

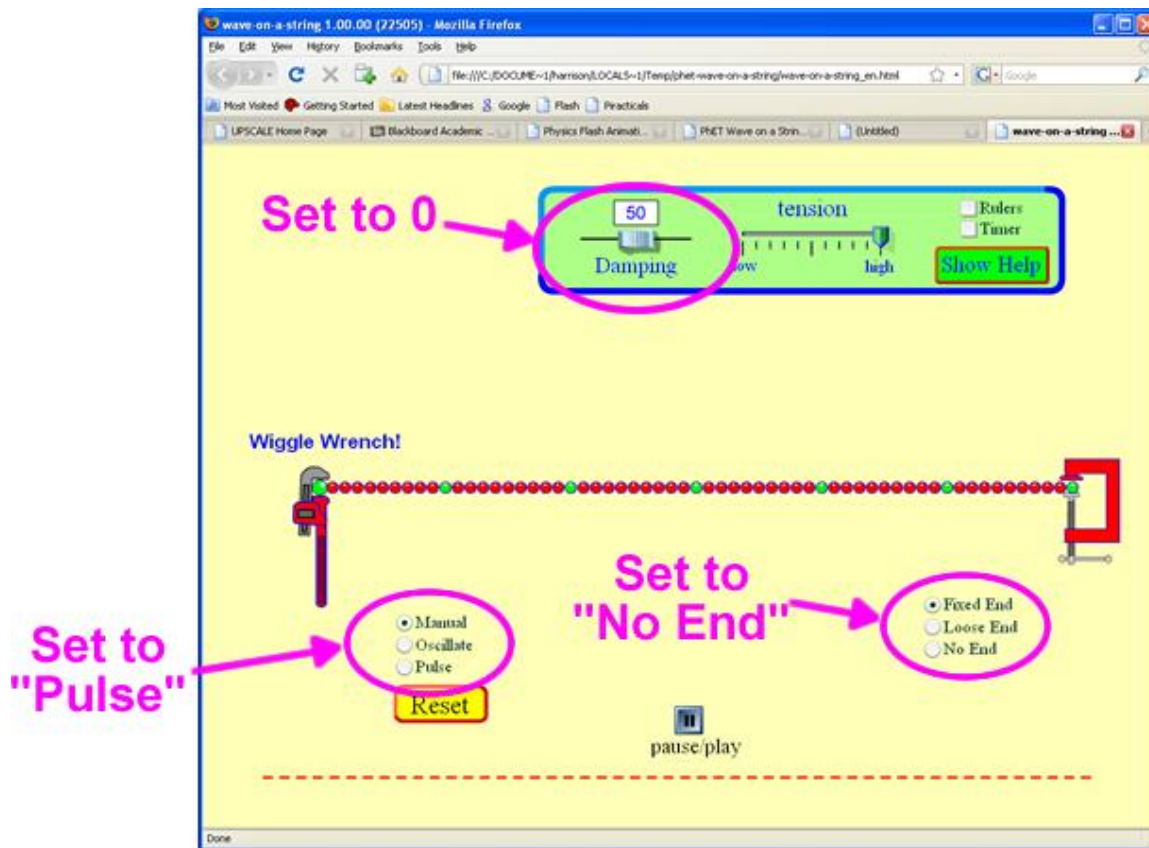
Concepts of this Module

- Traveling waves
- Intensity
- Reflection
- Superposition
- Beats
- Standing Waves



Course Concepts Activity 1

A. Open the Java applet `wave-on-a-string.jar` which is at: `Feynman:Public/Modules/Waves`.



The screenshot shows the 'wave-on-a-string' Java applet interface. Key features and annotations include:

- Control Panel:** A 'Damping' slider is set to 50. A 'tension' slider is also present. Checkboxes for 'Rulers' and 'Tuner' are visible. A 'Show Help' button is located to the right.
- Wiggle Wrench!:** A section with three radio buttons: 'Manual' (selected), 'Oscillate', and 'Pulse'. A 'Reset' button is below them.
- End Conditions:** Three radio buttons: 'Fixed End', 'Loose End', and 'No End' (selected).
- Other Elements:** A 'pause/play' button at the bottom center, a red dashed line at the bottom, and a 'Done' status indicator.
- Annotations:** Pink text with arrows points to the 'Damping' slider (labeled 'Set to 0'), the 'Pulse' radio button (labeled 'Set to "Pulse"'), and the 'No End' radio button (labeled 'Set to "No End"'). The 'Manual' radio button is also circled in pink.

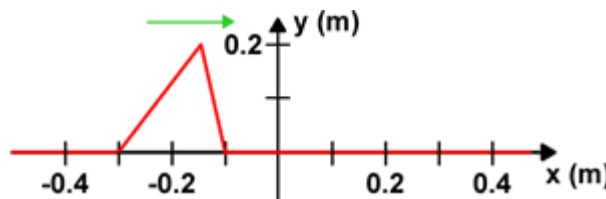
- Set the Damping to 0
- Set the wave type to “Pulse”
- Set the end to “No End” which will replace the vise on the right side with an open window for the waves to go through.

Click on the *Pulse* button that will appear. Imagine you are standing right beside the window as the pulse goes out of it, measuring the displacement as a function of time as it goes by you. Sketch the displacement as a function of time.

- B. Click on the *Rulers* control in the upper-right corner of the simulation. The rulers that appear can be moved with the mouse. Estimate the speed, width and amplitude of the wave pulse. Add labeled tick marks on the axes of the sketch of Part A.

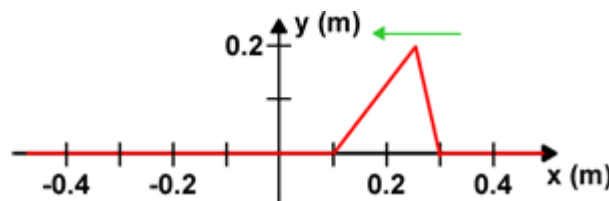
This is a good time to experiment with different values of the Damping and tension. What happens as the Damping is increased? What happens as the tension in the string is decreased? You may wish to explore some of the other settings of the simulation too.

- C. The triangular pulse of Parts A symmetric. Here is a plot of an triangular pulse traveling from moment shown the time $t = 0$. traveling with a speed of 0.5 displacement of the pulse at $x = 0$ time t as the pulse goes by. Include labeled tick marks on both the y and t axes.



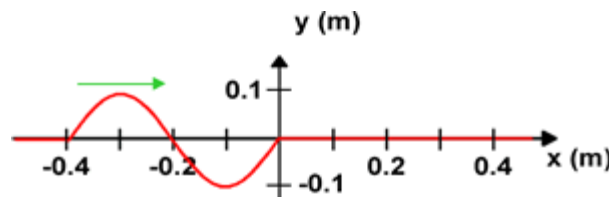
and B was asymmetric left to right. At the moment shown $t = 0$ as a function of

- D. Here is the same triangular pulse it is traveling from right to the moment shown the time t displacement of the pulse at $x = 0$ time t as the pulse goes by. Include labeled tick marks on both the y and t axes. Compare to the sketch from Part C.



