing, intonation or to change timbre (deeper for darker timbre).

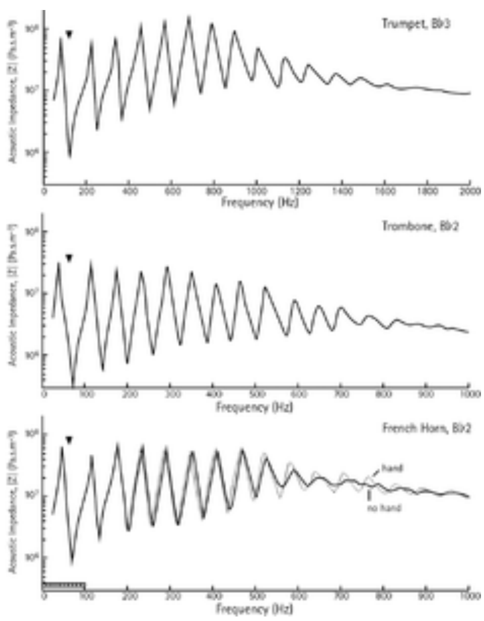

Figure 14.5. Input impedance magnitude spectra of a trumpet, trombone, and horn. Note the different frequency scale for the trumpet. Arrows indicate the pitch of the pedal note, whose frequency is the common factor, *f*, of the frequencies of the higher peaks at 2*f*, 3*f*, 4*f*, etc. The first peak lies below *f* (Music Acoustics, 2019).

How the mouthpiece, cylindrical tubing, flare, and bell combine to give the harmonic series is complicated. Compared with a cylinder of the same length, the bell and flare raise the frequencies of all resonances, with a greater proportional change for low frequencies.

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Demonstrations of the effects of these individual components are given by Music Acoustics (2019).

As with reed instruments, combinations of impedance peaks collaborate to produce the harmonics of notes in the low range. Playing the note near the second peak (B♭3 for that B♭ trumpet), all even peaks contribute[9]. For the third peak (F4), the third, sixth, and ninth are involved. And so on for higher notes.

For brass, the frequency ratio of the third and second peaks (3/2) gives the musical interval of a fifth. To fill in the semitones between these notes, most brass use rotary or piston valves that add extra pipe lengths corresponding to 2, 1, or 3 semitones (for respective index, middle, or ring fingers). A problem with using these in combination is that any valve makes a larger proportional change in length when used on its own than when used in combination with the other valves. To rectify this, one or more extra valves may be added, or the added length may be varied slightly with a small slide operated by another finger or thumb.

An interesting effect occurs in trombones and trumpets, which have long sections of narrow tubing, but not in tubas or flugelhorns, which have larger conical sections. When played very loudly (pressures in the bore being a substantial fraction of atmospheric), sound propagation in the narrow tubing is noticeably non-linear. With sufficient length of narrow tubing, this can produce shock waves, which give an especially bright (cuivré) timbre (Hirschberg et al., 1996).

Bells

The bell of a brass instrument transmits sound efficiently from the bore into the external acoustical environment. It does this more effectively for a range of moderately high frequencies; the resultant enhancement of several higher harmonics contributes to the characteristic timbre of brass instruments. Especially because these frequencies fall in a range where human hearing is fairly sensitive, bells make brass instruments louder, as is demonstrated by disconnecting the bell of a trombone. Bells also make the sound more directional, especially for high frequencies, which is why orchestral musicians seated in front of trumpets and trombones often request sound shields. A large flaring bore (e.g., a tuba compared with a trombone) radiates low frequencies better, giving a more mellow sound.

A very effective bell has a disadvantage: higher transmission means lower reflection, and this weakens the resonances at high frequencies (see Figure 14.5), so that players (p. 326) receive less help to play at a well-defined pitch in the highest registers. An example is shown in the impedance curve for the horn (Figure 14.5): with the player's hand in place (as is usual), the bell is less effective, but the higher resonances are stronger. Also, horn players know that the hand affects the tuning and timbre: observe the shifted peaks in Figure 14.5.

