Garden Hose Bugle

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Topic

The physical basis of the western musical scale

Time

1 hour

Safety

Please click on the safety icon to view the safety precautions. If more than one person will be using the apparatus, which will involve breathing into a tube, wash the mouthpiece to prevent the spread of colds.

Materials

1 trumpet, trombone, euphonium, or tuba mouthpiece. (See if you can obtain a used mouthpiece from your school's music department. Wash the mouthpiece thoroughly and soak it in alcohol so that it does not spread germs.)
5-m (16-ft) garden hose, with about 1-in. outside diameter. (Standard hose designations are 5⁄8 and 7⁄8 in. Either is suitable, so long as the mouthpiece fits snugly in an end.)
1 funnel to fit snugly in hose end
1 garden shears or utility knife
rubbing alcohol
masking tape
felt-tipped pen
graph paper
musical instrument on which notes can be played and identified, such as a piano or small electronic keyboard

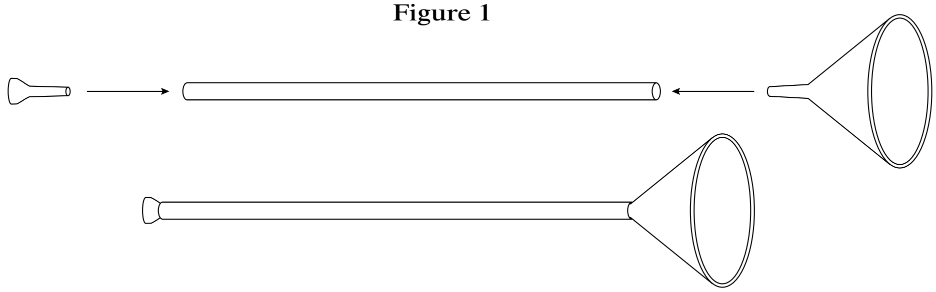
Procedure

It is best to perform this experiment with a partner or in a small group. The experiment makes a great deal of loud noise, so perform it in a place where you will not disturb others. If you are doing it in school, you may have to do it without the funnel to reduce noise.

1. If a member of your experiment group has played a brass instrument before, he or she is the logical choice to produce the sounds with the mouthpiece. Otherwise, have someone from the music department show you how to make it sound. The person who will be doing this should practice with the mouthpiece to gain some control over the pitch of sounds that can be made with it. (If different members wish to try making notes, remember to clean the mouthpiece thoroughly and soak it in alcohol each time before the next person uses it.)

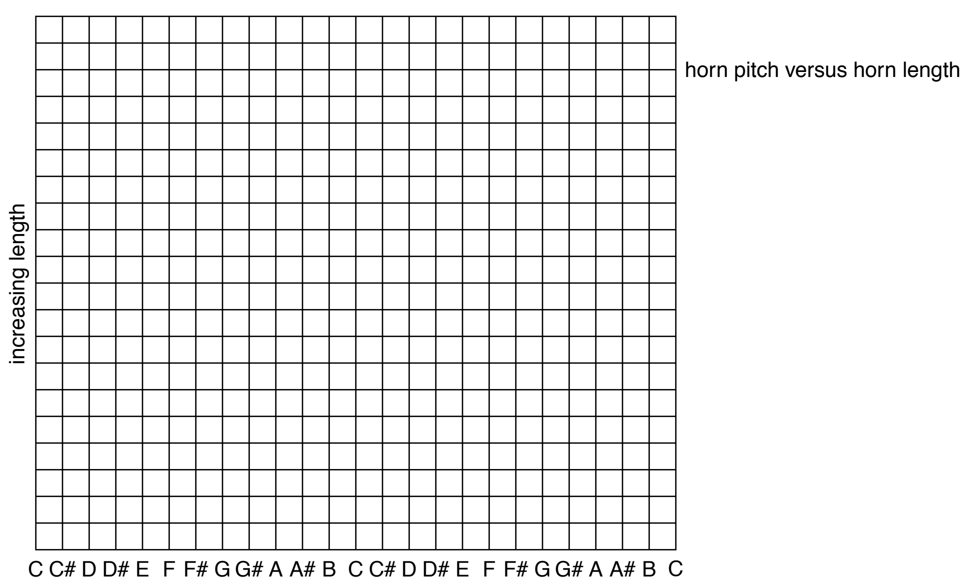
2. Cut a length of hose 0.6 m long, and, using the tape and marking pen, label this hose length "1." Fit the mouthpiece snugly in one end and the funnel in the other, as shown in figure 1. Try to get different notes from the "bugle" by changing the tightness of your lips. Then try to get the lowest-pitched clear note possible. Identify this note by playing the reference instrument and finding the note(s) that correspond to the sound coming from the bugle. Record this information on the data table as the fundamental resonant frequency note (FRFN) of the #1 (60-cm) horn.

