In the previous chapters we introduced concepts that are necessary if we are to understand the origin of musical sound, its transmission, and its perception. Let us now bring these concepts together and employ them to understand selected musical instruments that in the present context can be considered as the origin of the sound we call music. If the selection is made judiciously, insight into many other instruments will be achieved in the process.

THE STRINGED INSTRUMENTS

The orchestral stringed instruments consist of the violin, the viola, the cello, and the double bass. These are principally bowed instruments; however, some passages call for other special effects. As it can be seen in Figure 11.1, the violin has the widest range. Because of its smaller size, the violinist can play more complex rhythmic ideas and has greater agility in rapid passages. The viola, tuned a musical fifth lower in pitch than the violin, is correspondingly larger. The cello is tuned one octave below the viola and its size dictates that it be played differently; namely, the instrument stands on the floor. Both the cello and the violin often carry the melody in the orchestra or fill in the harmony. The double bass provides the harmonic foundation for the string section. Frequently, the double bass is accompanied by the cello playing an octave higher. With this arrangement, the double bass assumes great carrying power and furnishes the basic support for the string section.

The violin, viola, cello, and double bass each has four strings, a bridge, a top "plate," a bottom "plate," and sides connecting the two plates, thereby forming an enclosed volume of air. These components form a complex system. Each component has its individual natural frequencies of vibration as well as its individual damping characteristics.

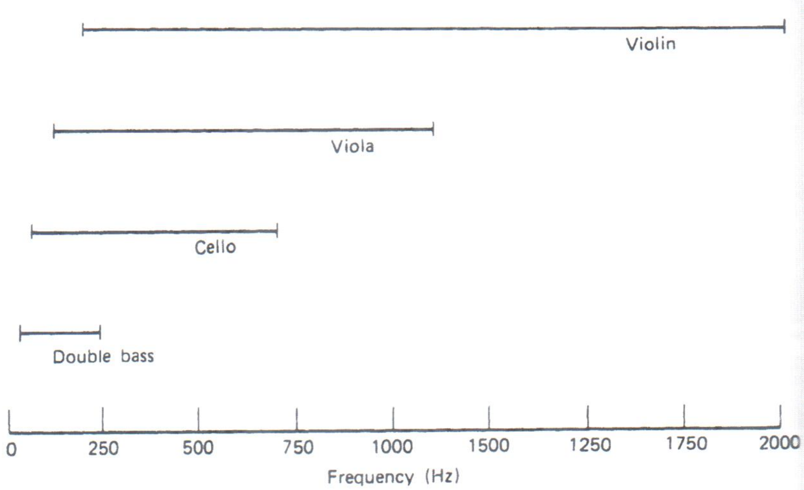


Figure 11.1
Frequency ranges of the orchestral stringed insruments.

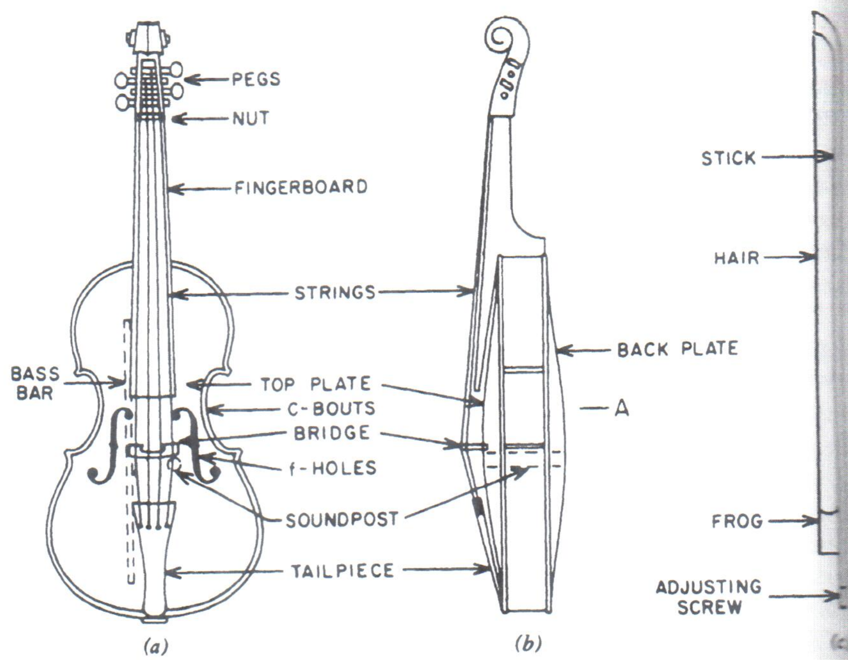


Figure 11.2
Parts of the violin. (Reprinted from *The Acoustical Foundations of Music* by John Backus. By permission of W. W. Norton & Co., Inc. Copyright © 1969 by W. W. Norton & Co., Inc.)

called the bass bar. Both the sound post and the bass bar dramatically influence the acoustical character of the violin.

Near the outside edge of both the top and bottom plates is a shallow groove. Inlaid in this groove is the purfling that consists of two strips of black-dyed pearwood plus a strip of white poplar. Since the plates are thin to begin with, the groove makes the edges extremely thin. After years of playing the purfling tends to loosen somewhat making both plates more flexible. This may be a factor in the improved tone qualities of older instruments. Finally, a matching pair of delicately shaped "f-holes" are cut into the top plate on each side of the bridge. The long axis of the instrument divides both the top and bottom plates into two almost symmetric halves.

The structure of the violin body is one of the more remarkable stories in the history of music, even though the story is far from complete. Acoustical knowledge apparently played a very small role in the evolution of the violin; rather, it was the product of ingenious hunches, tedious trial and error, and the brilliant intuition of the artisan. How was it determined, for example, that:

Maple was best for the bottom plates?

...ill more. The volume of air defined by the top, ...es of the violin body also participates in the spec-... process. Just as a Coke bottle can be made to "sing" ... air is forced to oscillate at its resonant frequen-... the fiddle body can be excited by gently blowing over ... The oscillation of the air space in the violin is commu-... the outside air via these f-holes. When the frequency of a ... equals the resonant frequency of the enclosed air ... that frequency will be selectively amplified.

