PC and PVC Acoustics Demonstrations

By Stephen Luzader

Two important topics included in most elementary acoustics courses are the structure of musical scales and the physical principles governing the operation of musical instruments. Scales seem mysterious because treatments given in textbooks tend to emphasize the numerical aspects of scale construction and, moreover, suitable demonstrations to illustrate the different scales have generally not been available. Musical instruments are more amenable to demonstrations, but certain aspects of their design and construction may seem somewhat mysterious if the subject of scales is not clear. Modern technology can be used to remedy the scale problem, and cheap, easily worked PVC pipe can be used to build a variety of wind instruments based on different scales. In this paper, I'll first describe the use of computerized synthesizers to play scales and chords. Then I'll describe four PVC instruments, two "woodwinds" and two "brasses."

Computer Demonstrations

Many popular personal computers contain sound synthesizers, or have synthesizers available as add-on peripherals, which are capable of producing a variety of waveforms over a frequency range of several octaves. The ability to have precise control over frequency makes the computer-synthesizer combination ideal for demonstrating different musical scales.

Most texts[1–6] used for elementary acoustics courses include a discussion of how musical scales are produced. Once the basic idea of a scale as a series of frequencies, $f_1, f_2, f_3, \ldots, 2f_1$, spanning one octave has been established, the subsequent treatment is usually numerological in nature, and students can't appreciate the differences between the scales because they don't get to hear the scales. Demonstrations requiring many signal generators are obviously impractical, but a synthesizer can easily be programmed to play scales.

Of course, the exact programming steps depend on the particular computer being used. In this discussion, I'll assume the reader knows how to get the synthesizer to produce tones with given frequencies. It is not enough to know how to produce a given named note or pitch (e.g., B-flat), since the actual frequency of a named note depends on the scale being used, and that's the whole purpose of this demonstration. All of the scales to be discussed here are "standard" diatonic scales, with seven intervals (eight notes) spanning one octave in the sequence whole tone – whole tone – half tone – whole tone – whole tone – whole tone – half tone. The scales all include one or more chromatic half-tone intervals (to go from DO to DO-sharp, for example), but they will not be discussed explicitly here, except for the equal-tempered scale, which only uses one half-tone interval. Refer to Refs. 1–6 for more information.

Historically, the oldest scale usually discussed is the Pythagorean scale, which is based on forming pleasing combinations of two tones sounded simultaneously. The frequency ratios that are important in the Pythagorean scale are 1:1 (unison), 2:1 (octave), 3:2 (musical fifth), and 4:3 (musical fourth). Once a frequency, f_1, has been chosen for the lowest note in the scale ("DO" in modern terminology), the other notes are multiples of that frequency. Calculation of the ratios can be found in any of Refs. 1–6; the results are summarized in Table I.

As a concrete example, suppose we choose 100 Hz as

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the frequency for the note "DO." (Keep in mind that the choice for the actual frequency corresponding to any particular note is purely arbitrary.) According to Table I, the next note will be RE, with a frequency of (9/8) × 100 Hz = 112.5 Hz. Then comes MI at (81/64) × 100 = 126.56 Hz, FA at (4/3) × 100 = 133.33 Hz, and so on up to DO′ at 200 Hz. A reasonable demonstration might involve a program that stores the frequencies for each of the notes, playing them in the sequence DO-RE-MI-FA-SOL-LA-TI-DO′ with each tone having a duration of about 1 s.

Table I. Frequency ratios for three scales.

NOTE	PYTH	JUST	EQ TEMP*
DO	1	1	1
RE	9/8	9/8	r^2
MI	81/64	5/4	r^4
FA	4/3	4/3	r^5
SOL	3/2	3/2	r^7
LA	27/16	5/3	r^9
TI	243/128	15/8	r^{11}
DO′	2	2	2

*$r = 2^{1/12} = 1.05946$

The two notes DO and MI sounded together form a musical third, which has a harsh, raspy quality in Pythagorean intonation. The "just" scale is a modification of the Pythagorean scale that keeps pleasant-sounding fifths and fourths while adding more pleasing thirds by changing from a frequency ratio of 81:64 to 5:4. Table I gives the frequency ratios for a just scale. In our sample scale, the frequency of MI would change from 126.56 Hz to 125.00 Hz. The notes LA and TI will also have different frequencies. A demonstration program would play one set of frequencies, then the other. Most listeners will be hard pressed to hear the difference when the notes are played one after the other, but with some practice the changes can be detected by ear.