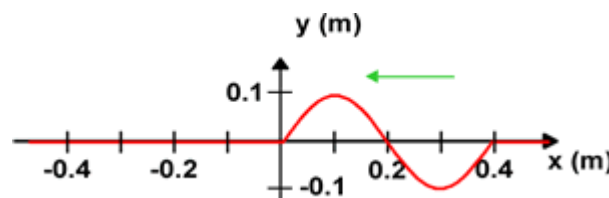
pulse as Part B, but left at 0.5 m/s. At the moment shown $t = 0$ as a function of time t as the pulse goes by. Include labeled tick marks on both the y and t axes. Compare to

- E. Here is a sinusoidal wave pulse traveling from left to right at $v = 0.5$ m/s. At the moment shown $t = 0$. Sketch the displacement of the pulse at $x = 0$ as a function of time t as the pulse goes by. Include labeled tick marks on both the y and t axes. What is the wavelength λ of the pulse? From your sketch what is the period T , frequency f , and angular frequency ω of the sinusoidal pulse? What is the relation between



the pulse at $x = 0$ as a function of time t as the pulse goes by. Include labeled tick marks on both the y and t axes. What is the wavelength λ of the pulse? From your sketch what is the period T , frequency f , and angular frequency ω of the sinusoidal pulse? What is the relation between

- F. Here is a sinusoidal wave pulse traveling right to left at $v = 0.5$ m/s. At the moment shown $t = 0$. Sketch the displacement of the pulse at $x = 0$ as a function of time t as the pulse goes by. Include labeled tick marks on both the y and t axes. What is the wavelength λ of the pulse?



pulse traveling from the moment shown $t = 0$ as a function of time t as the pulse goes by. Include labeled tick marks on both the y and t axes. What is the wavelength λ of the pulse?

From your sketch what is the period T , frequency f , and angular frequency ω of the sinusoidal pulse? What

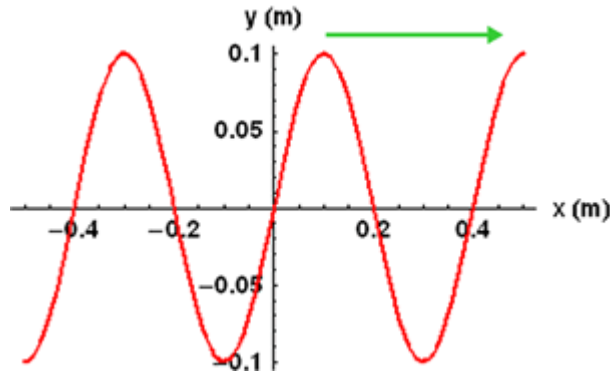
is the relation between λ , f and v ?

- G. Here is a sine wave traveling with $v = 0.5$ m/s. The wave extends to infinity in both directions along the x axis. At the moment shown the time $t = 0$. At the moment shown the displacement as a function of position is:

$$\Psi(x, t = 0) = 0.1 \sin\left(2\pi \frac{x}{\lambda}\right)$$

In your own words, explain the above equation. We can describe

as the wave passes $x = 0$ either as $\Psi(x = 0, t) = 0.1 \sin\left(2\pi \frac{t}{T}\right)$ or as $\Psi(x = 0, t) = 0.1 \sin\left(-2\pi \frac{t}{T}\right)$. Which form is correct? Explain your own words. Write down a form of $\Psi(x, t)$ which is valid for all values of x and t . You may find the following Flash animation useful in visualizing this situation:



from left to right extends to the x axis. At the the moment function of

factor 2π in the the displacement

<http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/ClassMechanics/TravelWaves/TravelWaves.html>

The above link is to a fixed size animation which works nicely if only one person is viewing it. If more than one person is viewing the animation, a version which can be resized is better. Here is a link to a resizable version of the same animation:

<http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/ClassMechanics/TravelWaves/TravelWaves.swf>



Course Concepts

Activity 2

Here is a link to a simple little Flash animation of a plane wave traveling through two different mediums:

<http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/Waves/TwoMediums/TwoMediums.html>

Here is a link to a resizable version of the same animation, which is nicer if more than one person is trying to view it:

<http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/Waves/TwoMediums/TwoMediums.swf>

Open one of the versions of the animation.

- At what rate do the wave fronts from the left strike the medium in the centre? What is the period, frequency, and angular frequency of the wave to the left of the medium in the centre?
- For the medium in the centre, at what rate do the wave fronts leave the left-hand side? Is this the same as your answer to Part A? Explain. Do the wave fronts strike the right side of the medium in the centre at this same rate? What is the period, frequency, and angular frequency of the wave while it is traveling through the medium in the centre?
- Click on the Show Ruler checkbox, and measure the wavelength of the wave traveling from the left to the medium in the centre. Measure the wavelength of the wave while it is traveling through the medium in the centre. Compare the ratio of the wave speed to the wavelength for these two cases. Explain your result.

- D. The wave leaves the medium in the centre and travels off to the right. How do the period, frequency, angular frequency, and wavelength of the wave traveling to the right of the medium in the centre compare to the same quantities for the waves in the other regions?

 **Course Concepts** **Activity 3**

In Activity 2 the waves strike the interface between the two mediums straight on, with zero angle of incidence. Here is a link to a Flash animation where the angle of incidence is not zero.

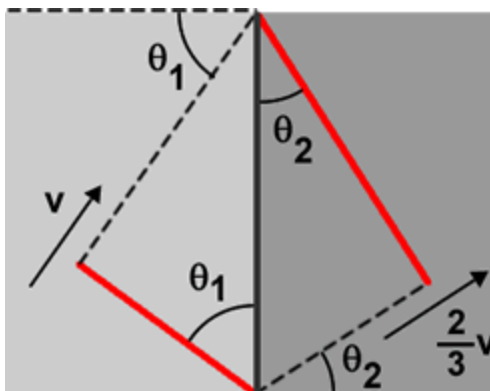
<http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/Waves/Refraction/Refraction.html>

Here is a link to a resizable version:

<http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/Waves/Refraction/Refraction.swf>

Open one of the versions of the animation.

- A. At what rate do the wave fronts from the left strike the medium in the centre? Is the rate the same regardless of what vertical position you are considering? What is the period, frequency, and angular frequency of the wave to the left of the medium in the centre?
- B. For the medium in the centre, at what rate do the wave fronts leave the left-hand side? Is this the same as your answer to Part A? Explain. Do the wave fronts strike the right side of the medium in the centre at this same rate? What is the period, frequency, and angular frequency of the wave while it is traveling through the medium in the centre?
- C. How does the wavelength of the wave traveling from the left to the medium in the center compare to the wavelength of the wave while it is traveling through the medium in the centre? Show how you arrived at your answer.
- D. The wave leaves the medium in the centre and travels off to the right. How do the period, frequency, angular frequency, and wavelength of the wave traveling to the right of the medium in the centre compare to the same quantities for the waves in the other regions?
- E. The figure to the right shows a portion of the animation. What is the relation between θ_1 and θ_2 ? Notice that there are two right triangles with a common hypotenuse.



of two wave fronts between θ_1 and θ_2 triangles in the

 **Course Concepts** **Activity 4**

Here is a Flash animation of a molecular view of a sound wave traveling through the air:

http://faraday.physics.utoronto.ca/IYearLab/Intros/StandingWaves/Flash/long_wave.html

The above link is to a fixed size animation which works nicely if only one person is viewing it. If more than one person is viewing the animation, a version which can be resized is better. Here is a link to a resizable version of the same animation:

http://faraday.physics.utoronto.ca/IYearLab/Intros/StandingWaves/Flash/long_wave.swf

Open one of the versions of the animation.