...is a complicated material, no two pieces are exactly alike. ... the body of the violin is a complex structure. It is reasonable to expect that the response curve of the violin will be complicated. This expectation is verified by Figure 11.4. This jagged curve was obtained by some clever experimentation. The violin was suspended by rubber bands attached to the four corners of the instrument. A device, called a transducer, which converts an electric signal into a mechanical signal, was attached to the violin. The violin is forced to vibrate at a frequency determined by the frequency of the electrical signal. With the amplitude of the driving frequency kept constant, the amplitude of the violin's vibrations can be determined by monitoring the sound radiated from it with a sound-level meter. At the resonant frequencies, the violin vibrates more vigorously as indicated by the peaks in the response curve. (For more details, see Hutchins and Fielding, 1968, at the end of this chapter.)

FFT 2

Two of the peaks in the response curve have names: the *main wood resonance* (MWR) and the *main air resonance* (MAR). The main air resonance is the lowest resonant frequency of the enclosed air

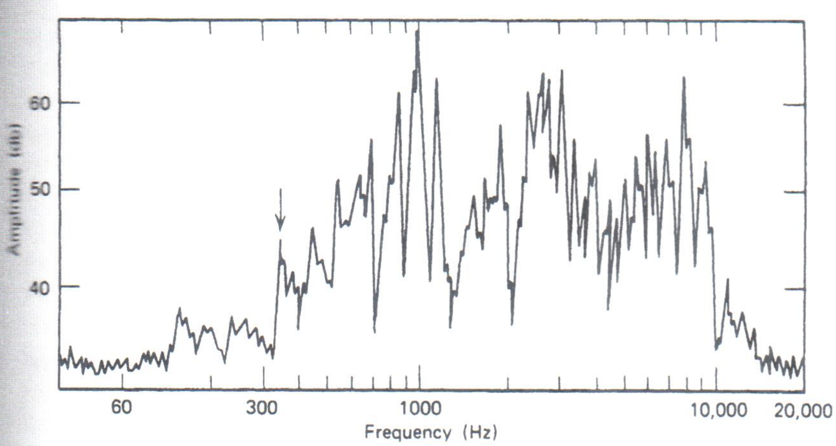


Figure 11.4
Response curve for a violin. (From "Acoustical Measurement of Violins," by Carleen M. Hutchins and Francis L. Fielding. *Physics Today*, 1968. Reprinted with permission.)

space in the fiddle. The main wood resonance is the lowest resonant frequency of the fiddle body. The two peaks corresponding to the MAR and the MWR are among the first few peaks on the left side of the response curve illustrated. The exact frequencies at which the MAR and the MWR occur are very important and determine the quality of the violin.

The relationship between the MAR, MWR, and the quality of an instrument can be more clearly ascertained from a different kind of response curve called a *loudness curve.* To determine a loudness curve, a violin is bowed without vibrato so as to produce the loudest tone possible at each semitone interval throughout the frequency range of the instrument. The sound-intensity level is determined for each semitone with a sound-level meter and the results are plotted on a graph.

The loudness curves for two violins are shown in Figure 11.5. The lowest frequency of the violin is the open G-string; therefore, this frequency defines the origin of the graph. The other open-string frequencies are identified on the graphs by vertical lines intersecting the frequency axis. From these loudness curves it is clear that some pitches are considerably more intense than others. The

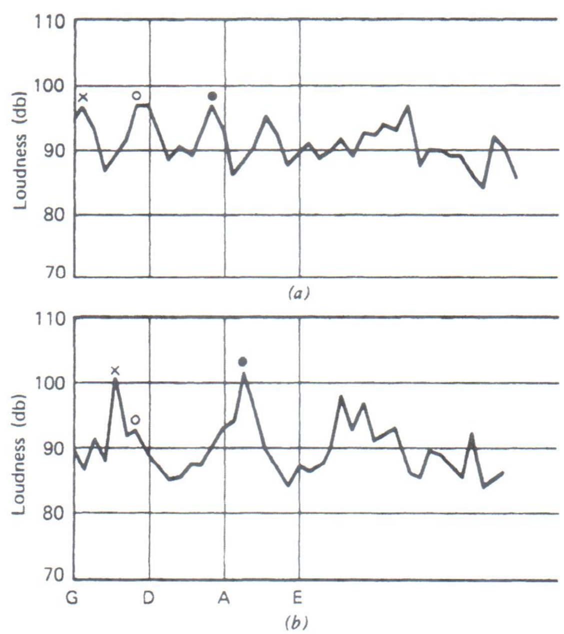


Figure 11.5
Loudness curve for a violin. (From "The Physics of Violins" by Carleen M. Hutchins. Copyright © 1962 by Scientific American, Inc. Reprinted with permission.)

has the correct pitch. As early as 1830 it was reported by Savart that "a top of spruce and a back of maple tuned alike produced an instrument with a bad, weak tone." He actually dismantled a number of Stradivarius and Guarnerius instruments and determined their tap tone frequencies. He found that the pitch of the back was always one semitone higher in frequency than the top. Furthermore, he found that the tap tone of the tops varied between 138.6 Hz ($C^{\#}_3$) and 146.8 Hz (D_3) while the back plates varied between 146.8 Hz (D_3) and 155.6 Hz ($D^{\#}_3$). More recent studies have confirmed that the tap tones of the top and bottom plates cannot have the same frequency, nor can they be more than a whole tone apart

