Digitally Re-Create an Instrument ~ *Project* Name: ___________

Inquiry Question
We have all tried playing digital musical instruments on our computers (or battery-operated electronic instruments). Although they never sound quite like the real thing, the improvements over the past decade have been outstanding. Can you imitate the sound of a simple instrument with a computer?

Creating digital music with your laptops or phones has become mainstream in the past decade. People are capable or generating amazing sounds and arrangements simply by selecting and modifying the digital sound databases already present.

Who creates these databases? How does one go about replicating the sound of a violin, piano, or drum kit? For this project we will exam a method that involves *superimposing* pure frequencies (*harmonics*) on top of each other to generate the richer sounding instrument. We will also use something called an *FFT* (fast *Fourier Transform*) to isolate the frequencies present from a given musical instrument (for a specific note).

Instructions
Using a pencil, answer the following questions. The lab is marked based on clarity of responses, completeness, neatness, and accuracy. Do your best! Please ensure that any data measured (or recorded) includes the appropriate number of significant digits (only one uncertain digit).
This activity is divided into three sections: • Core – this first section explores only the basic "core" ideas involved in understanding. Students must demonstrate a sound understand with all of their answers in this section BEFORE attempting the next section. • Mastery – Your instructor will NOT review this section if the Core section above shows any misconceptions. In this section students will make predictions and apply the concepts and ideas learned above. For complete mastery it is expected that data collection and scientific procedures will be as accurate as possible. All work shown should be clear with any units included. Answers should be rounded off to the correct number of significant figures based on the data collected. • Ace – Once again, your instructor will only look at this section provided he/she is confident that the above Mastery criteria has been met. In this section students will demonstrate a deeper understanding of the concepts through error analysis, experimental design etc. Physics concepts from other units already covered will often be required here.
This Project will be graded according to this Marking Rubric (link).

You are to re-create the sound generated by a common, simple musical instrument. Your digital instrument will be capable of playing one note. You are to demonstrate your digital recreation by recording both the original note and the digital note. We can then compare the quality of the reproduced sound

Objectives:

1. Create a digital recreation of a musical instrument using common software (for both analysis and creation)
2. Demonstrate and explain physics concepts inherent in your digital synthesizer.

Rules:

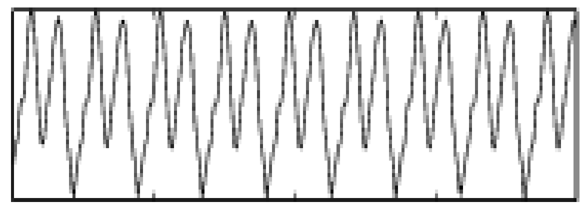
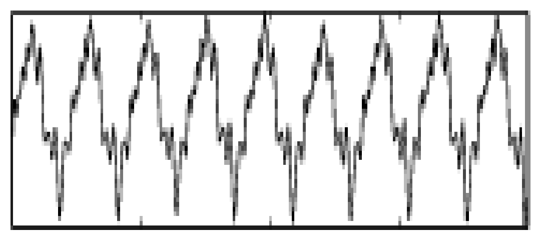
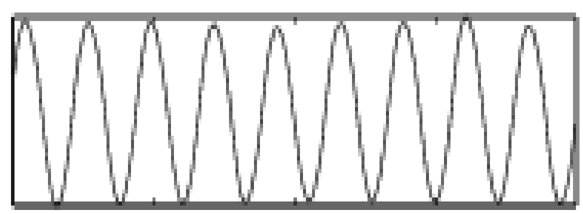
- Your recreated wave (each note) must consist of a superposition of all of the harmonics present in the real note (as made by the instrument itself).
- You must show all of the harmonics involved as well as the final, superposition.

Core Level:

"Simple musical instruments create simple wave patterns".

More complex the instruments, such as guitars and pianos, will generate complicated waves since they are a superposition of many harmonics. Let's see what we mean by this?

1. **Match** the waveform on the right with the instrument that you think generated it from the left.

Tuning Fork 	
Recorder 	
Violin 	

2. Explain your choices above:

____

____

Background:

