MI-001 v1.0	**Title:** Pen Pipes	**Target Grade Level:** 5-12	
Categories	Physics / Waves / Sound / Music / Instruments		**Pira** 3D
Standards	**US:** NSTA Science Content Std B, 5-8: p. 155, 9-12: p. 180		**VT:** S5-6:29
	Regional: McREL Science Standard 9, Levels II-IV		
Keywords	Resonance, Frequency, Pitch, Musical Instruments, Aerophone, Wavelength, Closed Tube, Timbre, Reflected wave, Standing Wave		
Project Type: Workshop	**Complexity:** Easy	**Materials:** Readily Available	
Project Duration: 0.5–1.0 hr Prep, 0.5-1.0 hr Build		**Recommended Team Size:** 2-6	

Note: optional material is highlighted in red.

Workshop: Pen Pipes

Fig. 1 Six-note pen pipes with decorative half-caps at top

Purpose

The primary purpose of this project is to understand the connection between the length of a **closed tube** and the fundamental resonant frequency of its air chamber. This objective is accomplished by building and playing a set of pan pipes made from ballpoint pen tubes. An optional goal is to develop an intuitive understanding of the mathematical relationship between the tube length and the frequency. Extensions of the project could include a discussion of the structure of musical scales.

Background

A set of pen pipes are a small version of pan pipes, which is a musical instrument in the **aerophone** category. Aerophones, commonly referred to as wind instruments, produce sounds by vibrating the air in a hollow object. For pen pipes, the hollow objects are the tubes used for ballpoint pens. Other aerophones include flutes, oboes and trumpets.

The **fundamental resonant frequency** of a material is the frequency that requires the lowest energy to cause the material to vibrate. If the air within a tube is vibrated at frequencies that include the fundamental resonant frequency, the fundamental frequency will usually be the loudest sound produced. Assuming the fundamental frequency is in the audible range for humans, this frequency will be heard as the **pitch** of the object.

In aerophones, multiples of the fundamental frequency (**harmonics** or **overtones**) may also be produced. The human ear may hear these sounds, but usually identifies the primary pitch as that of the fundamental frequency. The combination of the harmonic frequencies is heard as a slight change which musicians refer to as the **timbre** (pronounced `*tam·bər*) of the sound.

Materials & Tools

Materials per student:
(6-8) Tube pens (e.g., BiC ™ Round Stic ™ Pen: 8 mm OD, 122 mm long),
(3-4) Standard pencils (or standard pencil erasers, 6.5 mm OD, 11 mm long)
(1) Sheet for recording data (e.g., eraser position for each note)

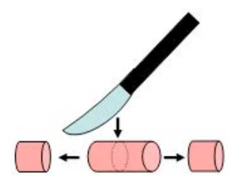
Tools per student:
(1) Dowel, 5 mm OD, ~150 mm long (e.g., wooden chop stick)

Tools per team:
(1) Needle-nose pliers
(1) Sharp pair of scissors or knife
(1-3) Ruler(s), metric
(1) Packing tape, roll
(1) Electronic tuner (or pitch-matching instrument)

Tools for Instructor:
(1) Dowel, 5 mm dia., ~150 mm long, marked with eraser positions for each note
(1) Oscilloscope, preferably with FFT frequency display (e.g., Winscope 2.51)

Procedure

(1) If erasers are attached to the pencils, remove them carefully. Return pencils to the instructor.



(2) With sharp scissors or knife, cut each eraser in half as shown.

(3) With pliers, pull the pen tip and ink tube out of the pen and return them to the instructor.

(4) With pliers, remove the plug from the pen end. It may require squeezing the tube several times until the plug becomes loose.

(5) Insert an eraser half into each tube and push them to the starting positions with the dowel shown in the attached table (tube length). Wrap a piece of masking tape around the bottom of each tube and mark it with the musical note corresponding to each length.

(6) To play each tube, place your bottom lip on the near side of the top of the tube and blow across and slightly downward. Optimize the angle and width of the air stream to get the best tone.

(7) Compare the note to a reference instrument (e.g., electronic tuner, reference tube, another musical instrument). With the dowel, adjust the eraser position to match the reference tone. Measure the eraser positions by inserting the dowel, marking the depth of the cork on the dowel and measuring the marked distance with the ruler. Record the positions in the data table

Note	Frequency (Hz)	Eraser Position (mm)		K Values ( )	Inverse Length (mm^{-1})
		Starting Value	Actual Value		
G_5	784.0	104			
A_5	880.0				
B_5	987.8				
C_6	1046.	76			
D_6	1175.	66			
E_6	1318.	59			
F_6	1397.	55			
G_6	1568.	49			
		Average K:			

(8) Using the relationship between frequency and tube length (eraser position), calculate the positions of the A_5 and B_5 notes.