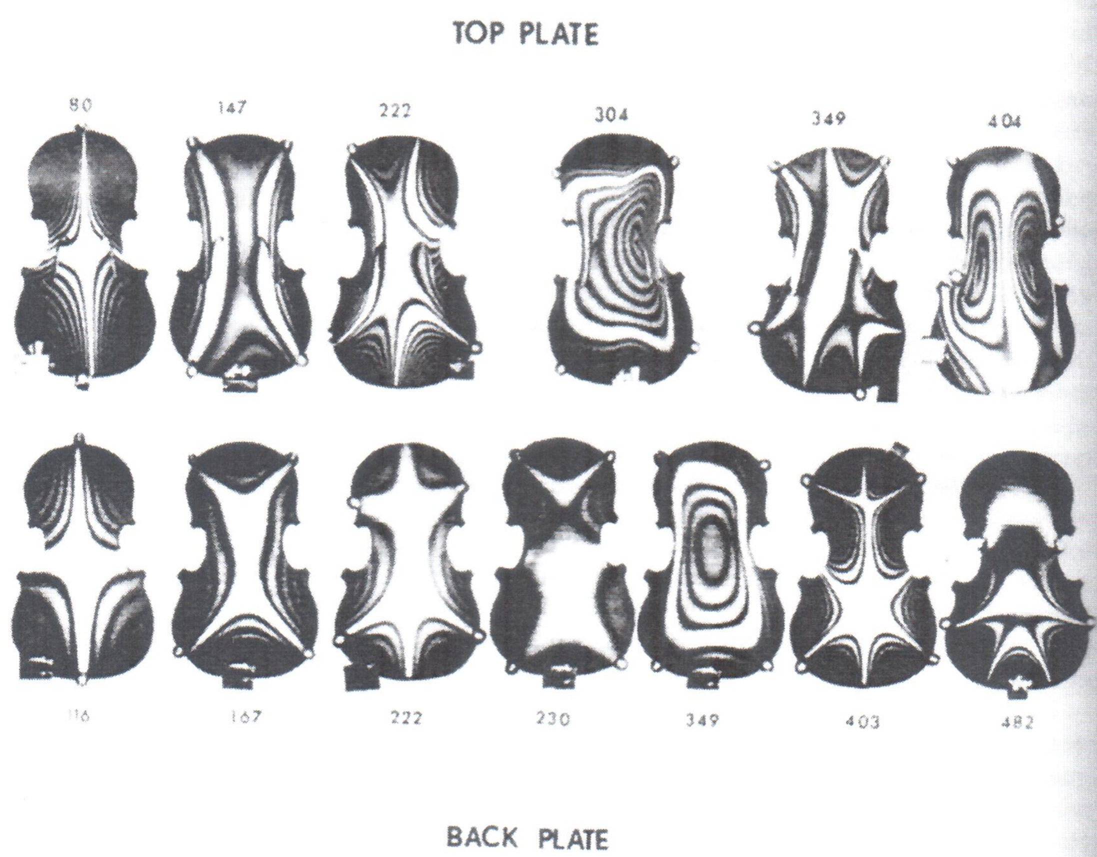
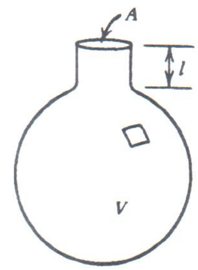


Figure 11.6
The vibrational modes of the top and back plates of a violin are shown through holographic methods. The top row shows the top plate vibrating at frequencies of 80, 147, 222, 304, and 349 Hz. The bottom row shows the back plate vibrating at frequencies of 116, 167, 222, 230, 349, and 403 Hz. (From "The Acoustics of Violin Plates" by Carleen M. Hutchins. Copyright 1981 by Scientific American, Inc. Reprinted with permission.)

the resulting instrument is to be judged favorably. (See [illegible] of the chapter.)

The pitch of the tap tones is determined by the vibrational characteristics of each plate. With new methods such as hologram interferometry, the vibrational modes of both the top and bottom plates can be made visible. Several vibrational modes are shown in Figure 11.6. Some of these modes (for example, modes 1, 2, and 5) are particularly influential in determining the pitch of the tap tones; however, all vibrational modes make a contribution.

The finished instrument also has a characteristic tap tone. The first strong low-frequency resonance (marked with an arrow) in the response curve shown earlier (in Figure 11.4) corresponds to the tap tone of the particular violin tested.



As the violin maker designs and cuts the f-holes, he or she is having a determining influence on the frequency of the MAR. The air within the fiddle body is a somewhat complicated example of a Helmholtz resonator. Imagine a vessel such as that illustrated in the margin. The volume of the vessel is V, the length of the neck is l, and the cross-sectional area of the neck is A. The resonant frequency of the air enclosed in such a vessel is given by

$$f = \frac{v}{2\pi}\sqrt{\frac{A}{lV}}$$

where v is the speed of sound in air.

FFT 3

The formula above indicates that f increases as A increases while f decreases as V increases. In our example of the violin, the f-holes are the mouth of the vessel, l is the thickness of the top plate where the f-holes are cut, and V is the volume of the air enclosed in the violin body. The MAR therefore depends on the area of the f-hole openings and on the air volume in the violin. It should be pointed out that any attempt to substantially modify the frequency of the MAR by altering either A or V is not only risky, it is also impractical. In order to change the MAR frequency by one whole tone, a 20 percent reduction in volume or a 59 percent increase in the f-hole area is required.

Finally, the violin maker can influence the resonant properties of the violin by the design of the bass bar and sound post. Small changes in the wood quality, the tightness of the construction, and the position of the sound post result in a greatly altered tone of the violin. So critical is the sound post that the French call it the soul of the instrument. If the sound post is removed entirely, the violin sounds something like a guitar.