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The effect on tuning of changing the geometry of the bell raises a challenge for the makers of mutes, which act as a filter to change the timbre of a brass instrument, but which ideally should not change the pitch. (An exception is the stopping mute for a horn.) Mutes reduce the radiation and impedance matching effects of the bell and thus (as the name “mute” implies) lower the loudness. Practice mutes for brass instruments reduce the loudness of the radiated sound considerably but allow the player to hear via tubes to the ears, or via microphone and earphones.

For woodwinds, the smaller bells of oboes and clarinets also help radiate high frequencies. However, removing the bell of a woodwind has much less effect on timbre or loudness than doing the same to a brass instrument. Putting a cloth in a woodwind bell makes the instrument less loud and less bright, but also disturbs the intonation, especially for the lowest notes. This is a pity, because low, soft entries are where oboists and bassoonists would most like to use it.

Vibrato

Vibrato is important to expressive playing on many wind instruments. Varying activation in the torso muscles can vary the blowing pressure in the mouth and thus the power input to the instrument, at a rate of several variations per second. Vibrato is also sometimes produced by varying muscular forces on the lips or reed and, possibly, by varying the aperture of the glottis. Without compensating adjustment of other control parameters, varying the parameters that vary power often varies the frequency, so, as well as a cyclic variation in loudness, vibrato in brass and woodwind also involves varying pitch and spectrum.

Vibrato on most winds is thus different from that on strings, where vibrato is produced by rocking the finger stopping the string, which produces primarily a cyclic change in pitch, but also changes in loudness and spectrum. Analogously, trombone players can produce (pitch) vibrato by oscillating the slide.

The fundamental frequency f_o for a note usually lies quite close to a bore resonance. For notes in the lower range of the instrument, one or more of the higher harmonics produced by the input vibration then lie close to higher instrument resonances (Figures 14.3 and 14.5) and this enhances output at these harmonics, which makes the tone brighter. Another consequence concerns vibrato: as f_o varies, the variation in nf_o is n times greater, so some higher harmonics move further from a bore resonance, giving rise to cyclic variations in the spectral envelope during vibrato.

(p. 327) Body movements

Players often move while playing. One reason is to communicate with other musicians: for example, to coordinate entries, to terminate a chord, to “shape” a phrase, or to vary timing. Body movements may change the blowing pressure and one’s control of it. They also change the embouchure, by changing the relative angle of instrument and lips. Movement of the instrument is expected to have direct acoustic effects, too, because the reflec-

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tions from the floor and wall will have altered phase, and this may produce interference effects that change the spectrum. Large movements may also draw visual attention to the player, and this may draw auditory attention to the line that that person is playing—one notices this occasionally when a player performs a solo in an orchestra or stands in a big band.

The Player's Vocal Tract: An Upstream Resonator

The instrument bore is a resonant duct lying downstream from the air jet, reed, or lips. Upstream lies another resonant duct: the vocal tract of the musician. This is sometimes used to influence sound.

The fluctuating jet in a flute or recorder can generate and be affected by pressure variations in the player's mouth. Varying mouth shapes can vary their relative phase, which in turn vary the spectral content produced by the recorder (Auvray et al., 2015). A flautist's mouth resonance has a small effect on pitch in the middle range and increases the losses at nearby frequencies (Coltman, 1973).

The acoustic pressure difference acting across the reed or brass player's lips is simply the acoustic flow into the instrument times the (series) sum of the acoustic impedances of the bore and vocal tract. Over most of the normal range, the resonances of the bore have much higher Z, and so dominate the interaction, with the result that the acoustic pressure in the mouthpiece is much greater than that in the mouth. But this is not always true for the high range, or for some exotic effects.

The saxophone has particularly weak higher resonances (Figure 14.3), which means that its third and higher registers (the *altissimo* range) are virtually unplayable unless the player tunes one of the tract resonances near to the frequency of the desired note (Chen et al., 2008; Scavone et al., 2008). Such tuning is also used on single reeds for pitch bending and multiphonic control (Chen et al., 2011).