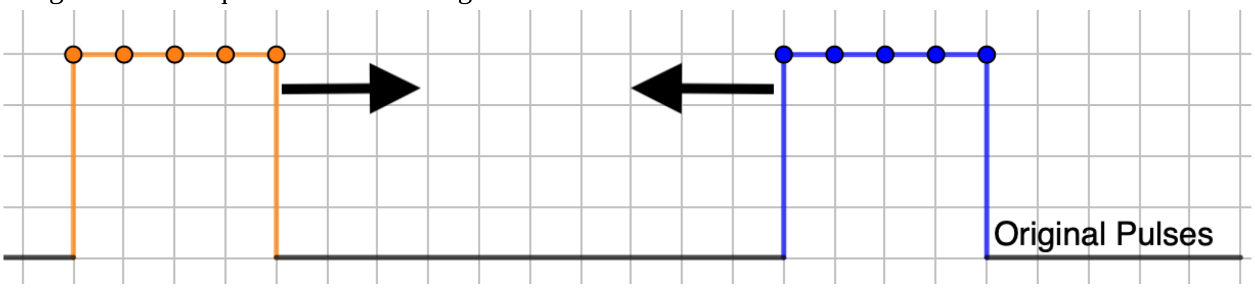
When you pluck a guitar string the note (*frequency*) is defined the **fundamental frequency**, f_0, (creates the **longest standing wavelength** that exists between the ends of the string).

But why doesn't this note sound the same on a piano or a tuning fork even though they represent the same frequency? This is because different instruments generate unique musical frequencies creating their own musical "fingerprint" that helps us identify the instrument by sound alone. This "fingerprint is known as the *timbre* of the instrument.

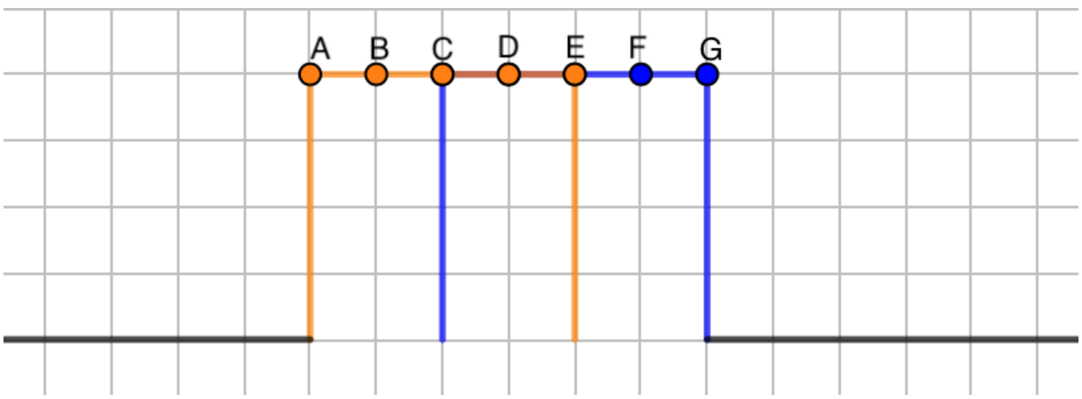
But first, we need to understand the **principle of superposition**.

3. When two waves meet or overlap, their individual amplitudes add together at every point of overlap to create a new amplitude. The combined wave is known as the *superposition* of both individual waves. When the individual crests are both on the same side, the amplitude grows when they overlap. This is known as (**constructive/destructive**) interference (*circle choice*).

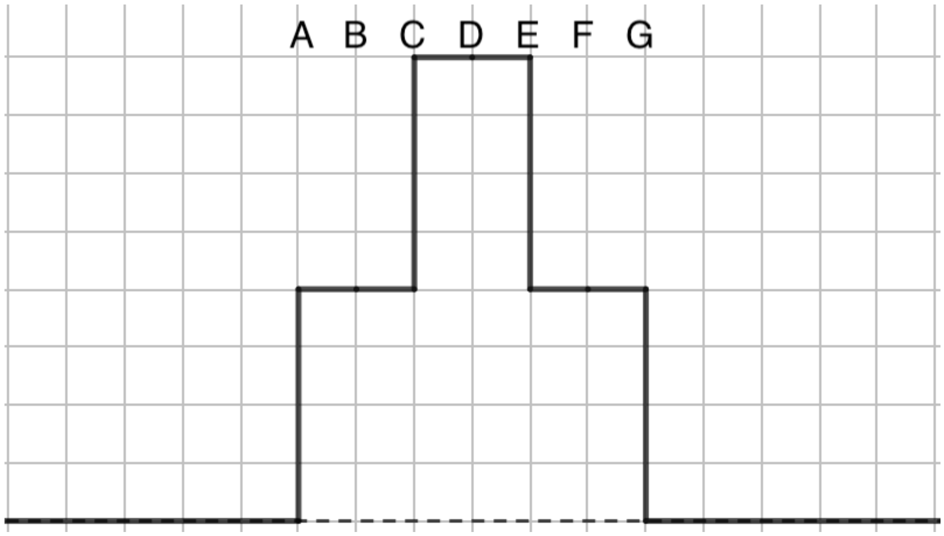
4. Imagine the two square crests travelling towards each other as shown below:



What will the resultant pattern look like when they partially overlap some time later as shown below:



The two waves overlap between C and E. The wave we will actually see will be the superposition of theses two individual waves as shown below:



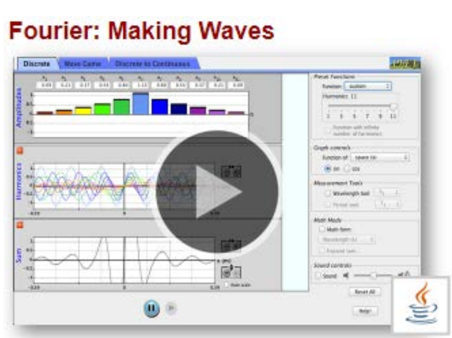
The final shape (amplitude) of the wave can be predicted by adding individual amplitudes together from the original two waves along the vertical lines labeled A through G. (note: amplitudes above the equilibrium, dotted, line are considered positive, while those below will be negative.

Determine the missing amplitudes and check to ensure that they make sense with the image above.

- Location A = Red wave amplitude at A + Blue wave amplitude at A = 4 + 0 = 4
- Location B = Red wave amplitude at B + Blue wave amplitude at B = ________
- Location C = Red wave amplitude at C + Blue wave amplitude at C = ________
- Location D = Red wave amplitude at D + Blue wave amplitude at D = 4 + 4 = 8
- Location E = Red wave amplitude at E + Blue wave amplitude at E = ________
- Location F = Red wave amplitude at F + Blue wave amplitude at F = ________
- Location G = Red wave amplitude at G + Blue wave amplitude at G = 0 + 4 = 4

Open up the ***Phet*** simulation entitled *Fourier:Making Waves* by clicking on the image below:

https://phet.colorado.edu/en/simulation/legacy/fourier

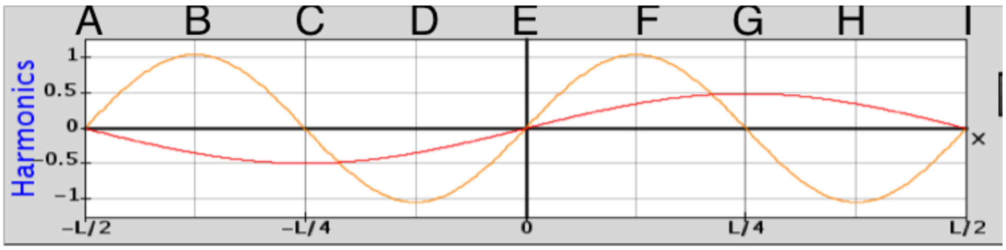


Select *Auto scale* (to the right of the bottom *Sum* graph)

A **harmonic** of a wave is a wave with a frequency that is a positive integer multiple of the frequency of the original wave, known as the fundamental frequency. Simply put, there are many frequencies that can create wavelengths that "fit" nicely along the string (or pipe if it is a wind instrument). These higher frequencies create additional standing waves that are called harmonics.
Better instruments are capable of resonating with many harmonics simultaneously. All of these harmonics superimpose to create the unique sounding wave (timbre) of the instrument.

Let's try few simpler harmonics and predict the overall wave shape (the fingerprint that defines the instrument) based on the principle of superposition.

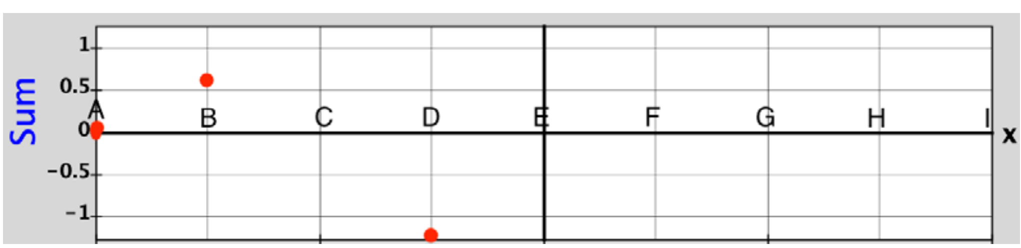
5. Imagine a guitar string is plucked and the two harmonics shown below are excited simultaneously: (***Note: the amplitude of the Red wave is 0.5 while the orange is 1.0***)



Predict the overall wave pattern generated by summing up the amplitudes at each location A through I and plotting these sums on the graph below:

- Location A = Red wave amplitude at A + Orange wave amplitude at A = 0 + 0 = 0
- Location B = Red wave amplitude at B + Orange wave amplitude at B = -0.4 + 1.0 = 0.6
- Location C = _______________
- Location D = -0.4 + -1.0 = -1.4
- Location E = _______________
- Location F = _______________
- Location G = _______________
- Location H = _______________
- Location I = _______________

Plot these points on the graph below: (note: a few are done for you)



Connect your dots with a smooth curve and check your answer with the simulation setting $A_1 = 0.5$ and $A_2 = 1.0$.