Figure 1



3. Next, try to produce the next two higher-pitched notes, and identify them by matching their sound with notes produced on the reference instrument. Record these notes on the data table as the second and third harmonics.
4. Plot your data on a graph with two or three octaves of notes identified with half-intervals (semitones) marked off along the horizontal axis and horn length in centimeters on the vertical axis. Plot the range of notes on the graph that most nearly matched the lowest note your bugle produced, and make a dot in the center of this range, which should be the best estimate of the fundamental resonant frequency for your 60-cm bugle. (See the sample graph, figure 2.) The musical scale that uses half-intervals or semitones, as on your reference instrument, is the Western, or equally tempered chromatic, scale, and each note's frequency is 1.06 times the frequency of the preceding notes. This produces a note with twice the frequency of any given note 12 notes below it. For example, C above middle C is one octave above middle C, has a frequency twice that of middle C, and is 12 semitones above middle C. On a piano, each key produces a note one semitone higher than the note below it. The black key that follows the white key for middle C is referred to as either C sharp or D flat, and the frequency is 1.06 times that of middle C.

Figure 2



5. With the remaining length of hose, cut lengths that are ⅘, ¾, and ⅔ of the length

(60 cm) of your original bugle. Label the new horns according to these fractions. Transfer the mouthpiece to each of these lengths in turn, and find the fundamental resonant (lowest) frequency for horns of each length. Record these notes on the data table opposite the horn numbers (fractions) and their lengths. Plot the data on your graph alone with the data from your original horn. Cut and label lengths that are 5/4, 4/3, and 2/3 of the first length. Find, record, and plot their fundamental resonant frequencies as well.

DATA TABLE				
Horn no.	*L*, horn length in cm	Note(s) identified by reference instrument	*f*, frequency in vibrations/second	l, wavelength in cm
1		FRFN		
1		Second harmonic		
1		Third harmonic		
4/5		FRFN		
3/4		FRFN		
2/3		FRFN		
5/4		FRFN		
4/3		FRFN		
3/2		FRFN		

Note: Because this experiment uses relatively crude measurements and tries to match pitches with those that are not precisely the same, and because of different mouthpieces and abilities to produce pure notes, the data actually obtained in this experiment will not exactly replicate data obtained under more accurately controlled circumstances. However, results within one or two half-intervals often result.

6. As the hose gets longer, what happens to the pitch? As it gets shorter, what happens? Can you make a general statement that relates the length of the resonating air column in the horn, the fundamental frequency as identified by the reference instrument, and the pitch? What is the main effect when the funnel is inserted into the opposite end of the hose from the mouthpiece?
7. Referring to the formula that relates velocity *V*, frequency *f*, and wavelength *l* of sound ($V = fl$), and assuming that the velocity of sound at room temperature is about 345 m/sec, can you calculate the wavelength *l* of each of the notes you have identified? (Assume that the frequency of the note middle C is about 260 vibrations a second, and remember that each note is 1.06 2 the frequency of the preceding note one semitone below it.) Write the frequency and wavelength next to each note on the data table. Based on this frequency data and your graph, can you state a relationship between the lengths of the air columns of the horns and their fundamental resonant frequencies? If your graph is not a straight line, what could you plot that you believe would result in a straight-line graph? Can you write a

mathematical equation that represents this relation?

