THE PHYSICS OF OPEN PIPE WIND CHIMES

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TEACHER PAGES .
CONCEPT

This project explores sound waves with an item common to many households. Students will make a connection between music and science by using open pipes. The properties of wavelength, frequency, velocity, interference and resonance can be used qualitatively and/or quantitatively. Data can be collected using purchased wind chimes, or copper pipes can be cut and students can make their own set.

DESCRIPTION OF HOW THE ACTIVITY ILLUSTRATES THE CONCEPT

Different lengths of copper pipe will produce different musical notes when struck at a specific point. A pipe that is an incorrect length will produce many tones, while a pipe that is the perfect length for that note will vibrate with one clear tone. As each pipe is struck the students can hear the note, record data from an instrument (a tuning machine from the music room, an oscilloscope, or a computer program that records frequency), and calculate many variables (see below). The amount of analysis done depends on the abilities of your students.

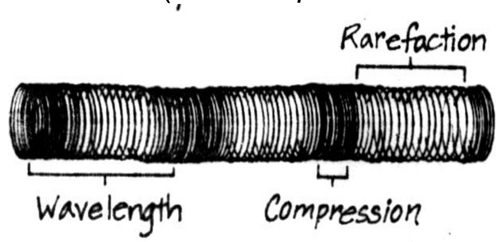
Two or more pipes can be struck together to produce interference that is decided to be pleasant (a musical cord) or unpleasant (noise). Two pipes with slightly different lengths will produce obvious beats to demonstrate how musical instruments are tuned. A tuning fork held over a pipe will start it vibrating if the frequencies are matched, showing resonance.

Reinforcement of the concepts involved can be done with Slinkys¤ and/or string. The famous video of the Tacoma Narrows Bridge can be used to show wave motion and resonance.

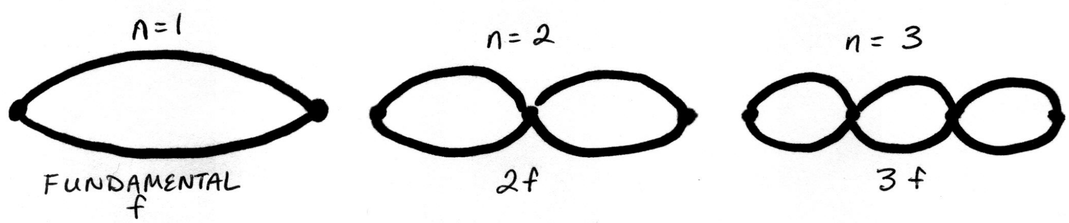
BACKGROUND FOR TEACHERS

Music from open and closed pipes has been documented for several thousands of years. In the tenth century the pipe organ in Winchester Cathedral in England had 400 pipes, producing 40 different notes. Many 18th century organs still survive in Europe, and such organs are suspected to have strongly influenced the music of Bach.

Sound waves travel as a *longitudinal wave*. The particles of the *medium* (air, water, steel) are gathered together, then spread out by the energy from the vibrating object. The distance between identical sections of the wave is called the *wavelength*. All sound waves in the same medium (at the same temperature) will travel at the same speed; at room temperature that *speed* is generally accepted to be 330 m/s. As the number of vibrations per second (the *frequency*) increases, the wavelength will decrease since the wave crests are closer together. We hear different vibrations as different musical notes or *pitches*. Louder sounds have taller waves (more *amplitude* because of more energy).



A wave can be sent along a medium, then inverts and reflects at a boundary. A *standing wave* happens when the reflected wave is exactly opposite the original wave, and nodes and antinodes are produced. You sometimes see this on vibrating car antennas or clotheslines. Pipes produce sounds when a standing wave in the air column vibrates. By controlling the length of the pipe, the number of nodes and antinodes are controlled, producing a specific sound. A node is NO movement while an antinode is maximum movement, or the large hump .



Note: sound travels in longitudinal waves, but for ease of drawing the waves will be shown as transverse waves.

The lowest note a pipe makes is the *fundamental*. Any note of higher pitch than the fundamental is called an *overtone*. If the overtone is exactly one octave (8 notes) higher, it is called a *harmonic*. The whole number ratios of the frequencies of notes were found by Pythagoras to produce what we consider pleasant musical cords. Depending on your music theory background, or the ability of your students this concept can be expanded. Open and closed (at one end) pipes have different rules because of where the standing wave is located inside them. A closed pipe and an open pipe that is twice as long will produce the same musical note.