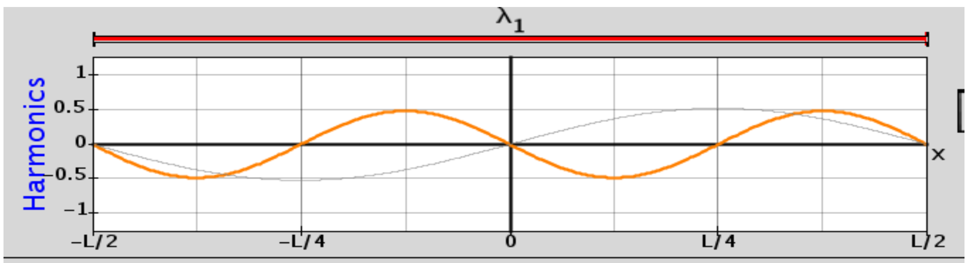
How close was your predicted curve? ____

How could you improve your prediction?

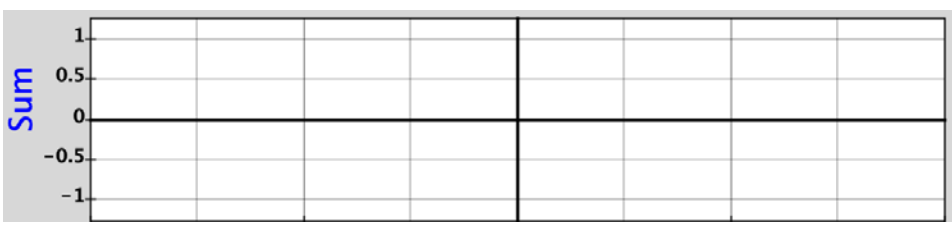
____

____

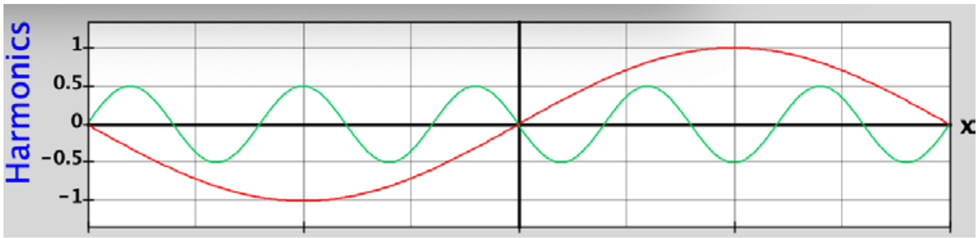
6. Using the technique above, predict the shape of the final waveform below given the harmonics present:



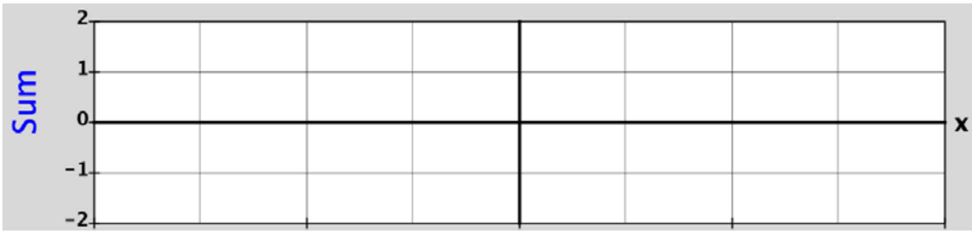
Sum (prediction)



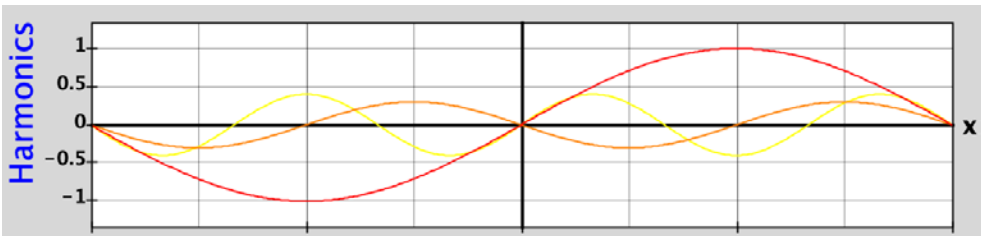
7. Predict the shape of the final waveform below given the harmonics present:



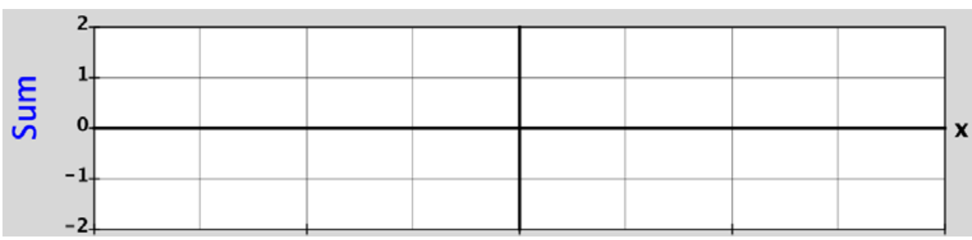
Sum (prediction)



