Lab 1: Introduction to Waves and Sound

OBJECTIVES

- To understand how a gaseous system may be characterized by temperature, pressure, and volume.
- To measure the speed of sound waves in air.
- To acquire an operational definition of wavelength and frequency.
- To introduce standing waves.
- To see the standing wave patterns for different situations that lead to resonances similar to those in various musical instruments.

Figure 1 A wave from throwing a pebble in a pond Notice the wavelength between ripples after you leave the center. (source: www.avoxtar.com/images/avoxtar_pebble.jpg

OVERVIEW

In the last lab activity you investigated how adding or removing heat energy to objects either changed the temperature of the object in question or changed its phase (melting or boiling for example). In this lab activity we will begin by looking at the relationship between pressure, volume, and temperature of a confined sample of gas.

Next, we will move to waves. Our emphasis will be sound waves, which are simply pressure variations that travel through the air. Many of the things we experience every day are waves: not just water waves on a pond (see figure 1) or ocean, but sound and light itself. A wave carries energy and momentum from one place to another. In a water or sound wave, this energy is in the movement of individual water or other molecules. However, these molecules may stay almost in place (moving up and down or backwards and forwards), while the wave itself moves forward. A simple wave has a characteristic repetition length, the "wavelength" λ, (the distance between high points or low points, for example; see Figure 2), and a characteristic frequency of oscillation f (cycles per second.) For anything traveling, we can relate f and λ to its speed v by $v = f\lambda$. You can see this by imagining a wave with wavelength λ moving past you at speed v. How many times per second does a wave crest pass you? This is the "frequency" of the wave. The speed is a characteristic of the material. Sound in air at room temperature and pressure has a speed of about 340 m/s.

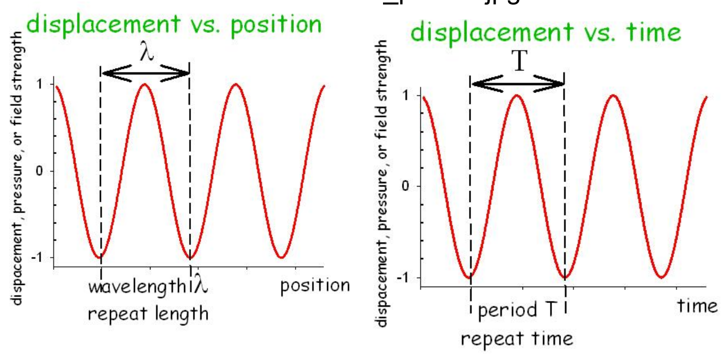


Figure 2. You can take a snapshot of a wave in time (at left), to focus on the characteristic wavelength λ, or you can measure something in time, at a fixed point (at right), to see the characteristic repeat time or "period" T. The frequency f is defined by $f \equiv 1/T$.

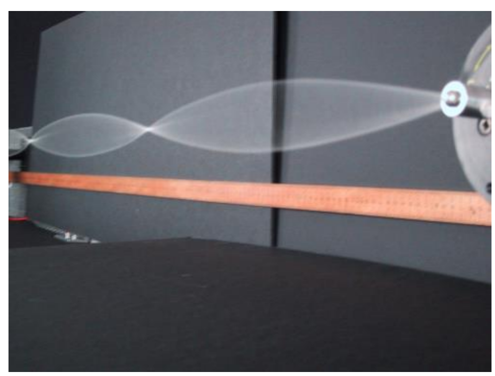


Figure 3 A standing wave on a string (from http://www1.union.edu/newmanj/lasers/Light%20as%20a%20Wave/light_as_a_wave.htm). Note that the points that pass through "0" on the left of Figure2 are stationary, and that any snapshots would see a wave like in that figure, but with different sizes (Note that at a moment when the string on one side of a noted is "up, that on the other side is "down".)

