

# *Building a Guitar to Showcase High School Mathematics and Physics*

*Louisiana Tech University College of Engineering and Science*

*Presented at the ASEE 8<sup>th</sup> Annual Workshop on K-12 Engineering Education*

*Vancouver, Canada*

*June 25, 2011*

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## **Introduction**

This workshop provides an overview of a model for high-school teacher professional development and student learning based on a program developed and implemented at Louisiana Tech University referred to as NASA-Threads. In this program, university engineering and science faculty work collaboratively with high-school teachers to develop and implement a project-based high school physics curriculum. NASA-Threads is supported by a grant from NASA (Award Number NNX09AH81A).

NASA-threads consists of a hands-on project-based curriculum and primarily uses the Parallax Boe-Bot (microcontroller) as the learning platform. The curriculum contains three main sections: Electricity & Magnetism, Work & Mechanics, and Waves, Light & Frequency all of which are intertwined with a series of projects. Using the Boe-Bot for many of the NASA-Threads project provides an engaging atmosphere for the students. The Boe-Bot is utilized in many ways throughout the projects. The breadboard is used to build complex circuitry and the servos for navigation; additionally, the microcontroller is used as a data acquisition device.



The curriculum begins with the Electricity and Magnetism section which is contrary to the typical high school physics course that usually begins with Work and Mechanics topics. The Boe-Bot acts as a hook to engage the students, therefore the Electricity and Magnetism section is the obvious starting point for the curriculum. Within the first week of class student have the Boe-Bot moving; this leads to inquiry from the students as to how that movement happens and opens the door for discussion of Electricity and Magnetism topics. The students become comfortable with the Boe-Bot while also learning key Electricity & Magnetism concepts. Students complete projects as simple as building circuits on the Boe-Bot breadboard and measuring components with a multimeter to as complex as using a photoresistor and capacitor to make the Boe-Bot follow a line. Students are also tasked with projects that are not Boe-Bot related such as making a Beakman motor out of magnets and batteries as well as fabricating a functional speaker out of Styrofoam and magnets. From the Electricity and Magnetism section the course easily transitions into the Work and Mechanics section, where the students again use the Boe-Bot for projects but additionally use the microcontroller as a data acquisition device. One of the first projects in the Work and Mechanics

section discusses the efficiency of the servo motors on the Boe-Bot. In order to understand the efficiency of the motor students have to recall the concept of electrical power as well as understand the newly presented concept of mechanical power. The curriculum then transitions into the Waves, Light, and Frequency, where students are presented with projects like building a guitar in order to illustrate concepts of sound and frequency.

All the lesson plans, master notes, homeworks, quizzes, and sample exams can be found online at the NASA-threads website ([nasathreads.com](http://nasathreads.com)). Having the course documents completely online reduces the cost of the course making it more feasible for implementation. The cost of the Boe-Bot and a project supplies add up to be comparable to the cost of a textbook in a typical high school class.

The NASA-Threads curriculum was developed through a collaborative partnership between university engineering faculty and K12 teachers. The curriculum was piloted in 2009 by three partner school. In 2010, the program expanded to 14 schools. During the summer proceeding the 2010-2011 school year, the teachers were invited to a two week workshop where the curriculum was presented. At the workshop, teachers had the opportunity to work through the curriculum in depth by completing many of the projects. Teachers were also able to create a network with university faculty and other K12 teachers many of which they interact with throughout the various programs sponsored by the Louisiana Tech College of Engineering and Science.