8. Try to determine the mathematical relation between the wavelength (in centimeters) of a horn's fundamental resonant frequency note and the length of the air column (also in centimeters) that produces it. Remember the uncertainties in your data as you search for these specific relationships.
9. Look at your data identifying the second and third harmonics of the first horn. Can you notice any relationship between the frequencies of these notes and the fundamental resonant frequency of the horn that produces them?
10. Compare the number of semitones between the pitch of the fundamental frequency of the $\frac{5}{4}$ horn and the original (60-cm) horn and between the original horn and the $\frac{4}{5}$ horn. Is there any regularity? Do the same for the $\frac{4}{3}$ horn, the original horn, and the $\frac{3}{4}$ horn, and then for the $\frac{3}{2}$, original, and $\frac{2}{3}$ horns. Is there any regularity?
11. The $\frac{3}{2}$ horn is twice the length of the $\frac{3}{4}$ horn. (The $\frac{3}{2}$ horn is 90 cm long and the $\frac{3}{4}$ horn 45 cm.) What would you predict the frequency relation would be for the fundamental for each of these lengths? What would their pitch relation be? What do the data show? Within the limits of experimental uncertainty, do your data verify this prediction?
12. Considering your conclusions relating air column length to frequency and pitch of produced sounds, how would you go about designing a complete set of horns that would play every note on the piano?

What's Going On

In a bugle, as in all brass instruments (like the trombone, French horn, euphonium, or tuba), the source of vibration is the lips of the player, while in other instruments the source may be a vibrating reed or the air itself. In a piano, violin, or guitar, the source is a vibrating string. In every case, these vibrating sources alone do not cause enough air to move to produce a loud sound, so something is caused to vibrate in sympathy with the original source of vibration to increase the loudness of the resulting sound. (In the bugle, this is a column of air, which greatly increases the amplitude of the motion of the air molecules carrying the sound away from the tube, and thus the loudness.)

Only if the wavelength of the sound is related in a specific way to the length of the air column, will the vibrations reinforce as they travel back and forth in the bugle itself. There must be what is known as a *standing wave* for this to occur, and this depends on the velocity of sound in air and the length of the air column (the horn length). As the horn (and the air column it contains) gets longer, the pitch gets lower. As the horn gets shorter, the pitch gets higher. While the lips vibrating in the mouthpiece produce the basic sounds (and can produce a full range of frequencies and pitches) when the mouthpiece is inserted into a particular length of hose, only certain specific notes can be supported and amplified by the resonating air column. The fundamental resonant frequency gets higher as the length of hose gets shorter, and the perceived pitch gets higher. The main effect of the funnel is to increase the volume of the sound, much like a cheerleader's megaphone. The data should show that the frequency of the fundamental is *inversely* proportional to the length of the air column. To obtain a graph of a straight line, you could plot horn length (L) as a function of 1/frequency ($1/f$) with L on the vertical axis and $1/f$ on the horizontal. L is directly proportional to $1/f$. Mathematically, this relation is written L } $1/f$ or $L = k/f$, where k is some constant. Wavelength (l) is directly proportional to horn length (l } L).

V = l*f*. Dividing both sides by *f*, we obtain l = *V/f*. As explained above, since *V* is a constant, this means l is proportional to 1/*f* (l } 1/f). As stated above, *L* } 1/*f*, so, l } *L*. The harmonics you are most likely to obtain from your horn will be notes one and two octaves above the horn's fundamental frequency note. Their frequencies will be 2 and 3 times that of the fundamental. When the length of the horn is reduced by any given fraction, the difference in pitch (represented by the number of semitones difference on the reference instrument) is constant for that fraction. Since frequency varies inversely with column length, a proportional increase in length represents a proportional decrease in frequency and always lowers the pitch by the same number of semitones.