If you place a wave within boundaries (say, fixing the ends of a string), the wave bounces back and forth between the ends. This sets up a resonance, where the wave oscillates much more strongly with particular wavelengths (and thus frequencies.) This kind of wave is called a "standing wave" (See figure 3.)

INVESTIGATION 1: WORK DONE BY A GAS: HEAT ENERGY TRANSFER, INTERNAL ENERGY, AND THE FIRST LAW OF THERMODYNAMICS

One system we will meet often in our study of thermodynamics is a mass of gas confined in a cylinder with a movable piston. The use of such a gas-filled cylinder is not surprising since the development of thermodynamics in the eighteenth and nineteenth centuries was closely tied to the development of the steam engine, which employed hot steam confined in just such a cylinder.

In thermodynamics we are interested not only in heat energy and work, but in how the two interact. For example, if we transfer heat energy to a gas, can we get it to do work? In this investigation, you will begin with some qualitative observations to examine the concept of work done by the gas in a cylinder.

At your lab station you will find a number of syringes that are basically cylinders with movable pistons. By making some simple observations with these syringes, you can begin to appreciate how an expanding gas can do work.

You will need

- 10-mL plastic syringe with the end sealed
- Mouse pad

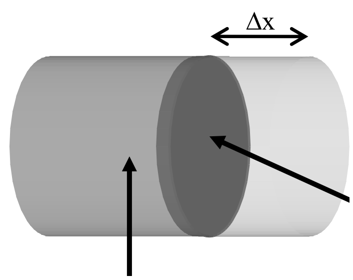
Activity 1-1: Work Done by a Gas in a Cylinder

Try compressing the air in the syringe with the **end sealed** by pushing the piston (the moveable part that you usually press on with your thumb) down against the mouse pad on the table. Then let it go, and see what happens.

Question 1-1: Does it take effort to compress the gas? Do you have to do work on the gas to compress it? (Did you apply a force over a distance?) What happens when you let go—Does the gas spring back?

In thermodynamics, pressure (defined as the component of force that is perpendicular to a given surface for a unit area of that surface) is often a more useful quantity than force alone, since it is independent of the cross-sectional area of the cylinder. It can be represented by the equation

$$P = \frac{F_\perp}{A}$$



In the next activity you will explore why pressure is more useful than force in describing the behavior of gases. You will also extend the definition of work developed earlier in the course and combine it with this definition of pressure to calculate the work done by a gas on its surroundings as it expands out against the piston with a (possibly changing) pressure P.

From your experience with the syringe, do you expect an expanding gas inside a cylinder to do work? You have probably heard the definition of work in a lecture or seen it in your text. If a force F acts on an object and the object moves a distance Δx, the work is $W = F\,\Delta x$. Using this definition of work and the definition of pressure, you can show that the work done by a gas on its surroundings as it expands out against the piston with a (possibly changing) pressure P can be calculated from

$$\Delta W = P\,\Delta V$$

Question 1-2: Show that the above expression for ΔW follows from $\Delta W = F\,\Delta x$. (Hint: See the preceding diagram.)

Suppose you lift a ball of mass m up from the floor through a distance y. The change in the ball's potential energy is $\Delta U^{grav} = mgy$. The work done by you against the force of gravity is related to the change in the ball's potential energy so that $\Delta U^{grav} = = - W^{grav}$. (Keep in mind that the force of gravity on the ball and the displacement y are vectors.) This relationship is true for any system where mechanical energy is conserved. By doing work against gravity, you are storing energy in the form of potential energy. But what about systems where mechanical energy is apparently not conserved?

Is it possible to generalize this relationship for some of these systems? The answer is yes, but we have to give a new meaning to our potential energy. In thermodynamics, U is called the internal energy, and represents any way of storing energy inside a system. The internal energy of a system is the sum of all sorts of energies, including the helter-skelter translational kinetic energies of molecules in a gas, the vibrational energies of gas molecules or atoms in a crystal, and the rotational energies of spinning gas molecules. One way to increase the internal energy of a system is to transfer heat energy to it as you did when you melted ice or produced steam.