A brief overview of musical cords: There are several musical scales around; I used the Just scale. See your band teacher for more information.
The C Major cord consists of the notes C, E, and G. The frequencies of these notes on the Just scale are C = 264 Hz, E = 330 Hz, and G = 396 Hz. Dividing each frequency by 264 Hz, the following ratios are found:

C: 264/264 = 1	E: 330/264 = 5/4 (or 1.25)	G = 396/264 = 3/2 (or 1.50)

Ideally, once the length of a copper pipe for note C is found, the length for E should be 1.25 times the size, and the length for G should be 1.5 times the size.

Other cords can include: C-D-G, where D is 296 Hz and G is 396 Hz, cord C-E-A, where A is 440 Hz and E is 330 Hz, and C-F-A where F is 352 Hz and A is 440 Hz. Another octave of C at 528 Hz can be added to all these cords.

A clarinet and a trumpet can play the same note as the note on your copper pipe, but everyone knows there are three different instruments playing. Each instrument produces a unique set of overtones with a characteristic complex sound wave. We recognize the difference and say each has a different *timbre*.

More of the physics of standing waves in pipes is presented in the Quantitative Applications section.

QUALITATIVE APPLICATIONS

- Use a Slinky¤ on the floor to demonstrate the concepts of longitudinal versus transverse waves and when the frequency increases the wavelength decreases. Show changes in amplitude. Have students send wave pulses from each end at the same time to show interference.
- As the pipes are cut (see Construction Instructions) students can listen to the pipes to tell one that is exactly a note and one

that is not quite the correct length. You can ask them if the pipe needs to be shorter or longer to make it right? A flat note means the pipe is too long and must be shortened; a sharp note means the pipe is too short. In that case you ll have to start over or cut the pipe shorter to the next note.

- Once a correct length is found, a tuning fork of that same frequency can be struck, then held over the open pipe. The sound from the tuning fork should get louder and the pipe should start to vibrate because of resonance. Have the students listen for the difference in loudness and feel the pipe afterwards.

- Two pipes that are slightly off in length can be struck together to produce *beats*. These happen because the sound waves superimpose and cancel in some places, and add in others. It is heard as a wah-wah-wah sound. Humans can detect up to 7 beats per second. If your school has a set of the huge tuning forks set on boxes, use these here to demonstrate this concept.

- Bring in band instruments and/or the band director. Listen for the different timbre of each instrument playing the same note. Demonstrate how to tune instruments to each other or the machine. In band, each instrument is played against another player or the tuning machine. When the notes match there are no beats. If the person being tuned is off, the machine or the director tells them how to fix their instrument so they are in tune (no beats). Relate this to what is happening in the pipes.

- Once the pipes are the correct length, find combinations of pipes that sound good together, or don t sound good together. Have students explain or draw wave pictures from those combinations. Play the pipes together in any of the instruments mentioned above and talk about the pictures or numbers they get. Look at these waves in the oscilloscope.
- Striking the same pipe in different locations produces different sounds. A tuner that displays the name of the note being played is very helpful here. You can go into detail on the node

and antinode location in the pipe and why hitting it in different places causes different notes.

- Research the history of pipes in music, the effects music or noise can have on human health, the use of ultrasonic sound in medicine, or the history of a musician. Writing, art, or social studies ties can be made here.

QUANTITATIVE APPLICATIONS

- Use an oscilloscope to see the sound waves produced by a pipe of correct length.

Calculate the frequency of the note using this formula:

From the largest & smallest horizontal readings between the number of COMPLETE waves

From the right list on the screen.

Count from the same place on the waves; see how many whole ones are on the screen.

$(T_2 — T_1)$(__ ms/division) / # complete waves = the period of the wave in milliseconds.

The period is the time for once complete wave.

Convert that to seconds by multiplying by 0.001 (there are 1000 ms in one second).

Since period (T) is 1/f, you must now invert the number. Use the 1/x key on your calculator.

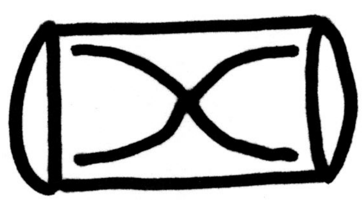
Your final answer is the frequency in cycles per second, or Hertz. Repeat multiple times for each pipe, then take an average.