An equal-tempered scale is one in which the octave is divided into some number of equal intervals, which determines the multiplier to get from one note to the next. To span an octave with N intervals, the ratio to go from one tone to the next is given by

$$r^N = 2 \tag{1}$$

from which we get

$$r = 2^{1/N} \tag{2}$$

A choice of $N = 12$ happens to give tones that are nearly the same as those in the historic scales already discussed, where $r = 2^{1/12} = 1.05946$ corresponds to a musical half step. Table I shows the appropriate multipliers to give a "standard" diatonic scale like those already discussed. Now, taking DO to be 100 Hz gives RE at $r^2 \times 100 = 112.25$ Hz, MI at $r^4 \times 100 = 125.99$ Hz, etc. Essentially all of the notes have slightly different frequencies from their counterparts in the other two scales. Now a program can be run that plays all three scales for comparison. Students can be challenged not only to tell if two scales are different from each other, but also to identify a given scale just by listening.

Table II gives a summary of the frequencies for each of the three scales with a starting frequency of 100 Hz for the note DO. Here we see why a computer-controlled synthesizer is really the only practical tool for demonstrating scales. The frequency differences between some of the notes are so small that they would be almost impossible to set on a laboratory signal generator, even with the help of a frequency meter. Also, unless a very large number of generators was used, each set to one of the 17 frequencies given in the table, the unavoidable time delay incurred while making adjustments would cause students to forget one scale before they hear the next one. Note: I have used 100 Hz for DO to simplify calculations. Since 100 Hz does not correspond to any "standard" note—it lies between A-flat and G—the reader should practice musical calculations by figuring out the frequencies for a scale starting on (say) C, about 131 Hz.

Table II. Frequencies (in Hz) for three scales.

NOTE	PYTH	JUST	EQ TEMP
DO	100.00	100.00	100.00
RE	112.50	112.50	112.25
MI	126.56	125.00	125.99
FA	133.33	133.33	133.48
SOL	150.00	150.00	149.83
LA	168.75	166.67	168.18
TI	189.84	187.50	188.77
DO′	200.00	200.00	200.00

Some simple modifications may be instructive here. For example, a complete 12-tone, half-step (chromatic) scale can be demonstrated by playing frequencies produced by using the ratio r for each step. It is also fun to play around with values of N other than 12. A choice of 7, for example, yields a whole-tone scale with $r = 2^{1/7} = 1.10409$, which is occasionally encountered in music.

The examples given so far only play scales. It is also instructive for students to listen to combinations of notes in order to appreciate some of the reasons for changing the scales in the first place. A multivoice synthesizer is obviously required for these demonstrations. Simultaneously playing the notes DO and MI in the three scales given in Table I produces a musical third, as mentioned earlier. When played in Pythagorean or equal-tempered intonation, this interval has a slightly raspy quality because of beats. In just intonation, a "smoother" sound is heard. (To our modern ears, just intonation may seem rather dull because of its perfection.) A true musical chord consists of three simultaneous tones such as DO-MI-SOL. Chords played in the three scales in Table I sound different, and the differences are clearly audible. Students can listen to other combinations of tones when a multivoice synthesizer is used. All intervals except the octave are slightly "out of tune" in equal temperament, but they tend to sound "normal" to our modern ears.

Those who are ambitious might want to try composing music in the different intonations. I haven't done that, but I have used a commercial program[7] for the Commodore 64 that is capable of playing in Pythagorean and just intonation as well as in equal temperament. I have also written a program for the C64 that plays a variety of scales and combinations of tones. I'll be happy to give a copy of my program to anyone who sends me a disk formatted for the C64. The sound synthesizers can also be used to demonstrate a variety of other acoustic effects related to the perception of sound, such as pitch discrimination and the effect of loudness on pitch.[8]

PVC Musical Instruments

Once students have been introduced to scales, they are ready to tackle the design and construction of musical instruments. Many types of wind instruments can be fabricated using inexpensive and easily worked PVC water pipe. Before building playable instruments, however, it is instructive to demonstrate some features of open vs closed pipes using 1.5-in PVC piping. (These demonstrations can also be done using the cores from paper towel rolls.)

These demonstrations have been described in a DOING Physics column,[9] but I'll give a brief summary here. A single open pipe will produce a tone of definite pitch when one end is slapped with the hand. If the slap is done so that the hand hits the pipe and is quickly pulled away, a familiar "boink" is heard. If one listens carefully to the sound, one hears the pitch rise one octave during the "boink." The pitch change is caused by the change in boundary condition from closed to open as the hand hits the pipe and is removed. Slapping the pipe with the palm of the hand and holding the hand over the end results in a low-pitched "bonk," since the pipe is closed by the hand. Slapping with the fingers spread apart produces a "bonk" with a pitch about one octave higher than the palm slap, because now both ends of the pipe are open. A "private" demonstration of this effect can be done by putting the end of the pipe over your ear. If the pipe is held tightly against the ear, a low-pitched noise is heard, while moving the pipe slightly away from the ear causes the pitch of the noise to rise by about one octave.