TechSTEP is an example of a program that is partnered with NASA-threads all the schools involved in NASA-Threads are also involved in TechSTEP. TechSTEP utilizes university engineering and science faculty working collaboratively with high-school teachers to present challenging engineering design projects to high-school students. TechSTEP is supported by the National Science Foundation through a Science, Technology, Engineering, and Mathematics (STEM) Talent Expansion Program grant (NSF STEP Grant Number 0622462). TechSTEP consists of a series of Teacher Workshops, each followed by a Discovery Weekend with their students and culminating in a Challenge Weekend (a total of three Teacher Workshops, two Student Discovery Weekends, and a Final Challenge Weekend). The Discovery and Challenge Weekends are a collaborative effort with both university faculty and high-school teachers working together with the students. The collaboration between university faculty and high-school teachers maximizes the benefit to the students by having both their regular teachers and university faculty directly involved in their projects. It also effectively demonstrates to the students how diverse teams can often provide better solutions to problems. While engaging high-school students in engineering design projects has had an immediate impact on increasing STEM enrollments at our university, we believe the interactions and relationships developed with high-school teachers are the most significant aspects of the program that will lead to the long-term impact we are seeking.

Both NASA-Threads and TechSTEP emphasize a thorough integration of mathematics, science, and engineering. They share common goals of developing a deeper understanding of how the mathematics and science topics taught in high school are related to engineering design. NASA-Threads and TechSTEP work to provide relevant applications of high-school mathematics and science to help teachers answer the question, “*Why do I need to know \_\_\_\_\_?*”

## Project Overview

The topic for this 2011 ASEE K-12 workshop is *Building a Guitar to Showcase High School Mathematics and Physics*. This is one of the many projects Louisiana Tech University has developed in the NASA-threads curriculum to illustrate the connections between mathematics, science, and engineering in a high school physics course. This particular project involves designing and building a guitar. Our goal is to show that with easily accessible materials students can learn concepts like sound, waves, and frequency while staying engaged. The project calls for the proper construction of a guitar by understanding key physics concepts. Moreover, we do not use a trial-and-error approach to design. Instead, the project relies on the development of underlying mathematics and physics principles so that students can determine the exact construction of the guitar prior to plucking the first string.

This workbook is designed to be used in multiple ways to accommodate the needs of individual teachers and their classes. It can be used as an entire unit which can be integrated into a mathematics or physics class. It can be used as supplementary material for a newly-implemented STEM course, such as *Project Lead the Way*. Finally, if there is insufficient time to incorporate all the sections, another option is to use any of the individual sections as independent modules.

The format of the workbook is structured to illustrate how we go through a project in our NASA-threads program. The style is intentionally conversational to try to recreate the collaborative environment we set up for our NASA-Threads Teacher Workshops. Please recognize that this workbook is in the draft stage. We would welcome comments on how to improve its effectiveness. Also, if you have any questions, please contact any of us at the emails listed at the end of the workbook.

## Materials

The materials that compose the guitar are all items that are easily accessible, whether at the local hardware store or the music store.

The materials\* to make the guitar are as follows:

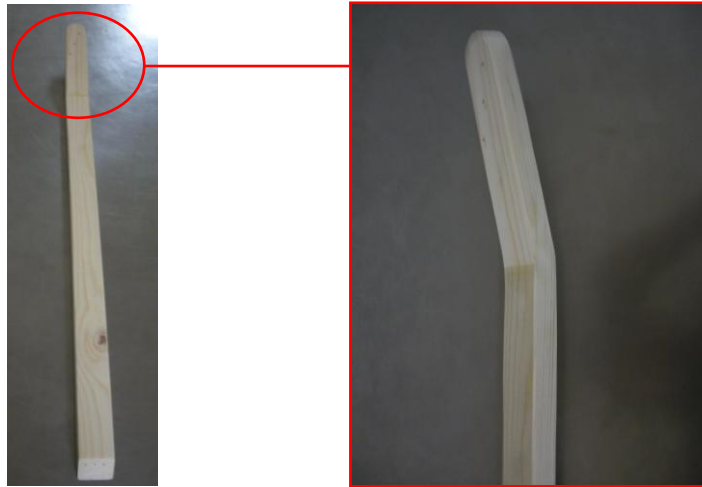
- (1) 1"x2"x4' Wooden Board
- (3) #8-32thread x 1 1/8" Eyebolts
- (9) #8-32 Nuts
- (6) #8 Washers
- (3) 1 1/8" Drywall Fasteners
- (2) 10-24x2" bolts
- (2) Rubber Bands
- (3) Guitar Strings
- (8) Zip Ties
- (1) Cardboard Box
- Philips Tip Screw Driver
- Pliers
- Drill
- Hand Saw
- Mass Scale (capable of measuring 0.1 g)

\*The quantity of the items listed is for a three string guitar. The number of hardware materials will increase proportionally as the number of strings increase.

