A Conceptual Introduction To Wave Properties and Quantum Physics

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Activity 1: Exploring Waves   Name: .

Introduction: When you hear the word 'wave' you may picture an ocean shore or think of sounds moving through the air. We are going to explore a much smaller world where tiny things like light and particles possess wave characteristics. To get warmed up, we are going to make some waves with a spring and observe some of the important characteristics of waves.

Materials: Slinky or other spring

Procedure:
1) Get a partner and a slinky.

2) Find a place where you can stretch out the slinky on a table top or on a tile floor. Slinky must be on floor!

3) Hold one end of the slinky and have your partner hold the other end and stretch the slinky 4-6 meters.

4) Use the time you are given to investigate waves with the slinky. Investigate as many things as possible in the time allowed. As you investigate, record your observations and any data that you may collect. At the conclusion of this activity, you will be reporting your findings to the class.

Here are some suggestions.

- How many different ways can you make waves move through the slinky?
- How many waves can you make in the slinky at one time?
- How big can you make waves?
- How is the size of a wave related to the number of waves you make at the same time?
- How are waves related to energy? (Does it take more energy to make more waves?)
- How does the tension in the slinky affect the waves? (You can increase the tension by gathering some of the slinky at one end and holding it while you make waves)
- Do waves have displacement, velocity and acceleration?

Questions:
1) You may already know some things about waves. Write down any terms that you associate with waves. Can you define these terms?

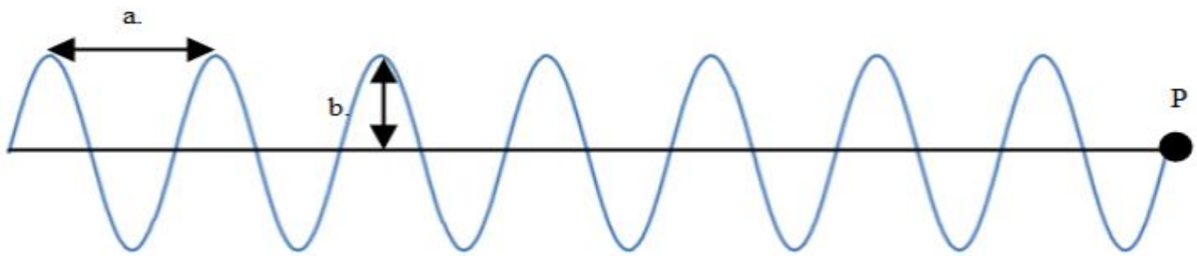
2) If you were describing the waves that you made to another person, what are some characteristics of the waves you would use?

3) Draw a picture of one wave.

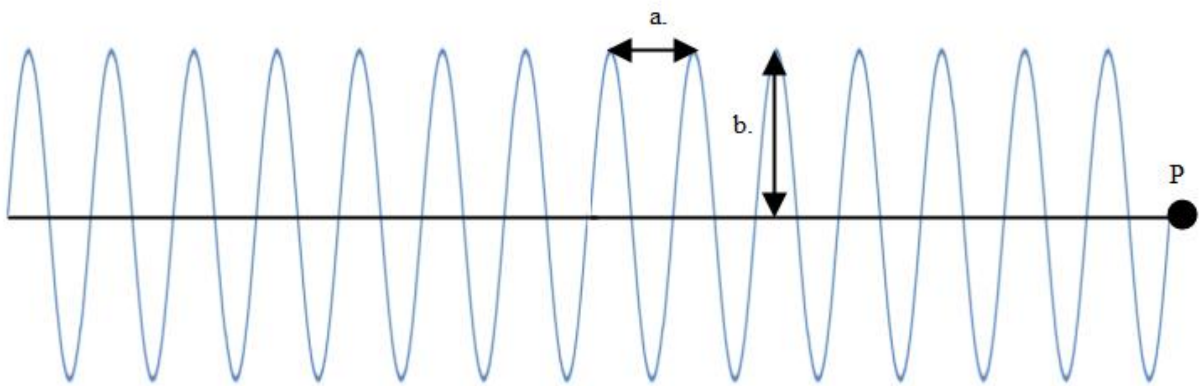
4) Draw a picture of multiple waves with one line.

Present your finding to the class

Activity 2: Wave Characteristics Name: .



Wave A



Wave B

Shown above are two waves that are moving from left to right passing the same point P in one second.

<u>Concept Questions:</u> Refer to Model 1 while answering the following questions about wave characteristics.

1) a) Use a ruler to measure distance ‘a’ in millimeters for both waves.

1b) Compare characteristic length ‘a’ for wave A and B.

2) Measure and compare characteristic length ‘b’ for wave A and B.

3) Define wavelength (a).

4) Define amplitude (b).

5) Identify the number of complete wavelengths shown in the model for both waves.

6) Determine the frequency of each wave by dividing your answer to question 5 by 1 second.

7) Compare the frequencies of wave A and wave B.

8) Write a sentence describing the relationship between the wavelength and the frequency of a wave.

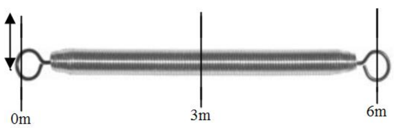
9) In Activity 1 you learned that it took more energy to make more waves, write a statement describing the relationship between frequency and energy.

Activity 3: Wave Interactions Name: .

Purpose: You have recently learned about wave properties. In this activity you will observe the changes in the amplitude of two waves that meet in the middle of a long spring.

Part 1: Making waves

1) Place a 1 meter piece of masking tape on the floor. Measure a distance of 3m away from the center of the first piece of tape and place an identical piece of tape on the floor. Place a third identical piece of tape at 6m from the first piece of tape. Mark the center of each piece of tape.
2) Hold the end of the spring at the center of the 0m tape mark. Have your partner hold the other end of the spring and stretch it to the 6m tape mark and hold it at the center. The third person should sit at the 3m mark and observe the displacement of the spring from the center mark during the activity.



3) Your partner should hold the spring at the center mark at 6m. Using a quick snap movement, move the end of the spring from the center of the tape mark to end of the tape mark and back to the center. This should create a wave that travels down to your partner and back to you. We will call this a transverse wave. Have your partner create a wave in the same way while you hold your end at the center mark. Take some time to practice making transverse waves with the spring until you and your partner can make consistent waves. Record your observations of the displacement along the 3m tape mark. How does the displacement compare to the displacement at the 0m tape mark?

Draw 3 pictures of the wave as it travels down and back.

Part 2: Wave Interaction

4) You and your partner will snap the slinky from the center to the end and back to the center of the tape at the same time and in the same direction. Practice your timing so that the two waves meet in the middle of the spring. The third person will observe the displacement along the 3m tape.
Record your observations of the displacement along the 3m tape mark. How does the displacement compare to the displacement at the 0m tape mark?

Draw a picture of the wave before, during and after they meet in the middle.

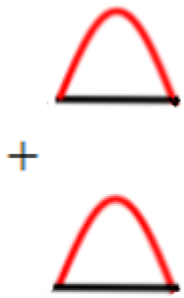
5) You and your partner will snap the spring from the center to the end and back to the center of the tape at the same time but in the opposite direction. Practice your timing so that the two waves meet in the middle of the spring. The third person will observe the displacement along the 3m tape.

Record your observations of the displacement along the 3m tape mark. How does the displacement compare to the displacement at the 0m tape mark?

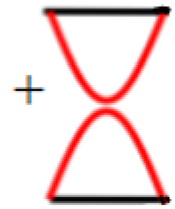
Draw a picture of the wave before, during and after they meet in the middle.

Activity 4: Wave Interference Name: .

Set A:



Set B:



Sketch Result: **Sketch Result:**

The model above shows two different ways that waves can interfere with each other.

Concept Questions:

1) Predict how the waves in Set A combine and sketch the result above.

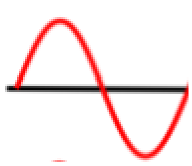
2) Predict how the waves in Set B combine and sketch the result above.

3) Set A represents constructive wave interference. In your own words, define constructive wave interference.

4) Set B represents destructive wave interference. In your own words, define destructive wave interference.

For the following, assume the two waves have the same frequency and velocity.

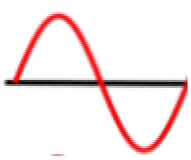
5) On the right, sketch a wave that will destructively interfere with the wave on the left.



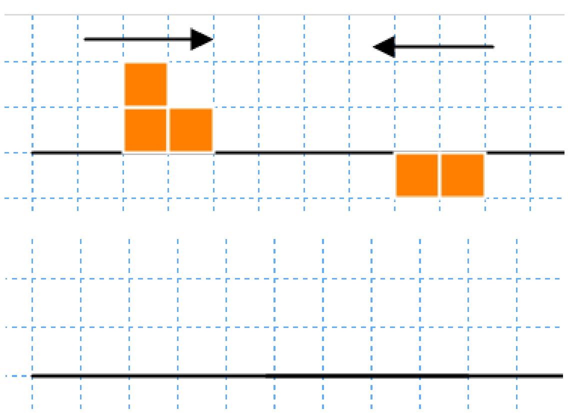
6) Sketch two waves that are different from the previous drawings that will destructively interfere.

7) Sketch two waves that will only partially experience destructive interference.