8. Predict the shape of the final waveform below given the THREE harmonics present:



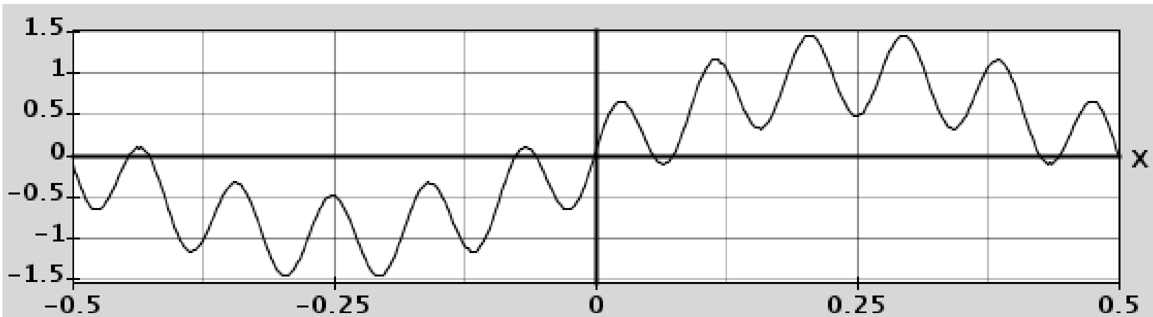
Sum (prediction)



Mastery Level

In Core you have seen how it is possible to predict the final, superimposed, waveform given the original harmonics. Can you work backwards? Are you able to identify the harmonics present in a given waveform, then recreate it?

1. Which **two** harmonics would you need to include to produce the following "Sum" graph?



Steps:

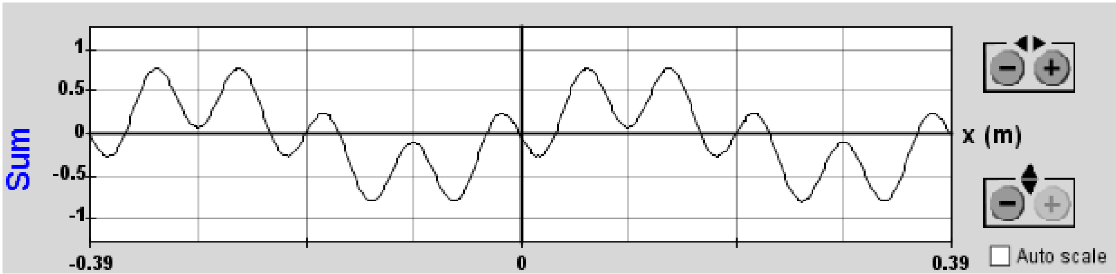
Hopefully you can see the two waves that are present. All we need to do is establish what the wavelength or frequency for each wave and put together.

a. Measure the wavelength of the overriding larger wave by selecting the *Wavelength Tool* (to the right under *Measurement Tools*). For this tool you simply select each wavelength from the dropdown menu and slide the bar along the wave to test for a match.
   What was the match for the **outer wave**? (which wavelength from λ_1 to λ_{11} matches?) ________________

b. What was the match for the smaller **inner wave**? (which wavelength from λ_1 to λ_{11} matches?) ________________

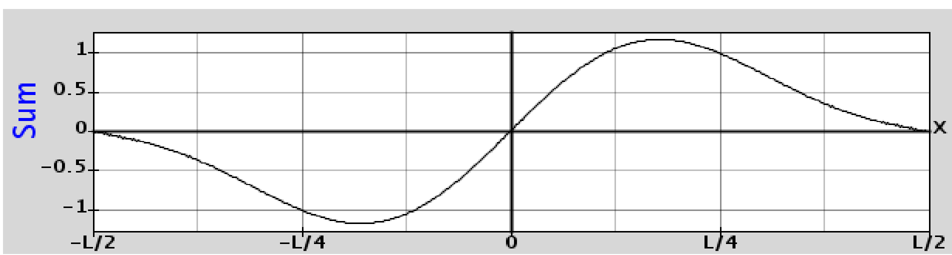
c. Now that you know the wavelengths all that is left is to decide on the initial configuration (up or down), and amplitude for each. Remember your principle of superposition. At any point on the SUM wave, the two individual amplitudes on the harmonics graph (at this same location) must add to this total. Record these amplitudes below.
   Outer wave amplitude, A = _____________
   Inner wave amplitude, A = _____________