For many materials, the pressure P, volume V, and Temperature T are related to each other through what is called an "equation of state." In the next activity, we will exam the relationship between pressure P and volume V at approximately constant temperature T. First make a prediction.

Prediction 1-1: As you compress the air in a syringe by pushing the piston in slowly, what will happen to the pressure? What do you think will be the mathematical relationship between pressure P and volume V?

To test your prediction you will need

- 20-mL plastic syringe (with the needle removed)
- computer-based laboratory system
- pressure sensor
- **RealTime Physics Heat and Sound** experiment configuration files

Activity 1-2: Isothermal Volume Change for a Gas.

The approach to obtaining measurements is to trap a volume of air in the syringe and then compress the air slowly to both smaller and larger volumes by pushing or pulling the piston. The gas should be compressed slowly so it will always have time to come to equilibrium with the room (and thus be at room temperature) You should take pressure data for about 5 different volumes.

1. Position the piston of the 20-mL syringe at the 10-mL line while the syringe is open to the air, after positioning the piston connect the end of the syringe to the pressure sensor.
2. Open the experiment file called *Pressure vs. Volume* (Sound 2A1-2) to display the axes that follow. This will also set up the software in **event mode** so that you can continuously measure pressure and decide when you want to keep a value. Then you can enter the measured volume.
3. Enter the volume of the Pressure sensor, 0.1 cm^3, in the second column of Table 1-1.
4. As you pull or squeeze down on the piston slowly, the computer will display the pressure. When the pressure reading is stable, you can keep that value and then enter the total volume of air from Table 1-1.
5. Repeat this for at least five different volumes of the syringe between 4 and 20 mL.
6. Use the fit routine to find a relationship between P and V.

Table 1-1

Volume of air in syringe (cm^3)	Volume of sensor (cm^3)	Total volume of air in the system (cm^3)	Pressure

7. Print the graph and attach it.

Question 1-4: What is the relationship between P and V? Is it proportional linear, inversely proportional, or something else? Did this agree with your prediction?

Question 1-5: Write down the relationship between the initial pressure and volume (P_i,V_i) and the final pressure and volume (P_f,V_f) for an isothermal (constant-temperature) process.

The relationship that you have been examining between P and V for a gas with the temperature and amount of gas held constant is known as Boyle's law. If we additionally find the relationship between the Pressure and Temperature with the volume of the gas held constant and the relationship between the volume and temperature with the pressure held constant, we can deduce the ideal gas law.

Question 1-6: Is the relationships you found in the this activity consistent with the ideal gas law PV=constant $\cdot$ T? Explain.

Note that changing the temperature also affects the gas. We don't have time to explore this quantitatively now, but you can still feel it happen:

Activity 1-3: The Heated Syringe

You should have concluded from the last activity that the transfer of heat energy to a system can either cause it to do work on its surroundings or increase its internal energy. What is the relationship between heat energy transfer, changes in a system's internal energy, and the work done by the system? We picture U as the "true" energy of the system. In the theory of thermodynamics, U is called a "state" variable, a quantity that tells us some things we need to know to calculate useful things about a system, such as its temperature

Suppose that the piston of the syringe is clamped in place while the syringe is immersed in hot water. The piston can't move, so no work can be done. However, since the water is initially at a higher temperature than the gas in the syringe, we expect that heat energy is transferred from the water to the gas. This causes the temperature of the gas to increase and the temperature of the water to decrease. The heat energy transfer can be calculated using the equation $Q= cm \Delta T$, where c is the specific heat and ΔT is the temperature change of the water.

Assuming that the system is insulated so that no heat energy can be transferred to the surroundings, the transferred heat energy Q must equal the increase in internal energy of the gas. This is based on a belief that energy is conserved in the interaction between the hot water and the gas.