- A. The bottom shows the motion of the air molecules. You may wish to imagine that the molecules are connected to their nearest neighbors by springs, which are not shown. There is a wave of increasing and decreasing density of the molecules. Is the wave moving to the right or to the left? Explain. Is the wave longitudinal or transverse? Explain.
- B. Often instead of describing the wave as one of density we talk about a *pressure* wave. Does the higher density of molecules correspond to higher or lower pressure? Can you explain?
- C. The top shows the displacement of the molecules from their equilibrium positions. It too is a wave, often called a *displacement* wave. Is the wave moving to the right or to the left? Explain. Is the wave longitudinal or transverse? Explain.
- D. Use the *step* controls, pause the animation and position molecules 3 and 9 at their equilibrium position with molecule 6 at maximum displacement. The amplitude of the displacement wave is zero for molecules 3 and 9. Is the amplitude of the pressure wave at the position of molecule 3 also zero, or is it a maximum or a minimum? What about the pressure wave at the position of molecule 9?
- E. Use the *step* controls to position molecules 3 and 9 at their equilibrium position with molecule 6 at minimum displacement. Is the amplitude of the pressure wave at the position of molecule 3 zero, or is it a maximum or a minimum? What about the pressure wave at the position of molecule 9?
- F. From your results for Parts D and E, what is the phase angle between the pressure wave and the displacement wave?



Course Concepts

Activity 5

- A. Open the Java applet `wave-on-a-string.jar` which is at: `Feynman:Public/Modules/Waves`. Part A of Activity 1 shows a screen shot of the applet.
 - Set the Damping to 0
 - Set the wave type to “Oscillate”
 - Set the end to “No End” which will replace the vise on the right side with an open window for the waves to go through.

How does the amplitude of the wave change as it propagates down the string? Is this a one dimensional, two dimensional, or three dimensional wave? You may wish to look over Parts B and C before answering this question.

- B. A two dimensional wave, such as a water wave, is propagating away from its source equally in all directions. Assume damping is negligible. How does the amplitude of the wave change with distance from the source?
- C. A three dimensional wave, such as a sound wave, is propagating away from its source equally in all directions. Assume damping is negligible. How does the amplitude of the wave change with distance from the source?
- D. What physical principle or conservation law gives the answers to Parts A – C? Explain



Course Concepts Activity 6

- A. Open the Java applet `wave-on-a-string.jar` which is at: `Feynman:Public/Modules/Waves`. Part A of Activity 1 shows a screen shot of the applet.
- Set the Damping to 0
 - Set the wave type to “Pulse”
 - Leave the end in its default state of “Fixed End” which clamps the right side of the string with a C-clamp.
- Click on the *Pulse* button. What is the behavior of the wave pulse when it is reflected by a fixed end?
- B. Change the end of the string to “Loose End” which terminates the right hand side of the string with a frictionless loop around a vertical rod. Click on *Reset* and then on *Pulse*. What is the behavior of the wave pulse when it is reflected by a free end?
- C. Set the end of the string back to “Fixed End,” click on *Reset* and then on *Pulse*. Use the *pause/play* button and then the *step* one to step the wave pulse through a complete reflection at one end of the string. There is a point where the wave pulse nearly disappears. Where did the wave go? Where did the wave’s energy go? Explain what is happening.
- D. Set the end of the string back to “Loose End,” click on *Reset* and then on *Pulse*. Click on the *Rulers* control in the upper-right corner of the simulation. The rulers that appear can be moved with the mouse. Measure the maximum amplitude of the wave pulse; you may already have done this measurement in Activity 1 Part B. Use the *pause/play* button and then the *step* one to step the wave pulse through a complete reflection at one end of the string. There was a point where the amplitude of the wave at the position of the free end was large. Use the ruler to estimate its amplitude. Explain your result.
- E. Set the end of the string back to “Fixed End.” Set the *Damping* to 10. Set the wave type to “Oscillate” and click on *Reset*. You will see a “standing wave” on the right hand side of the string. Use the *pause/play* button and then the *step* one to step the wave pulse through a complete reflection at the right end of the string. There is a point where the wave pulse near the right hand side nearly disappears. Where did the wave go? Explain what is happening.
- F. Set the end of the string back to “Loose End,” click on *Reset*. You will once again see a “standing wave” on the right hand side of the string. Is there a difference between this standing wave and the one you saw in Part E? Explain. Is there a point where the wave displacement near the right hand side nearly disappears, as in Part E? Explain.
- G. Set the end of the string back to “Fixed End.” Leave the wave type as “Oscillate.” Set the *Damping* to 0. Click on *Reset*. What happens? Explain.

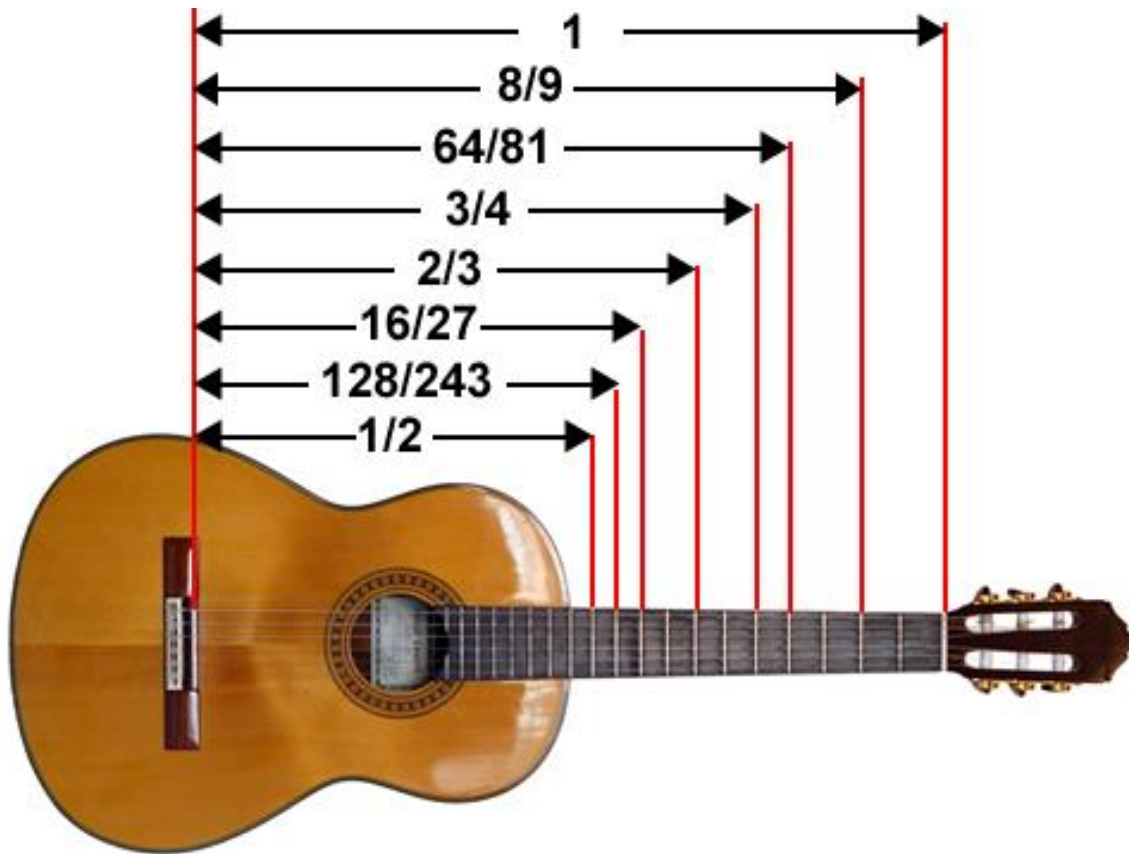
Although we have used the *wave on a string* applet in Activities 1, 5, and now here, there is still lots more Physics that you can learn from it. You are invited to explore further.