2. Which **two** harmonics would you need to include to produce the following "Sum" graph?



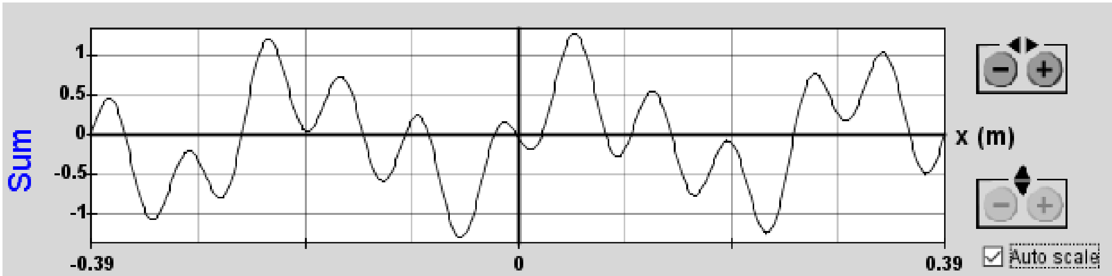
   a. What was the match for the **outer wave?** (which wavelength from λ_1 to λ_{11} matches?) ________________
   b. What was the amplitude for this **outer wave** (you set this with the slider on the top window)? A = ____________
   c. What was the match for the smaller **inner wave**? (which wavelength from λ_1 to λ_{11} matches?) ________________
   d. What was the amplitude for this **inner wave** (you set this with the slider on the top window)? A = ____________

3. Which **two** harmonics would you need to include to produce the following "Sum" graph?



   a. What was the match for the **outer wave?** (which wavelength from λ_1 to λ_{11} matches?) ________________
   b. What was the amplitude for this **outer wave** (you set this with the slider on the top window)? A = ____________
   c. What was the match for the smaller **inner wave**? (which wavelength from λ_1 to λ_{11} matches?) ________________
   d. What was the amplitude for this **inner wave** (you set this with the slider on the top window)? A = ____________

4. Which ***THREE*** harmonics would you need to include to produce the following "Sum" graph?



a. What was the match for the **outer wave?** (which wavelength from λ_1 to λ_{11} matches?) ________________

b. What was the amplitude for this **outer wave** (you set this with the slider on the top window)? A = ____________

c. What was the match for the smaller **middle wave**? (which wavelength from λ_1 to λ_{11} matches?) ________________

d. What was the amplitude for this **middle wave** (you set this with the slider on the top window)? A = ____________

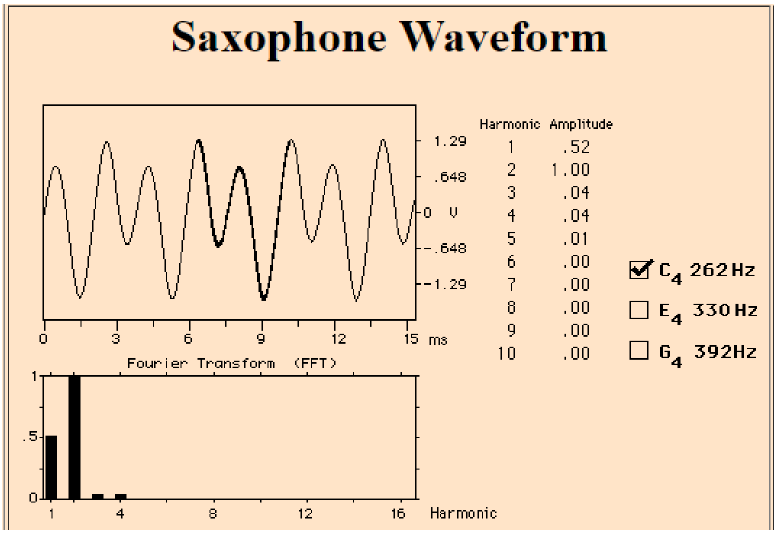
e. What was the match for the smaller **inner wave**? (which wavelength from λ_1 to λ_{11} matches?) ________________

f. What was the amplitude for this **inner wave** (you set this with the slider on the top window)? A = ____________

Part 3: Ace

Let's see if we digitally recreate an actual note from a real musical instrument.

The picture below (taken from *Hyperphysics*) shows a waveform capture from a saxophone playing the note of C_4.



Below the waveform is a Fourier Transform showing the composition of the wave above. Fourier Transforms (or FFTs) are extremely useful when analyzing waves. They not only tell what frequencies are present (i.e. what harmonics are present), but also tell us their relative intensities based on the height of the bar graph.

Turn on the *Sound* on the lower right of the *Fourier: Making Waves Phet* simulation used above.