Suppose instead that we release the piston and allow the gas to do work as it expands against the piston. We could calculate the amount of work W the expanding gas did by evaluating $\Delta W = P \Delta V$ for the whole process. Where did the energy to do this work come from? The only possible source is the internal energy of the gas, which must have decreased by an amount W. The total change in the internal energy of the air trapped in the syringe must be given by

$$\Delta U = Q - W$$

This relationship between transferred heat energy, work done on the surroundings, and the change in internal energy is believed to hold for any system not just a syringe filled with gas. It is known as the first law of thermodynamics.

The first law of thermodynamics has been developed by physicists based on a set of very powerful inferences about forms of energy and their transformations. We ask you to try to accept it on faith. The concepts of work, heat energy transfer, and internal energy are subtle and complex. For example, work is not simply the motion of the center of mass of a rigid object or the movement of a person in the context of the first law. Instead, we have to learn to draw system boundaries and total the mechanical work done by the system inside a boundary on its surroundings outside the boundary.

The first law of thermodynamics is a very general statement of conservation of energy for thermal systems. It is not easy to verify in an introductory physics laboratory, and it is not derivable from Newton's laws. Instead, it is an independent assertion about the nature of the physical world.

There are many ways to achieve the same internal energy change ΔU. To achieve a small change in the internal energy of gas in a syringe, you could transfer a large amount of heat energy to it and then allow the gas to do work on its surroundings. Alternatively, you could transfer a small amount of heat energy to the gas and not let it do any work at all. The change in internal energy, ΔU could be the same in both processes. ΔU depends only on Q - W and not on Q or W alone.

Question 1-9: Can you think of any situations where W is negligible and $\Delta U = Q$? (Hint: Is it necessary to do work on a cup of hot coffee to cool it? Can you think of similar situations?)

Question 1-10: How could you arrange a situation where Q is negligible and in which $\Delta U = -W$? Such situations have a special name in thermodynamics. They are called adiabatic processes. (Adiabatic means with no heat energy transferred into or out of the system.)

Investigation 2: Speed of Sound in the Air

1. You recall that we can also measure the speed of a wave – or anything else moving uniformly – by:

$$d = v\ t$$

where **d** is the distance traveled in a time **t**. Sound travels quickly, but with a good computer program, we can measure the small time required for sound to move a significant distance.

With care (you remember The Three Stooges trying to carry long boards? Let's not look like that here!) place a 3.0 m long piece of sewer pipe across your lab table and your neighbor's. (Lab groups at stations 5 and 6, place yours across the room on a couple of chairs.)

Slip a plastic pipe cap over the end away from you to reflect sound waves back.

2. Open the file called "Speed of Sound.aup" from the "Sound Lab" folder on your computer desktop. Choose Record Sound.
Hold the microphone from your computer at the very edge of the pipe and facing into it. Hold your hand, ready to snap your fingers, just behind the microphone. Or, hold a small hardback book in that position, ready to smack it closed.
The microphone will receive the sound pulse directly from your finger-snap or book-slam, and an instant later it will receive the fainter echo of that sound from the far end of the tube. Since we are making all time measurements relative to the microphone, we don't need to know the distance to your hand or book.

3. Be ready to click the round Record button, have your lab partner make the snap, then click the square Stop button. You have now grabbed the entire event, and much more.

Then click View and Fit Vertically to adjust the amplitude to fit. Click and drag from just to the left of the big peak (which includes the snap and the echo) all the way off to the left. Then press the Delete key to zap out that unwanted section. Click View and Zoom In (or click the magnifying glass) to look more and more closely at that very beginning. Again, click and drag from the very peak of the snap to the left and press Delete. Repeat until you feel comfortable that the peak is at time zero.

Zoom Out a bit to locate the next bunch of vertical peaks, which is the echo we are looking for. Click the cursor on that second bunch and Zoom back In until you can confidently estimate the time, off the scale above the wave, at which that wave arrived. (It should be around 0.016 to 0.018 sec.) That's the time for the sound wave to travel down the tube and back!