There are four semitones between the 5/4 horn and the original and between the original and the 4/5 horn. There are five semitones between the 4/3 horn and the original and between the original and the 3/4 horn. The 3/2 horn is about seven semitones lower than the original, and the original is seven semitones higher than the 2/3 horn. Frequency and horn length are inversely related. Doubling the horn length halves the frequency. The 3/2 horn has a frequency half that of the 3/4 horn. A proportional change in frequency always raises or lowers the pitch a constant number of semitones. The 3/2 horn should produce a fundamental frequency pitch one octave (12 semitones) below the 3/4 horn. You have observed that a proportional change in horn length changes the pitch by a fixed number of semitones. You know also that frequency is inversely proportional to air column length, so jumps in pitch represent a fixed change in frequency. You have seen that occur when multiplying frequency by 4/3 (by multiplying horn length by 3/4 causes the pitch to rise by five semitones).

To generate all the notes on the piano, you could start with a horn whose resonant frequency gives a low C and repeatedly multiply frequency by 4/3 to move up the keyboard and obtain F, A#, D#, G#, C#, F#, B, E, A, D, G, and then halve and double each of these frequencies to fill in the corresponding notes in the rest of the octaves. Alternatively, you could start with a horn whose fundamental resonant frequency was that of middle C and then produce horn lengths of any fraction to produce frequencies that would be that of middle C times the inverses of those fractions.

On a violin, any note within its register can be produced by making a length of string at any point. On the piano, notes are provided only at fixed intervals where the pitch increases by 1/12 of an octave. This relatively new kind of scale was developed in the 16th century. Starting from the fact that frequency doubles when pitch goes up an octave, mathematicians broke up the octave into 12 equal divisions. They reasoned that if they could find a number that when multiplied by itself 12 times yielded 2 (^{12}= 2), this number would provide the size of the interval between 12 equally spaced notes within an octave. The number 1.059 raised to the 12th power = 2, so the frequency of any note in this system is approximately 1.06 times the frequency of the previous note. If you used a piano as your reference instrument, you were using an instrument tuned to this newer system, known as equal temperament, instead of the tuning system of harmonic proportions that you were developing with the garden hose bugles.

Connections

Sound is the term we use for vibrations in a medium (most often air) and for our perceptions of those vibrations. When an object vibrates in air, it moves back and forth, first pushing air molecules ahead of it closer together, and then, when it moves back, leaving a space with air molecules farther apart. The sound wave is actually the disturbance itself that moves away from the source as air molecules bump into adjacent air molecules and transfer the extra energy and momentum they gained from the vibrating source. The waves, consisting of areas of compression (molecules closer together) and rarefaction (molecules farther apart), move out in all directions from the vibrating source in much the same way that waves move away from a spot where a stone is thrown into a pond. When these regions of high and low pressure (compressions and rarefactions) reach our ears, they cause our eardrums to vibrate at the same rate as the original vibration.

Wavelength is the distance between successive areas of compression in the sound wave. *Frequency* is the rate of vibration, the number of back-and-forth motions, or cycles, a vibrating object makes in 1 sec. The velocity of sound is always equal to the frequency times the wavelength ($V = fl$). *Pitch* is the musical term used to describe our perceptions of sound at different frequencies. When an object vibrates rapidly, it produces sound waves of a high frequency, which we perceive as a high-pitched sound. A low-frequency vibration is perceived as a low pitch. In this project, you explored the relationships between the length of the vibrating air column in a garden hose "bugle," the frequencies of sound it produces, and the pitches that are perceived.

Safety Precautions

READ AND COPY BEFORE STARTING ANY EXPERIMENT

Experimental science can be dangerous. Events can happen very quickly while you are performing an experiment. Things can spill, break, even catch fire. Basic safety procedures help prevent serious accidents. Be sure to follow additional safety precautions and adult supervision requirements for each experiment. If you are working in a lab or in the field, do not work alone.