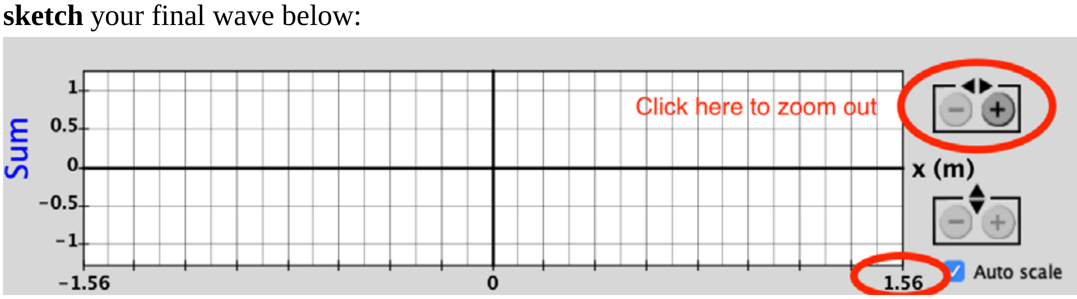
1. Recreate the waveform above by selecting the appropriate harmonics and adjusting their amplitudes to match the suggestions on the table above. Note: the above suggestions DO NOT take into account whether the amplitude should be positive or negative. You must decide based on the shape of your waveform. Once it matches, record the settings below.

Harmonic amplitude, A, settings:

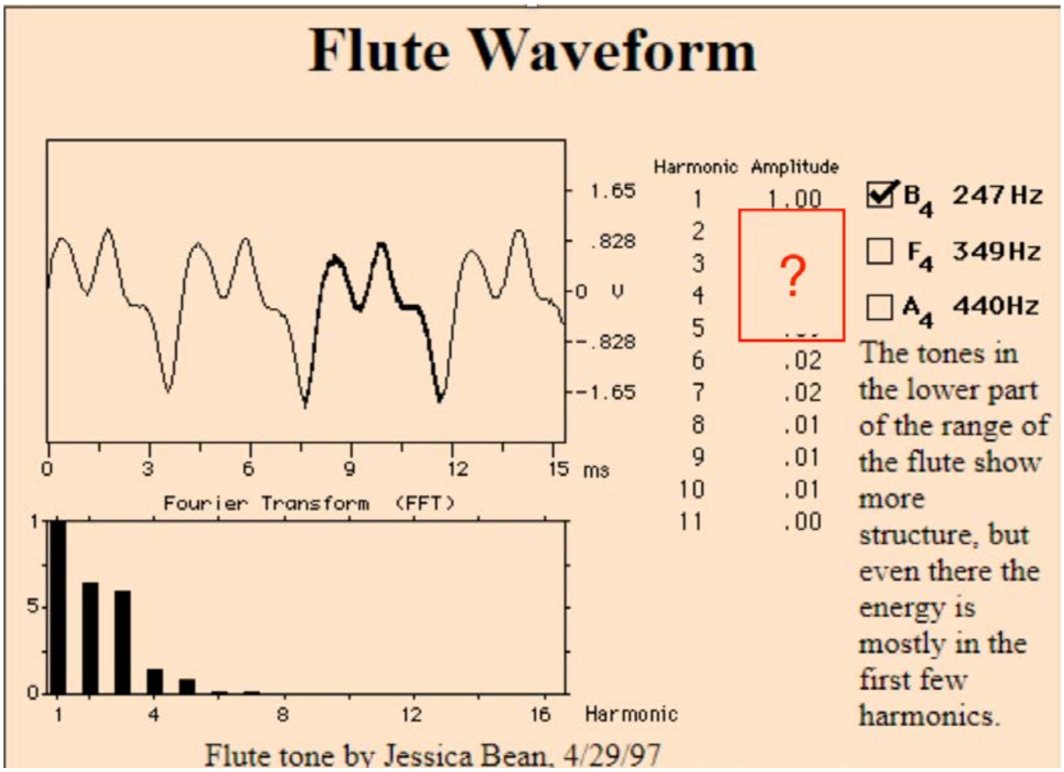
A_1 = ________, A_2 = ________, A_3 = ________, A_4 = ________, A_5 = ________, A_6 = ________,

A_7 = ________, A_8 = ________, A_9 = ________, A_{10} = ________, A_{11} = ________

Adjust the scaling on your horizontal axis until you see as many waves as possible. Then **sketch** your final wave below:



2. Repeat the above procedure with data for a **Flute** (shown below). This time you must decide on the missing amplitudes based on the Fourier Transform shown below the waveform.