Activity 7

“Music is a hidden practice of the soul, that does not know it is doing mathematics.” --Leibniz

If Pythagoras had a guitar, it might have looked like this:



We assume that Pythagoras was a large man, so the length of the strings from the bridge to the nut is 1 m, as shown.

The second string of six from the top is conventionally tuned to A two octaves below concert A. This is often written as A_2 , and has a frequency of 110 Hz.

The notes of an A scale starting at A_2 are: $A_2 - B_2 - C_3\# - D_3 - E_3 - F_3\# - G_3\# - A_3$. Here are the frequencies of these notes in a Pythagorean tuning; also shown are the frequencies of the notes in an equally tempered tuning which is more common today.

Note	Pythagorean Tuning (Hz)	Equally Tempered (Hz)
A_2	110.00	110.00
B_2	123.75	123.47
$C_3\#$	139.22	138.59
D_3	146.67	146.83
E_3	165.00	164.81
$F_3\#$	185.63	185.00
$G_3\#$	208.83	207.65

You will need to know that, as discussed in the textbook, the speed of a traveling wave on string with tension T_s is

$$v_{string} = \sqrt{\frac{T_s}{\mu}}$$

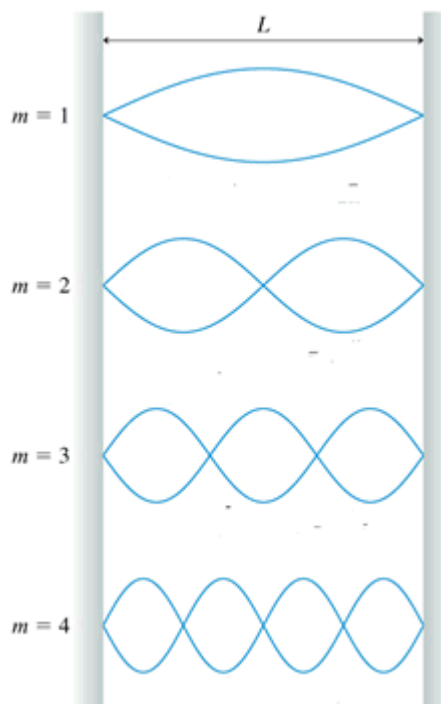
where μ is the string's mass-to-length ratio

$$\mu = \frac{m}{L}$$

Note that the speed is independent of the

To the right are shown the first four normal string.

Here is a link to a simple Flash animation that of the string for the first three normal modes:



textbook, the speed of a

frequency.

modes of a vibrating

shows the actual motion

<http://faraday.physics.utoronto.ca/IYearLab/Intros/StandingWaves/Flash/sta2fix.html>

- When the second string from the top is playing the note $A_2 = 110$ Hz the frequency f of the first normal mode is also 110 Hz. What is the wavelength of the first normal mode? What is the speed of a traveling wave on the string? Explain why increasing the tension in the string increases the frequency of the note the string plays.
- What is the wavelength of the *second* normal wave of the string? What is the frequency of the standing wave?
- If you place your finger just to the right of the 12th fret the effective length of the string becomes 0.5 m, as shown in the figure. What is the wavelength of the first normal mode, and the frequency? What musical note is the string playing? How do your values compare to your result for Part B? Explain.
- If you place your finger just to the right of the 7th fret the effective length of the string becomes $\frac{2}{3}$ m, as shown in the figure. What is the wavelength of the first normal mode and the frequency? What musical note is the string playing? Explain.
- Is there a pattern between the positions of the labeled frets in the figure of the guitar and the notes of the A scale in a Pythagorean tuning? What is the pattern? Are the lengths shown in the figure rational or irrational numbers? You may wish to know that if the guitar frets were set up to be equally tempered, except for the 12th fret the lengths would not be rational numbers.
- As indicated in the table, the frequencies of the notes in a scale are slightly different in the Pythagorean tuning and the equally tempered tuning commonly used today. You may see if you can hear the difference by listening to a scale played with the Pythagorean tuning in the file `Pythagorean.mid` and a equally tempered tuning in `EqualTempered.mid`; both files are located at `Feynman:public/Modules/Waves`. You may also wish to explore further at: <http://faraday.physics.utoronto.ca/PVB/Harrison/Flash/Temperament/Temperament.html>



At some position two sound waves have the form:

$$D_1 = a \sin(\omega_1 t)$$
$$D_2 = a \sin(\omega_2 t)$$

They have the same amplitude a and different angular frequencies ω_1 and ω_2 . In terms of the frequencies f_1 and f_2 , the two waves have the form:

$$D_1 = a \sin(2\pi f_1 t)$$
$$D_2 = a \sin(2\pi f_2 t)$$

The superposition of the two waves is:

$$D_{\text{tot}} = D_1 + D_2$$
$$= A(t) \sin(\omega_{\text{avg}} t)$$

where:

$$\omega_{\text{avg}} = \frac{\omega_1 + \omega_2}{2}$$
$$A(t) = 2a \cos(\omega_{\text{mod}} t)$$
$$\omega_{\text{mod}} = \frac{|\omega_1 - \omega_2|}{2}$$

The amplitude of the wave, $A(t)$, is *modulated* by the modulation angular frequency ω_{mod} .