For brass instruments, the bore resonances are also weaker at high pitch (Figure 14.5). In high trombone playing, the acoustic pressure in the mouth can exceed that in the bore, which indicates involvement of a vocal tract resonance (Freour & Scavone, 2013). Surprisingly, however, direct measurements of tract resonances of trumpeters playing (p. 328) the high range did not show resonance tuning, suggesting that they rely largely on embouchure effects (Chen et al., 2012).

At low pitch, strong mouth resonances can affect high harmonics of the note. On the didjeridu, peaks in the vocal tract impedance strongly suppress nearby harmonics of the sound, so the broad minima in the vocal tract impedance create the prominent formants in the sound that are characteristic of the instrument (Tarnopolsky et al., 2006). Similar effects are possible with the lower brass, but the effects are less dramatic because these instruments have input impedances peaks much higher than those of the didjeridu, which

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has a large-diameter, irregular bore. The contrary effect is seen in the saxophone, where peaks in the mouth impedance produce modest increases in the sound spectrum (Li et al., 2015). In all these cases, the timbre effect is much more salient for the player, who hears the sound in the mouth by bone conduction, than for the listener.

Control in Performance

The note frequency does not depend solely on bore resonances: it also depends on other parameters under the player's control, such as speed and length of the air jet, distribution of forces on the reed, muscular tension and geometry in the lips, blowing pressure, and sometimes vocal tract geometry. As well as the pitch, the loudness and timbre also depend on these control parameters. Playing a *crescendo* at constant pitch therefore requires not only control of blowing pressure, but also compensatory control of other parameters—which partly explains why slow *crescendo-decrescendo* at constant pitch is an important exercise. Similarly, playing very different pitches at controlled loudness requires compensatory controls.

Control parameter adjustment is also required for transients. Elegant initial transients require control of the tongue, usually coordinated with blowing pressure variation; smooth *legato* transitions between notes may similarly require embouchure control adjustments (especially for brass), rather than just moving the fingers. Vocal tract adjustments are sometimes required, too.

Brass players face the problem that the return of the first reflection of a sound wave from the bell may exceed several periods of the note. During this transient, the lip vibration frequency receives no help from an instrument resonance, so it must be controlled fairly precisely by the embouchure and blowing pressure. The problem is worst playing high notes on long bores, which is why hornists[12] especially fear "cracked" notes.

Smooth final transients may involve reducing the blowing pressure a little below that at which gain from the air jet, reed, or lips exactly balances losses in the bore and from radiation. Control of articulation is an active area of research (see, e.g., Chick et al., 2013; Hofmann & Goebl, 2014; Li et al., 2016; Almeida et al., 2017; Pàmies-Vilà et al., 2018).

(p. 329) Adjustments are also required because of the behavior of instruments, which are never perfect: some notes are inherently flat, others sharp, some louder, others softer, and some brighter and others darker. The player must maintain a mental map—whether conscious or subconscious—of which notes require how much correction at different pitches and loudness. Fortunately for the player, intonation is less important for very short notes: the precision with which listeners can determine pitch decreases for short notes (in part due to a mathematical result known as the Fourier limit and analogous to Heisenberg's Uncertainty Principle). Consequently, a note that needs substantial pitch correction in a sustained chord can be played with a generic embouchure and often a simpler fingering when it occurs in a rapid scale passage or trill.

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All this is expected of the good musician, before coming to the control of musical expression. One of the purposes of scales, arpeggi, crescendi-decrescendi, and technical exercises is to train the player to perform the coordinations mentioned here automatically, so that s/he can attend to expression at the level of the phrase and above. How all the control parameters are coordinated in performance is an important area of research (see, e.g., Bouhuys, 1969; Fuks & Sundberg, 1999; Cossette et al., 2008; de la Cuadra et al., 2008; and Bianco et al., 2012; Vauthrin et al., 2015).

Acknowledgements

I thank the UNSW Music Acoustics team, especially my long-term collaborator, John Smith, and the Australian Research Council for supporting our research.

Key Sources

Of these listed books, Chaigne & Kergomard and Fletcher & Rossing are highly technical; Campbell, Greated and Myers and Music Acoustics are non-technical introductions. Benade and Campbell, Gilbert and Myers fall between these.