The bass bar is also critical. Small changes in the height of the bass bar can shift not only the frequency of the tap tone, but also the shape of the tap-tone resonance. The removal of only a few shaves of wood causes noticeable effects. In one reported case, the

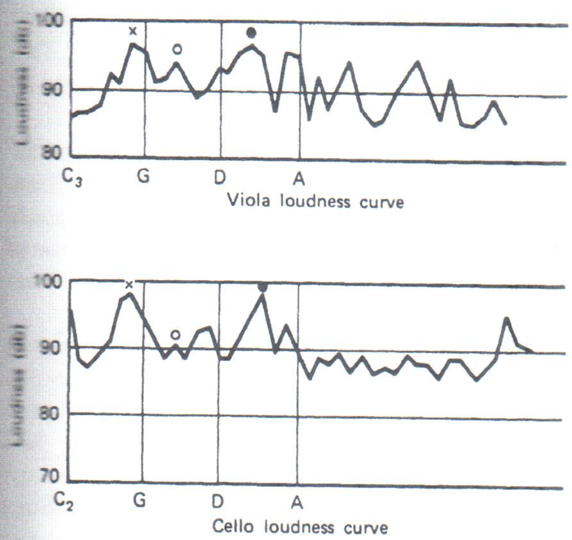


Figure 11.7
Loudness curves for a viola and cello. (From "The Physics of Violins" by Carleen M. Hutchins. Copyright © 1962 by Scientific American, Inc. Reprinted with permission.)

Since the dimensions of the cello are approximately twice those of the violin, the air resonance will be approximately an octave lower (one-half the frequency) than the air resonance of the violin. This puts the air resonance near D_3 rather than the desired frequency near G_2. The lower frequencies of the cello are therefore inadequately supported by air and wood resonances.

FFT5

It is reasonable to assume that practical considerations as to how these instruments should be played guided the artisans in the design of the viola, cello, and double bass. A viola 1.5 times larger than the violin could not be played in the conventional manner. A cello 3.0 times larger than the fiddle would be as large as the present-day double bass and would have to be both played and tuned differently. (The strings in the present-day double bass are tuned a fourth apart—E_1, A_1, D_2, and G_2—to minimize the necessary finger spacings and the distances traversed by the hand.) The double bass is tuned one octave below the cello. From the scaling theory we can conclude that the double bass should be twice the theoretical size of the cello or six times larger than the violin. Such a double bass would be twice as large as its present size. (The double bass is 3.09 times larger than the violin.) Clearly an instrument of such a size would present practical difficulties in handling. The compromises made between scaling and playing convenience have resulted in shifting the MAR and MWR to higher frequencies leaving the lower frequencies of the viola and cello without the resonance support comparable to that of the violin. Loudness curves for the viola and cello are shown in Figure 11.7. Comparison of these curves with the analogous curve for the violin shows the critical differences.

FFT6

The "Wolf" Tone

The frequencies emanating from a stringed instrument are normally determined by the strings. There is the possibility, however, that the body

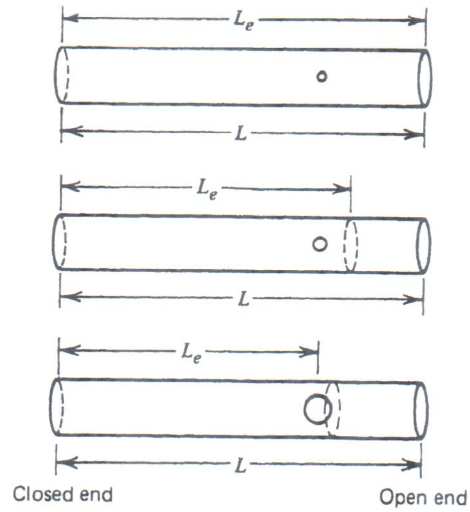


Figure 11.9
The size of the tone hole affects the effective length, L_e.

quired to play the scale on the clarinet. This is because the clarinet is a semiclosed cylindrical tube for which the second harmonic is missing. The third harmonic is a twelfth above the fundamental.

To continue raising the pitch beyond the first octave, the flute player continues overblowing (working from the second harmonic) and successively uncovers the lowermost hole thereby shortening the tube. The

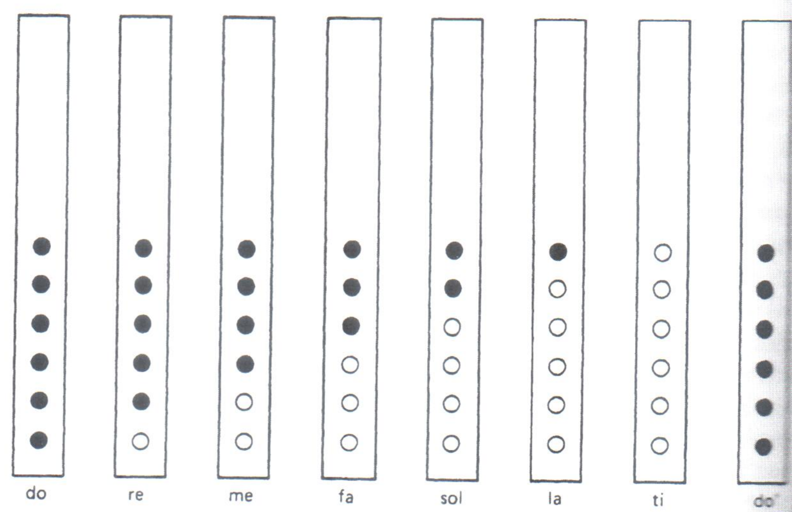


Figure 11.10
The musical scale can be played with six side holes on a cylindrical tube (o, side hole open; •, side hole covered).

horns, and as you learned in Chapter 8, they are the only shapes that can be conveniently handled by a performer.

A cursory examination of a woodwind instrument reveals additional features of the side holes that can be understood. First, and most obvious, there are more than the six (or ten) side holes along the length of a woodwind instrument. Additional holes are present so that sharps and flats, that is, a chromatic scale, can be played. Second, the holes are not equally spaced along the length of the tube. The spacing between the holes increases as their distance from the mouthpiece increases. If a tone is being played that utilizes a length L of the tube and a new hole is covered to lower the pitch one semitone, that hole must add an increment of length approximately equal to 6 percent of L, or $0.06L$. Each time the pitch is lowered by covering an additional hole, L is increased and the next increment $0.06L$ is necessarily larger than the previous increment. Thus we can understand why the spacing between holes far from the mouthpiece is larger than it is for holes close to the mouthpiece. (See Figure 11.11.)