Frequency = K / Length, where K is a constant

HINT: Solve for K for each length, average the K values and substitute into the equation to obtain the A_5 and B_5 lengths. Record values in the table.

What are the units of K?

(9) If there are available materials, make the A_5 and B_5 pipes. Test and adjust them as described in step (7).

(10) Align the tubes about 20 mm apart with the longest on the left. Tape them together with packing tape. This step may be more easily accomplished by first laying a piece of tape on a table (sticky side up), aligning the tubes on it, and then applying another piece of tape across the top. .

(11) Calculate the inverse value of the eraser position lengths and enter them into the appropriate column on the data table.

Inverse Eraser Position = 1/ Eraser Position

(12) Plot the frequencies as a function of both the eraser position length and the inverse length. Describe and explain the shape of the curves. Why would you want to plot the data as a function of inverse length?

(13) If an oscilloscope with amplitude vs. frequency is available (see Tools for Instructor), play one of the tubes into a microphone connected to the oscilloscope and observe the result. Identify the fundamental frequency and any harmonics.

(14) Become a pen piper! Try to play a simple tune on your instrument. Even with just the basic six notes in your pan pipes, you can play the first part of "Ode to Joy" by Beethoven.

Instructor Notes

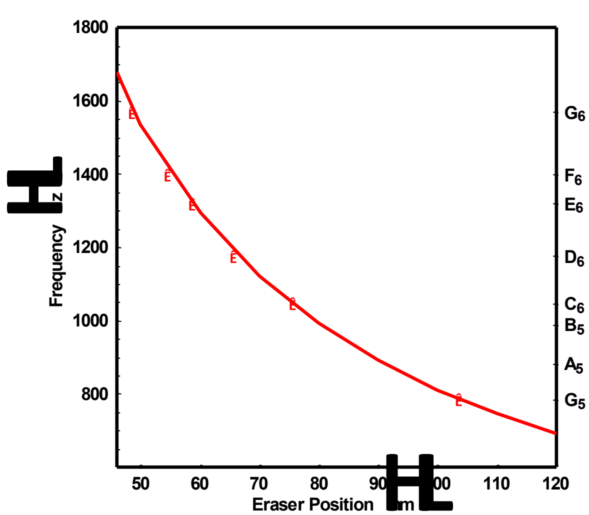
(1) Assistance may be required for step (4), removing the plugs from the tubes. This step can be skipped, but if the erasers are pushed too far into the tubes, removing the plug allows the erasers to be easily readjusted from the alternate end of the tube.

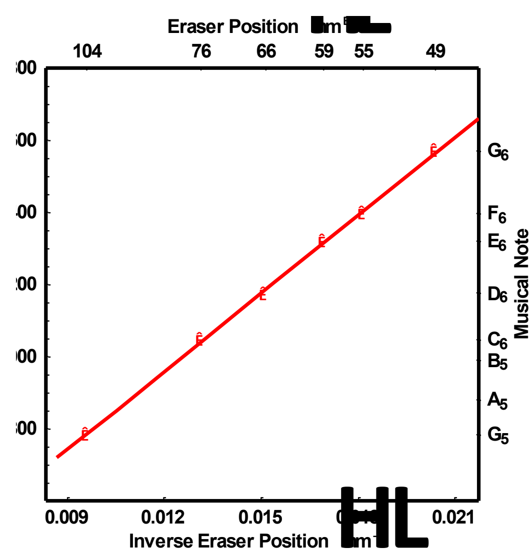
(2) For younger students, the dowels can be pre-marked with the starting length of each note. Marking the dowels in this fashion can also be used as part of the procedure for older students to illustrate a method for simplifying the fabrication process.

(3) The top of the pen caps can be cut off to produce decorative tube caps as shown in Fig. 1. However, beveling the top edge using a knife or file may then be required to produce the desired tones. Some experimentation may be required. Make sure to remove any plastic debris that may result.

(4) Table values and sample frequency vs. tube length plots are shown below.

Note	Frequency (Hz)	Length (mm)	K Values (mm/s)	Inverse Length (mm^{-1})
G_5	784.0	104	81536	9.61×10^{-3}
A_5	880.0	89	-	?
B_5	987.8	79	-	?
C_6	1046.	76	79526	1.31×10^{-2}
D_6	1175.	66	77524	1.51×10^{-2}
E_6	1318.	59	77786	1.69×10^{-2}
F_6	1397.	55	76824	1.82×10^{-2}
G_6	1568.	49	76832	2.04×10^{-2}
		Average K:	78338	





(5) There are numerous free oscilloscope software packages available on the internet. If a package with amplitude vs. frequency plotting capability can be obtained, it is useful in identifying the fundamental and harmonic frequencies of most instruments. A sample display from Winscope 2.5.1 (by Konstantin Zeldovich) is shown below for a note from a pen pipe.