4. Now that you have that time, divide it into the distance the sound traveled. (Remember, the distance the sound traveled is not the length of the pipe!)

5. Repeat the measurement twice more, record the values in the table below, find the average speed, and **round it to the nearest whole number.**

Table 2-1.

Distance sound traveled, d (m)	Time for sound to travel, t (s)	Speed of sound, v (m/s)
	Average	

Question 2-1. Check with your lab instructor to find the temperature in the room, T, in degrees Celsius. Recalling that the speed of sound in air is given by

$$v = 331 \text{ m/s} + (0.6 \text{ m/s}^{o}\text{C})T$$

What is the expected value of the speed of sound?

Investigation 3: Waves on a string

In this investigation, you will try to oscillate the string at different frequencies. You will find that only a few frequencies lead to waves that are large enough so that you see the wave clearly. You will see parts of the string are nearly stationary ("nodes": see figure 3) while other parts move strongly around equilibrium (the biggest motion is at the "anti-nodes.")

For a string, the velocity of the wave depends almost entirely on properties of the string (material and tension), not on the frequency. This means that every frequency corresponds to a particular wavelength. Only some wavelengths can fit "properly" on a string. You will find that the "proper" wavelengths depend only on how you hold the string. The corresponding frequency is called a "resonance" frequency, because energy can build up at these frequencies until there is enough motion for you to see.

Question 3-1: Draw a still image of a wave below, marking the wavelength. Also mark possible nodes (where the wave doesn't move).

Question 3-2: How is the distance between nodes related to the wavelength?

Prediction 3-1: If you fix a string on two sides, draw what the longest "standing wave" could look like. What is the wavelength for this wave, compared to the length of the string?

Equipment:

- Elastic String
- Oscillator / Mechanical Vibrator
- Vertical stand with horizontal posts
- Meter stick

Activity 3-1: Both ends fixed

Figure 4. General layout of equipment for vibrating string.

1. The oscillator has rubber feet on its bottom and also on one side. Lay the oscillator on its side, on the rubber feet and align it so that the small plastic fork holds the string but does not displace it. A slight forward displacement will help keep the string in the fork when oscillating.
2. Check that the elastic string is attached to the posts on the vertical stand by the loops that are tied on each end. The posts should be 1 meter apart, if not adjust the clamps so they are, the lower post should be between the table and the string vibrator, as figure 4.
3. Measure the length of the string between the two attach-points.
   L=____________
4. Turn the oscillator on and set it to the lowers frequency setting. The amplitude knob should only be set a quarter turn or so from the lowest setting, it doesn't take much movement. Slowly sweep frequency of oscillator. You will find that only a few frequencies have a large enough amplitude that you see the wave clearly. Measure the distance between nodes (points that don't move) for the largest wavelength you can find, and write down this distance and the frequency in the table below, as well as in the experimental file. Find at least 3 other frequencies with large amplitude waves, and fill out Table 3-1.

Table 3.1 Two fixed ends.

	Longest wavelength	2	3	4
Frequency				
Distance between nodes				
Wavelength				

Question 3-3: Did your longest wave fit your prediction 3-1?

Question 3-4: Can you find a relation between this "resonant" wavelength and the other ones that you found? What about the frequencies?

5. Now take a wave with at least 2 nodes, and lightly pinch the string, first at a node and then at an antinode.

Question 3-5? What difference did you see? Did pinching the string at the node stop the wave? At the antinode?

Prediction 3-2. Now consider a string with one free end. A free end is always at a peak or valley, since that is the only way forces can balance at the end of the string without something holding the other side. Draw the longest resonant wavelength that will fit properly on this string.

> **Comment:** The velocity on the string depends on the tension in the string. To keep an end of the string free to move while keeping the string under tension requires that the "free end" slide on a post holding it in tension, but without any tension. Note that if there is any friction between the post and the string, the string isn't "free. It's not easy to keep the friction low enough with simple equipment, but it is very easy using the computer to simulate the action. In the next activity we are going to use such a simulation.