Now let's return to the design of instruments. The first two instruments I'll describe, panpipes and a clarinet, make direct use of the scales discussed above. The other two, a posthorn and an alphorn, are "brass" instruments that play only the overtones of the basic pipe.

Panpipes

Panpipes, one of the earliest of musical instruments, consist of a set of small pipes of different lengths, one for each note to be played, that are closed at one end and sounded by blowing across the open end. I used ½-in pipe closed with OO rubber stoppers and bound together with masking tape. A sketch is shown in Fig. 1, and Table III gives approximate lengths for a diatonic scale starting at about the pitch C_5 (523 Hz) in each of the intonations discussed earlier. The rubber stoppers stick far enough into the pipes to affect the pitches of the higher notes, and somewhat better intonation is obtained if the pipes are closed with tape.

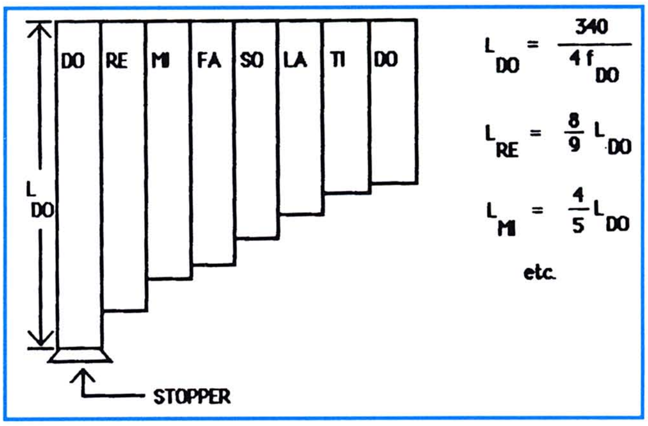

Fig. 1. PVC Panpipes. The lengths were calculated using 340 m/s for the speed of sound in air. Each pipe is closed with a rubber stopper, although only one is shown in the figure to avoid clutter. All the pipes are made from ½-in rigid tubing.

Table III. Panpipe lengths (cm).

	PYTH	JUST	EQUAL
1	16.5	16.5	16.5
2	14.7	14.7	14.7
3	13.0	13.2	13.1
4	12.4	12.4	12.4
5	11.0	11.0	11.0
6	9.8	9.9	9.8
7	8.7	8.8	8.7
8	8.3	8.3	8.3

Clarinet

I made this from ¾-in pipe to demonstrate the use of holes to shorten the effective length of the resonant air column, thereby raising the pitch. The total length of the instrument (including mouthpiece) is 66 cm, giving it a basic (lowest) pitch of about C_3 (131 Hz). Seven finger holes were drilled to give a diatonic scale. A clarinet mouthpiece will fit nicely into a standard ¾-in coupler, so no special parts are needed to attach the mouthpiece to the instrument. A sketch of the clarinet is shown in Fig. 2, and the locations of the holes are given in Table IV for each of the scales. A word of caution before building your own clarinet: hold the undrilled pipe in playing position with the mouthpiece attached and in your mouth, and note where your fingers fall on the pipe. The holes cannot be drilled in a neat row, because you won't be able to reach all of them. Remember also that thumbs can be used to cover holes.

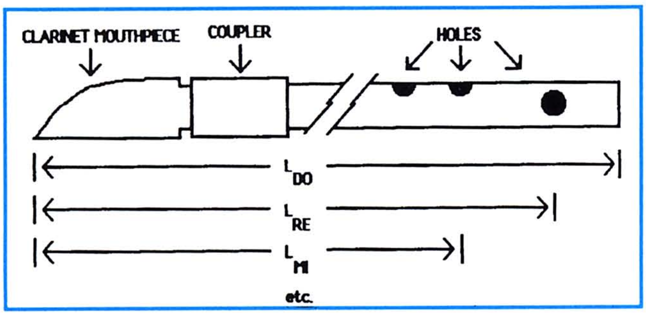

Fig. 2. PVC clarinet. Only three holes are indicated schematically. The holes should have diameters of about ⅜ in. Be sure to put them where you can reach them with your fingers.