## Constructing the Guitar

### Neck

The neck of the guitar is constructed from the 1"x2"x4' wooden board. In our construction of the neck, we make alterations to the board mainly for aesthetic reasons. It is important to note that if you do not have access to an angle cutting saw, it is not necessary to make these alterations. Simply using the wooden board as is will suffice for the project. That being said, we will step through the process of altering the neck as shown in the figure below.



Given that you are performing the alterations to the neck, there are a few additional materials for this optional design: angle cutting saw, wood glue, clamps, and sand paper.

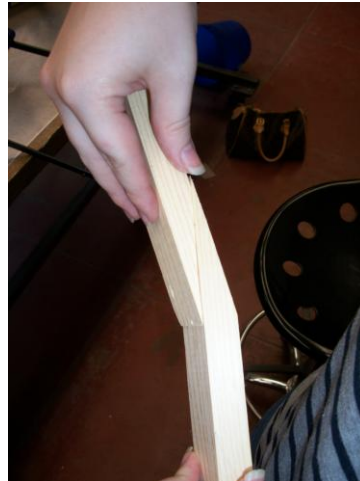
To begin the alterations, initially one end of the wooden board is cut at a 15° angle about 7" down from the end of the board. Set aside the smaller piece that was just cut.



Now, from the opposing end that was just cut, mark 10" and cut a 45° angle. Regardless of whether you are making optional alterations to the neck or not, cutting approximately 10" off the end of the board is necessary. You will use this 10" section of wood to fasten the neck to the cardboard box. The optional portion of this step is the 45° angle. Set aside the 10" section of wood. At this point you are finished with the saw.



Next place the 15° angle cut piece on the underside of the longer piece and glue them together with wood glue. It is best if you clamp the pieces and allow them to dry for 24 hours before stressing them. The functional purpose behind having the neck at an angle is to create a downward force on the nut holding the strings which will help to maintain the correct tension in the string.

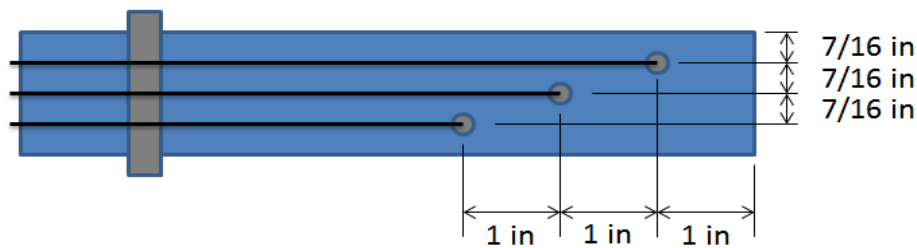


After the wood glue has dried completely, remove the clamp; you are now ready to sand down the joint made by gluing the two pieces together. Another optional aesthetic addition you can do with the sand paper is to sand a curvature about the end of the neck.





Next you need to drill holes in the neck (also shown in above picture), these holes will be occupied by the eyebolts of which the guitar strings will be tied and will act as the tuners for the guitar, which will both be discussed in more detail soon. The figure below shows the location of the holes for the tuners. The diameter of the holes will depend on what size eyebolts you are using. For this guitar, 3/16 inch diameter holes were drilled. It is recommended to use a drill press if one is available; however, acceptable results can be achieved with a hand held drill.



Alternative neck designs can be found in Appendix A.