- The same oscilloscope can directly measure the frequency with the correct settings. Find the setting that shows a Hz reading on the screen. While looking at a sine wave, press Hold . Use the Mark 1 key to move the vertical line to a spot on the wave. Use the Mark 2 key to move a second vertical line to an identical spot on another wave. Undo the Hold , press auto, and take a measurement when you see a sine wave. When you freeze the screen it will give a reading in hertz. Remember to divide by the number of complete waves if you have more than one.

- For two pipes that produce an unpleasant sound, calculate the beats per second by finding the difference in their frequencies. Use the oscilloscope or any other method of obtaining the frequencies of the two notes. Add a third pipe.

- For two or more pipes that produce pleasant cords, calculate the frequencies of the notes, the whole number ratio of them, and the lengths of the pipes as they relate to the ratios. Use the smallest pipe as a base for the length calculations.

- For an open pipe the length of the tube L is related to the number n of half wavelengths (or one node) since the ends of the pipe each have an antinode. The pipe that produces the fundamental note has a standing wave inside that looks like an hourglass .two open antinodes at the ends, and one node in the middle.



The frequency of that note can be found by $f_n = n\ (v/2L)$ where n is the number of nodes and v is the speed of sound in that pipe. *(Tuned wind chimes are very expensive due to the fact that the diameter, thickness, and quality of the inside of the tube are also factors. I have ignored those factors, other than keeping all the tubes _ inch diameter copper.)

Have students calculate the frequency they should get if there are n = 1, 2, 3, etc nodes at a specific speed of sound. (n=1 is the fundamental note f, n=2 is the next octave or 2f, n=3 is 3f and so on.

- Open pipes will resonate for a certain note at lengths of $\lambda/2$, $2\lambda/2$ ($=\lambda$), $3\lambda/2$, $4\lambda/2 = 2\lambda$, and so on. Lambda (λ) represents wavelength. Students can predict the length needed for each octave of a fundamental if they know the wavelength. Assume a speed v at room temperature, assign the frequency to use, and solve for wavelength. Turn those values into pipe length. You ll have to ignore pipe thickness.

- More music theory info:
  For open pipes

n	Harmonic	Overtone	Ex: frequency
1	1st	fundamental	220 Hz
2	2nd	1^{st} overtone	440 Hz
3	3rd	2^{nd} overtone	660 Hz

Ratios and example notes:
Octave: 2:1 ratio such as C_4 and C_5
2^{nd} : 9:8 such as D & E, C & D, or G & A
Minor 3^{rd}: 6:5 such as E & G
Major 3^{rd}: 5:4 such as C & E
4^{th} : 4:3 such as D & G, or E & A
5^{th} : 3:2 such as G & D, D & A, A & E
6^{th}: 5:34 such as C & A

ACTIVITY INSTRUCTIONS

1. Opener: The teacher or another student plays a musical instrument of any type. Ask the students to describe what is happening (something is vibrating) and how that is harnessed into music .

2. Give background information on the terms longitudinal wave, wavelength, frequency, and speed of the wave using a Slinky ¤ or other method.

3. Demonstrate standing waves using a piece of thin rope. Anchor one end somewhere and either move the other end up and down or use a jigsaw to produce a wave. As it goes down the rope it is inverted when it hits the boundary, then it travels back to produce a pattern. One big hump is the fundamental frequency f, two humps is 2f, 3 humps is 3f and so on. The students should note that in order to increase the frequency you have to shake harder and the wavelength gets smaller.

4. Ask how this occurs if the anchored end is allowed to move? Loosely tie the rope to a pipe or place a washer at the pipe so that the same rope is now free to move when the wave gets there. Ask if there will still be a standing wave. Demonstrate that there is a standing wave, but the placement of the nodes (no movement) and the antinode (humps) is different from the tied rope. Emphasize that this is why closed pipes (tied end) and open pipes (loose end) are different lengths for the same sound.

5. If you re using a purchased set of wind chimes, begin the activity ideas found above (qualitative and/or quantitative). You won t be able to do anything with beats unless you destroy one of the pipes by altering it.

   If you are constructing your own wind chimes, begin the Construction Instructions. At the appropriate times in the process add the activity ideas found above.

   Complete the activity with your assessments. Display the student-made wind chimes where they will not be bothered, then have the students give them as gifts.