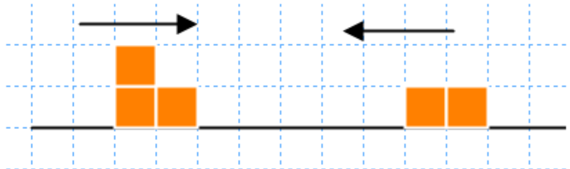
8) Sketch a wave that will constructively interfere with the following wave:

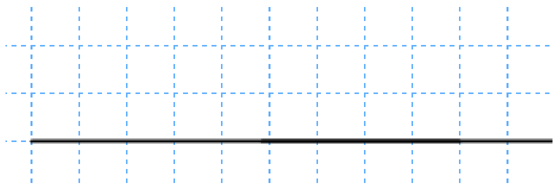


9) Two pulse waves are sent through a spring in opposite directions as shown below. Sketch the result of the pulse waves at the instant they combine. Is this constructive or destructive interference?

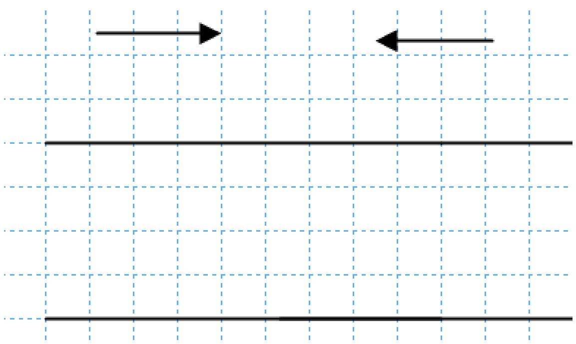


10) Two pulse waves are sent through a spring in opposite directions as shown below. Sketch the result of the pulse waves at the instant they combine. Is this constructive or destructive interference.





11) Sketch an original pulse wave pattern and show the result of the combined pulse waves.



Activity 5: Phet Simulation: Fourier: Making Waves

Purpose: In this activity you will use a simulation to learn more about how waves combine through constructive and destructive interference by playing a game.

Play the 'Wave Game'

1) Open the URL: https://phet.colorado.edu/en/simulations/category/physics/quantum-phenomena
2) Open the simulation named: Fourier: Making Waves
3) Select the 'Wave Game' tab.
4) Click and drag the amplitude bar until you match the given wave pattern.
5) When you feel you have mastered level 1, change the level setting to level 2.
6) Continue moving up the levels. As you level up you will begin to combine waves. As you do this, think about how the waves are combining through constructive and destructive interference.
7) Continue moving up the levels until you reach the highest level or you run out of time.

Teachers: There are many activities you can do with this simulation. Click the 'teacher' link on the page that you used to download the simulator.

Activity 8: Determining Fundamental Units Name:

Materials:

Electronic balance (not provided)
Sealed envelopes numbered 1-30
Computer with Microsoft Excel or other spreadsheet software
(if computers are not available, students can create graphs on paper or one graph can be sketched on board)

Procedures:

Evenly distribute the 30 envelopes out to different groups to weigh.
Create a data table and graph in Excel or write data on the white board.

Analysis:

1.) What patterns do you notice about the class data? Do you have any suggestions to better organize the data?

2.) Obtain one of the envelopes labeled with an asterisk (*). Measure the mass of the envelope and use your data to determine where it fits in with the other data..

3.) Determine the increase in mass between the similar groups of envelopes. In the space below, explain how you arrived at your answer.

4.) What is your best estimate for the mass of the *envelope*? In the space below, explain how you arrived at your answer.

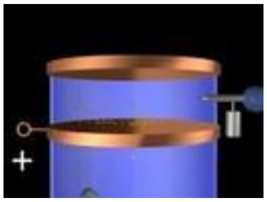
5.) Based on your data, do you think that an identical envelope could have a mass value of 12.0 grams? Justify your answer.

6.) The mass values in this lab were “quantized” because the additional mass in the envelopes was limited to using only whole numbers increments of the amount you determine in step 3. Based on the results of this lab, how would you define “quantized”.

7.) Is mass in “real life” quantized? Explain your answer.

Extension:

Show Video: Millikan Oil Drop Experiment



https://www.youtube.com/watch?v=XMfYHag7Liw

8.) In 1909, Robert Millikan performed a famous experiment with charged oil drops to measure the charge of an electron. Each oil drop contained at least one extra electron to cause unbalanced charge. Although Millikan did not know how many extra electrons were on each drop, he measured the unbalanced charge on many drops and used this data to determine the charge of a single electron. Suppose that the measurements listed below represent the charges of some of the oil drops used by Millikan. Based on this data, what is the charge on an electron?

1.6×10^{-19} C

3.2×10^{-19} C

4.8×10^{-19} C

6.4×10^{-19} C

9.) According to your results from Question #8, what would a charge of $.8 \times 10^{-19}$ C represent? Do you think it is possible for a particle to exist with this amount of charge?

Activity 9: Mathematical Relationships in Electromagnetic Waves: Name:

1) Based on your observations in Activity 2, complete the following statement:

As the wavelength of a wave decreases, the frequency of the wave ___________________________________.

Is the relationship between wavelength and frequency directly proportional or inversely proportional?

Table 1: Show below are sample data from electromagnetic waves in a vacuum tube.

Wavelength (m)	Frequency (s^{-1})	Speed (m/s)
1.0	$3.0x10^{8}$	
$6.0x10^{-3}$	$5.0x10^{10}$	
$5.0x10^{-7}$	$6.0x10^{14}$	
$2.0x10^{-12}$	$1.5x10^{20}$	

2) For each row in the table 1, combine the wavelength and frequency values in a way that will give the speed of the waves. Think about the units.

3) Based on the data table 1, what is the value of the speed of the waves?

4) Using the symbols λ (wavelength), *v* (frequency), and c (speed), write an equation that is consistent with the data in the table above.

5) Based on your observations in Activity 2, complete the following statement:

As the frequency of a wave increases, the energy of the wave ___________________________________.

Is the relationship between the frequency and the energy of the wave directly proportional or inversely proportional?

Show below are sample data from electromagnetic waves in a vacuum tube.

Frequency (s^{-1})	Energy (J)	Constant (J·s)
$3.0x10^{8}$	$1.98x10^{-25}$	
$5.0x10^{10}$	$3.3x10^{-23}$	
$6.0x10^{14}$	$3.96x10^{-19}$	
$1.5x10^{20}$	$9.9x10^{-14}$	

6) For each row in the table above, combine the frequency and energy values in a way that will give a constant value with the unit J·s.

7) Based on the data in the table, what is the value of the constant?

8) Using the symbols *f* (frequency), E (energy) and h (Planck's constant), write an equation that is consistent with the data in the table above.

9) A wave of red light has a wavelength of 6.5×10^{-7}m. Calculate the frequency and energy of the red light using the equations you wrote in questions 4 and 8.

10) A wave of green light has a wave length of 5.1×10^{-7}m. Calculate the frequency and energy of the green light.

11) A wave in the ultraviolet spectrum has a wave length of 2.5×10^{-7}m. Calculate the frequency and energy of the ultraviolet wave.

12) A cell phone uses a wave with a frequency of 8.0×10^{8} s^{-1} or 800 MHz (Megahertz). Calculate the energy of this wave.

13) Use your answers to 9, 10 and 11 to compare the energy of red, green and UV light.

Activity 10: Photoelectric Effect Simulation Name: .

1) Open: https://phet.colorado.edu/en/simulation/legacy/photoelectric
2) Start simulator. Open the three graphs on the right side of the simulator.
3) Use the pull down menu to change the metal to zinc which is the metal used in our electroscope.
4) Set the wavelength of light to about 650 nm which is visible red light like the light produced by our laser pointer.
5) Set the intensity to 50%. You should now see red light coming from the source and directed at a zinc plate. The zinc plate is located inside a vacuum tube with another metal plate on the opposite side of the tube. The plates are connected in a circuit with an ammeter and a battery.
What do you observe happening?

6) Slowly shorten the wavelength until you observe something happening. Record your observation.

At which wavelength are electrons ejected from the zinc metal?

Is this consistent with what you observed with the electroscope?

Based on your observations, what causes the electrons particles to become ejected from the zinc?

7) Set the wavelength of the UV at 240nm. Investigate the effect of changing the intensity. Observe the current value and the graphs.
The current will increase as more electrons are ejected over time.
Intensity is a measurement of the number of UV photons striking the zinc plate at a given time.
Record your findings.

Observe the graph of intensity and current. Describe the relationship between the intensity of light and the current.

Observe the frequency vs kinetic energy graph. What is the effect of the light intensity on the kinetic energy of the electrons?

8) Repeat step 7 with the 650 nm red light. Record your findings.

9) Set the wavelength back at 240 nm with 50% intensity. Slowly decrease the wavelength while observing the frequency(f) of wave verses kinetic energy(KE) of electrons graph.
Describe the graph curve.

Write a mathematical equation for the graph curve in terms of y, m, x and b.

Identify the y and x variables in the equation.

The slope represents Planck's constant, h. Use data from the graph to calculate the value of Planck's constant.

Convert your slope value into Joules using the conversion 1 Joule = 6.242×10^{18} electron volts.

The y-intercept, b, is known as the work function, Φ. The work function is the energy required to ionize an electron on a piece of metal. In chemistry this value is the ionization potential or ionization energy of an electron.
Write the mathematical equation in terms of KE, f, h and Φ.