In terms of the frequencies the above relations become:

$$D_{\text{tot}} = A(t) \sin(2\pi f_{\text{avg}} t)$$

where:

$$f_{\text{avg}} = \frac{f_1 + f_2}{2}$$
$$A(t) = 2a \cos(2\pi f_{\text{mod}} t)$$
$$f_{\text{mod}} = \frac{|f_1 - f_2|}{2}$$

- A. If the frequencies of the two waves are close to each other you will perceive a wave with frequency f_{avg} whose amplitude is varying with a beat frequency $f_{\text{beat}} = 2f_{\text{mod}}$. Say that the two waves have frequencies of 510 Hz and 512 Hz. Then you will hear a sound wave with frequency 511 Hz with a beat frequency of 2

Hz. In your own words, explain why the beat frequency is double the modulation frequency.

- B. If the frequencies of the two waves are far apart, many but not all people will perceive an additional sound whose frequency is related to the difference in the two frequencies. Say that the two waves have frequencies of 220 Hz and 330 Hz. What is the frequency of the perceived sound? Explain. There are two audio files which you may use to see whether or not you hear the additional sound, one in .wav format and the other in .mp3. They are both named 330_220Hz_mix and are located at Feynman:public/Modules/Waves.

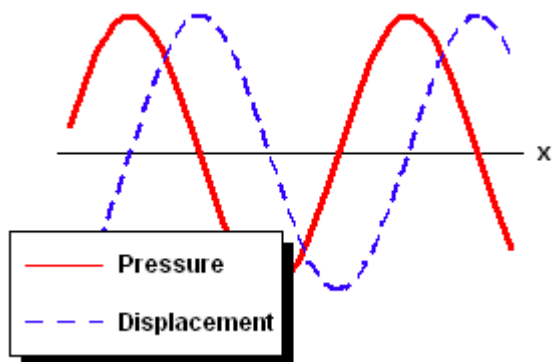


Expt Activity 9

As investigated in Activity 4, we can think of a sound wave two different ways:

1. A pressure wave. The pressure oscillates around atmospheric pressure.
2. A displacement wave. The displacements of the air molecules oscillate around their equilibrium positions.

These two waves are 90 degrees out of phase: when one has a maximum or minimum the other is at zero amplitude.



You will want to know that microphones measure the *pressure* wave. You will also want to know that the accepted value of the speed of sound is:

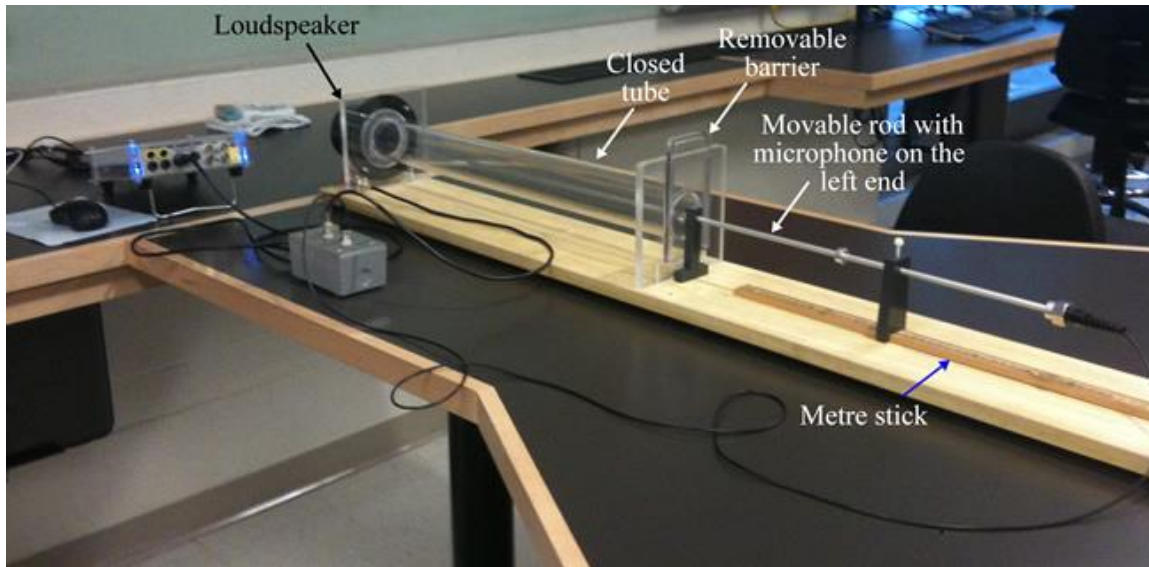
$$v_{\text{accepted}} = 331 + 0.61T \text{ (m/s)}$$

where T is the temperature of the air in Celsius.

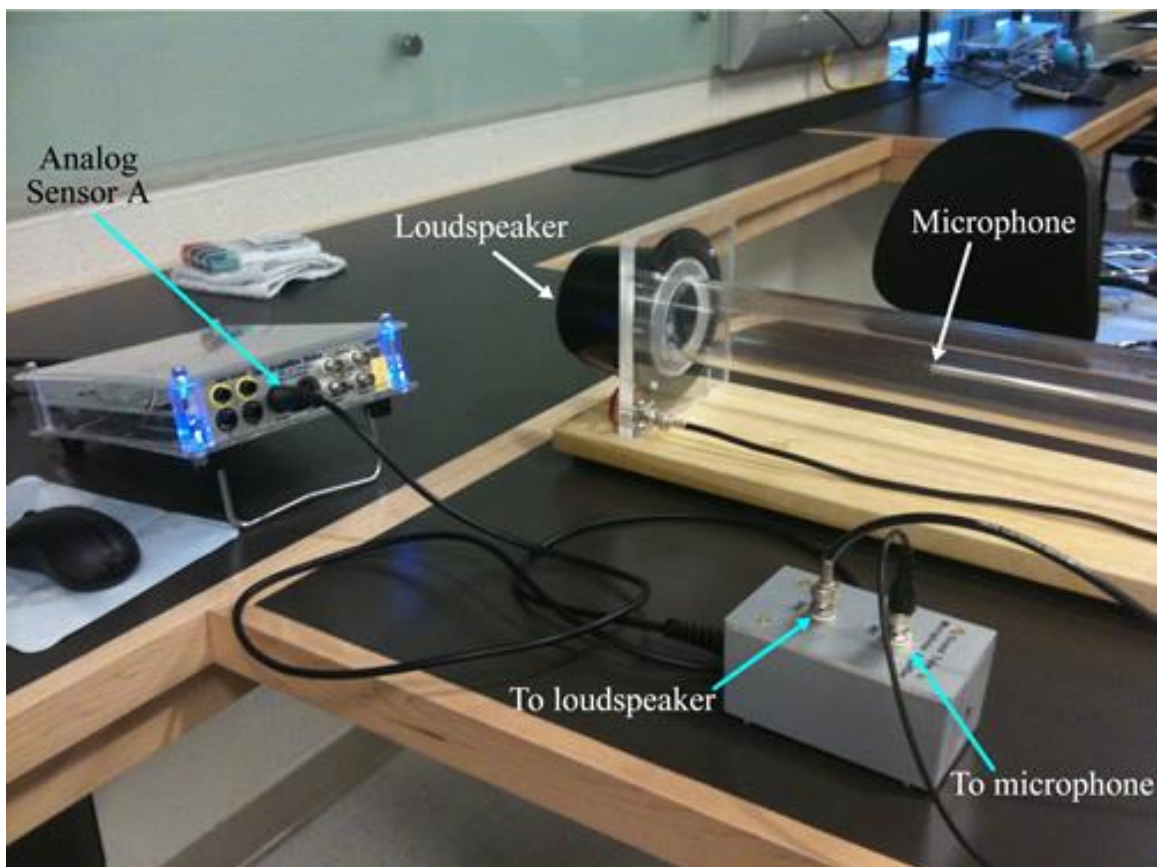
In this Activity you will set up standing sound waves in a tube filled with air and determine the speed of sound.