CONSTRUCTION AND SET-UP INSTRUCTIONS

1. Gather all materials. If constructing the chimes, you can decide if you want to pre-drill and pre-cut the pipes. (see Materials List)
2. Copper pipe with _ in. diameter was cut in these lengths: 15 & 15/16 inches, 15 inches, 13 & 5/8 inches, 12 & 7/8 inches, and 12 inches. Home Depot made the initial cuts when I purchased the pipe. A pipe cutter can be used (with practice) to fine tune the pipes.
3. Drill a hole straight through one end of each pipe. Use a _ inch drill bit and make the holes 3/8 inch from the end of the pipe. Observe safety rules!
4. This is for testing purposes only. If you re going straight into hanging the tubes as wind chimes, proceed to how to hang the final project (step 6). For testing cut off 2 meters of strong fishing line; I used 20 pound test. Double the line, thread both loose ends all the way through both holes and catch the end. Take the two loose ends back over and through the same holes again. Pull all to an equal length. There should be four strands of line from each hole; knot at the top.
5. Proceed with all your testing. I used a soft wood mallet for all the striking. Don t strike too hard or you ll dent the pipe.
6. **Finishing instructions**: I used scrap plywood, screw eyes, decorative chain, and more fishing line. The very top piece was a 5 inch diameter piece of 1/2 inch plywood; I used a circle because I had access to a band saw. The striker was a pentagon of 1/2 inch plywood with 1.5 inches on a side. The wind catcher was a rectangle of 1/2 inch plywood that was 3 x 1 x 0.5 inches. The last two were cut with a skill saw.

   Arrange a screw eye above where you ll hang each pipe. Make sure they ll hang straight down under the top piece to hit the striker but not each other. Put a screw eye in the center for the striker. Use decorative chain or fishing line to run down to the striker, and then the wind catcher. I put two screw eyes in the striker to keep it level. Make sure the wind catcher goes below your longest pipe.

To hang the pipes, use fishing line threaded through the pipes and the screw eye. Use a figure 8 knot, then adjust it so the pipe hangs where the striker will hit at the best spot. Below are my approximate distances from the top of the pipe to the spot for the striker:

Pipe Note	Length (inches)	Striker spot (from top, in.)
D	15 15/16	8
E	15	7 1/2
G	13 5/8	7 1/2
A	12 7/8	6 1/2
B	12	6 1/2

Add 3 medium screw eyes and rings with chains to the top. Add an S hook to the top, and you re done! The plywood can be painted or varnished if you prefer. The copper pipes can be cleaned with Brasso, or left to change naturally.

MATERIALS LIST

Material	**Cost per set**
_ in. diameter copper pipe, 70 inches	$8.00 per 120 inches
20 pound test fishing line	$3.00 per spool
1 box size 110 screw eye hooks (10)	$1.20 per 10
1 box size 112 screw eye hooks (10)	$1.20 per 10
1 S hook	$1.19 for 6
Scrap plywood, wood, or any material	none
4 key chain rings (from junk drawer!)	$1.00?
	TOTAL PER SET:
	LESS THAN $15
Pipe cutter (**one time purchase for class**)	$10.00
Oscilloscope and/or chromatic tuner ( )	$87.00/ $75
Wood handle for striking pipes	
Tools: screwdriver, pliers, saws if needed	
Calculator	

My results. **I had great difficulty with this because I started with poor information. There is not much on the Internet about _ inch copper pipe, although you ll find a lot on _ inch pipe. I finally just used my ear to find what was pleasing, then took off from there. I actually found several pipes that resonated nicely but were sharps or flats and did not use them in the final wind chimes. The best tool was the chromatic tuner; it told me what note I was approaching and if it was sharp or flat. I cut off small sections of the pipe with the pipe cutter, then sanded by hand or with a grinder to fine tune the pipes. The oscilloscope was a wonderful way to make all this quantitative. When I was finished with my project, I purchased a wind chime set from Orscheln ($35.00). The material is aluminum or steel, painted with enamel. Those pipes have very clear tones, and I was pleased to find that my hand-made ones sound just about as good. Surprisingly, I chose the same 5 notes for my set, although some are an octave higher or lower.**

My set		**Calculated frequency**	**Measured frequency**
E		647 Hz	34.4 Hz
B		255 Hz	1037 Hz
D		200 or 600 Hz	30 Hz
G		800 Hz	20 or 200 Hz
A		440 Hz	440 or 880 Hz

Most are multiples of the lowest f; open pipes have lots of things going on and I could hear multiple overtones.