The energy of a photon of light is given by the formula, $E_{photon}=hf$.
Write your mathematical equation with E_{photon}.

Based on the equation you wrote, when will the ejected electron have no kinetic energy?

10) Change the metal from zinc to sodium. Find the maximum wavelength that causes electrons to be ejected from sodium atoms.
Record your finding.

How do the energy of these photons compare to the energy of the photons of light required to eject electrons in zinc?

Does sodium have a larger or smaller work function than zinc? Explain.

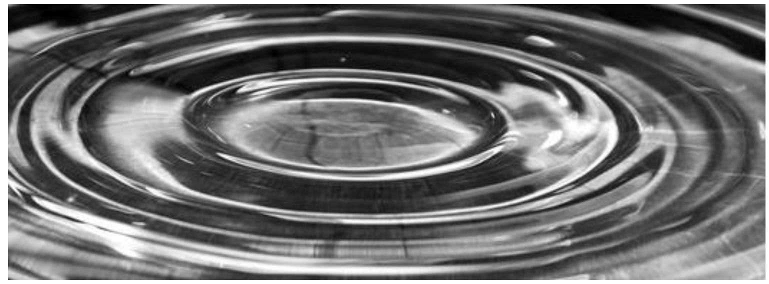
11) Find the maximum wavelength that causes electrons to be ejected from the other metals on the list.
Record your findings.

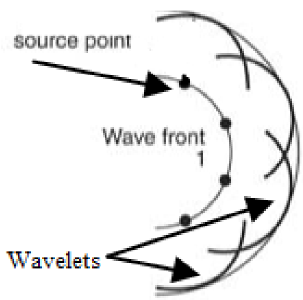
Rank all of the metals in increasing order of work function. You can do this by finding the point on the x-axis where the electrons first obtain energy. The closer the point is to the y-axis, the smaller the work function.

12) Predict the position of the unknown metal (?????) in the series above.

Activity 11: Diffraction of Waves Name ______________

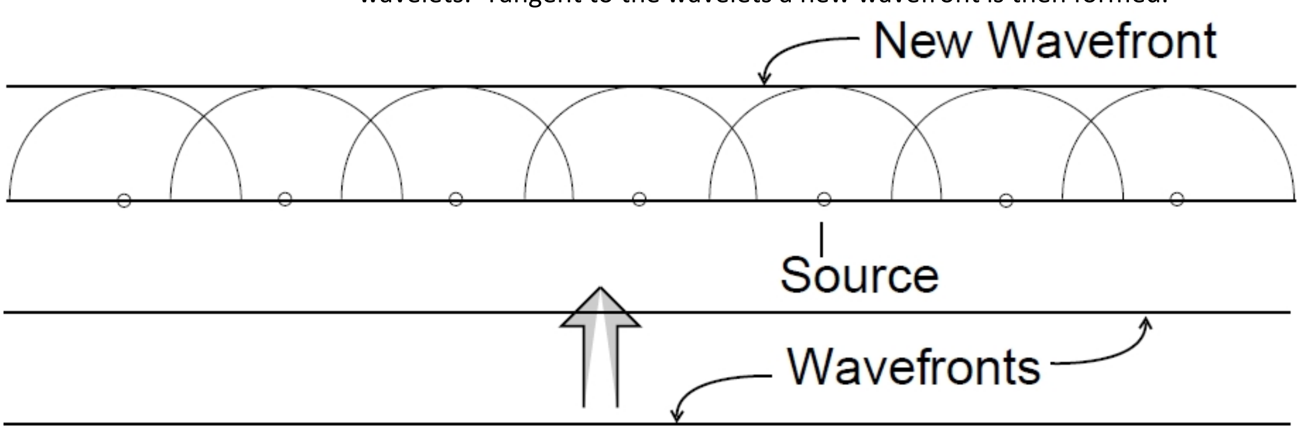
When a rock is thrown into a pond it causes ripples in the water. These are transverse waves which means that the water oscillates up and down, but the water molecules are not carried outward with the wave. The waves carry the energy of the disturbance radially outward.





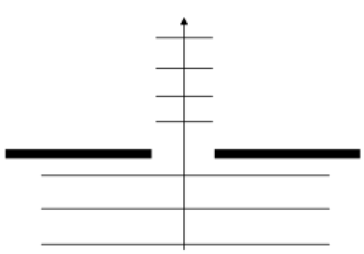
The Huygen-Fresnel Principle states that every point on an outward moving circular ripple (wavefront) can be treated like a point source creating its own wavelet. The individual wavelets move outward, and tangent to all of these wavelets a new wave front is created like in the diagram to the left.

Generating a plane wavefront like in the image below that is straight rather than curved requires a large number of point sources in a line that are all oscillating in phase with one another. This could be accomplished in water by moving a board up and down to produce a straight wavefront moving away parallel to the board. Each point on the new wavefront then acts like a point source to produces its own wavelets. Tangent to the wavelets a new wavefront is then formed.

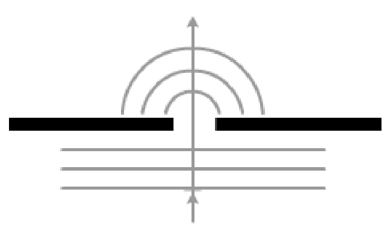


This treatment of wavefronts as being composed of an infinite number of point sources helps explain how wavefronts diffract when they go around a barrier or through an opening in a barrier.

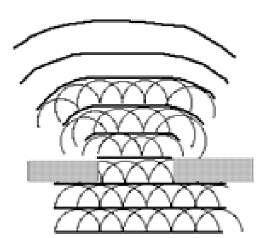
If light traveled through a slit in the barrier with no diffraction, light would only be observed directly behind the slit (a). If light diffraction occurs, the light will spread out will be observed outside of the area directly behind the slit. The light will be most intense directly behind the slit but can also be observed moving outward from that point. Diagram (c) includes the wavelets created by the point sources on each wavefront to show how each successive wavefront diffracts farther into the shadow zone of the wall.



(a)



(b)

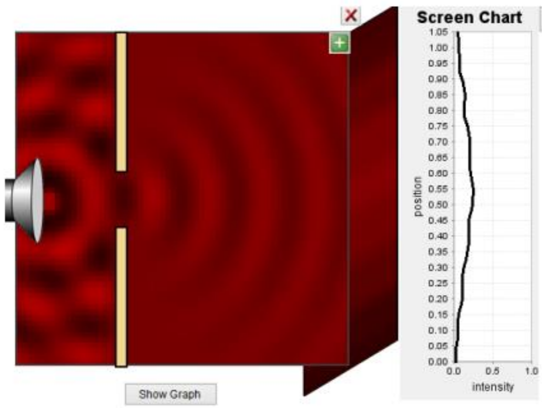


(c)

Open the PhET Wave Interference Simulation: https://phet.colorado.edu/en/simulation/wave-interference

Instruction for simulation:

- -Click on the “Light” tab.
- -Click ‘Show Screen’
- -Click ‘Show Intensity’
- -Click on “One Slit” on the toolbar on the right. Move the ‘Barrier Location’ slide bar to the second mark to the right of the zero.
- -Observe the intensity graph



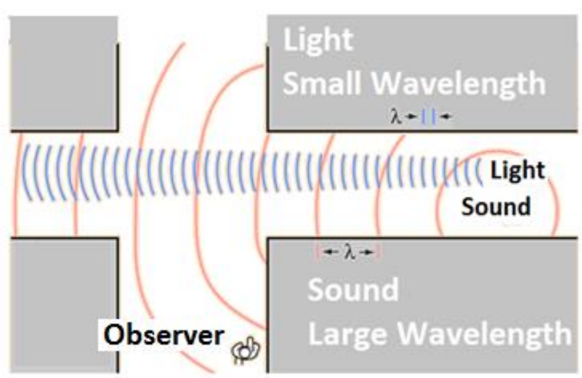
a.) Is the intensity graph consistent with diagram (a) or (b) shown above? What does this indicate about light diffraction?

b.) Change the red light (lower frequency) to blue (higher frequency). Did the diffraction increase or decrease? (The greater the diffraction, the lower the intensity directly behind the slit)

Write a statement that relates the frequency of the light to the amount of diffraction.

c.) Use the Huygen-Fresnel Principle that any point on a wavefront can be viewed as a new point source to justify the diffraction pattern as the frequency increases?

c.) Why can you hear your friend yelling from around the corner even though you cannot see him? Both light and sound are waves that diffract, and so why is there a difference?