Activity 3-2: Compare: both ends fixed and one free end using computer simulation.
One Free end.

6. Open the simulation by opening the stlwaves.htm file in the Sound Lab folder on the desktop. This simulation is also available on the internet at http://www.walter-fendt.de/ph14e/stlwaves.htm
7. Choose the length of the string (1 m). Notice that the author of this simulation chose the wave speed of 343.5 m/s.
8. Choose "both sides closed".
9. For now, focus your attention on the first graph (the middle picture.) Find the lowest wavelength. Write down the distance between nodes, the wavelength, and the frequency in Table 3-2.
10. Now choose "one side open". Write down the distance between nodes, the wavelength, and the frequency in Table 3-2, including the longest wavelength one (called the "fundamental" for a sound wave in music.) You can find those with shorter wavelengths (higher frequency) by pressing "higher."

Table 3-2. Compare: One free end and both ends fixed

		Longest wavelength	2	3	4
2 ends fixed	Frequency				
	Distance between nodes				

	Wavelength				
1 end fixed, one end free	Frequency				
	Distance between nodes				
	Wavelength				

Question 3-6. Did your longest wave with one free end and one fixed end fit your prediction 3-2?

Question 3-7. Can you find a relation between this "resonant" wavelength and the other ones that you found? What about the frequencies?

Comment: The resonance wavelengths for any wave depends only on the conditions at the ends of the waves (boundary conditions: here, one or two fixed ends.) We can find these by just drawing the waves, fitting them in the space, and realizing that any fixed end has to be a node, while a totally free end has to be an anti-node.

Once we figure out the resonance wavelengths, we can figure out the resonance frequencies, as long as we know the relation between wavelength and frequency (by knowing the speed of the wave, for example.)

These ideas hold true not just for waves on a string, where we can visualize the string moving up and down, but also for sound and light waves, where it is harder to visualize what is moving. We'll see how they work for sound in Investigation 4.

INVESTIGATION 4: Sound waves in a tube

The computer simulation you just explored was in fact for sound in a tube. The wave speed was taken to be the speed of sound at 20°C. The graph you were looking at was for the motion of particles within that tube: this motion is back and forth along the tube (the direction of the wave), instead of up and down (perpendicular to the wave direction) as on a string. These two types of waves are called "longitudinal" and "transverse" respectively. You can get an idea of the "longitudinal" motion of sound from the picture above the graphs. Note that the picture is very schematic, and doesn't show what happens to air that was originally outside the tube.

Note that at an open end, the air is free to move back and forth as it will (but with the same pressure as the outside air), but at a closed end, the air must be stationary.

Prediction 4-1: What standing wave pattern (displacement of the air) do you expect for the various situations for each of the tubes in each of the configurations given in Table 4-1 (sketch them in the spaces provided in the table)?

Prediction 4-2: You haven't measured the lengths of the tubes use in this activity yet, so use the letter L to represent each particular length. What do you expect the wavelength to be for the various resonant patterns you sketched (right this next to λ= under each sketch in Table 4-1)?

Prediction 4-3: Consider the short tube, lowest frequency, both one end open and two ends closed. Use your predicted wavelengths for those situations from Prediction 4-2 and the speed of sound as being 343m/s (approximation) to calculate the frequency you would expect for each (you will still have L in these expressions, but later you'll actually measure it and have a number to put in…).

Equipment:

- Computer
- Acoustic Driver Head
- Plastic tubes, two lengths
- Plastic End Cap
- Meter stick

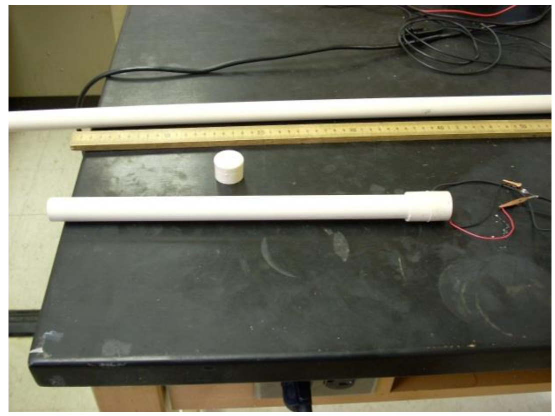


Figure 5. Short tube in acoustic driver head.

