Lab Guide
Intensity of Sound

I. Objectives

After completing this simulation, the student will be able to:
1. Calculate the intensity of a spherical wave at a given distance
2. Describe the change in intensity of sound with distance from the source
3. Describe the decibel unit of measure of sound level.
4. Define the threshold of hearing
5. Calculate the sound pressure level in decibels from intensity

II. User Interface and Simulation Features

This simulation provides a Cartesian coordinate grid with a stationary source of sound waves at the origin. A sound receptor can be dragged to any desired location on the grid. The receptor is shaped like an ear. The actual point of reception is a red dot in the middle of the ear. The power of the source is variable. A graph at the left of the screen automatically plots sound pressure level in decibels (dB) versus the logarithm of the intensity $\log(I)$. A digital display at the lower left of the screen gives the values of distance, intensity and sound pressure level. A repetitive audio signal allows you to hear the variation in intensity and sound pressure level. Make certain that your sound card is not muted before you open the simulation. The audio signal can be muted independently of your sound card from within the simulation.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Sound intensity is measured in terms of the energy impinging on a given surface area per unit time, or $\mathrm{W/m^2}$. Intensity for a spherical wave is given by $I = \frac{P}{4\pi r^2}$ for a source of power P at a distance of r from the source. Calculate the intensity of sound at a distance of $5.00\ \mathrm{m}$ from a $1.0\ \mathrm{W}$ source. What value do you obtain? Set the power level to $1.0\ \mathrm{W}$. Drag the ear to the point $(5.0\ \mathrm{m},0)$ on the grid. What value does the simulation report?

2. Set the power level to $1.0\ \mathrm{W}$. Drag the ear to the point $(5.0\ \mathrm{m},0)$ on the grid. What intensity value does the simulation report? Now drag the ear to any other point at a distance of $5.0\ \mathrm{m}$ from the source. What intensity value does the simulation report now? Does the direction from the source make a difference in the intensity?

3. Set the power level to 1.0 W. Drag the ear to the point $(5.0 \text{ m},0)$ on the grid. What intensity value does the simulation report? Now drag the ear to the point $(2.5 \text{ m},0)$ on the grid. What intensity value does the simulation report now? If you move to half the distance from a sound source, by what factor does the intensity increase? If you moved to a distance of 10.0 m from the source (beyond the range of the simulation), what value would the intensity have?

4. Set the power level to 1.0 W. Drag the ear to the point $(5.0 \text{ m},0)$ on the grid. Turn the audio signal on by unchecking the mute button. Note how "loud" the audio signal seems to you. Now drag the ear to the point $(2.5 \text{ m},0)$. Does the "loudness" of the audio signal increase or decrease? Does it seem four times as loud? Drag the ear back and forth along the *x*-axis. What do you have to do to obtain a significant increase in the loudness of the audio signal?

b. Intermediate Level

5. The human ear does not hear loudness as a function of intensity, but rather the logarithm of intensity. However, on the average, the human ear cannot detect intensity levels below $1\times10^{-12} \text{ W/m}^2$. This value has been defined as the "threshold of hearing." Even though there is no zero value on a logarithmic scale of positive numbers, we have established a unit of measure of sound pressure level, the decibel, dB, that relates perceived "loudness" to intensity: $\beta_{(dB)} = 10\log\left(\frac{I}{I_0}\right)$ where $I_0 = 1\times10^{-12} \text{ W/m}^2$. This simplifies to $\beta = 120 + 10\log I$. What would the value of the sound pressure level (in decibels) be at the threshold of hearing? What would the value be for an intensity of $I = 1\times10^{-6} \text{ W/m}^2$? What would the value be for an intensity of $I = 1 \text{W/m}^2$?

6. How close must you be to a 1.0 W sound source for the sound pressure level to be 120 dB?

c. Advanced Level

7. The inputs for the displayed values from the grid are digital. Use a 1.0 W sound source. What is the greatest decibel value you can obtained before the display indicates "INFINITE"? How close must you be to the source to achieve this? What is the intensity of the sound at this distance?

8. Use a 1.0 W sound source. Find a position for the ear so that the sound pressure level is very close to 110 dB. Now reduce the power to 0.1 W. What is the new sound pressure level? Try the same thing starting with a sound pressure level that is very close to 100 dB. What is the new sound pressure level?

Lab Guide
Tone Beats

I. Objectives

After completing this simulation, the student will be able to:
1. Measure the beat frequency between two audio signals.
2. Verify the difference in frequency in two known audio signals
3. Using two known audio frequencies, measure the frequency of an unknown signal.

II. User Interface and Simulation Features

This simulation provides one or two audio frequency inputs to an amplifier and speaker. The inputs are selectable from four known frequencies and four unknown frequencies. The simulation is started and stopped by turning the speaker input on and off. Changes to the inputs can be made only when the speaker input is off. A digital timer is provided to assist in counting the beat frequency. It measures time in seconds. The “Start” button starts the timer. Once running, the “Start” button has no effect. The “Stop” button halts the display, but the timer continues to run in the background. Once stopped, the “Stop” button has no further effect, but the “Start” button will begin the display again with the total time (including the time the display was halted). The “Reset” button will start the timer over at zero. The “Reset” button may be pressed with the display either running or halted. It may be desirable to wear headphones while running this simulation.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Drag the $400\ \mathrm{Hz}$ signal into one of the speaker input boxes (it doesn’t matter which). Turn the speaker input on. Listen to the tone. Stop the simulation. Drag the $401\ \mathrm{Hz}$ signal into one of the speaker input boxes. Listen to this tone. Are you able to tell the difference between the two frequencies?