Third, for some woodwinds the hole diameters increase as their distance from the mouthpiece increases. Figure 11.12 shows a saxophone stripped of all the keys and hole covers, which makes the changing size obvious. For a tenor saxophone the bottommost hole (not visible in the figure) has a diameter of 4.45 cm, while the topmost hole's diameter is 1.22 cm. Recalling that a hole is supposed to behave like an open end, it would be expected that for any tube whose cross-sectional area varies the hole area would also have to vary. The larger the tube, the larger must be the diameter of the hole. The hole sizes in a flute—a cylindrical tube having a uniform cross section—are all essentially the same size.

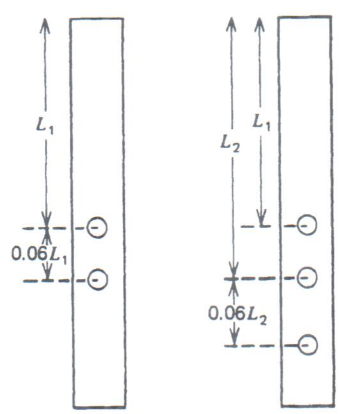


Figure 11.11
Variation in spacing between adjacent side holes.

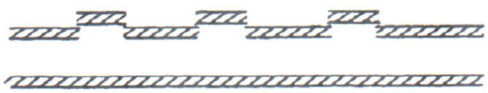


Figure 11.13
The presence of closed side holes adds to the effective cross section of the tube.

Tubes with Mouthpieces

The resonant frequencies of a tube *plus* mouthpiece are different from the resonant frequencies of the tube alone. The mouthpiece in essence adds an increment of length to the tube. For the conical tube, however, the increment of length is different for different frequencies. In particular, the mouthpiece on a conical tube "looks" longer at high frequencies than it does at low frequencies.

The mouthpiece on all reed instruments effectively closes the end of the tube to which it is attached. The natural frequencies of a semiclosed cylindrical tube were given in Chapter 8 as

$$f_n = n\frac{20.1}{4L}\sqrt{T_A} = n\frac{5.025}{L}\sqrt{T_A} \qquad n = 1, 3, 5, \ldots$$

Suppose the cavity of the mouthpiece has a volume V. Furthermore, suppose the cylindrical tube to which the mouthpiece is attached has a radius b_0. The length L of this tube having the same volume V as the mouthpiece cavity is given by

$$\Delta L = V/\pi b_0^2$$

The mouthpiece makes the tube behave as though it was increased in length by the amount ΔL. Accordingly, the resonant frequencies are given by

$$f_n = n\frac{5.025}{L + \Delta L}\sqrt{T_A} = n\frac{5.025}{L + (V/\pi b_0^2)}\sqrt{T_A} \qquad n = 1, 3, 5, \ldots$$

For conical-bore instruments the situation is more complicated; however, an expression can be derived that closely approximates the effect of the mouthpiece. Again, let us assume the mouthpiece has a volume V and we shall further assume that V is small. If the open end of the cone has a radius b, the effective length of the cone is increased by

$$\Delta L \simeq \frac{\pi V}{b^2}n^2 \qquad n = 1, 2, 3, \ldots$$

Notice that this mouthpiece correction changes for different harmonics; that is, for different values of n. The higher the harmonic, the longer the

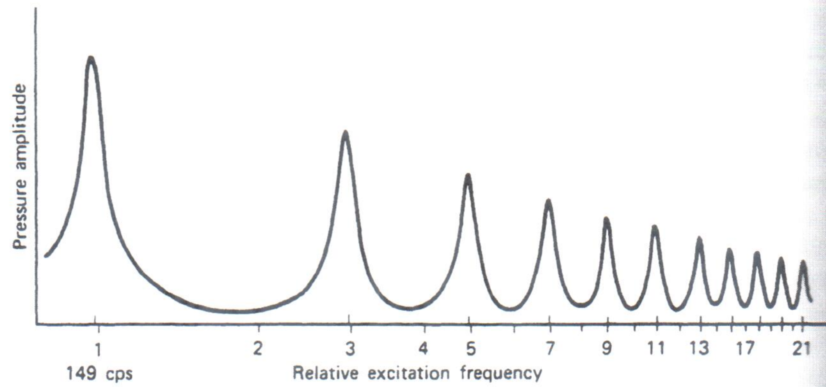


Figure 11.14
Resonant frequencies of a clarinet-length tube. (From *The Acoustical Foundations of Music* by John Backus. By permission of W. W. Norton & Co. Copyright © 1969 by W. W. Norton & Co., Inc.)

quencies are odd harmonics of the fundamental frequency. The tube behaves pretty much as one would expect. The spectrum of the sound radiated from such a tube is characterized by the absence of even harmonics.

The resonant frequencies of an actual clarinet can be found using the same experimental technique as that used for the 47.6-cm tube. With the results of such an experiment the sound spectrum of the clarinet can

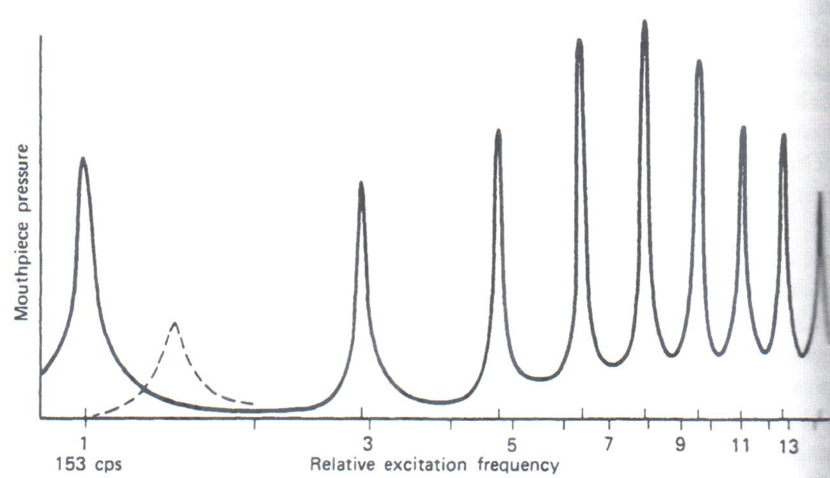


Figure 11.15
Resonant frequencies of a clarinet. The presence of side holes shifts the resonant frequencies from the expected values. Compare with Figure 11.13. (Reprinted from *The Acoustical Foundations of Music* by John Backus. By permission of W. W. Norton & Co., Inc. Copyright © 1969 by W. W. Norton & Co., Inc.)