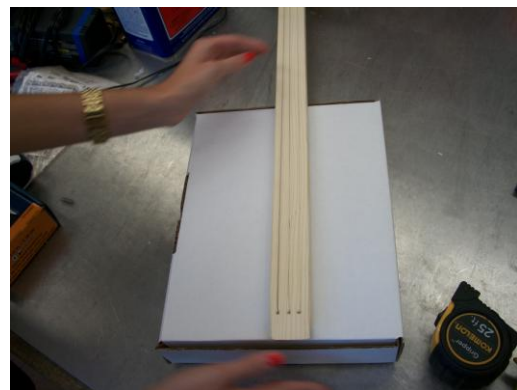
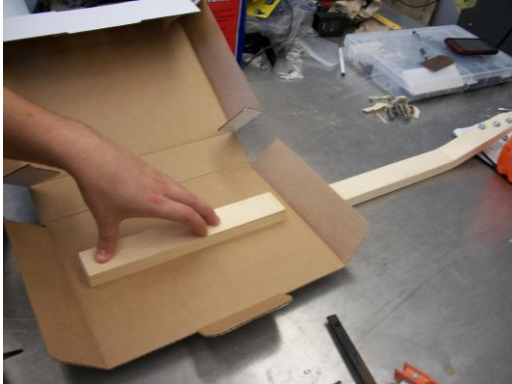
After drilling the holes for the tuners (eyebolts), on the opposite end of the neck holes need to be drilled which will hold the ball end of the strings. By drilling 3 small holes spaced 7/16 inch apart, you will create the tail piece of the guitar where the ball end of the strings will rest. Note the #8 nuts that are used as a washer to hold the ball end of the string, this helps prevent the string from working its way through the hole, but more details on that later. If you did not cut the 45° angle at the end of the wooden board, you should drill the aforementioned holes at an angle so that the holes open up to the butt of the wooden board.



Now that the base of the neck is finished you need to fasten it to the cardboard box aka the body of the guitar. Remember that 10" piece of wood you set aside; time to pull it back out. You will sandwich the box lid between the neck and the left over 10" board, refer to picture. Be careful to use the appropriate length screws, otherwise the screws tips will come through the front of your guitar's neck. You will use



the three 1 1/8" Drywall Fasteners to fasten the 10" board through the cardboard box lid and to the neck of the guitar. The pictures show an electric screwdriver being used, however a standard Philips tip screwdriver will work. An alternative that will let you use longer screws is to screw the two boards together from the front side which will leave the screw heads showing on the neck.



## Tuners

Now that the neck is constructed and attached to the guitar body, you can fasten the tuning mechanism on the guitar. The tuning mechanism, as mentioned earlier, is constructed from the eyebolts, nuts, and washers.

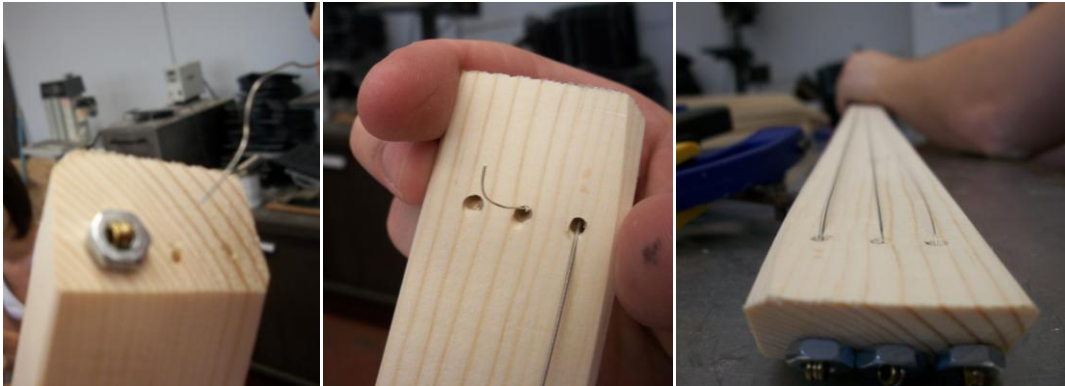


The eyebolts, nuts, and washers will be assembled by screwing one of the nuts all the way up the threads of the eyebolt. The washer is then placed flush with the nut. Insert the eyebolt through one of the three holes at the top end of the guitar neck. Lightly screw the remaining nut onto the eyebolt. Once, the bolt is securely on the eyebolt you can use the pliers to hold onto the nut then use your fingers to tighten the eyebolt and the nut. Repeat this process for the remaining two tuning holes.