2. Drag the $400\ \mathrm{Hz}$ signal into one of the speaker input boxes. Now drag the $401\ \mathrm{Hz}$ signal into the other speaker input box. Start the simulation. Describe what you hear. Start the timer. Measure the beat frequency: click on the “Reset” button the instant you start counting “beats.” Count 20 beats and immediately stop the timer. How many seconds did it take to produce the 20 beats? Count 40 beats in the same manner. How many seconds did this take? It is always good practice to make several measurements in lab experiments like this. What is the beat frequency? What is the difference between the two input frequencies?

3. Drag the $401\ \mathrm{Hz}$ signal into one of the speaker input boxes. Now drag the $402\ \mathrm{Hz}$ signal into the other speaker input box. Start the simulation. Can you tell the difference between what you

heard in Item 2 and this experiment? Measure the beat frequency between these two frequencies using the timer. Count 20 beats and immediately stop the timer. How many seconds did it take to produce the 20 beats? Count 40 beats in the same manner. How many seconds did this take? What is the beat frequency? If you know the frequency of one signal, can you tell whether a second signal is higher or lower in frequency by doing this experiment?

4. Drag the $401\ \mathrm{Hz}$ signal into one of the speaker input boxes. Now drag the $405\ \mathrm{Hz}$ signal into the other speaker input box. Start the simulation. Measure the beat frequency between these two frequencies using the timer. With faster beats it is often helpful to count by fours or fives, e.g., **1**-2-3-4; **2**-2-3-4; **3**-2-3-4; etc. Count 40 beats and immediately stop the timer. How many seconds did it take to produce the 40 beats? Count 80 beats in the same manner. How many seconds did this take? What is the beat frequency? Is this frequency the same as the difference of the input frequencies?

<u>b. Intermediate Level</u>

5. Using the technique you have learned in Items 1 through 4, measure the beat frequency between the $400\ \mathrm{Hz}$ signal and the $401\ \mathrm{Hz}$ signal. What is its value? Then replace the $401\ \mathrm{Hz}$ with the $402\ \mathrm{Hz}$ signal and measure the beat frequency. If you know only the frequency of the $400\ \mathrm{Hz}$ and the $401\ \mathrm{Hz}$ signal, can you tell with certainty that the third frequency is in fact $402\ \mathrm{Hz}$ and not $398\ \mathrm{Hz}$? What one other measurement would you have to make between the three frequencies in order to determine this?

6. What is the beat frequency between $405\ \mathrm{Hz}$ and $403\ \mathrm{Hz}$? Suppose you had the choice of these two known frequencies. You measured an unknown frequency against the $403\ \mathrm{Hz}$ signal and found a beat frequency of $2\ \mathrm{Hz}$. How would you determine the unknown frequency with certainty?

<u>c. Advanced Level</u>

7. Utilize the techniques you have learned in Items 5 and 6. Compare unknown frequency W to the known $400\ \mathrm{Hz}$ and $401\ \mathrm{Hz}$ signals. What is the frequency of W?

8. What is the frequency of X?

9. What is the frequency of Y? Hint: Count carefully.

10. Which two frequencies would you most likely use to compare with frequency Z? Why? What is the frequency of Z?

Lab Guide

Doppler Shift I

I. Objectives

After completing this simulation, the student will be able to:

1. Describe the relationship between sound source motion and wavelength at a distance
2. Describe the relationship between sound pitch and frequency
3. Describe the relationship between sound source motion and frequency perceived at a distance.
4. Explain why a medium is necessary for the propagation of sound waves.
5. Describe the effect of period on wavelength

II. User Interface and Simulation Features

This simulation provides a moving source of sound waves on a Cartesian coordinate grid. Each division on the grid represents 400 meters. The source moves back and forth in the x-direction at a selectable velocity. The speed of sound can be varied. Rings emanating from the source represent wave crests. A digital timer operates during the running of the simulation. The timer operates faster than real time. The period of the sound wave is selectable. The period is synchronized with the timer. A coordinate display shows the position of the cursor to assist with distance measurements. You can pause the simulation at any time to make distance measurements.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Set the source velocity to zero. Run the simulation. Pause the simulation after a few seconds and use the cursor to measure the distance between several wave crests. How far apart are the individual wave crests?

2. Set the source velocity to zero. Set the period to 4 s.Run the simulation. How far apart are the wave crests? The wavelength is the distance between wave crests. Does the period have an effect on the wavelength?

3. If you decrease the period of the sound wave, how does that affect the wavelength? How does the change affect the frequency? If you decrease the period, would that change the way you perceived the sound? How?

4. Run the simulation. Notice the motion of the sound source. Look at the distance between crests in front of the source. Now look at the distance between crests behind the source. What do you observe? What causes this?

b. Intermediate Level

5. Run the simulation. Compared to a stationary sound source, how would you perceive the sound if you were in front of the moving source? How would you perceived the sound if you were behind the source?

6. Accept the default value for the speed of sound. Set the source velocity to the speed of sound. Run the simulation. What do you observe about the wave crests in front of the source? What is the wavelength behind the source? How does this value compare with the value for the stationary source in Item 1?

c. Advanced Level

7. Set the source speed to $660\,\mathrm{m/s}$; Run the simulation. Is there a place where the wave crests start to "line up"? The crest of a sound wave is a region of high pressure. Suppose the sound source was an aircraft and you were an observer on the ground in the negative *y*-direction. If you were on the ground, how would you perceive this "lining up" of wave crests?

8. Set the source speed to $660\ \mathrm{m/s}$. Run the simulation. Pause the simulation. Observe the "lined up" wave crests. Using trigonometry, find the angle that the "lined up" wave crests make with the horizontal. What is the sine of this angle? What is the ratio of the speed of sound to the source speed? Is the sine of the angle nearly the same as this ratio of speeds?