The Apparatus

The apparatus is shown on the next page. The loudspeaker generates the sound wave. The rod inside the tube has a small microphone mounted on the end, so the sound wave inside the tube can be measured at different positions.



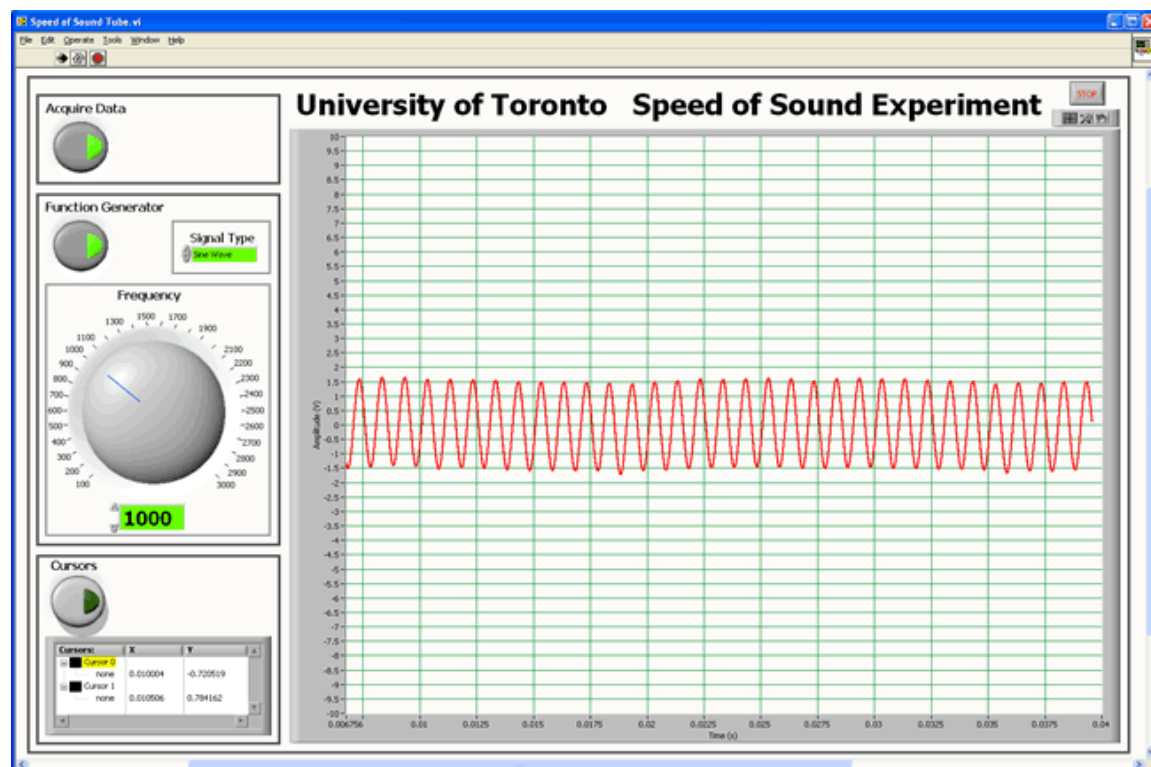
The figure below shows a close-up of the left side of the apparatus.



The gray box in the lower-right corner is the *Sound Tube Microphone Amplifier*. It is connected to the Analog Sensor A connection on the *Data Acquisition Device*. The connector on the top of the box labeled *SPK* is connected to the loudspeaker, and the connector labeled *MIC* is connected to the microphone.

The Software

The `Sound_vs_time` program both drives the loudspeaker and measures the output from the microphone. Here is a screen shot of the software.



To use the software for this Activity:

- Click on *Acquire Data* in the upper-left corner. The button will turn green as shown.
- Click on *Function Generator* just below the *Acquire Data* button. It too will turn green as shown. This causes the loudspeaker to begin generating a sound wave.
- Choose a *Sine Wave* as the *Signal Type*
- Adjust the frequency of the sound produced by the loudspeaker with the *Frequency* knob and the control just below the knob.

The plot on the right is what the microphone measures. It is a plot of wave displacement versus time. You will be interested in the amplitude of the wave, which is about 1.5 V in the screen shot.

Getting a Standing Wave in the Tube

The most challenging part of this Activity is getting a standing wave set up in the tube. The actual tube differs from the ideal case because of a number of factors:

- The cone of the loudspeaker is moving back and forth, so is only approximately a closed end.

- The sound wave will reflect off the rod, the hole in the right hand side barrier, etc. This means that you are unlikely to measure nodes that have exactly zero amplitude. Instead the amplitude at the nodes will only be close to zero but will be much less than the amplitude at the antinodes.

Here are some tips for getting a standing wave. You may wish to repeat some of the steps as you get closer and closer to a good standing wave.

- Step 1: When a standing wave is established, this is called *resonance*, and you will be able to hear that the sound that leaks out of the tube is louder than for a non-resonant condition.
- Step 2: Place the microphone at the closed end of the tube. Slowly adjust the frequency so that you get a maximum amplitude from the microphone.
- Step 3: Place the microphone at a node, and slowly adjust the frequency so that you get a minimum amplitude from the microphone.

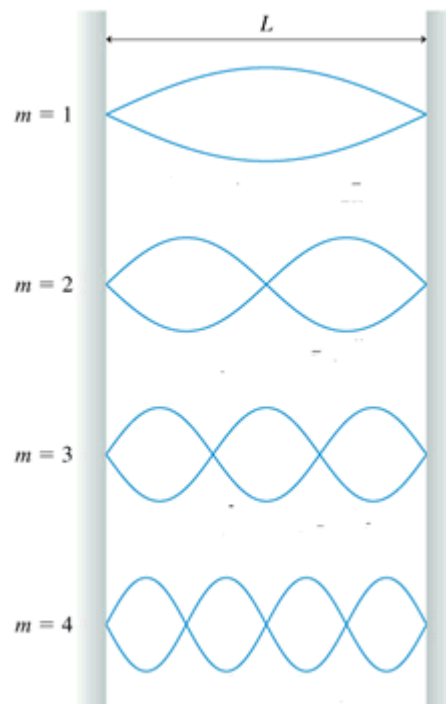
For each standing wave that you study, be sure to record the range of frequencies for which you can not see any difference in the quality of the standing wave. This will determine the error in your value of the frequency.