This book assumes that you will read the safety precautions that follow, as well as those at the start of each experiment you perform, and that you will *remember* them. These precautions will not always be repeated in the instructions for the procedures. It is up to you to use good judgment and pay attention when performing potentially dangerous procedures. Just because the book does not always say "be careful with hot liquids" or "don't cut yourself with the knife" does not mean that you should be careless when simmering water or stripping an electrical wire. It *does* mean that when you see a special note to be careful, it is extremely important that you pay attention to it. If you ever have a question about whether a procedure or material is dangerous, stop to find out for sure that it is safe before continuing the experiment. To avoid accidents, always pay close attention to your work, take your time, and practice the general safety procedures listed below.

PREPARE

- Clear all surfaces before beginning work.
- Read through the whole experiment before you start.
- Identify hazardous procedures and anticipate dangers.

PROTECT YOURSELF

- Follow all directions step by step; do only one procedure at a time.
- Locate exits, fire blanket and extinguisher, master gas and electricity shut-offs, eyewash, and first-aid kit.
- Make sure that there is adequate ventilation.
- Do not horseplay.
- Wear an apron and goggles.
- Do not wear contact lenses, open shoes, and loose clothing; do not wear your hair loose.
- Keep floor and work space neat, clean, and dry.
- Clean up spills immediately.
- Never eat, drink, or smoke in the laboratory or near the work space.
- Do not taste any substances tested unless expressly permitted to do so by a science teacher in charge.

USE EQUIPMENT WITH CARE

- Set up apparatus far from the edge of the desk.
- Use knives and other sharp or pointed instruments with caution; always cut away from yourself and others.
- Pull plugs, not cords, when inserting and removing electrical plugs.
- Don't use your mouth to pipette; use a suction bulb.
- Clean glassware before and after use.
- Check glassware for scratches, cracks, and sharp edges.
- Clean up broken glassware immediately.

- Do not use reflected sunlight to illuminate your microscope.
- Do not touch metal conductors.
- Use only low-voltage and low-current materials.
- Be careful when using stepstools, chairs, and ladders.

USING CHEMICALS

- Never taste or inhale chemicals.
- Label all bottles and apparatus containing chemicals.
- Read all labels carefully.
- Avoid chemical contact with skin and eyes (wear goggles, apron, and gloves).
- Do not touch chemical solutions.
- Wash hands before and after using solutions.
- Wipe up spills thoroughly.

HEATING INSTRUCTIONS

- Use goggles, apron, and gloves when boiling liquids.
- Keep your face away from test tubes and beakers.
- Never leave heating apparatus unattended.
- Use safety tongs and heat-resistant mittens.
- Turn off hot plates, bunsen burners, and gas when you are done.
- Keep flammable substances away from heat.
- Have a fire extinguisher on hand.

WORKING WITH MICROORGANISMS

- Assume that all microorganisms are infectious; handle them with care.
- Sterilize all equipment being used to handle microorganisms.

GOING ON FIELD TRIPS

- Do not go on a field trip by yourself.
- Tell a responsible adult where you are going, and maintain that route.
- Know the area and its potential hazards, such as poisonous plants, deep water, and rapids.
- Dress for terrain and weather conditions (prepare for exposure to sun as well as to cold).
- Bring along a first-aid kit.
- Do not drink water or eat plants found in the wild.
- Use the buddy system; do not experiment outdoors alone.

FINISHING UP

- Thoroughly clean your work area and glassware.
- Be careful not to return chemicals or contaminated reagents to the wrong containers.
- Don't dispose of materials in the sink unless instructed to do so.
- Wash your hands thoroughly.
- Clean up all residue, and containerize it for proper disposal.
- Dispose of all chemicals according to local, state, and federal laws.

BE SAFETY-CONSCIOUS AT ALL TIMES