Lab Guide
Lissajous Figures

I. Objectives

After completing this simulation, the student will be able to:
1. Estimate the plot of one sinusoidal wave against another
2. Described the effect of phase shift on the shape of a plot in Objective 1
3. Describe the effect of the ratio of frequencies on the shape of a plot in Objective 1

II. User Interface and Simulation Features

This simulation plots one sinusoidal function against another. These are parametric equations, since the angles are functions of time. You can think of it as plotting sine against cosine or sine with some displacement (the phase shift). As you perform this simulation, remember that $\sin\theta = \cos(\theta + \pi)$ where θ is in radians. In the formula just given, the phase shift was π radians. The display in this simulation looks like the cathode ray tube (CRT) of an oscilloscope. You provide input functions to both the *x*-axis and the *y*-axis. You can vary the frequency of the input, its phase shift, and its amplitude. An amplitude of 100 just fills the CRT in either the *x*- or *y*-direction. The phase shift is variable through one complete waveform ($0 - 2\pi$ radians). You can turn the trail of the plot on or off. It may be necessary to cycle the Trails On/Off button in order to display a full trail of the inputs you have selected.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Recall that for a sinusoidal function, one complete wavelength is traversed in 2π rad. Every unit of frequency (1 Hz) is therefore 2π rad/s. Turn the trails off. Notice that the frequency of both inputs is 1 Hz. Run the simulation. What is the frequency of both inputs? How long does it take the blue dot to make one revolution? What is the angle at time zero? At time zero, what trig function represents the x-value? What trig function represents the y-value? Notice the phase shift in *x*; we'll use this later.

2. Verify that the trails are on. Run the simulation. What is the shape of the trail? Now change the frequency of both x- and y-inputs to 2 Hz. Run the simulation again. What is the shape of the trail? Change both frequencies to 10Hz. Run the simulation again. Does the shape remain the same?

3. Set the frequency of the x-input to $2\ \mathrm{Hz}$. Run the simulation. What do you observe? What is the shape of this curve? Turn the trails off. For every cycle on the y-axis, how many cycles does the blue dot go through on the x-axis? Is the trail a closed curve or an open curve?

4. Set the frequency of the x-input to $3\ \mathrm{Hz}$. Run the simulation. What do you observe? Is the curve open or closed? For every cycle on the y-axis, how many cycles does the blue dot go through on the x-axis? It is easiest to start at some maximum or minimum value for *x*, trace out the path, and count the number of complete cycles made in the x-direction. Then starting at the same point, count the number of cycles in the *y*-direction.

5. Keeping the y-frequency at $1\ \mathrm{Hz}$, run the simulation with the *x*-frequency at $4\ \mathrm{Hz}$, $6\ \mathrm{Hz}$ and $8\ \mathrm{Hz}$. Are the curves open or closed? Now run the simulation with the *x*-frequency at $5\ \mathrm{Hz}$, $7\ \mathrm{Hz}$ and $9\ \mathrm{Hz}$. Are the curves open or closed?

<u>b. Intermediate Level</u>

6. Remember that we have been using a phase shift of 0.5π in the x-input. This means that we have been adding that value to the angle before we calculate the trig function value to plot. Turn the trails off and set the phase shafts to zero. Set both frequencies to $0.5\ \mathrm{Hz}$ to make the plot easier to see. Run the simulation. How long does it take the blue dot to go through one complete cycle? What angle does the blue dot go through in that period? For the first quarter cycle, is the x-value increasing or decreasing? Does the sine or cosine function behave this way? Is the y-value increasing or decreasing? Look at the pattern of how the *x*- and *y*-values are increasing and decreasing for the rest of just one cycle. What trig functions are we plotting here? What is the shape of the path? What is its slope m? Is this consistent?

7. From the information you gained in Items 1 and 6, by how what angle in radians are cosine values offset (shifted) from the sine values? If we shift the phase of the angle by $\pi/2\ \mathrm{rad}$, what function does the sine become? What function does the cosine become?

8. Change the phase shift for the x-input to $\pi\ \mathrm{rad}$. Run the simulation. What function does the phase-shifted *x*-value represent now? If we plot this versus $\sin\theta$, what is the shape of the path? What is its slope m?

<u>c. Advanced Level</u>

9. Change the phase shift for the *x*-input by increments of $\pi/2$ starting with a phase shift of zero. Run the simulation after each change. Can you state a general rule for the phase shifts that result in a circular path?

10. What settings would you use to produce a closed curve that goes through 4 cycles on the *y*-axis in the same time that it goes through 3 cycles on the *x*-axis?

Lab Guide
Interference Patterns

I. Objectives

After completing this simulation, the student will be able to:
1. Describe the algebraic addition of wave amplitudes
2. Explain constructive and destructive interference
3. Given wavelength and distance from two sources, predict interference effects.
4. Locate regions of constructive and destructive interference in an interference pattern.

II. User Interface and Simulation Features

This simulation produces interference effects resulting from the interaction of waves from two sources. The wavelength of both sources is $\lambda = 1\ \mathrm{m}$. One source is identified as the red center, with a red dot at its center. The other is the blue center. By default, red and blue lines extend from the red and blue centers to the cursor position. The lines can be turned off by unchecking the Lines On/Off button. A digital display at the bottom left of the screen gives the position of the cursor and the two wave centers. Another digital display at the bottom right of the screen gives the distance from the cursor to each of the red and blue centers, and the difference between them. Waves radiate outward from each wave center. The rings represent the crests of the waves. The wave crests from the blue center occur every integral wavelength radially away from the blue center. The wave crests from the red center occur at integral wavelengths away from the red center. Where a crest from each center is located at the same point on the grid, the amplitudes add, and constructive interference occurs.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Turn off the lines on the simulation. Position the cursor at the origin. Notice that the cursor is equidistant from both centers, and the difference between distances is zero. Notice that the origin is a point where a wave crest from each center touches or intersects. Is this a point of constructive or destructive interference?

2. Move the cursor to the point $(0,-4.3)$. Compared to the origin (in Item 1), this is the next point in the negative *y*-direction where two crests intersect. How far is the cursor from each center? What is the difference between the distances? Is this a point of constructive or destructive interference?