Activity 11 Part 2: Double Slit Interference of Waves **Name** :

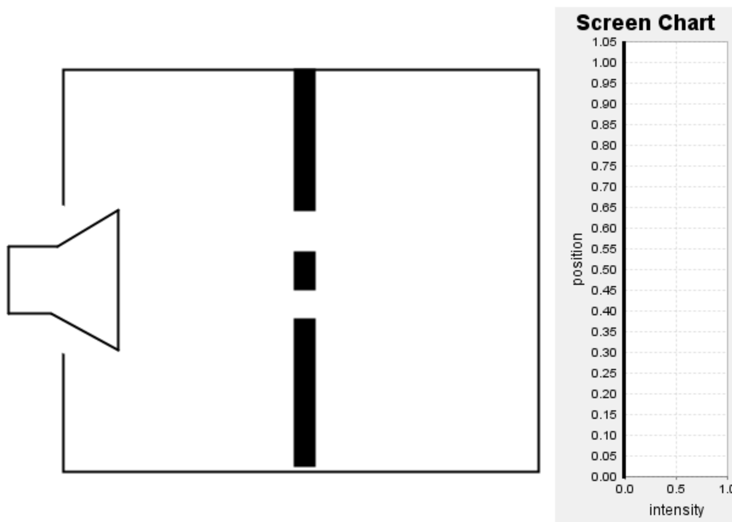
Open the PhET Wave Interference Simulation: https://phet.colorado.edu/en/simulation/wave-interference

1.) Set up Instructions for simulation:

-Click on “Light” on the top left tab.
-Click on “Reset All,” and click “Yes” on the pop up screen to reset all of the settings.
-Slide the “Wavelength” bar on the left to the dark blue color.
-Slide the “Amplitude” bar on the left all of the way to the right to produce maximum amplitude.
-Click on “Double Slit” on the right toolbar.
-Slide the “Slit Width” bar to one mark to the right of 0nm.
-Slide the “Barrier Location” bar to two marks to the right of 2590nm.
-Slide the “Slit Separation” bar to one mark to the right of 1750nm.
-Click on “Show Screen.”
-Click on “Intensity Graph” when it pops up after clicked “Show Screen.”

a.) Draw what appears on the screen and the position vs. intensity graph on the diagram.

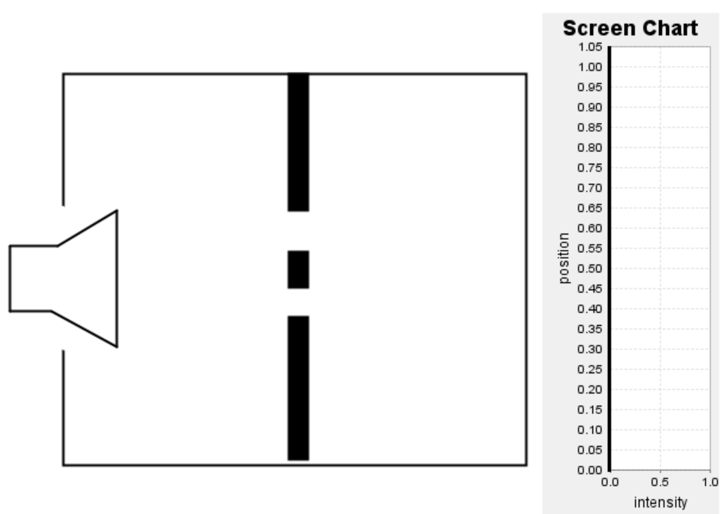
b.) Explain why this pattern appeared on the screen.



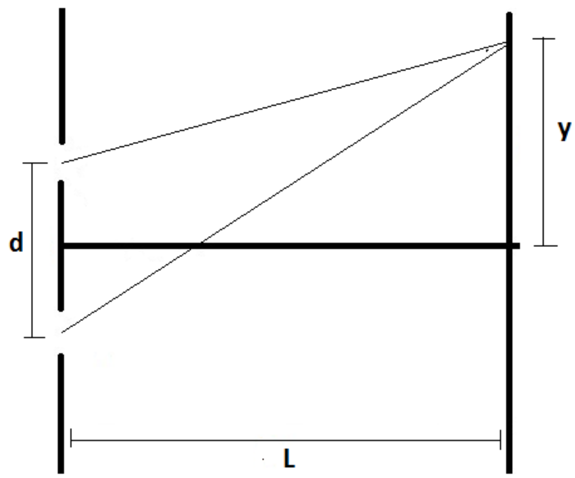
2.) Slide the “Barrier Location” bar to one mark to the left of 2590nm, and give the simulation a few seconds to produce the new pattern.

a.) Draw what appears on the screen and the position vs. intensity gap on the diagram.

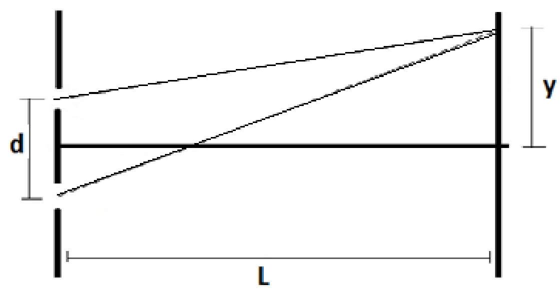
b.) What is different about this pattern compared to the pattern in problem number one?



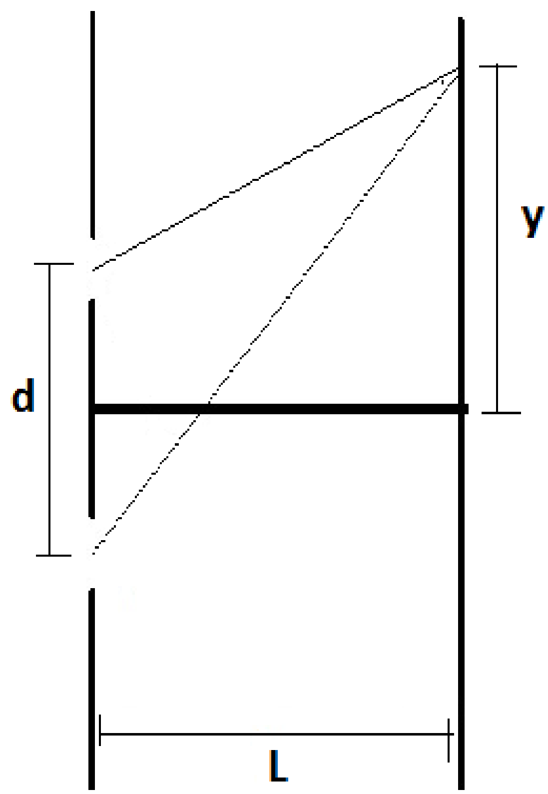
c.) What is weird about this pattern?



3.) Change the wavelength of light to determine how it changes the separation of the bright and dark fringes. Use the “Wavelength” slide bar on the left.



4.) Change the distance between the slits (see diagram to left) and record how it changes the separation of the bright and dark fringes. Use the “Slit Width” slide bar on the right toolbar. Be aware that if d is too big the interference pattern will disappear when the waves no longer overlap.



5.) Change the distance between the double slit barrier and the screen (L) and record how it changes the separation of the bright and dark fringes. Use the “Barrier Location” slide bar on the right toolbar. Be aware that if L is too small the interference pattern will disappear when the waves no longer overlap.

Activity 11 Part 3: Reviewing Classical Wave Addition Name:

Open the Quantum Wave Interference Simulation:

https://phet.colorado.edu/en/simulation/quantum-wave-interference

1.) Click on the "2 Lasers" tab at the top left of the simulation.

a.) Turn on the laser on the left, and record what happens on the screen then turn the laser off.

b.) Turn on the laser on the right, and record what happens on the screen then turn the laser off.

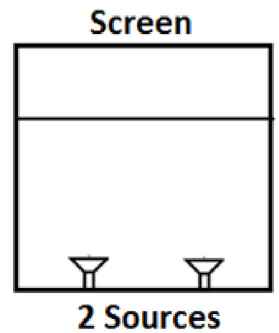
c.) Predict if there will be an interference pattern if you turn on both lasers at the same time.

d.) Turn on both lasers, and record what happens.

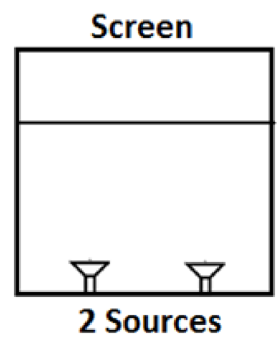
e.) What do you need to change to change the result of part d?

f.) Change that variable, and record the results of doing the experiment.

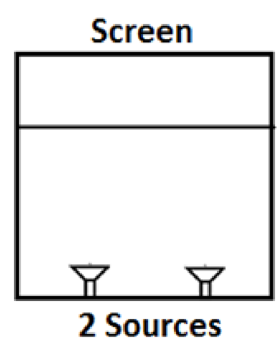
Part A



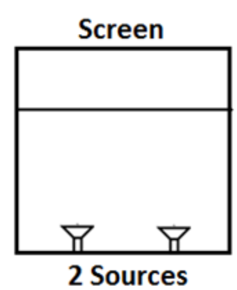
Part B



Part D



Part F



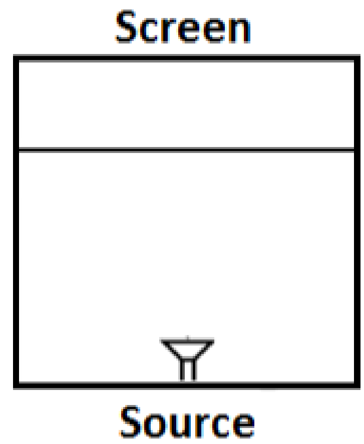
2.) Click on the “High Intensity” tab at the top left of the simulation.

a.) Turn on the laser. Record the pattern on the screen, and explain why it is there.