QUESTIONS TO GUIDE STUDENTS THINKING

These can be used throughout the activity as needed:

Why do we hear a sound when I play the ____?
What are some things that make sounds?
Why does sound need air to get to our ear?
Why did scouts put their ear to the railroad track?
Can sound hurt us? Can it help us? Think of a time and then tell me .
Use the fact that our ear drum is flat to explain why sound waves are (longitudinal) (a series of flat pushes of energy).
Describe the difference in the sound of a clarinet and a tuba. Make your throat do the same kind of sounds.
Make your throat make a high note and a low note. What was the difference in how your throat felt?

Why does the sound stop if you re humming and you pinch your nose?
Are all wind chime pipes the same size?
Do different sets of wind chimes have the same sounds?
What if we made pipes of plastic, metal, paper, etc. Would they sound the same?
How can you tell someone specific is on the phone?
Why can t you get a pure tone with an arbitrary length?
Do you predict high notes to come from long or short pipes if you strike them? What if you blow across them? What is vibrating in each case and why are they different?
How is a standing wave produced if there is nothing for the wave to bounce off of? How do nodes and antinodes determine the frequency of the note we hear? How many of each occur in one wavelength two?
What would happen to a tuned set of wind chimes if they were taken into a very hot house? ..outside on a cold winter day? Why does temperature affect sound?

STUDENT PAGES FOLLOW THIS PAGE ..

The Physics of Wind Chimes Name __________________

Date _________ Block ____

Introduction:

Man discovered long ago that sounds can be produced from open tubes, probably in the form of plant stalks. In this activity you will investigate the relationship between music and the physics of sound waves. When considering pipes, the diameter, density of the material, thickness of the wall of the material, and length of the pipe all make a difference. We will assume that our pipes all have a _ inch diameter and are all made of the same thickness of copper.

Hypothesis: If the length of a pipe is increased, then the pitch of the musical note should ________________.

Materials:

- 1/2 inch diameter copper pipes of lengths: 15 & 15/16 in, 15 in, 13 & 5/8 in, 12 & 7/8 in, and 12 in.
  Each should have a hole drilled 3/8 inch from one end and all edges should be lightly sanded to prevent rough copper.
- 2 meters of fishing line per pipe
- a wood mallet
- an automatic tuner from the bandroom and an oscilloscope

- tuning forks
- calculator
- line of wire suspended across at least 1 meter (for hanging the pipes)
- supplies for finishing the wind chimes after testing: 3 pieces of wood, fishing line and/or decorative chain, 10 small and 3 medium screw eyes, one S hook, and 4 key chain rings or similar rings.
- pipe cutter, sand paper, screw driver to tighten the pipe cutter when needed, wire cutters if using decorative chain, pliers to open chain ends
- patience and persistence when listening to tones

Procedure:

1. Decide among your group how you want the hypothesis to be worded.
2. Construct your wind chimes and hang by doubling the fishing line and threading it through the holes **twice**. There will be 4 strands coming out of each hole, then make a knot at the top.
3. Hang each pipe with some distance between them. Go in order of size from shortest to longest pipe.
4. Strike each pipe near the middle with the wooden mallet. Check the results of the musical note on the tuner from the bandroom. Make a data table to record the results of each pipe and the musical note. Repeat several times, striking the pipe in the SAME spot.
5. Repeat the test in step 4, but strike the pipe in a spot each time that is NOT where you hit it on step 4. Repeat several times, record.
6. Take time in your data section to record some observations from the data between those last two tests.
7. Turn on the oscilloscope and set it to AUTO so it will show the sine wave of the sound. Striking the pipe in the middle, push the Hold button when you see a clear sine wave. Record this information in a table for each pipe: T2 and T1 from the horizontal axis, the number of complete waves, and the ms/division setting from the top, right screen. T2 and T1 should be places where the first and the last identical wave cross the x-axis. Repeat at least 5 times for each pipe.
8. Change the format of the oscilloscope and measure the frequency directly. Record your results in a table.
9. Find two pipes that you think have an unpleasant sound when struck at the same time. Note those in your data section. Find three more unpleasant combinations.
10. Find two pipes that you think have a pleasant sound when struck together. Note those in your data section. Find a third pipe you can add, or find a different combination of three pipes that are pleasant. Note those.
11. Finish your wind chime set as directed.

Analysis:

a. Data

(*Students insert data here and on their own paper*)

B. Calculations and Graphs

1. Calculate all the frequencies from the data in procedure step 7. Find an average for each pipe. Show one calculation and the average here for each pipe.