3. Check some of the other wave crest intersections on the y-axis. Is the difference of distances to the cursor always zero? What kind of interference always occurs at these points?

4. Check other points on the x-axis where wave crests from the two centers are tangent to each other. Is the difference of distances to the cursor always zero? What kind of interference occurs at these points?

b. Intermediate Level

5. Can you find wave crest intersections that do not lie on either the x- or the y-axis for which the difference between the distances is still zero?

6. Now move the cursor to the point $\left(0,-8.7\right)$. What is the difference between the distances? Is this an area of constructive or destructive interference? Are wave crests or wave troughs interfering here? Notice that this point is equidistant from two wave crests from both the red center and the blue center.

c. Advanced Level

7. Areas of constructive interference appear as light bands or wedges, and areas of destructive interference appear as darker bands or wedges. Move the blue center so that it is at the same location as the red center. Do you see any areas of constructive or destructive interference? Slow drag the blue center along the *x*-axis away from the red center. Does the number of bands of constructive interference increase or decrease? From where do the bands appear to propagate?

8. Notice that the wave crests from the two centers are in constructive interference on the x-axis (Item 4). Watching the display of path difference, slowly move the red center in the positive x-direction toward the blue center. What is the path difference when the wave crests from the red center (on the *x*-axis) are exactly halfway between the wave crests from the blue center? To what part of the wave from the blue center are the crests from the red center being added? What kind of interference is this?

Lab Guide
Wave Addition

I. Objectives

After completing this simulation, the student will be able to:
1. Relate the period of a wave and its frequency
2. Describe algebraic addition of wave amplitudes
3. Describe constructive and destructive interference
4. Demonstrate beat frequency between waves of two close frequencies

II. User Interface and Simulation Features

This simulation graphs two sinusoidal waves plus the wave resulting from their algebraic addition. You are able to select the period, amplitude and phase shift for each wave by means of slider bars. The waveforms are graphed on a Cartesian coordinate grid versus time on the x-axis. Each of the two input waves has a “handle” at the origin of the graph by which the entire plot of that wave can be moved vertically for visual separation. Amplitude is given in meters. Quantitative information about the wavelength or speed of the wave is not provided because it is not necessary for the completion of this simulation..

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Set the amplitude of the blue wave to zero. What is the period of the green wave? Count the number of complete waveforms that occur in $3.0\ \mathrm{s}$ on the graph. How many are there? What is the frequency of the green wave? Is this consistent with the formula $fT = 1$?

2. Run the simulation. The red wave is the sum of the amplitudes of the green and blue wave. Does the red wave include any amplitude of the blue wave now? Drag the “handle” of the green wave upward. Does the green wave separate vertically from the red wave?

3. Set the period of the blue wave equal to that of the green wave, $T = 0.30\ \mathrm{s}$. Do you see both the green and blue waves? Drag the handle of the green wave downward so that it is visible. Run the simulation. What is the amplitude of the blue wave? What is the amplitude of the green wave? Is the maximum amplitude of the red wave the sum of those of the green and blue waves?

4. Set the period of the blue wave equal to that of the green wave, $T = 0.30\ \mathrm{s}$. Drag the handle of the green wave downward so that it is visible. Run the simulation. Is the wavelength of the red wave the same as that of the green and blue waves?

5. Set the period of the blue wave equal to that of the green wave, $T = 0.30\ \mathrm{s}$. Set the amplitude of the green wave to $2.0\ \mathrm{m}$. Drag the handle of the green wave downward so that it is visible. Run the simulation. What is the maximum amplitude of the red wave?

b. Intermediate Level

6. Set both amplitudes to $2.0\ \mathrm{m}$. Set the period of the blue wave to $0.35\ \mathrm{s}$. What is the frequency of the green wave? What is the frequency of the blue wave? What is the difference of their frequencies? What period corresponds to this difference? Run the simulation. What is the period of the red wave? Measure the distance from one tallest crest to the next. The red wave represents the beat frequency resulting from interference of the blue and green waves.

7. Set the period of the green wave at $0.07\ \mathrm{s}$. Set the period of the blue wave to $0.08\ \mathrm{s}$. Run the simulation. What is the period of the beat frequency? What is its frequency?

c. Advanced Level

8. Can you come up with an expression for the beat frequency f_b expressed only in terms of the periods of the two original frequencies?

9. Set the period of the blue wave to $0.30\ \mathrm{s}$, the same as the blue wave. Recall that one wavelength is an angular displacement of 2π radians. Displace the blue wave exactly one-half wavelength by setting the blue wave phase shift to $\delta = \pi$. Where are the crests of the blue wave compared to the troughs of the green wave? Run the simulation. What is the shape of the red wave? Why is it this shape?

Lab Guide
Standing Waves

I. Objectives

After completing this simulation, the student will be able to:
1. Describe a standing wave on a string in a closed pipe
2. Describe a standing wave in an open pipe
3. Calculate the fundamental frequency of a string or pipe
4. Experimentally locate natural resonant frequencies of a pipe or string.

II. User Interface and Simulation Features

This simulation provides a stylized graphic of a wave on a string. The string can also represent the amplitude of a pressure (sound) wave in a pipe such as an organ pipe. The point of this experiment is to find combinations of length, wave speed and frequency that make a naturally resonant system. You may select a closed pipe or an open pipe (a pipe open at one end). You may choose the speed of the wave, the frequency of the wave, and the length of the tube (or string). A digital timer is provided at the lower right of the screen for timing oscillations. The timer and the oscillations of the string or the air in the pipe are synchronized. Both operate much slower than real time. At long wavelengths and low frequencies, the simulation speed may be carefully increased with the slider bar in order to gain results more quickly.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Run the simulation. What is the frequency of oscillation? Try frequencies of $\pm 1\ \mathrm{Hz}$ above and below the default frequency. Is the amplitude larger or smaller for these other frequencies? Is the frequency naturally resonant for these conditions?