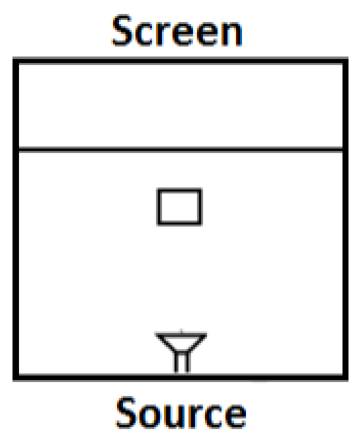
b.) Click on “Potential Barriers” on the toolbar on the right, and then click “Add Barrier.” Slide the barrier directly above the laser and near to the screen at the top. Record the pattern on the screen, and explain why it is there.

c.) Slide the barrier directly above the laser and near to the laser at the bottom. Record the pattern on the screen, and explain why it is there.

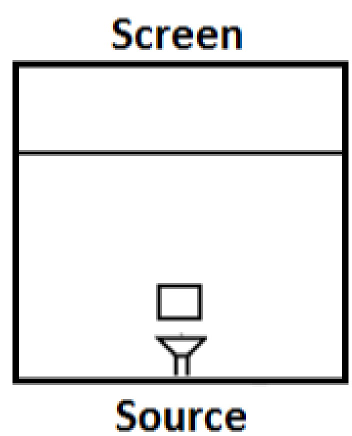
Part A



Part B



Part C



3.) Instructions to set up simulation:

-Click on the "X" on the barrier to remove it.

-Click on "Double Slits" on the right toolbar.

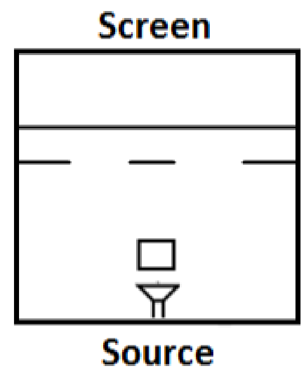
-Slide the "Slit Width" bar to the middle.

-Slide the "Slit Separation" bar all the way to the right to push the slits apart.

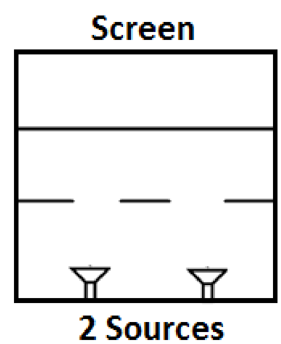
a.) Slide the "Vertical Position" bar all the way to the left to raise the slits. Record the pattern on the screen, and explain why it is there.

b.) Slide the "Vertical Position" bar all the way to the right to lower the slits. Record the pattern on the screen, and explain why it is there.

Part A:



Part B:



Notes: And Then . . . It Got Weird – The Quantum World

What is the big deal? Waves spread out (diffract) as they move because the Huygen-Fresnel Principle which states that each point of the wavefront can be viewed as a point source creating its own expanding wavelet.

A wave can interfere with another wave with the same wavelength if the waves overlap, or a wave can interfere with itself when barriers block part of its wavefront and the divided parts of the wavefront later overlap each other. When the overlapping waves hit a screen there will be a series of bright and dark spots (an interference pattern) that corresponds to constructive and destructive interference between the waves. How many more simulations are you going to make us do? We get it.

Scientists are thorough, and it is important to test theories in extreme cases to see if the theory is supported by the new data or if a new theory is needed. For example, Newton's 2^{nd} Law ($\Sigma F = ma$) matches experimental data very well at day to day speeds, but as you approach the speed of light it changes from a linear relationship between force and acceleration to an asymptote that requires an infinite amount of force to have any change in speed.

Testing the boundaries of the double slit experiment includes firing one photon at a time at the slit rather than multiple photons at the same time, which would obviously prevent the photons from interfering with each other. Each individual photon that was not blocked by the barrier would either pass through one slit or the other.

DeBroglie's Idea:

As a result of the photoelectric effect, photons were found to have properties of particles. Photons behaved as particles colliding and delivering quantized amounts of energy to electrons. An important property of objects colliding is their momentum. Momentum is the product of an objects mass and velocity. At the time a mathematical relationship for the momentum of a photon had been formulated: $p=h/\lambda$.

A scientist by the name of Louis De Broglie had proposed an important question. If photons have particle-like properties, do particles also have wave-like properties? He rearranged the equation above in the following ways:

$$\lambda = \frac{h}{p} \quad \text{or} \quad \lambda = \frac{h}{mv}$$

λ is wavelength in meters
h is Planck's constant: 6.63×10^{-34} J·s
m is mass in kilograms
v is velocity in meters per second

Derivation:
For photons moving near the speed of light: $E^2=m^2c^4+ p^2c^2$
m=0 for photons of light: $E^2=p^2c^2$ or $E=pc=mc^2$
$E=hc/\lambda = pc \rightarrow h/\lambda = p \rightarrow h/p = \lambda$

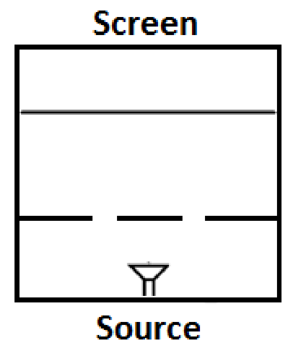
De Broglie suggested that if this relationship works for photons, it could also work for things like subatomic particles. How can we test this idea? Scientist would need to do a double slit experiment with particles.

Predict what pattern should show up on the screen when one electron at a time is fired.

Activity 11 Part 4: Particles passing through the double slit

https://phet.colorado.edu/en/simulation/quantum-wave-interference

1.) Instructions to set up simulation:
 -Click on the "Single Particles" tab at the top left of the simulation.
 -Click on "Double Slits" on the right toolbar.
 -Slide the "Slit Width" bar to the left to decrease the slit size.
 -Slide the "Slit Separation" bar all the way to the right to push the slits apart.
 -Slide the "Vertical Position" bar all the way to the right to lower the slits.



a.) Click "Fire" on the laser. Record observations of what happens.

b.) Click "Auto Repeat" in the Gun Controls box, and record observations after a few photons.

c.) Click "Rapid" next to the stop button at the bottom of the simulation, and record observations after a minute of observation.

d.) Does the data support your prediction? Be specific about what was expected or unexpected.

Firing photons through one at a time came up with a really weird result, which did not match the classical view of the world. Scientists wanted more information, and so they decided to put detectors at the slits so that they could know which slit each photon was passing through on its way to the screen.

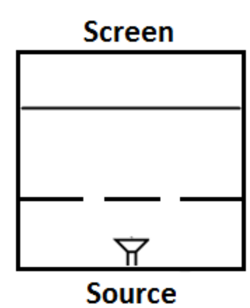
2.) Instructions to set up simulation:
 -Click on the "High Intensity" tab at the top left of the simulation.
 -Click on "Double Slits" on the right toolbar.
 -Slide the "Slit Width" bar to the left to decrease the slit size.
 -Slide the "Slit Separation" bar all the way to the right to push the slits apart.
 -Slide the "Vertical Position" bar to the middle.

a.) Turn the gun on. Record observations of what happens.

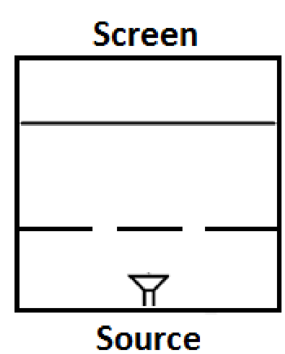
b.) Click on both the detector on the left slit and the detector on the right slit on the right toolbar, and record observations of what happens.

c.) What is strange about the result to part b?

Part A:



Part B:



You can get the same result if you do this experiment is the “Single Particle” part of the simulation, but the result is a little more difficult to see since the single particle simulation only shows number of hits rather than average intensity on the screen.

Since the world was already showing signs of being very different from what we observe in every day life Louis De Broglie thought that there might be symmetry between waves and particles. He proposed that since light was able to exhibit particle and wavelike properties a particle like an electron might exhibit wavelike properties.

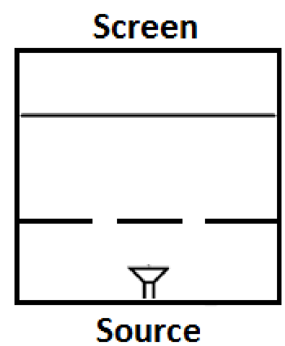
3.) Begin with the same settings as you ended with in problem 2.

a.) To shoot electrons click on the drop down menu above the gun controls panel and click “Electrons.” Record observations of what happens.

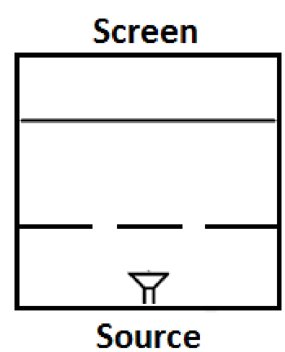
b.) Turn off the detectors by clicking “Detector on Left Slit” and “Detector on Right Slit.” Record observation of what happens.

You can get the same results in the simulation with neutrons and helium atoms which are much more massive than electrons.

Part A:



Part B:



Activity 12: Palm Pipes Name:

If you bang the open end of a piece of PVC pipe against the palm of your hand, you'll make a musical sound. Play with the pipes. What property of the pipes determines the pitch?