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(p. 330) Reflective Questions

1. How many ways can you think of to adjust the pitch of a note? In terms of concepts presented here, how do they work? Musically, what are their advantages and disadvantages?

2. Think of some difficult slurs between two notes. Can you think of why they are difficult in terms of the resonances and harmonics associated with each of the notes, or for other reasons?

3. Consider an instrument in which some of the higher resonances (when played in bugling) are sharp. What do you think that this effect (alone) would have on the pitch change during a crescendo?

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4. From Baroque to Classical to Modern, tone holes on woodwinds increased in size and number. Although this increases the mass of air in the tone hole, it also gives the sound pressure more area on which to act to oscillate air in and near the tone hole, and also more flow for the same speed. What effects would this change be expected to have on the relative magnitude of high harmonics, and on the possibilities for cross-fingering?

5. Before the invention of valves, horn players used hand stopping to play notes that could not be "bugled" with an open bell. Listening to a performance on a natural horn, how would you expect to tell from the timbre which were the stopped notes? (Good players may be able to hide the difference.)

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Notes:

([1]) The website Music Acoustics (2019) illustrates most of these topics at length, often with sound files.

([2]) This comes from basic physics: the extra kinetic energy of the air in this narrow passage equals the work done by the blowing pressure in accelerating the air into that passage.

([3]) In one sense, a wind instrument in normal playing is analogous to a bowed string. The oscillation is driven by the steady flow of air, somewhat as the periodic stick-slip bow-string interaction is driven by the steady motion of the bow. When a tongue slap inputs a

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brief pulse of energy, however, the wind instrument behaves a little like a plucked string and need not be harmonic; see Chapters 15, 16.

([4]) If the flautist shortens the jet length by pushing the lips forward or rolling the instrument, this also increases the occlusion of the embouchure hole, which lowers the resonant frequencies of the bore.

([5]) For example, a plume of cigarette smoke rising in still air deflects spontaneously left and right.

([6]) Different lip forces and blowing pressure control the position of this operating point. High values move it closer to the reed closing range, where oscillations can more easily close the reed completely during the vibration; as discussed earlier. Reducing the aperture, however, reduces power into the instrument, all else being equal.

([7]) Double reed players can also play a note on the reed alone, though it’s not what one usually does when testing reeds.

([8]) For example, pressing the second valve on a trumpet or horn introduces a few tight bends that complicate the flow, but the “feel” of the instrument is only a little different.

([9]) Departures from cylindrical shape (e.g., the varying diameter of the flute head and the flare in the clarinet lower joint) are important to intonation.

([10]) As a note gets louder, its high harmonics increase proportionally more than the low. One result is that loud notes sound brighter (as mentioned). Another is that the frequencies of the higher resonances contribute more to the overall pitch: a flat higher resonance will usually flatten the note more when playing loudly. The interaction of bore resonances and embouchure parameters to determine the playing pitch is complicated and of course interesting to instrument makers (Dalmont et al., 1995; Nederveen, 1998).

([11]) For the trumpet and trombone in Figure 14.5, see the raised peaks near the sixth and fifth respectively. The relation to the popping frequency is not simple.

([12]) Modern horns are “double”: the player can use a valve to choose between a horn in F and a shorter horn in B♭. The shorter bore has shorter transients, and the gaps between resonances are greater, both of which make it easier to play high notes without “cracking.”

Joe Wolfe

Joe Wolfe has a BSc from the University of Queensland and a PhD from the Australian National University. He is Emeritus Professor of Physics at UNSW Sydney. Joe has worked at Cornell University, CSIRO and the École Normale Supérieure in Paris. His early research was in biophysics, studying thermal physics and mechanics in cellular ultrastructure. More recently, he and collaborator John Smith set up a lab in musical and voice acoustics, publishing in Nature and Science as well as in specialist

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journals. Their work on woodwind and brass instruments concentrates mainly on the player-instrument interaction. Joe has won awards from the Acoustical Societies of America, Australia and France, as well as international awards for his online educational resources in introductory physics and music acoustics. In his spare time, he composes and plays orchestral and chamber music.

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