2. Run the simulation. How many complete wavelengths are present? Can you vary the frequency to find a lower number of wavelengths that still produces a resonance? How many wavelengths? What is the frequency? Can you vary the frequency to find a fraction of a wavelength that produces a resonance? What is the fractional part of the wavelength? What is the frequency?

3. Notice that in Item 2 you found the lowest frequency that you could obtain with a given pipe length. This is called the fundamental frequency. Set the wave speed to $50\,\mathrm{m/s}$. What shorter length of tube gives a resonance? Can you find a second even shorter tube length? What is the length? What fraction of a wavelength is present in the tube?

4. As you reduce the length of the tube, does the wavelength of the shortest possible resonant wave increase or decrease? Does the frequency increase or decrease?

b. Intermediate Level

5. Suppose you wanted to select a string for a piano that would have a fundamental frequency of $64\ \mathrm{Hz}$ (2 octaves below middle C). The speed of the wave in this string is $95\,\mathrm{m/s}$. What would the shortest length be for this string? How many wavelengths would be vibrating on this string?

6. Resonant frequencies higher than the fundamental frequency on a string or in a pipe are called overtones, or harmonics. Musicians and physicists differ slightly in how they number these. For a resonance to occur, a string or a closed pipe must have an integral number of half-wavelengths. This means that $\frac{n\lambda}{2} = L$ and because $v_{wave} = f\lambda$, $f = \frac{nv_{wave}}{2L}$. We have the lowest (fundamental) frequency when $n = 1$. When $n = 2$ and $n = 3$, we hear higher frequencies from the same string or pipe. These two would be the second and third harmonic. Calculate the second and third harmonic frequencies for the piano string in Item 5.

c. Advanced Level

7. Standing waves on strings or in closed pipes are dependent on the existence of nodes, or points where no vibration or displacement can occur. In a stringed instrument, this happens at the ends of the strings. In an organ pipe, this happens because the ends are closed and pressure waves cannot pass through the closed ends. If one end of an organ pipe (or other musical wind instruments) is open, then the air column is able to vibrate at the open end. This means that only one end is fixed, and we are allowed an integral number of quarter wavelengths. In such a pipe. However, we are not allowed the even numbers of quarter wavelengths, just the odd ones. Does a closed pipe have a higher or lower fundamental frequency than an open pipe of the same length? Set the length of an open tube to $0.8\ \mathrm{m}$. Experimentally find the fundamental frequency and the frequencies of the third and fifth harmonic.

8. We have only addressed the variables of length, wave speed, harmonic number and frequency. These seem to be adequate to fully describe the frequency of a standing wave. But we know that when a musician tightens a guitar string, the frequency of the sound changes. Which of these independent variables changes value when a string is tightened?

Lab Guide
Waves on a Rope

I. Objectives

After completing this simulation, the student will be able to:
1. Describe the reflection of a wave traveling on a rope
2. Describe the effect of tension in a rope on the speed of a transverse wave
3. Describe the effect of the mass of a rope on the speed of a transverse wave
4. Describe the effect of the wavelength of a transverse wave on the speed of the wave
5. Explain the interaction of waves as they pass each other

II. User Interface and Simulation Features

This experiment simulates a transverse wave pulse traveling from one end of a string or rope. At the other end, opposite the initial propagation, the wave is reflected. You may choose whether the other end of the rope is fixed in place or is free to move up and down. The rope conveniently has a length of 1.0 m. The rope is under tension produced by the force of gravity on a mass. You may vary the size of the mass, the mass per unit length of the rope, and k, which changes the wavelength of the wave. The variable k is known as the wave number. You may choose to create a small, medium or large amplitude pulse. You start this simulation by clicking on one of the "Create Pulse" buttons. You may create more than one pulse on the rope at a time. The digital clock in the lower right of the screen restarts from time zero each time you start the simulation.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Notice that the default setting is to have the opposite end of the rope fixed in place. Run the simulation by creating a small pulse. What happens to the wave when it is reflected from the fixed end? Now uncheck the "Fixed/Free End" button. Create another small pulse. What happens to the wave this time when it is reflected?

2. Create a small pulse. When the pulse has traveled the entire length of the rope, pause the simulation and read the digital timer. How long did it take the wave to reach the end of the rope? Repeat this with a medium pulse. Did the time change? Repeat this with a large pulse. Did the time change? What is the speed of the wave?

3. Create a small pulse. When the pulse has traveled the entire length of the rope, pause the simulation and read the digital timer. How long did it take the wave to reach the end of the rope? What is the speed of the wave? Now change the hanging mass to 2.0 kg. Time a small pulse again. How long does it take this time? What is the wave speed with the lower tension?

Now increase the mass to 4.0 kg. Time a small pulse. What is the new wave speed? How does wave speed change with a change in tension?

4. Set the mass per unit length of the rope to 0.02 kg/m (twice the default). What is the speed of a small pulse now? Double the mass per unit length again, to about 0.04kg/m. What is the speed of a small pulse with this rope? A traveling wave involves the acceleration of the mass of the rope. Why does a change in the mass per unit length affect the wave speed? Does the size of the pulse make any difference with this changed setting?

5. Create a small pulse. What is the speed of the wave? Pause the simulation and measure the length of the pulse at the axis of the rope. Change the k-value to $3.9\pi/\text{m}$. Create another small pulse. What is the speed of the wave now? Is the wavelength greater or smaller? Now change the k-value to $5.9\pi/\text{m}$. What is the speed of the wave with this greater value? Is the wavelength greater or smaller? How does the wavelength change with increasing k?

b. Intermediate Level

6. Create a small pulse. About three seconds later, create a second small pulse. Watch carefully as the first pulse is reflected and interacts with the second pulse. Do this experiment several times, interrupting with the “Pause” button at different points during the interaction. What do you observe?