Explain the relationship:

Note	Length (cm)	Frequency (Hz)
C	15.8	523
D	14.0	587
E	12.5	659
F	11.8	698
G	10.5	784
A	9.4	880

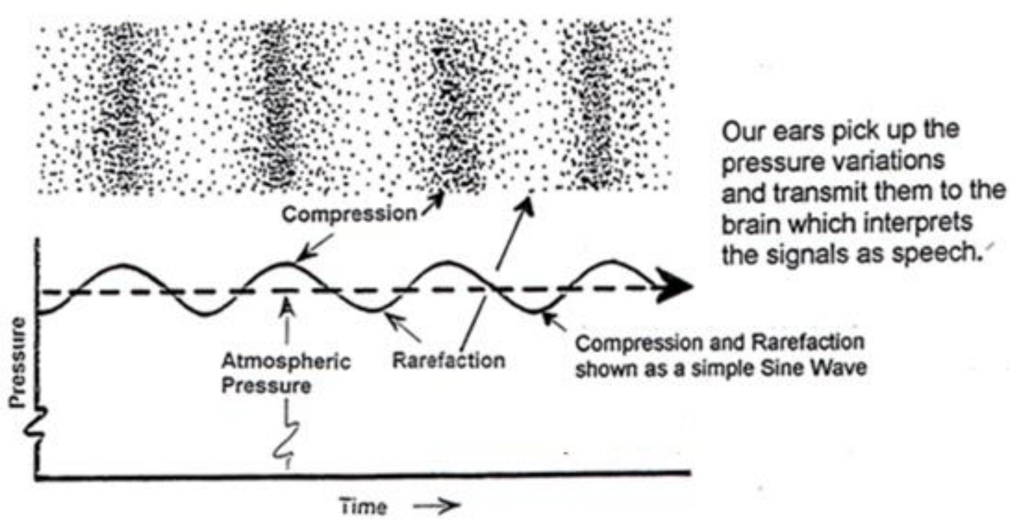
Mary Had a Little Lamb (C, D, E, G)
E D C D E E E D D E E G G
E D C D E E E E D D E D C

Twinkle, Twinkle, Little Star (C, D, E, F, G, A)
C C G G A A G F F E E D D C
G G F F E E D
G G F F E E D
C C G G A A G F F E E D D C

Oh Susanna (C, D, E, F, G, A)
C D E G G A G E C D E E D C D
C D E G G A G E C D E E D D C
F F A A A G G E C D
C D E G G A G E C D E E D D C

Farmer in the Dell (C, D, E, G, A)
G C C C C C
D E E E E E
G G A G E C
D E E D D C

London Bridge (C, D, E, F, G, A)
G A G F E F G
D E F E F G
G A G F E F G
D G E C



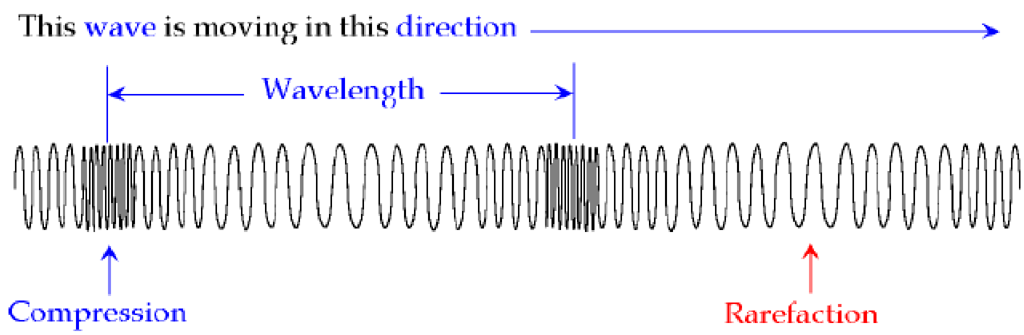
Fundamental Frequency and Overtones

Speed is defined as the distance traveled per unit time. If a wave travels a distance equal to one wavelength, the time elapsed is equal to the period (T) of the wave. Period (T) is actually the time for one complete vibration of a wave.

Thus, for a wave, the speed is equal to the wavelength (λ) divided by the period (T). $v = \lambda / T$

But period (T) is the reciprocal of frequency (f). Frequency tells us how many waves/vibrations there are per unit time. So, substituting the period in the equation by $T = 1/f$, we get $v = \lambda f$.

Sound waves are longitudinal or compressional waves, which means that the wave form consists of compressions are rarefactions as shown below.

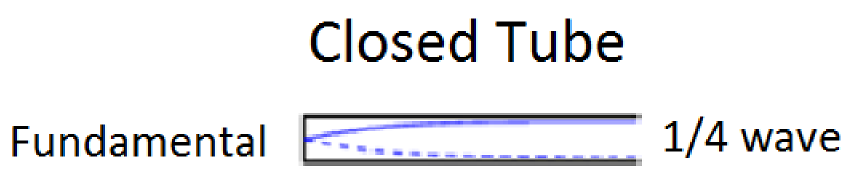


In a palm pipe, the air molecules in the bottom of the tube are squeezed together as you hit the pipe against your palm. The compression pulse travels up, reflects from the open end as an expansion, the expansion reflects from your hand, then if reflects from the open end as a compression, and the process repeats.

The repetition of this process results to standing sound waves. Since the pipe is closed on one end and open on the other end, the wave profile will look like the figure below where there is maximum displacement at the open end. At the fundamental frequency (first harmonic), the length of the pipe is ¼ of the wavelength.

Since $L = \lambda / 4$

Solving for λ would give us $\lambda = 4L$



1.) If you substitute $\lambda = 4L$ into $v = \lambda f$, what would be the formula for the wave speed (v)?

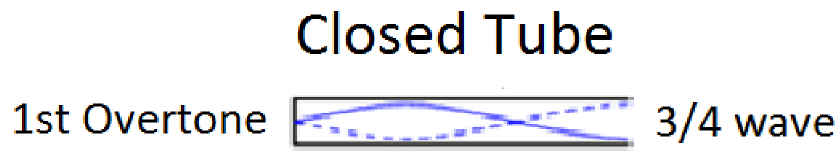
2.) Choose one of the palm pipes and calculate the wave speed, which is the speed of sound.

3.) Using the value of the speed of sound calculated in #2, what would be the frequency of sound produced in a 30.0cm palm pipe?

Since $L = 3\lambda / 4$

Solving for λ would give us $\lambda = 4L / 3$

4.) If you substitute $\lambda = 4L / 3$ into $v = \lambda f$, what would be the formula for the wave speed (v)?



5.) Using the same 30cm palm pipe with the same speed of sound found in #2, calculate the frequency of the 1st overtone?

Since $L = 5\lambda / 4$

Solving for λ would give us $\lambda = 4L / 5$

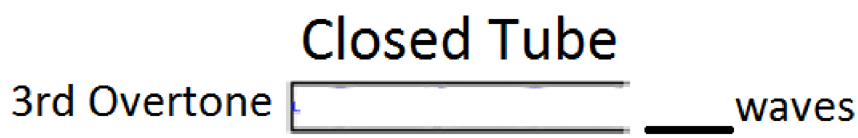
6.) If you substitute $\lambda = 4L / 5$ into $v = \lambda f$, what would be the formula for the wave speed (v)?

7.) Using the same 30cm palm pipe with the same speed of sound found in #2, calculate the frequency of the 2nd overtone?

Since $L = 7\lambda / 4$

Solving for λ would give us $\lambda = 4L / 7$

8.) Draw the wave inside the tube for the 3rd overtone.

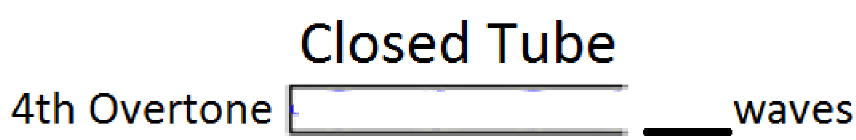


9.) Using the same 30cm palm pipe with the same speed of sound found in #2, calculate the frequency of the 3rd overtone?

Since $L = 9\lambda / 4$

Solving for λ would give us $\lambda = 4L / 9$

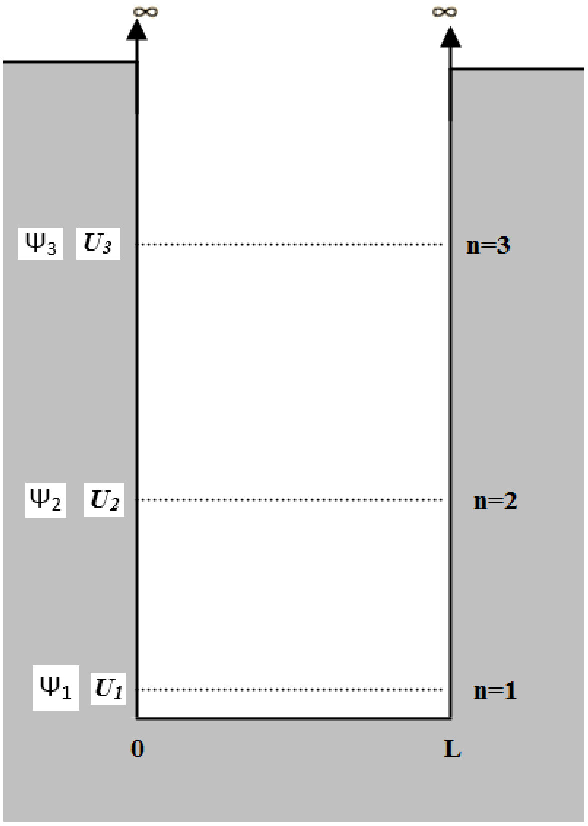
10.) Draw the wave inside the tube for the 4th overtone.