Tables III and IV illustrate an important practical feature of scales. While a synthesizer can play the scales "perfectly," real instruments have unavoidable errors associated with measurement, cutting, drilling, etc. In the panpipes, the length differences are comparable to the overall precision with which the tubes can be measured and cut. The differences are larger in the clarinet because of its lower pitch, and the numbers illustrate the compromise nature of the equal-tempered scale. However, actual tone frequencies are strongly influenced by such factors as temperature, the type of reed used, how the reed is blown, how far the fingers are from open holes, etc. In fact, it is possible to play half tones on the clarinet by partially uncovering holes. (It doesn't sound very nice, but it does work.)

Table IV. Distances from mouthpiece tip to holes (cm).

	PYTH	JUST	EQUAL
1	58.7	58.7	58.8
2	52.1	52.8	52.4
3	49.5	49.5	49.4
4	44.0	44.0	44.0
5	39.1	39.6	39.2
6	34.8	35.2	35.0
7	33.0	33.0	33.0

The "Brass" Takes the Stage

Brass instruments are somewhat more complicated acoustical devices than the simple cylindrical-bore instruments just described. The bore of a brass instrument is a combination of conical, cylindrical, and flared sections, and the resonances are strongly affected by the non-cylindrical parts of the tube. I can't go into details here, but more information is available in Refs. 1–6.

Posthorn

I use ½-in pipe to illustrate the transition from the odd harmonic resonances of a closed cylindrical pipe to a series of resonances corresponding roughly to those of an open pipe of the same length (Fig. 3). A pipe can be blown by just buzzing the lips at one end, and usually the first three resonances (f, 3f, 5f) can be sounded. (Fitting a ½-in coupler to the blown end of the pipe makes this a bit easier on the lips than just trying to play a cut end.) Using a tube length of about 140 cm gives a fundamental near B-flat, about 116.5 Hz. A trumpet mouthpiece will just fit inside the pipe, or a short length of ⅜-in flexible tubing can be used to provide an extra taper. The flexible tubing needs to be shaved a bit to allow it to fit inside the ½-in rigid pipe. The mouthpiece alone will shift the higher resonances of the pipe enough to play a reasonable bugle-like harmonic series. Sticking a funnel in the other end of the pipe gives quite a respectable trumpet-like sound. This posthorn works much better than others I've made from rubber hose; the rigid PVC pipe absorbs less energy from the standing waves, raising the Q and making the "horn" easier to play.

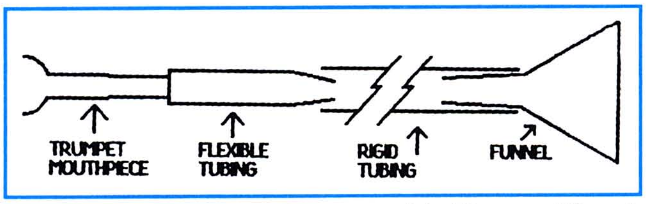

Fig. 3. PVC posthorn (not drawn to scale). The overall length is about 146 cm.

Alphorn

My largest construction project was an alphorn, which is sketched in Fig. 4. Alphorns are very long instruments of low fundamental pitch that are played high in their overtone series, like a French horn. The one I built is designed to be approximately in the key of F, with a fundamental frequency of 44.7 Hz and length of about 3.8 m. An essential feature of a real alphorn is its conical bore, which is simulated by using different sizes of pipe connected with appropriate adapters. Unfortunately, there seems to be no adapter to make the step from ¾-in water pipe to 1.5-in drain pipe, so I wrapped some thick weather stripping around the small water pipe to make it fit snugly inside the drain pipe. The whole thing ends (with some more step-up adapters) in a 3-in sewer elbow. Since high overtones are played, pitches are very sensitive to changes in the lengths of the mouthpiece part of the horn and in the

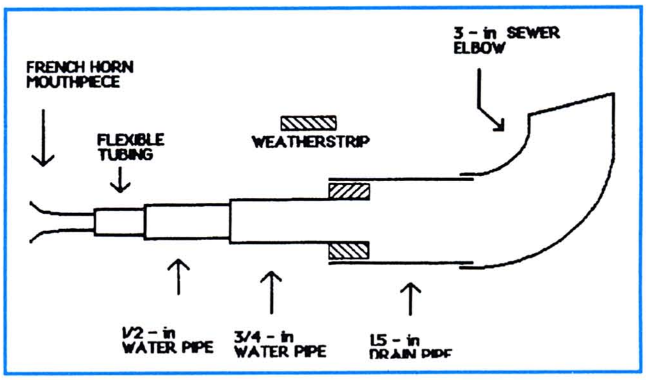

Fig. 4. PVC alphorn (definitely not drawn to scale!). The lengths of the various tube diameters are: ½ in, 1.5 m; ¾ in, 1.5 m; 1.5 in, 40 cm. The overall length of the "bell" section (including adapters to get from 1.5 to 3 in) is about 20 cm.