7. Create a large pulse. About 3 seconds later, create a small pulse. Watch carefully as the first pulse is reflected and interacts with the second pulse. Do this experiment several times, interrupting with the “Pause” button at different points during the interaction. What do you observe this time?

c. Advanced Level

8. Uncheck the “Fixed/Free End” button. Create a small pulse. About 3 seconds later, create another small pulse. Watch carefully as the waves pass through each other. What do you observe about the amplitude? Why is this happening?

9. Can you create an “extra-large” pulse? Click 2 or 3 times in very rapid succession on the “Large” button. What do you observe? Complex waveforms such as triangular waves and sawtooth waves can be made by combining simpler waves. Try constructing a complex wave. Clicking very rapidly, create this series of large pulses: 1-2-3-2-1. The numbers represent the number of very rapid mouse clicks and the hyphen represents a very short pause – roughly the time of one mouse click or less. Practice with this a bit. What is the shape you observe?

Lab Guide
Doppler Shift II

I. Objectives

After completing this simulation, the student will be able to:
1. Describe the interference of sound waves from two moving sources
2. Demonstrate constructive interference from two moving sources
3. Quantitatively describe a “sonic boom” from two moving sources.

II. User Interface and Simulation Features

This simulation combines the Doppler effect with wave interference. It has provisions that are similar to Doppler Effect I. We recommend that you work through Doppler Effect 1 so that you will have an initial understanding of the concepts and ideas before you attempt Doppler Effect 2. In this simulation there are 2 sound sources, Source A and Source B on a Cartesian coordinate grid. The grid spacing is $400\ \mathrm{m/division}$. You can choose to show or hide the grid. Sometimes the grid interferes when you are trying to detect the details of wave interference, and it helps not to show it. The period of the sound waves and the translational velocity of the source can be varied using slider bars. Crests of waves are represented by rings radiating from the source. You can choose the number of rings to be shown up to a maximum of 25 using another slider bar. The speed of sound in the medium is likewise variable. There is a digital timer near the bottom right of the screen. The timer is synchronized with the motion of the sources, and operates faster than real time.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

<u>a. Introductory Level</u>

1. Run the simulation. As the two sources approach each other closely, pause the simulation every second or two. Do you see the intersection of rings? What type of interference is this? What type of interference occurs where the ring of one source is at the same point as the space between rings of the other source? Remember that constructive interference appears as light bands and destructive interference appears as dark bands.

2. Set the velocities of both sources to zero. Set the periods of both sources to $2\ \mathrm{s}$, and the number of rings for both sources to 25. Place Source A at the origin. Place Source B at the point $(1.00\ \mathrm{km}, 0)$. Run the simulation. How many bands of constructive interference do you observe? Now move Source B in the y-direction only through a displacement of about $\pm 0.4\ \mathrm{km}$. What do you observe about the bands of constructive interference?

3. Set the velocities of both sources to zero. Set the periods of both sources to $2\ \mathrm{s}$, and the number of rings for both sources to 25. Place Source A at the origin. Place Source B on the x-

axis at the point $(6.60\text{ km},0)$. Run the simulation. Consider the speed of sound and the period of the waves. How many wavelengths apart are the two sources? Is the x-axis a location of constructive or destructive interference?

4. Place Source A at the point $(-10,0)$ and Source B at the point $(10,0)$. For both sources, set the velocities to $10\,\text{m/s}$, the wave period to 2 s and the number of rings to 25. Run the simulation. As the rings begin to overlap, describe what happens at the x-axis regarding the type of interference that occurs. As the sources themselves approach each other very closely, describe the areas of constructive interference and how they move. Note that this source speed as not very great compared to the speed of sound.

<u>b. Intermediate Level</u>

5. Place Source A at the point $(-10\text{ km},0)$ and Source B at the point $(10\text{ km},0)$. For both sources, set the velocities to $150\,\text{m/s}$, the wave period to 2 s and the number of rings to 25. Run the simulation. As the sources approach each other, what does the interference pattern look like between the sources? As the sources pass each other, do they produce any uniform shape of constructive interference? What shape is it? After the sources pass each other (at a separation of 6-10 km) what does the constructive interference pattern look like?

6. Place Source A at the point $(-10\text{ km},-3\text{ km})$ and Source B at the point $(10\text{ km},3\text{ km})$. For both sources, set the velocities to $150\,\text{m/s}$, the wave period to 2 s and the number of rings to 25. Run the simulation. As the sources approach each other, what does the interference pattern look like between the sources? After the sources pass each other, look at the speed at which the pattern changes. Does it increase or decrease?

<u>c. Advanced Level</u>

7. Set the period for both sources to 2 s and the velocity for both sources to $900\,\text{m/s}$. Set the speed of sound to $300\,\text{m/s}$. What is the wavelength of the waves? Place both sources on the x-axis. Place Source A exactly 2 wavelengths behind Source B and moving in the same direction. You may have to start the sources near the edge of the screen to do this. Run the simulation. Pause the simulation when the sources are “out in the open” away from rings that have not yet been reflected. Fine-tune the position of Source A if necessary, restart and pause again. If the sources were two supersonic aircraft, how many sonic booms would an observer on the ground hear? Is there a time separation? If so, what is its value?

8. Set the period for both sources to 2 s and the velocity for both sources to $900\,\text{m/s}$. Set the speed of sound to $300\,\text{m/s}$. What is the wavelength of the waves? Place both sources on the x-axis. Place Source A exactly 2 wavelengths behind Source B and moving in the same direction. You may have to start the sources near the edge of the screen to do this. Run the simulation. Pause the simulation when the sources are “out in the open” away from rings that have not yet been reflected. If necessary fine-tune the position of Source A, restart and pause again. Is the interference constructive or destructive on the x-axis behind Source A? What is the maximum number of rings that intersect at a given point on the x-axis behind Source A?