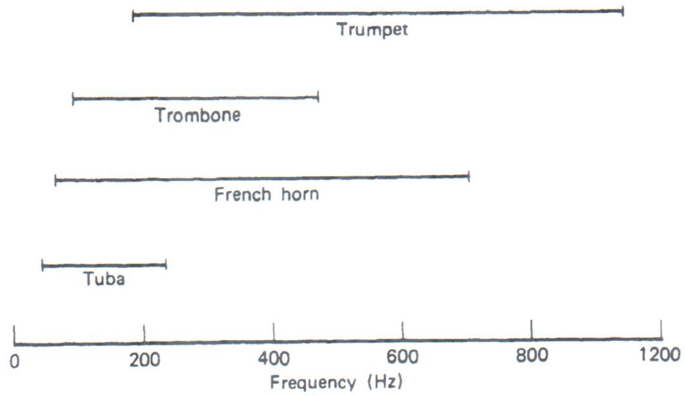


Figure 11.16
Frequency ranges of the orchestral brass instruments.

tually obligated to vibrate at the frequencies permitted to it by the air column. In the brass instruments vibrating lips excite the air column. Although feedback is important in brass acoustics, the lips are massive enough so that they can make the air column do unexpected things. A brass player can "lip up" or "lip down" a note and thereby exercise a much greater control over the air column than is possible for the woodwind player. (The woodwind player can vary lip pressure on the reed and can regulate the length of the reed free to vibrate by lip placement. Through both lip pressure and placement, the woodwind performer can shift frequencies slightly.)

The orchestral brass instruments consist of the trumpet, trombone, French horn, and tuba. The trumpet, trombone, and French horn have a lengthy cylindrical section between a rapidly flaring bell and a tapered mouthpipe. The tuba is essentially conical in form. The ranges of these instruments are shown in Figure 11.16. **FFT 14**

Tubes, Bells, and Mouthpieces

With the exception of the tuba, the brass instruments consist of three basic sections: the mouthpiece section, which is tapered, the cylindrical part, and the bell. These sections are represented diagrammatically in Figure 11.17. Each part actively influences the acoustical behavior of the whole.

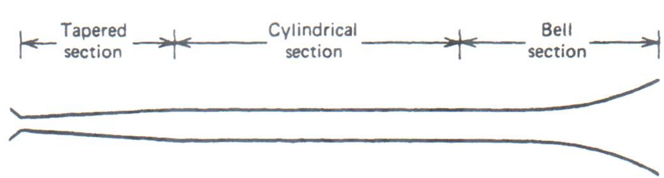


Figure 11.17
The three sections of brass instruments.

The relative dimensions of these three parts vary from one manufacturer to another; however, the figures below are "ballpark" figures and provide a useful frame of reference. The data below refer to the instruments' minimum length (slide in or valves open).

	Trumpet	Trombone	French Horn
Mouthpiece section (%)	21	9	11
Cylindrical section (%)	29	52	61
Bell section (%)	50	39	28
Total length (cm)	140	264	528

The physics of the brass instruments poses interesting problems that are by no means completely understood. We shall consider the trumpet in some detail, and in so doing, we shall recognize that the brass instruments are complicated acoustical systems. A trumpet is a tube closed at the lip end. The air column is most easily excited at one of its resonant frequencies and through feedback "tells" the vibrating lips what to do. Therefore, the blown frequencies coincide very closely to the resonant frequencies of the air column. The approximate blown frequencies of the B$^\flat$ trumpet—with all valves open—are given in Table 11.1. In the second column of the table it is seen that the blown frequencies are approximately multiples of 115 Hz. However, the fundamental in the series, namely 115 Hz, is missing.

Already there are problems. We have come to expect that a tube closed at one end will have only odd harmonics. Remembering, however, that the bore of a trumpet combines both cylindrical and conical sections, this result is somewhat more tenable. The missing fundamental raises another question that may point to a problem.

The overall length of a trumpet is in the 140-cm range. Suppose we start with a cylindrical tube 140 cm long and approximately 0.6 cm in radius. The resonant frequencies of the air column in such a trumpetlike

TABLE 11.1
Trumpet Frequencies

Blown Frequencies (Hz)	Breakdown of Frequencies
231	$231 \approx 2 \times 115$
346	$346 \approx 3 \times 115$
455	$455 \approx 4 \times 115$
570	$570 \approx 5 \times 115$
685	$685 \approx 6 \times 115$

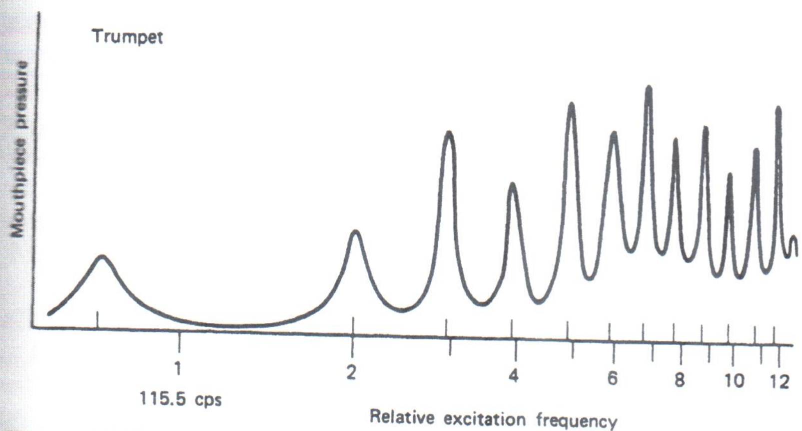


Figure 11.18
The resonant frequencies of the trumpet. (Reprinted from *The Acoustical Foundations of Music* by John Backus. By permission of W. W. Norton & Co., Inc. Copyright © 1969 by W. W. Norton & Co., Inc.)