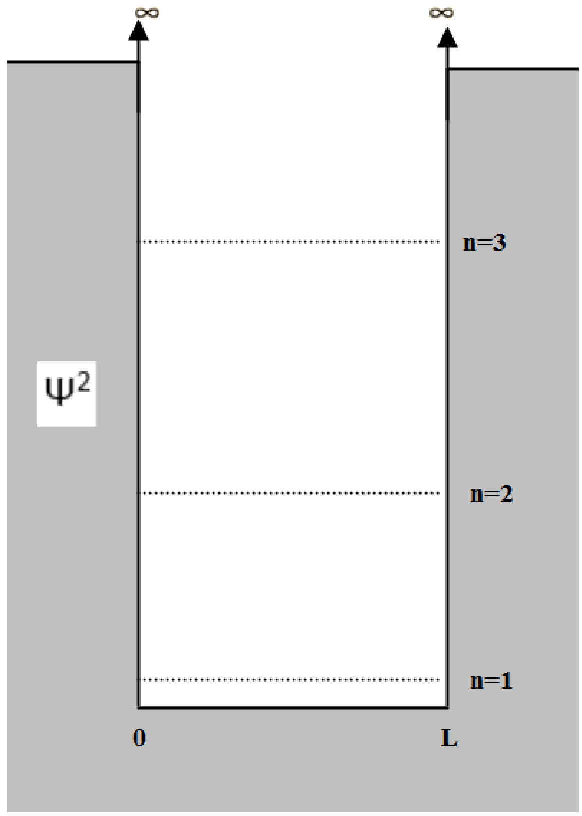
11.) Using the same 30cm palm pipe with the same speed of sound found in #2, calculate the frequency of the 4th overtone?

12.) Spend a minute and write down a general relationship for determining the frequency of any general overtone.

Activity 10: Particle in a 1-D Box   Name: ______________________



a)



b)

a) A one-dimensional box that contains an electron. The sides of the box are separated by the distance L. The depth of the well is defined by the potential energy of the particle which has a range of 0→∞. The electron cannot escape the box. The potential energies, U_1, U_2, and U_3 are shown on three different axis that are separated vertically for clarity. The separations are not shown to scale. This box will show the wave functions of the electron. A wave function, Ψ, is a mathematical description of the shape of the wave. The principle quantum number, n, represents the energy of the electron.

b) A one-dimensional box containing electrons that will show the probability densities of the electron (square of the wave functions) with three different energies.

Concept Questions:

As you answer the following questions, imagine the electron exists as a standing wave with nodes at the sides of the box.

1) On the dashed line, Ψ_1 U_1, sketch the simplest wave function for an electron that shows the wave contained in the box.

2) Write an expression for the wavelength of this wave in terms of L: _______________

3) Write a statement that describes the relationship between the energy and the wavelength of a wave.

4) On the dashed line, Ψ_2 U_2, sketch the next wave function that shows the wave contained in the box. This will represent the electrons at a different energy.

5) Write an expression for the wavelength of this wave in terms of L: _______________

6) Compare the wavelengths and the energies of the first two wave functions for the electron.

7) On the dashed line, Ψ_3 U_3, sketch the next wave function that shows the wave contained in the box.

8) Write an expression for the wavelength of this wave in terms of L: ______________

9) Compare the wavelengths and energies of the electron with this energy to the electron with the second energy described.

10) Predict three different wavelengths that will show the wave contained in the box.

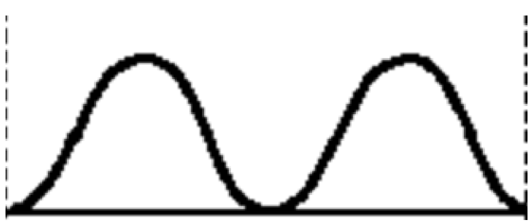
__________________ ____________________ _____________________

11) Sketch the square of the wave functions you drew in box (a) in box (b). Use a different axis for each sketch.

12) The square of the first wave function is shown below (label the y-axis Ψ^2).

Use your pencil to shade the area representing the probability density of the electron.
Label the following:
The most probable location for the electron.
The place(s) where the electrons cannot be found (nodes).

13) The square of the second wave function is shown below (label the y-axis Ψ^2).:



Use your pencil to shade the area representing the probability/probabilities density of the electron.
Label the following:
The most probable location(s) for the electron.
The place(s) where the electrons cannot be found.

14)The square of the third wave function is shown below (label the y-axis Ψ^2).:

Use your pencil to shade the area representing the probability/probabilities density of the electron.
Label the following:
The most probable location(s) for the electron.
The place(s) where the electrons cannot be found.

15) In the box below, sketch a wave that cannot fit in the box (label the y-axis Ψ^2)..

16) Estimate the principle quantum number for the wave you sketched.
17) Do you agree with the following statement? Explain.

An electron in a 1-D box can have any amount of energy.

18) How does the particle in a box support the idea of quantized energy?

Reinforcement: Open the Phet simulation 'Quantum Bound States':
https://phet.colorado.edu/en/simulation/legacy/bound-states
1) Reduce the width of the box to 0.5 nm.
2) Click on each of the three energy level lines and observe the probability densities for each.
3) Select the wave function button to the right and click the play button. Click each of the energy level lines to observe each wave function.

Activity 10 Extension: Notes: Probabilities of Electrons in Hydrogen Atoms:

As you learned in the previous activity, squaring the wave function of an electron in a box gives a probability density which helps you understand where an electron can and cannot exist and where it is most likely to exist.
Electrons in atoms have wave functions or mathematical descriptions of the shapes of the wave. For example:

$$\Psi_{1,0,0} = \Psi_{1s} = \frac{1}{\sqrt{\pi}} \left(\frac{1}{a_o}\right)^{3/2} e^{-r/a_o}$$

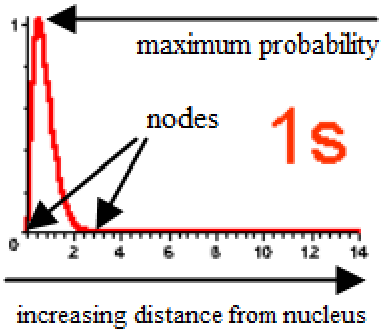
http://electron6.phys.utk.edu/phys250/modules/module%203/hydrogen_atom.htm

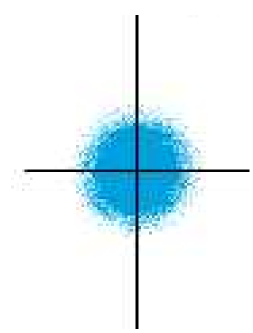
Squaring these wave functions produces probability densities in the space around the nucleus of the hydrogen atom. These probability densities in atoms are known as orbitals. In this activity we will examine some of the basic orbitals in hydrogen atoms.

We have established that electrons in atoms have different energy values and those energies are quantized. The energy of electrons is defined by the principle quantum number. You have already learned about the principle quantum number, n, which can have positive integer values (n=1,2,3,4…). The second quantum number is known as the angular momentum number, ℓ. The angular momentum number can have values from 0 to n-1. We will look at the first four values of ℓ which are 0, 1, 2 and 3. Together the principle and angular momentum quantum numbers produce a probability density known as an orbital. We will examine four types of orbitals known as s, p, d and f. These letters are abbreviations of the mathematical terms spin, principle, diffuse and fundamental. The mathematics (see paragraph 1) are beyond the scope of this discussion so we will use some graphs and images to understand the shapes of these orbitals.

Value of *l*	0	1	2	3
Letter used	*s*	*p*	*d*	*f*

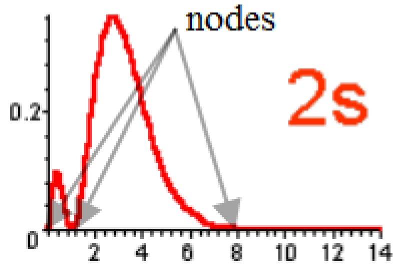
The following are probability densities of electrons in hydrogen atoms. Neutral hydrogen atoms have only 1 electron which allows us to ignore the effects of electron-electron interactions within atoms.
The lowest energy state for an electron in the hydrogen atom is known as the 1s orbital (n=1, ℓ=0). There is one s-type orbital for each value of the principle quantum number (1s, 2s, 3s ….).
The probability density is shown below (left) with a two dimensional rendering (right) where the axis intersect is the nucleus and the blue points are probable positions of electrons around the nucleus:

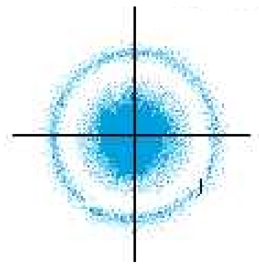




The diagrams indicates that the probability begins at zero at zero angstroms from the nucleus, reaches a maximum at a distance of about 0.5 angstroms and reaches zero again around 3 angstroms. In three dimensions, this would produce a spherically-shaped orbital. (1 angstrom = 10^{-10}m)