Be careful not to push the Sound Sensor all the way into the speaker, as the speaker is made of paper!

Preliminary Parts

When the tube is closed at both ends, the possible standing waves are the same as those for a standing wave on a string that is fixed at both ends: there is a node at each end of the tube. The figure to the right shows the first four possible standing waves that for a string we called Activity 7, and in fact this is the same figure that

- What are the wavelengths of the shown waves? What is the wavelength of the $m = 5$ wave which is not shown? Generalise to a formula for the wavelengths for any value of m .
- For the first two or three displacement waves, sketch the corresponding *pressure* wave.



way into the speaker,

displacement waves on a string that the tube. The figure waves. These are the normal modes in appears there!

standing
5 standing
formula for

standing
standing

Here is a link to a simple Flash animation that shows the displacement wave for the first three standing waves:

<http://faraday.physics.utoronto.ca/IYearLab/Intros/StandingWaves/Flash/sta2fix.html>

The Main Part

With the removable barrier in place so that the tube is effectively closed at both ends, get a standing wave in the tube. The stand that supports the rod straddles the metre stick. As you move the microphone from the nodes and antinodes of the standing wave, the distances between them can be determined by the position of the stand relative to the metre stick.

For a given node or antinode you will want to note how much you can vary the position of the microphone and not see any difference in the amplitude of the standing wave. This will allow you to determine the error in the position, which will allow you to determine the error in your determination of the wavelength λ of the sound wave.

Knowing the wavelength and frequency f of the standing wave you can calculate the speed of sound v from

$$\lambda f = v$$

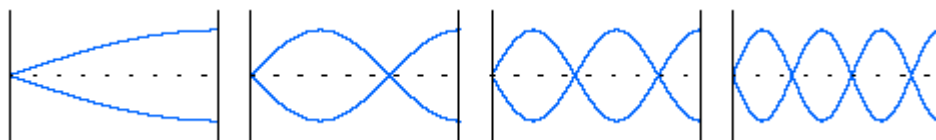
In your determination of the wavelength, you should think about how to get the most precise value, i.e. how to minimize the error in your value. Should you just measure the distance from an antinode to the next node, or from an antinode to the next antinode, or from the first antinode on the right of the tube to the furthest antinode on the left or the tube or ...?

Determine the speed of sound for a few different standing waves of different frequency.

- C. What is your final value of the speed of sound?
- D. How does your value for the speed of sound compare to the accepted value which is given near the beginning of this Activity?

Tube Open on One End

When one end of the tube is open to the air, the standing waves that are possible are the same as those for a vibrating string with one loose end. Here are some of these displacement standing waves for a tube closed on the left and open on the right:



These standing waves occur because part of the incident sound wave is reflected from the open end of the tube. However, the effective reflection point of the wave is not the exact position of the open end of the tube but is slightly beyond it, and so the effective length of the tube is greater than its real length:

$$L_{\text{effective}} = L_{\text{real}} + \Delta L$$

where:

$$\Delta L \approx 0.3D$$

and D is the diameter of the tube. Sometimes $L_{\text{effective}}$ is called the *acoustic length*.

Here is a link to a simple animation that shows the first three standing waves:

<http://faraday.physics.utoronto.ca/IYearLab/Intros/StandingWaves/Flash/stal fix.html>

Remove the barrier from the end of the tube and establish a standing wave.

- E. Determine the effective length of the tube. How well do your measurements agree with the above equation?
- F. If someone designs a pipe organ without being aware of the acoustic length, what will be the consequences?



Activity 10

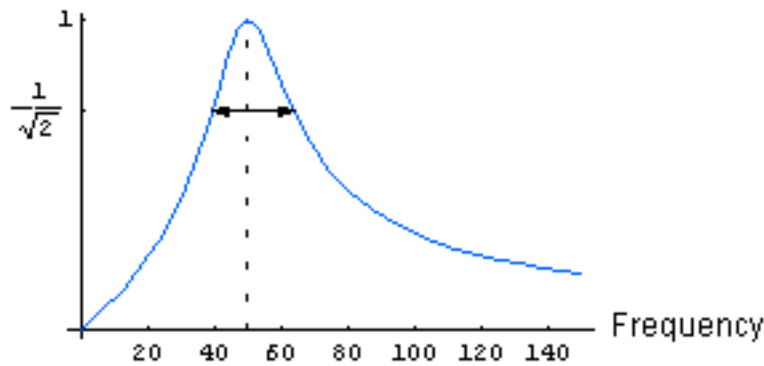
If the apparatus of Activity 9 were perfect, then when the tube is closed on both ends we would not hear any sound outside the tube. Similarly, if the air inside the tube were perfect, all molecule-molecule collisions would be perfectly elastic; this means that as a sound wave travels through the air none of its energy would be converted to heat energy of the air. However, neither the apparatus nor the air is perfect, The *Quality Factor* Q measures the degree of “perfection” of the system.

Say we have a standing wave when the frequency is f_0 . For frequencies close to the "resonant frequency" f_0 the amplitude A of the sound wave at the position where there was an maximum in the pressure wave is given by:

$$A(f) = A_0 \frac{I}{\sqrt{1 + Q^2 \left(\frac{f}{f_0} - \frac{f_0}{f} \right)^2}}$$

Note in the above that the amplitude $A(f)$ is equal to A_0 when the frequency f is equal to the resonant frequency.

The figure to the right shows $A(f)$ for A_0 equal to 1, Q equal 2, and for a resonant frequency of 50 Hz. Note that we have a curve where the amplitude is $1/\sqrt{2}$ times the



maximum amplitude is $1/\sqrt{2}$ times the maximum amplitude A_0 .

A nearly trivial amount of algebra shows that the frequencies when the amplitude A is $1/\sqrt{2}$ times the maximum amplitude A_0 for positive frequency is:

$$f = \frac{f_0}{2Q} (\sqrt{1 + 4Q^2} \pm 1)$$

Thus, if the width of the curve is Δf , then Q is:

$$Q = \frac{f_0}{\Delta f}$$

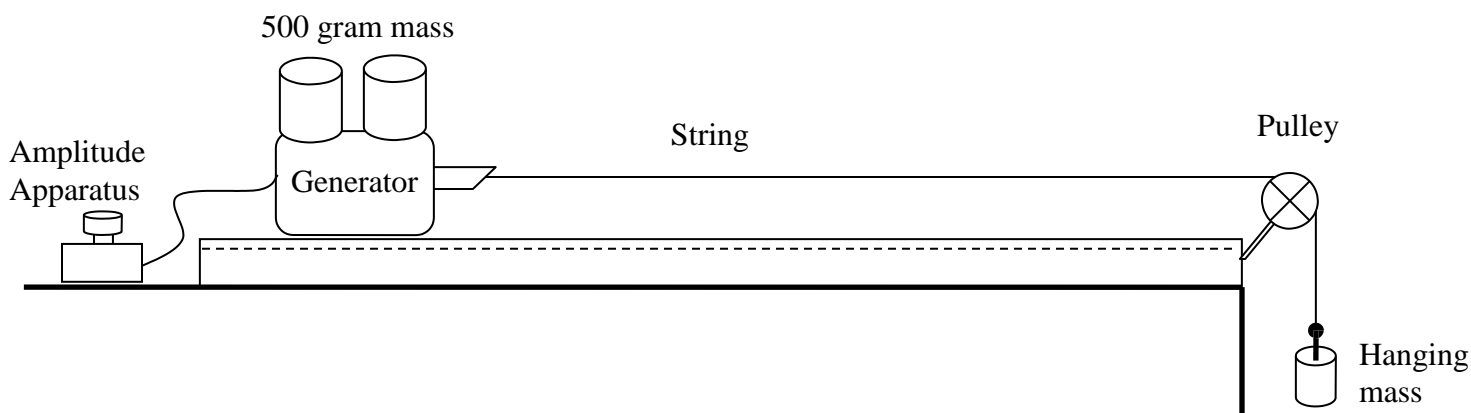
- For a given resonant frequency f_0 how does the width of the curve of amplitude versus frequency depend on the Quality Factor Q ?
- When the Quality Factor Q is zero, the maximum amplitude A_0 is zero. When Q is infinite so is the maximum amplitude. Explain.

- C. Close the tube at both ends and adjust for a standing wave in the range of 200 Hz - 1 kHz. Place the microphone at a maximum in the pressure wave and take data for the amplitude as a function of frequency for frequencies close to the resonant frequency. Calculate the Quality Factor of the tube.

Activity 11: Waves on a String – First Experiment

Open the ‘Vibrating String’ software package. The apparatus should be setup similar to the picture below. For this activity make sure to use the **nylon orange string**. Set the amplitude apparatus at maximum by turning the black knob on the grey box.

ATTENTION: When the vibrating metal bar starts hitting the edges making a noise, turn the amplitude *slightly* down just until the noise stops.



- A. Hang a 100 gram mass on the end of the string near the pulley and set the frequency to very low. (e.g. 5 to 10 Hz). Gradually increase the frequency until the amplitude of the wave changes dramatically indicating that you have reached a resonance (maximum amplitude). How does the amplitude change with the change in frequency (qualitative observation)? (**Make sure the TA agrees that you have found a resonance. The most common problem for this activity is difficulty in noticing a resonance**)
- B. Make a table in your lab book similar to the one below. Find four resonances (maximum amplitude) in a closed-closed end standing wave pattern, starting from the *first* resonance, and measure the distances between consecutive nodes to fill in the first *two* columns of your table. Be sure to draw the shape of each standing wave in your notebook.

	Frequency (Hz)	Distance between nodes (meters)	Wavelength (meters)	Speed of wave (m/s)
1				
2				
3				
4				

- C. Calculate the wavelength and wave speed for each of the standing waves to complete the table in your lab notebook. Find the average of these wave speeds.
- D. Determine the mass density of the string. Use this to calculate the theoretical wave speed value. Compare the average speed found above to the theoretically predicted speed value. Are they similar? Why or why not?

Activity 12: Waves on a String – Second Experiment

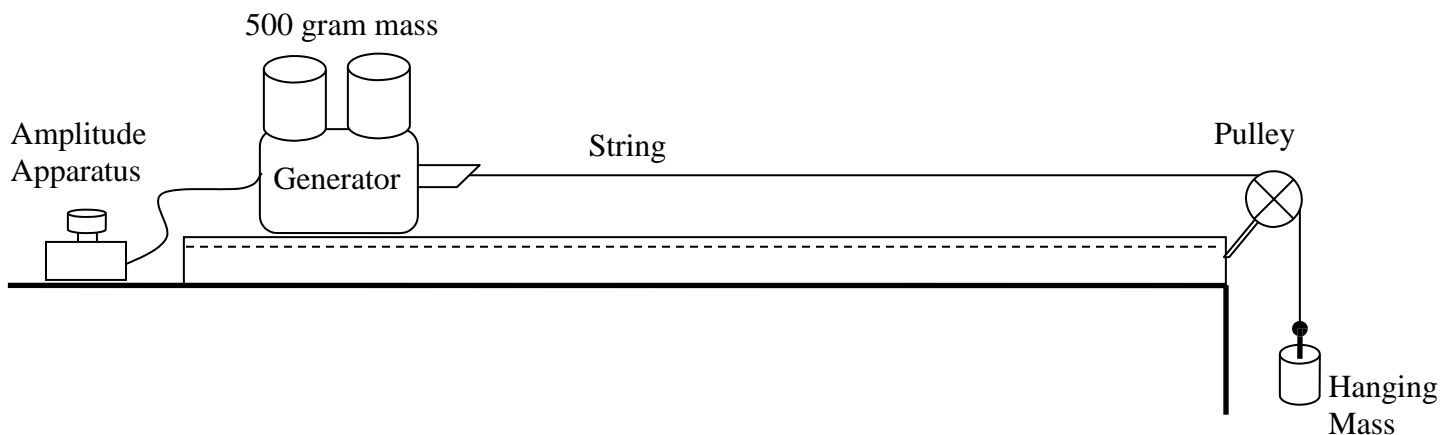
Open the ‘Vibrating String’ software package. The apparatus should be setup similar to the picture below. For this activity make sure to use the **white/green fishing line**. Set the amplitude apparatus at maximum by turning the black knob on the grey box.

ATTENTION: When the vibrating metal bar starts hitting the edges making a noise, turn the amplitude *slightly* down just until the noise stops.

- Using hanging masses of 50gr, 100gr, 150gr, vary the frequency to give a closed-closed end standing wave pattern. Fill out the following table in your lab notebook:

Mass (kg)	Tension (N)	Freq. (Hz)	Distance between nodes (m)	v (m/s)	v ² (m ² /s ²)

- Make a plot of v² vs. T (where T is the Tension) from the results in your table. What is the physical meaning of the slope?
- How does your measured slope compare with the theoretical value?



This Student Guide was written by David M. Harrison, Dept. of Physics, Univ. of Toronto in the Fall of 2008.

Revised: January 20, 2010 by Jason J.B. Harlow.

Revised: January 20, 2011 by David M. Harrison and Brian Wilson.

Revised: January 25, 2011 by David M. Harrison.

Revised: January 29, 2011 by David M. Harrison and Brian Wilson.

Revised: July 23, 2011 by David M. Harrison

The Java applet used in Activities 1, 5 and 6 was written by the Physics Education Technology (PhET) group at the University of Colorado, <http://phet.colorado.edu/index.php>. Retrieved November 9, 2008.

The figure of normal modes of a vibrating string in Activity 7 is slightly modified from Figure 21.22 of Randall D. Knight, **Physics for Scientists and Engineers**, 2nd edition (Pearson Addison-Wesley, 2008), pg. 640. The same figure is used in Activity 9.

The Pythagorean and equally tempered scales used in Activity 6 are from Wikipedia, http://en.wikipedia.org/wiki/Pythagorean_tuning. Retrieved November 15, 2008.

Activities 9 and 10 are based on a Student Guide written by David M. Harrison in October 1999 and revised in June 2001.