Activity 4-1

5. The acoustic driver head contains a microphone and a piezoelectric disk that acts as a speaker. The microphone plug should be plugged into the microphone jack of the computer sound card. This cord has a plastic box that contains the battery that powers the microphone. Turn this switch on. Please turn it off again when you are finished. You should find a cable with two alligator clips that is connected to the line out jack of the sound card. The alligator clips on this wire should be attached to the wires of the piezoelectric disk so that red is connected to red and black is connected to black.

6. Open the file named "Tube Resonance.aup" from the "Sound Lab" folder on the desktop. This file contains an audio track that is 5 seconds of white noise. Click the play button (the one with the triangle, to listen to it.

7. Click and drag to highlight the noise waveform. From the "Analyze" menu choose the Plot Spectrum option. This shows a representation of which frequencies are present in the sound you heard. Select the following options in the Frequency Analysis window:

Algorithm:	Spectrum
Function:	Rectangular Window
Size:	1024
Axis:	Linear Frequency

8. Close the Frequency Analysis window. Connect the driver head to the longer plastic tube; just push the tube into the collar of the driver. Be sure that the other end of the tube is open. Lay the assembly so that the open end of the tube extends slightly over the edge of the table so nothing causes interference with the movement of the air column.

9. Use the meter stick to measure the length of the tube from the opening to the piezoelectric disk on the end of the driver head. Record this length in Table 4-1.

10. Use the measured lengths and your Predictions 4-1 through 4-3 above tofill in the predicted wavelengths and frequencies for the various situations in Table 4-1.

11. Click the record button, the one with the circle, and the noise track will play. As this happens a new audio track containing the response of the tube will be produced. When the sound is recorded click and drag to highlight only the part of the audio track with the tube's response and avoid any pauses at the beginning or end of the track.
12. Plot the frequency spectrum as you did with the noise track. You can use the mouse to make the frequency measurements you need by moving the mouse pointer inside the Frequency Analysis window. A vertical line follows the mouse pointer. This line snaps to the peak that is nearest to the mouse pointer. When you have the line on the peak you are interested in, there is a display toward the bottom of the Frequency Analysis window that shows frequency that the mouse is pointing to and also the peak frequency that the vertical line is indicating. Record the frequencies of the first three peaks in Table 4-1.

Table 4-1

		Long Tube	**Short Tube**	**Short Tube**
		One end closed, one open	**One end closed, one end open**	**Both ends closed**
Measured Length				
f_0 (lowest frequency)	Predicted Standing Wave Pattern	λ=	λ=	λ=
	Predicted Wavelength			
	Predicted Frequency			
	Measured Frequency			
f_1 (next frequency)	Predicted Standing Wave Pattern	λ=	λ=	λ=
	Predicted Wavelength			
	Predicted Frequency			
	Measured Frequency			
f_2 (next frequency)	Predicted Standing Wave Pattern	λ=	λ=	λ=
	Predicted Wavelength			
	Predicted Frequency			
	Measured Frequency			

13. Remove the longer tube and connect the shorter tube. If the end cap is covering one end of the short tube you need to remove it for this step.
14. Repeat the measurements above for this tube and record your data in Table 4-1.
15. Close the end of the short tube with the end cap and produce a frequency spectrum for this situation in order to complete Table 4-1.

Question 4-1: Did your measured frequencies agree with the lowest frequencies (f_0) you predicted in Table 4-1? If not, what is different? Do you need to reconsider the form of your largest wavelength?

Question 4-2: Did the other measured frequencies agree with your predictions? If not, what is different?