2. Look at the data for step 9. Look up the frequencies on the Just scale for the combinations. Write them as ratios in the simplest form.

3. Look at the data for step 10. Look up the frequencies for these combinations and write them as ratios in the simplest forms.

4. Plot a graph of length of the tube on the x-axis and the average frequency from step 7 on the y-axis. (Attach graph paper). Make conclusions here:

C. Questions

1. Compare your results from steps 4 and 5. Make conclusions here:

2. Compare your results from steps 7 and 8. Make conclusions here:

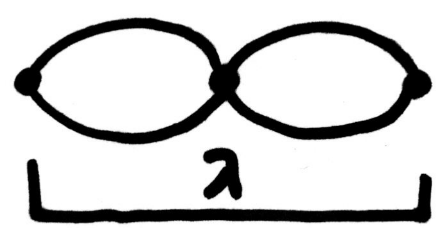
3. Look at your results from Calculation 3 above. You should have whole number ratios. Explain ..

Conclusion:

(Write one! Did your data support your hypothesis? Give some conclusions. State at least two possible errors. Give two future research ideas. Use complete sentences!)

PRACTICE PROBLEMS: Standing Waves **Name**_____________
Date ________ Block ___

I. Recall that two antinodes and three nodes made up one complete wavelength:



Calculate the distance for ONE wavelength, then use v = fΛ to solve these:

1. A standing wave in a flagpole line has 3 nodes and 2 antinodes. The line is 45.0 meters long. The velocity of the wave is 3.5 m/s. What is the frequency and period of the wave? SKETCH THIS FIRST.

2. A standing wave in a rope has 5 nodes and 4 antinodes. The rope is 24.0 meters long and is vibrating at 2.0 cycles per second. What is the speed of the wave? SKETCH THIS FIRST.

3. A standing wave has 2 nodes and 1 loop in a jump rope that is 8.5 meters long. It is vibrating at 1.5 cycles per second. What is the velocity of the wave?

II. For <u>OPEN</u> pipes such as wind chimes, the frequency is equal to the n number of the harmonic frequency times the quantity of the speed of the wave divided by two times the length of the pipe.

$$f = n\,(v/2L)$$

n = 1 for the fundamental, n=2 for the first harmonic or 2f, n = 3 for the second harmonic or 3f, etc . The speed of sound is 330 m/s unless noted. Length is in meters and f is in hertz. We will ignore pipe thickness, diameter and material for these calculations, although they make a huge difference.

1. If the length of a pipe is 0.45 meters and you hear the fundamental note, what frequency is produced?

2. If the length of the same pipe in #1 is placed in a different room, the speed of sound is 350 m/s. What frequency is produced?

3. If the length of pipe in #1 is taken back to a room where sound travels at 330 m/s, but forced to produce the first harmonic of the note (2f), what pitch SHOULD be heard? _____________ Prove it:

4. If an open pipe produces a frequency of 256 Hz when 1.29 m long, which harmonic is being produced in the pipe? Assume v = 330 m/s.

KEY TO PRACTICE PROBLEMS

I.

1. A sketch should show 3 nodes and 2 loops. The total distance for this sketch is 45.0 m, so ONE WAVELENGTH is 45.0 m. Remember, one wavelength is two humps . Then you know that Λ = 45.0 m.

f = v/Λ or 3.5m/s / 45.0 m. The frequency is 0.078 Hz.

T (the period or time for one wave) is T = 1/f. 1/0.078 Hz = 12.8 seconds.

2. The sketch shows 5 dots and 4 loops for a length of 24.0 m. This sketch shows 2 COMPLETE wavelengths, so Λ is 12.0 m. The f is 2.0 Hz, and v = fΛ. The final answer is 24.0 m/s.

3. The sketch shows 2 dots and 1 loop. This takes 8.5 meters, but is only ONE-HALF WAVELENGTH. It must be doubled to get 17.0 m for Λ. If f = 1.5 Hz, multiply f x Λ to get 25.5 m/s.

II.

1. L = 0.45 m, n = 1, v = 330 m/s, and f = x. f = 366.7 Hz

2. same as #1, but v = 350 m/s . f = 388.9 Hz

3. same as #1, but n = 2 . f = 733.3 Hz

4. f = 256 Hz, L = 1.29 m, v = 330 m/s, n = x. n = 2f or the first harmonic.

For questions contact Kim Brown at kime_100@hotmail.com