The pedal tone is out of tune with the other harmonics; however, it doesn't matter since that resonance is never used. Finally, higher harmonics are slightly flat; the performer must compensate for this by pulling the tone up slightly.

We now have an instrument that can play on several harmonic frequencies. Now we shall fill in the tones between these resonances so that a chromatic scale can be played.

Slides and Valves

The harmonic frequencies of a brass instrument are determined by the length of the air column. If the length is changed, the frequencies are changed. The most straightforward way of altering the length is accomplished by the trombone. Other brass instruments use a system of valves.

Whether a slide or a valve system is employed the same task must be accomplished. Namely, the interval between the harmonics f_2 and f_3 (the first two resonances used by a brass instrument) must be bridged. The interval f_2 and f_3 is a musical fifth with six semitones between. Thus there must be six definite lengths each giving rise to successive semitones between f_2 and f_3. Let's see how this works.

We shall start with the trombone. The trombone is equipped with a slide that can continuously increase the length of the instrument from its minimum to its maximum length. Between these extremes there are five positions that the trombone student quickly learns. These six positions, the five intermediate plus the maximum length, define six lengths that bridge the gap between f_2 and f_3. When the slide is all the way in (the first position), the trombone has resonant frequencies of *approximately* 116, 174, 233, 292, . . . Hz.

TABLE 11.2
Valve Action of the Trumpet

Note Sounded	Valve	Semitone Change	L(ideal) (cm)	L(actual) (cm)
$B^{\flat}$	0	0	140	140
A	2	1	140 + 8.4 (148.4)	148.4
$A^{\flat}$	1	2	148.4 + 8.9 (157.3)	157.3
G	1,2	3	166.7	165.7

pitch two semitones. What additional length is required? When valve 1 is depressed a length of 8.4 cm + 0.06(148.4 cm) or 17.3 cm must be added. So far so good, as Table 11.2 illustrates.

The next step is not so clear-cut. In order to lower the pitch three semitones both valves 1 and 2 are depressed. Valve 1 adds 17.3 and valve 2 adds 8.4 cm for a total added length of 25.7 cm or an overall length of 165.7 cm. What *should* the overall length be? It should be 157.3 cm + 0.06(157.3 cm) = 166.7 cm. Here is a discrepancy. When valves 1 and 2 are depressed, the actual overall length is 165.7 cm when it should be 166.7 cm. As a result the sounded note is somewhat sharp. There are two responses to this situation. The performer can lip the tone down. Or the performer can activate a trigger mechanism that slides a small tube section out and thereby adds to the overall length of the instrument.

With combinations of the three valves, the pitch can be changed a semitone at a time. With each change a new family of harmonics becomes available and the f_2 to f_3 interval is bridged; however, as we have observed, the three valves cannot do the job perfectly, and so compromises must be made.

FFT 18

Instruments of the Brass Section

We have already discussed the trumpet and trombone. The resonance curve of the trumpet has already been shown, and the corresponding curves for the trombone and French horn are shown in Figure 11.20. As with the trumpet, the first resonance of the trombone is out of tune with the other resonances; however, once again this resonance is not employed. For both the trumpet and the trombone only eight to nine resonances are employed. This is not so with the French horn, which utilizes resonances up to the sixteenth. This explains the very slippery intonation of the French horn. As can be seen from the curve, the resonant frequencies move very close together at high frequencies. If a French horn player wants to excite the fourteenth resonance frequency, the em-

To lower the frequency by one semitone is to decrease the frequency by about 6 percent. Therefore, the effective tube length must be increased about 6 percent. With the slide in the first position, the overall length of the instrument is approximately 270 cm; therefore, to lower the pitch one semitone, a length of 0.06(270 cm) $\cong$ 16 cm must be added to the instrument. This can be accomplished by moving the slide out 8 cm to the second position. In the second position a new family of resonances can be utilized. Their frequencies are approximately 110, 165, 220, 277, . . . Hz.

In the second position the instrument length is about 286 cm. To lower the pitch another semitone, a length of 17 cm must be added to the instrument (0.06 $\times$ 286 cm). Moving the slide out 8.5 cm to the third position does the trick. In this position a new set of resonant frequencies can be excited. In similar fashion, each succeeding position of the slide adds a definite length to the instrument, lowers the pitch by a semitone, and makes available a new set of resonances. Figure 11.19 illustrates the total process. As it can be seen, the gap between f_2 and f_3 has been closed.

FFT 16

The use of valves to close the f_2 to f_3 interval is more complicated. For example, let us consider the trumpet. Like some other brass instruments, the trumpet has three valves. We shall assume the trumpet's overall length is 140 cm when all valves are open. When the second valve is depressed, the length is increased by 6 percent, or by 8.4 cm, and the pitch is lowered by one semitone. When the first valve is depressed a new tube length is added to the trumpet, which lowers the

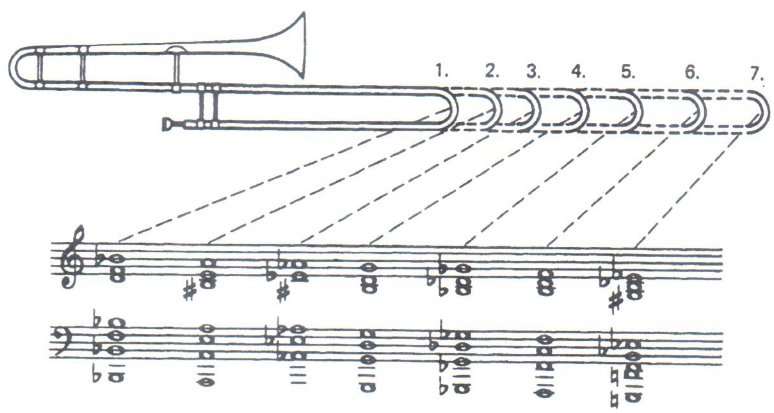


Figure 11.19
The slide positions of the trombone and the musical harmonics associated with each slide position. (Reprinted from *The Trumpet and Trombone* by Philip Bate. By permission of W. W. Norton & Co., Inc. Copyright © 1966 by Philip Bate.)

bouchure must be exact and the lip tension precise. Otherwise, the teenth or the fifteenth may be mistakenly and temporarily exc Novice (and professional) players have difficulties "hitting the note." (See Figure 11.20.)