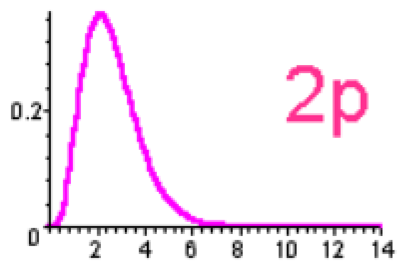
The next orbital is the 2s orbital (n=2, ℓ=0). The probability density is shown below (left) with a two dimensional rendering (right):

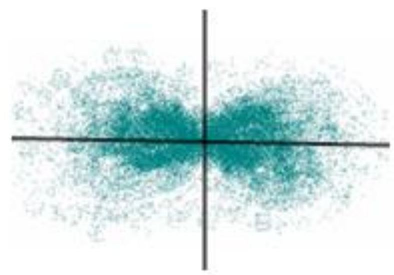




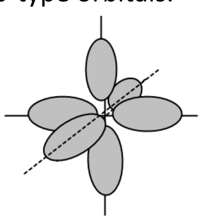
The diagrams indicates that the probability begins at zero at zero angstroms from the nucleus, increases around 0.5 angstroms, reaches zero at around one angstrom, reaches a maximum at a distance of about 3 angstroms and reaches zero again around 8 angstroms. In three dimensions, this would produce a spherically-shaped orbital with a node in the middle.

The next orbital is the 2p orbital (n=2, ℓ=1). The probability density is shown below (left) with a two dimensional rendering (right):

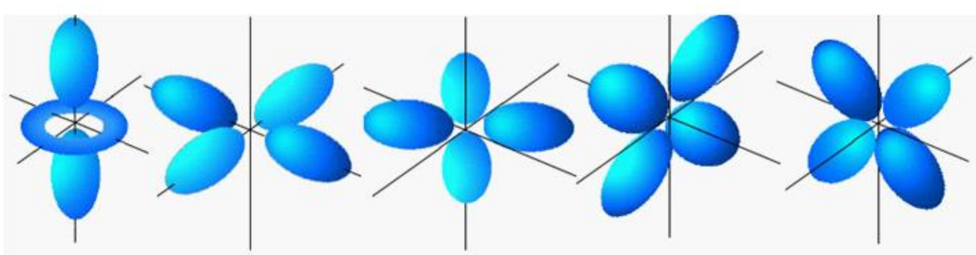




p-type orbitals have two lobes on either side of the nucleus with nodes at the nucleus and around 8 angstroms from the nucleus. There are three p-type orbitals for each principle quantum number beginning with n=2 (2p, 3p, 4p….). One of each pair of the three lobes is oriented along the x-axis, y-axis and z-axis. The following may help you visualize the three p-type orbitals.



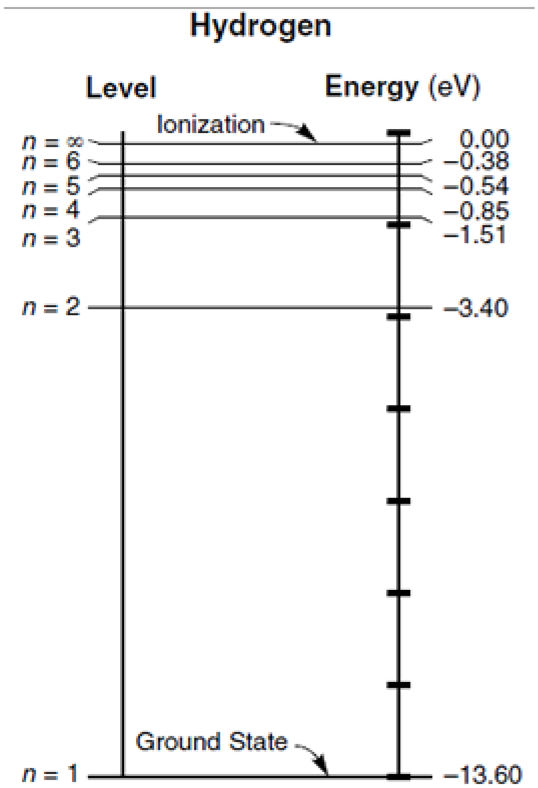
The next type of orbital is the d-type orbital ((n=3, ℓ=2). There are five d orbitals for each n value beginning with n=3 (3d, 4d, 5d, 6d….). The shapes of the five d-type orbitals are shown below.



There are other types of orbitals in hydrogen atoms. A different type of orbital exist with each increasing value of the angular momentum quantum number. The numbers and shapes of these orbitals quickly become more complex and will not be shown. See more about orbitals: https://en.wikipedia.org/wiki/Atomic_orbital

Watch a video: https://www.youtube.com/watch?v=K-jNgq16jEY

Activity 12: Electron Energy in Hydrogen Atoms **Name: .**



Energy Levels for the Hydrogen Atom

After observing the line spectra of hydrogen, the scientist Niels Bohr proposed that the electron in hydrogen atoms can have different energies and that the energies are quantized. Bohr used the principal quantum number, n, to describe the energy of the electron in hydrogen. The principal quantum number has positive integer values (n=1,2,3….∞).

The potential value on the right is obtained by using the formula: $E=(-13.6\text{ eV})/n^2$

If a charge is moving in the direction that it would normally move, its electric potential energy is decreasing. The electron would move toward the nucleus because opposite charges attract. Negative electrons are attracted to the positive nucleus.

The ground state describes the lowest energy state of the electron and the ionization potential is the energy state of an electron that has separated from the nucleus.

Concept Questions:

1) What is the lowest potential energy value an electron can possess in a hydrogen atom?

2) What is the highest potential energy value an electron can possess in a hydrogen atom?

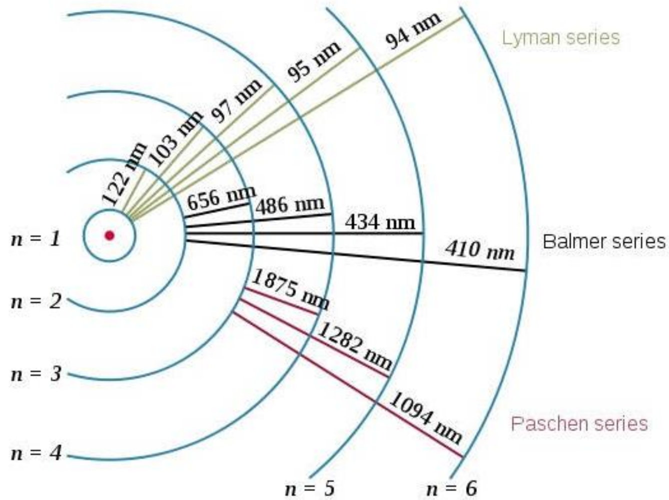
3) When an electron is in a state higher than its ground state it is described as being in an excited state. Which principal quantum numbers in the picture represent excited states in a hydrogen atom?

4) If an electron in the ground state gained energy, what could happen to the electron other than ionization?

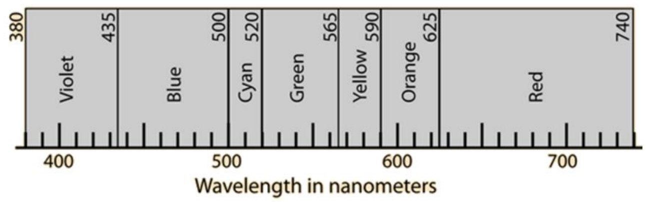
5) If an electron in an excited state returned to the ground state, what would happen to the energy?

6) Where would the lost energy go and how would that energy be transported? Think about what you learned in the 'Photoelectric Effect' activity.

Activity 12: Electron Energy in Hydrogen Atoms Name: .



Type of Radiation	UV	Visible	Infrared
Wavelength Range (nm)	100-400	400-700	700-1800



The Lyman series shows the wavelength of photons emitted from electrons in hydrogen atoms as they lose energy transitioning between excited states (n=2,3,4,5,6) and the ground state (n=1).
The Balmer series shows the wavelength of photons emitted from electrons in hydrogen atoms as they lose energy transitioning between excited states (n=3,4,5,6) and the ground state (n=2).
The Paschen series shows the wavelength of photons emitted from electrons in hydrogen atoms as they lose energy transitioning between excited states (n=4,5,6) and the ground state (n=3).
Wavelength is related to the difference in electron energy by the following formula: $\lambda = hc/\Delta E$

Concept Questions:

7) Write a statement that describes the relationship between wavelength and energy.

8) Which type of radiation is made up of photons possessing the largest energies?

9) Which energy transition is the most energetic? (n=1 to n=2 or n=2 to n=3 …)

10) Which energy transition is the least energetic?

11) If you were looking at electrons transitioning from n=3 to n=2, what would you observe? (yellow light, UV …)

12) Can you observe the Lyman series with your eyes? Explain.

13) Do hydrogen lamps emit photons from the Paschen series? Explain.

14) Which series would you be able to observe with your eyes?

15) When you observed the line spectra, why did you see a line(s) of violet color?

16) Why don’t you see a yellow line in hydrogen’s spectrum?

17) Based on the model shown above, explain the spectral lines you observed when you looked at the hydrogen lamp.

18) Explain how your observations in this activity support the idea that electron energies are quantized.