bell section. I got the best playing characteristics by using a French horn mouthpiece plugged into a piece (approximately 12-cm long) of 3⁄8-in flexible PVC tubing, which was shaved to fit into the 1⁄2-in rigid tubing at the small end of the horn. Unfortunately, this requires the use of an adapter on the mouthpiece. A trombone mouthpiece can also be used; this more closely resembles a true alphorn mouthpiece and will fit directly into the small tubing. You may want to experiment with the lengths of the small tubing and the bell section to adjust the intonation if you change to a different mouthpiece.

These are only a few examples of what can be done with PVC pipe. Here are some suggestions of other things to try.

- Make a flute or some other kind of whistle.
- Attach a 1⁄2-in faucet washer to the end of a wooden dowel so it will fit inside a piece of 1⁄2-in pipe to make a slide whistle. [This idea was brought to a Milwaukee Area Physics Sharing meeting by Marian Schraufnagel of Waterford (Wisconsin) High School.]
- Wrap some plastic tape around 1⁄2-in tubing, which will allow it to form a reasonably tight seal inside 3⁄4-in tubing, yet be able to slide freely. This becomes the basic unit of a slide trumpet or a trombone.

Concluding Remarks

I have used all of these scales and "instruments" in a descriptive acoustics course, and I have used the instruments for the standing waves lecture in a general physics course. I have found that they stimulate a great deal of student interest for a variety of reasons. One is that the students are curious about how music is actually made. They also seem to enjoy watching the alphorn grow as the various sections are assembled. Finally, the students are often surprised to discover that their physics professor not only has some real human interests, but that he also seems to have some small talent for something besides doing physics problems, since I always play some tunes to show that the instruments really work. (Being a ham at heart, I must confess that I enjoy the bursts of applause that I get during the lectures.) ♦

References

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2. R.E. Berg and D.G. Stork, *The Physics of Sound* (Prentice-Hall, Englewood Cliffs, NJ, 1982).
3. D.E. Hall, *Musical Acoustics* (Wadsworth, Belmont, CA, 1980).
4. J.S. Ridgen, *Physics and the Sound of Music*, 2nd ed. (Wiley, New York, 1984).
5. T.D. Rossing, *The Science of Sound* (Addison-Wesley, Reading, MA, 1982).
6. H.E. White and D.H. White, *Physics and Music* (Saunders, Philadelphia, 1980).
7. Musicalc 1 (Waveform Corporation, 1912 Bonita Way, Berkeley, CA). I don't know if this program is still available, but there are many music programs on the market for practically every popular computer.
8. A program illustrating a dazzling array of perceptual effects has been written for the C64 by Dr. Manfred Euler at the Technological University of Duisburg, Lotharstrasse 1, D 4100 Duisburg, Germany.
9. DOING Physics, *Phys. Teach.* **25**, 173 (1987).

Physics Haiku

Physics Haiku originally appeared in *TPT* in March 1990 on page 180 and again on page 244 in the April issue. Here are the remaining offerings by the class of **Bill Franklin,** *Memorial High School, Spring Branch ISD, Houston, TX 77024.*

Frictionless pulley
Two masses on a string
The tension's growing
—*Ryan Charbeneau*

Projectile motion:
Vertical, horizontal
Are independent.
—*Sheila Hayre*

Fifth force or sixth force
Undiscovered for so long
Your secrets await
—*Mitchell Garrett*

As we extend hands,
Universe extends its range,
As if to escape.
—*Atsushi Ohtaka*

Kepler told Tycho,
Give me your secret of Mars
(Or I will steal it).
—*Kala Venugopal*

The empirical
Is given by Kepler's laws,
But Newton explains.
—*Sheila Hayre*

A star gardener
No green thumb, but metal nose
Tycho, star plotter
—*Sohail Ahmed*

Circular motion
You feel force from the center
Which you imagine
—*Junko Tominaga*

The Guillotine blade,
The hangman's rope and gallows,
Work on gravity.
—*Hyonchol Kahng*

Newton and the moon
Have both created great waves
All over the world
—*Neera Mahajan*

Length, time, speed, and mass
Relativistic orphans
Dreams of dimensions
—*Sohail Ahmed*