Compare the intensity of the sound you would hear on the x-axis behind Source A to the intensity you would hear if only Source B were present.

9. Set the speed of sound to $300\,\mathrm{m/s}$. Set the velocities of both sources to $900\,\mathrm{m/s}$. Run the simulation. What angle does the wave front creating the “sonic boom” make with the horizontal (refer to Doppler Shift I if you need to)?

Lab Guide
Thin Film Interference

I. Objectives

After completing this simulation, the student will be able to:
1. Explain why specific colors are reflected from a thin film
2. Describe the phase change of light traveling from one medium to another
3. Explain the effect of changing the thickness of the thin film on which colors are seen
4. Describe the effect of the comparative magnitudes of the three refractive indices
5. Apply thin film interference to natural occurrences.

II. User Interface and Simulation Features

In this simulation, you are provided three layers of transparent media, each in contact with the next. You can select the refractive index of each medium. You can select the thickness t of the second layer of the media (the thin film). You can also select a wavelength of visible light with which to experiment. The screen is a graphic image of the three layers showing the sinusoidal light rays. It is interactive, and responds to your inputs. At the right side of the screen there is a gray information window that provides both a numeric and graphic display of the path difference of the two reflected light rays. This information is also interactive, responding to your inputs.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Observe the initial settings of the simulation. Is the refractive index of the top layer, n_1, greater or smaller than for the thin film, n_2? Does the electromagnetic wave stay in phase, or is its phase shifted, when it is reflected from the thin film (reflected ray #1)?

2. Change n_1 to a higher value than n_2. Use $n_1 = 1.27$. Is the reflected ray in phase with the incident ray or is its phase shifted?

3. What are the values of n_2 and n_3? Should reflected ray #2 be in phase or out of phase with the ray incident on the medium at the bottom? What does the simulation show? Set $n_2 = 1.60$. What happens to the phase relationship now?

4. The default settings show thin film constructive interference. Notice that in these settings, $n_1 < n_2 < n_3$. This is something like light propagating in air, then a thin film of water, and having the lower layer of glass. This is an important relationship. At 480 nm and 1200 nm film thickness, reflected ray #2 is in phase with reflected ray #1. The phase difference shown in the

gray box is zero. The difference in path length is $6.00\lambda_2$, an integral number of wavelengths. Change the film thickness to $900\ \mathrm{nm}$. Remember that the film thickness is the same order of magnitude as the wavelength of light. What is the phase difference now between the two reflected rays of light? What is the difference in path length? Is this constructive of destructive interference? Would you expect to see a band of light of $\lambda = 480\ \mathrm{nm}$ reflecting from a film of thickness $t = 900\ \mathrm{nm}$ under the given conditions?

5. Decrease the wavelength of light to $400\ \mathrm{nm}$. What is the difference in path length? What is the difference in phase difference? Is this constructive interference, destructive interference, or something in between. If you are able to see light of this short wavelength in the visible spectrum, will it be bright or faint?

6. Set the wavelength to $640\ \mathrm{nm}$. With a $1200\ \mathrm{nm}$ film thickness, would you see light of this wavelength reflected from the thin film? What color would this be?

<u>b. Intermediate Level</u>

7. Set both the film thickness and the wavelength to $700\ \mathrm{nm}$. What is the path difference? What is the phase difference? Change both the film thickness and wavelength to $560\ \mathrm{nm}$. Did the path difference or the phase difference change? Now set both the film thickness and wavelength to $410\ \mathrm{nm}$. Did either of the path difference or the phase difference change?

8. Set both the film thickness and the wavelength to $700\ \mathrm{nm}$. Set $n_3 = 2.00$. What value or values of n_2 will produce constructive interference? What value or values will produce destructive interference? Note that the underlying formulas produce a phase shift exactly where $n_1 = n_2$ or $n_2 = n_3$. Now set both the film thickness and the wavelength to $700\ \mathrm{nm}$.

<u>c. Advanced Level</u>

9. A familiar example of thin film interference is a soap bubble. A light wave propagates in air, $n_1 = 1.00$, is incident on a film of water, $n_2 = 1.33$, and then is reflected from the third medium, air again, $n_3 = 1.00$. This is a different situation than in Item 4. Here $n_1 < n_2$ but $n_2 > n_3$. The reason these relationships are important is that they reverse the conditions for constructive or destructive interference. Note that the soap keeps the surface tension of water from breaking the bubble, but does not materially affect the refractive index. Assume a film thickness of $1000\ \mathrm{nm}$ and set the refractive indices. Start with $\lambda = 400\ \mathrm{nm}$ and work your way up to $\lambda = 700\ \mathrm{nm}$. What three wavelengths are closest to constructive interference? What colors are these?

10. One indication of environmental petroleum contamination is a “sheen” on standing water. This is thin film interference through a film of some petroleum product. Suppose a ray of light in air passes through a film of thickness $t = 600\ \mathrm{nm}$ of a contaminant with $n_2 = 1.42$. What predominant colors would you see reflected from this film?

Lab Guide
Multiple-Slit Interference

I. Objectives

After completing this simulation, the student will be able to:
1. Describe the effect of change in wavelength on the interference pattern
2. Describe how changing slit width changes the interference pattern
3. Describe the effect on the interference pattern of increasing the number of slits
4. Describe the effect on the interference pattern of changing the spacing between slits
5. Identify one use of multiple-slit interference in everyday life.

II. User Interface and Simulation Features

This is a simulation of a system in which incident light diffracts around the edges of narrow slits in an opaque material. The waves of the diffracted light interfere, and the interference pattern is seen on a screen at the right. You can think of the screen as an electronic detector with CRT display, because the spacing of the principal and secondary maxima is measured and displayed at the bottom right corner of the screen. You can control the number of slits, the spacing between slits, the width of the slits, and the wavelength of the light by means of slider bars. A graphic image of the slits appears at the left of the screen. The display of the interference pattern is shown in two ways. There is a visual representation of the pattern falling on a screen. There is also a vertical plot of intensity versus displacement from the central maximum.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. Set the number of slits to 1. Run the simulation. Notice the two minima on either side of the central maximum, marked by the blue lines. How would you find the angle θ between the central axis and one of these minima?