FFT 19

Another significant difference between the French horn and the brass instruments is the mouthpiece. The trumpet and trom mouthpieces have cuplike structures with an edge at the entrance to tapered section. The mouthpiece of the French horn, on the other has neither a cup shape nor an edge, but has a gradual and smooth sition from the lip rim to the back bore. (See Figure 11.21.) These

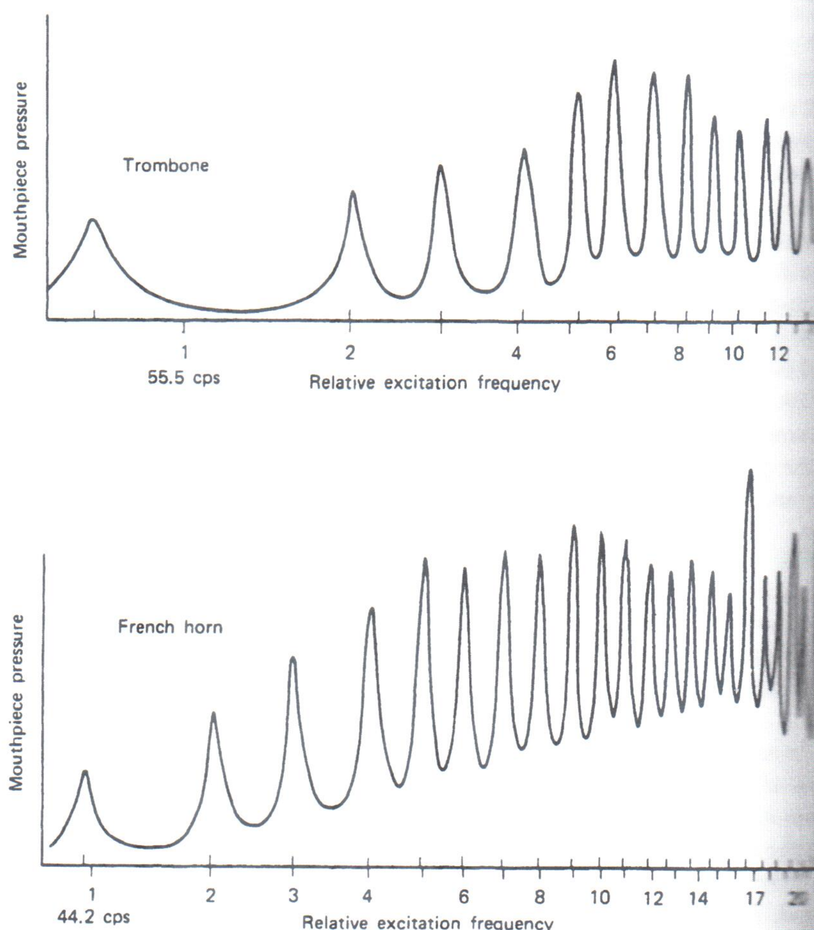


Figure 11.20
The resonant frequencies of the trombone and the French horn. (Reprinted from *The Acoustical Foundations of Music* by John Backus. By permission of W. W. Norton & Co., Inc. Copyright © 1969 by W. W. Norton & Co., Inc.)

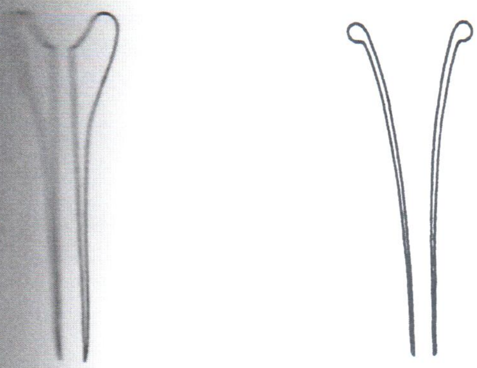


Figure 11.21
The mouthpieces of two brass instruments.

ferences in the mouthpieces affect the timbre of each instrument; however, the acoustical basis for understanding this has yet to be worked out.

The tuba is the low-voiced member of the brass family. It is a valve instrument. However, because of the great length of the tuba, the problems inherent with the valve system are magnified with the tuba. As a result, some models of the tuba have four valves, others five valves, which are included to keep the discrepancies to a minimum.

The acoustic energy is radiated entirely from the bell of the brass instrument. This means that the sound emanating from a brass instrument is more directive, particularly at the high frequencies. This also means that mutes can be used with these instruments. Mutes are hollow devices that have resonance properties of their own. Those frequencies radiating from the bell that are near the resonant frequency of the mute are strongly absorbed and significantly alter the timbre of the resulting sound.

FFT 20

THE PIANO

The piano took its present form in 1855 when Henry Steinway, an American piano manufacturer, introduced the cast-iron frame, which gave to this popular instrument a brilliance and power unobtainable by its predecessors. The clavichord, one of the ancestors of the piano, was a fifteenth-century accomplishment. Like the piano, the clavichord is a string-percussion instrument in which a metallic wedge strikes a taut string and initiates a vibration. The sound of the clavichord is so feeble that it is essentially limited to home use. The clavichord has difficulty holding its own in a small ensemble so that even in chamber music its usefulness is restricted by the smallness of the sound it produces.

The harpsichord is a more recent forerunner of the piano. The strings of this instrument are set into oscillation by a quill that plucks the