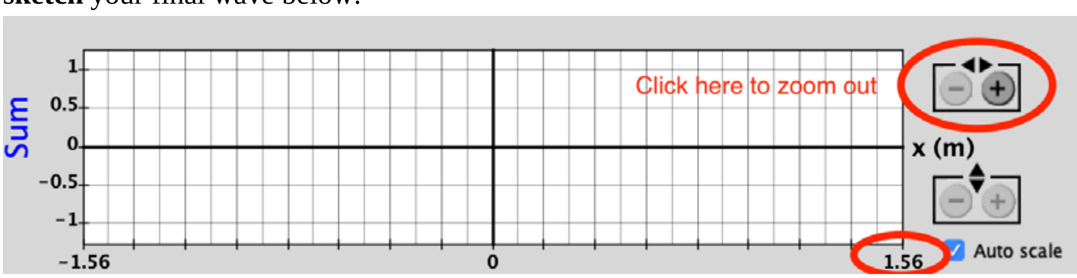


Harmonic amplitude, A, settings:

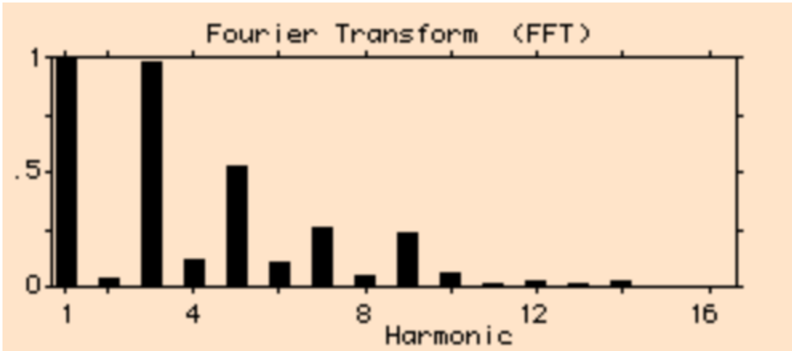
A_1 = ________, A_2 = ________, A_3 = ________, A_4 = ________, A_5 = ________, A_6 = ________,

A_7 = ________, A_8 = ________, A_9 = ________, A_{10} = ________, A_{11} = ________

Adjust the scaling on your horizontal axis until you see as many waves as possible. Then **sketch** your final wave below:



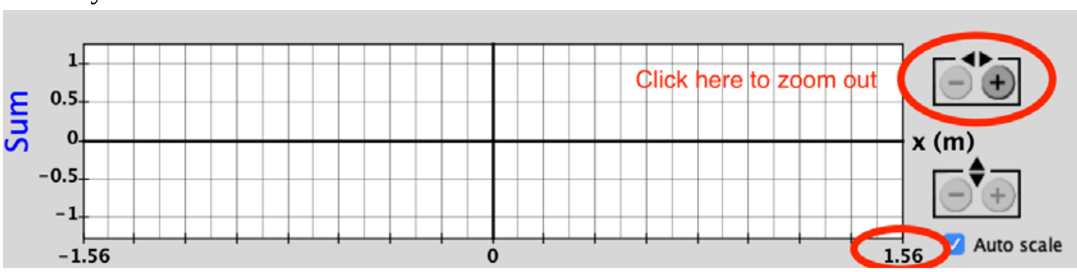
3. Finally, take a look at this actual FFT from a clarinet and see if you can recreate the waveform.



Harmonic amplitude, A, settings:

A_1 = ________, A_2 = ________, A_3 = ________, A_4 = ________, A_5 = ________, A_6 = ________,
A_7 = ________, A_8 = ________, A_9 = ________, A_{10} = ________, A_{11} = ________

Adjust the scaling on your horizontal axis until you see as many waves as possible. Then **sketch** your final wave below:



For extra credit (ask your teacher). Use the software below to create your own FFT. Then analyze the FFT generated and recreate your chosen instrument digitally by superposing all of the harmonics present in your FFT. *Audacity* works well for this as you can simply add tracks for each harmonic, then save the overall wave. When you open this saved wave, you should see your digitally created waveform and be able to compare it to the wave originally created by your instrument. How close can you make it? Did it sound realistic?

Software and tables (suggestions) for Project 1 above.

- Table of Frequencies: Here's a table of note frequencies. It also includes wavelengths calculated for v = 345 m/s
- Audacity: Free, open source sound editing program (windows, mac, linux). We'll use it for determining frequency of notes played. Simply record your note. Highlight your sound in the track and select "Plot Spectrum" from the "Analyze" menu. This will do a FFT (see picture).
- N-Track Tuner: Simple. Works well will Ipad and android devices. You'll have to figure out a way to screen capture but the frequency graph it generates is of good quality
- Visual Analyser: Free oscilloscope program for Windows. This one is a must for Windows users. It also includes real time FFT.
- The Physics of Musical Instruments by David Lapp: This is a must read. It is a free textbook written to teach sound and music. It covers the different instrument types and goes into way more detail than your students would need to finish their projects.