2. Set the number of slits to 1. Set the wavelength to $\lambda = 400\ \mathrm{nm}$. Run the simulation. The width of the central maximum is the distance between the two blue lines. What is the magnitude of this width? Now change the wavelength to $\lambda = 700\ \mathrm{nm}$. What is the width of the central maximum now? What is the relationship between the wavelength and the width of the central maximum?

3. Set the number of slits to 1. Set the slit width to $1600\ \mathrm{nm}$. Run the simulation. What is the width of the central maximum? Now change the slit width to $3000\ \mathrm{nm}$. Run the simulation again. Now what is the width of the central maximum? What is the relationship between central maximum width and slit width?

4. Set the slit width to zero. For one slit, what does the interference pattern look like? Increase the number of slits to 2. Now what does the pattern look like? Set the number of slits to 3. What is different about the pattern this time? Try it with 4 slits. What do you see? What is the relationship between the number of slits n and the number of secondary maxima?

5. Set the slit width to zero and the number of slits to 2. What is the spacing between primary maxima (multiply the red line spacing by the number of "red lines spaces" between primary maxima)? Try this for 3, 4, 5 and 6 slits. What do you notice about the positions of the primary maxima?

<u>b. Intermediate Level</u>

6. Set the slit width to zero and the number of slits to 3. What is the width of the primary maxima (twice the red line spacing)? Try this for 3, 4, 5, 6, 8 and 10. What does the relationship appear to be between the number of slits and the width of the primary maxima?

7. Set the slit width to $3000\ \mathrm{nm}$ and the wavelength to $400\ \mathrm{nm}$. What is the spacing between primary maxima? Now make the same measurement at $700\ \mathrm{nm}$, How does the spacing between primary maxima depend on wavelength?

<u>c. Advanced Level</u>

8. A diffraction grating is equivalent to a multiple-slit system, but with thousands of slits per meter. They aren't really slits, but grooves in the medium, through which the light passes, producing interference. In a practical mechanical device, why would we prefer to use a diffraction grating, than, say, a multiple-slit system with 2 or 3 slits?

9. Consider the relationship between wavelength and spacing of maxima (Item 7). Compact discs (CDs) and DVDs are reflection gratings which operate on the same principle as diffraction gratings and multiple-slit systems, except the light is reflected from the thousands of grooves in the plastic CD or DVD and undergoes constructive or destructive interference. Why do you think the entertainment industry invested so much money in developing the Blu-ray™ DVD system? This system uses a blue laser to read the data on the DVD instead of a red laser.

Lab Guide
Resolution

I. Objectives

After completing this simulation, the student will be able to:
1. Define resolution
2. Describe the effect of slit width on resolution
3. Determine resolution using Rayleigh's criterion
4. Analyze Rayleigh's Criterion
5. Describe the effect of wavelength on resolution

II. User Interface and Simulation Features

This simulation models an aperture through which light rays from two separate sources pass, forming an interference pattern on a screen. You can choose a slit or a circular aperture. Using slider bars, you can select the angular separation of the objects, the wavelength of light, and the width (or diameter) of the slit (or circular aperture). For any combination of these inputs, the simulation applies Rayleigh's Criterion for resolution and reports whether the objects are resolved or not.

III. Questions

In each case when you start a simulation for the following questions, reset the values using the icon in the control panel at the left side of the screen. Each question assumes that you have done this. Then set only the values indicated in the question.

a. Introductory Level

1. The default settings show two objects in red light with their central maxima resolved. At what circular aperture diameter are the two maxima just barely resolved? Did you have to decrease or increase the diameter? Does increasing or decreasing the diameter improve the resolution?

2. Choose a slit instead of a circular aperture. Can you find a slit width at which the two maxima are not resolved (retaining all the other default settings)? Of a circular aperture or a slit, which will resolve two maxima at the smaller diameter/slit width?

3. Select a slit instead of a circular aperture. Set the slit width to its minimum value. What is this value? What is the minimum angular separation that will be resolved at this slit width and wavelength?

4. Select a slit instead of a circular aperture. Set the slit width to $2000\ \mathrm{nm}$. What is the minimum angular separation that will be resolved at this slit width? What is the relationship between slit width and resolving power?

5. Select a wavelength of green light at $510\ \mathrm{nm}$. Using default values for all other settings, find the minimum angular separation that can be resolved using this wavelength.

b. Intermediate Level

6. Rayleigh's Criterion for resolution is $\theta > 1.22\lambda/a$ for circular apertures. Gradually decrease the angular separation while watching the guidelines on the graphic display. What happens to the guidelines at the point where an angular separation becomes unresolved?

7. Set the wavelength to $590\ \mathrm{nm}$. This is approximately the wavelength of the sodium doublet and close to the wavelength of maximum sensitivity for the human eye. Find the greatest angular separation that is not resolved. What is this value? Where is the center of the left pattern in relation to the central maximum width of the right pattern? Turn off the guidelines. Can you identify two distinctly separate "objects" on the screen or only one? Reduce the angular separation further, by $0.01\ \mathrm{rad}$ at each step. At what angular separation can you no longer visually distinguish two circular "objects" from one oblong or elliptical "object"? Is Rayleigh's Criterion too strict or too lenient for visual observation?

c. Advanced Level

8. Suppose you wished to maximize the resolution of two maxima using the apparatus in this simulation. What are all the settings you would use? What is the minimum angular separation you can resolve?

9. Apart from the reasons why deep space objects emit X-rays in the first place, why else would astronomers want to photograph these objects at X-ray wavelengths?