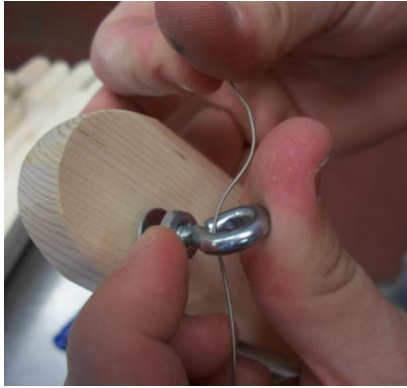


## Strings

In order to attach the strings to the guitar, thread each string through a #8-32 Nut, where the ball of the string is caught at the end of the nut. Thread the string through the end of the neck where the three holes were drilled on the 45° angle. It should be done such that the entire string is through the hole and the nut catches at the hole and holds the string in the wooden board.

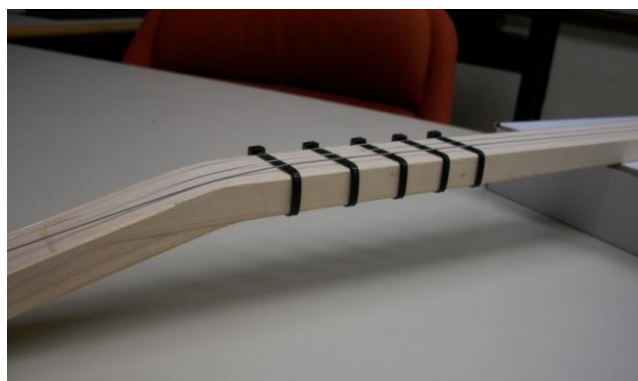


Now, run the string up the neck of the guitar and wrap each string around its corresponding eyebolt. It is necessary to note that you must wrap the string around the eyebolt so that when the string is plucked it is tightening the screw instead of loosening. This way it and keep the guitar from losing its tuning. After you wrap the string around the eyebolt thread it through the eyebolt and tie it in a knot to hold the string onto the eyebolt.



## Frets

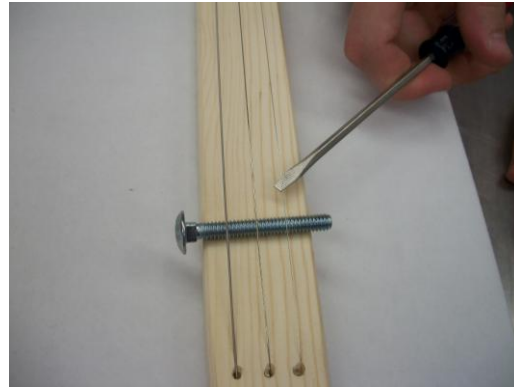
Technically, frets are created from fret wire. For this project, we are going to use zip ties. You may have trouble getting the ties to lay flat on the fretboard. However the ease of installation, combined with the relative safety of the ties may make them a favorable choice. To help in making the frets lie flat, tighten the zip ties initially by hand, but switch to using pliers to pull the zip ties as tight as possible, and thus lie flat on the fretboard. Be sure to place the zip ties such that the knot is on the top of the guitar neck (see picture below).



But the question forms, what is the proper placement of the frets on the fretboard? In order to answer the questions, we turn to basic physics principles, and will be discussed in an upcoming section.

## Nut/Bridge

The nut of a guitar is a specific piece of material that is located at the joint where the headstock meets the fretboard. To construct the nut we will use a 10-24x2" bolts, placement of the nut will be discussed in an upcoming section. The other 10-24x2" bolts mentioned in the materials list will be used as the bridge. The bridge is used mainly to transfer the vibration from the strings to the soundboard and is located on the opposite end of the guitar neck. The bolts for the bridge and the nut will be secured using the rubber bands. The bridge and the nut go hand in hand, and the spacing between the two is very specific and is called the scale length.



## Basic Music Theory

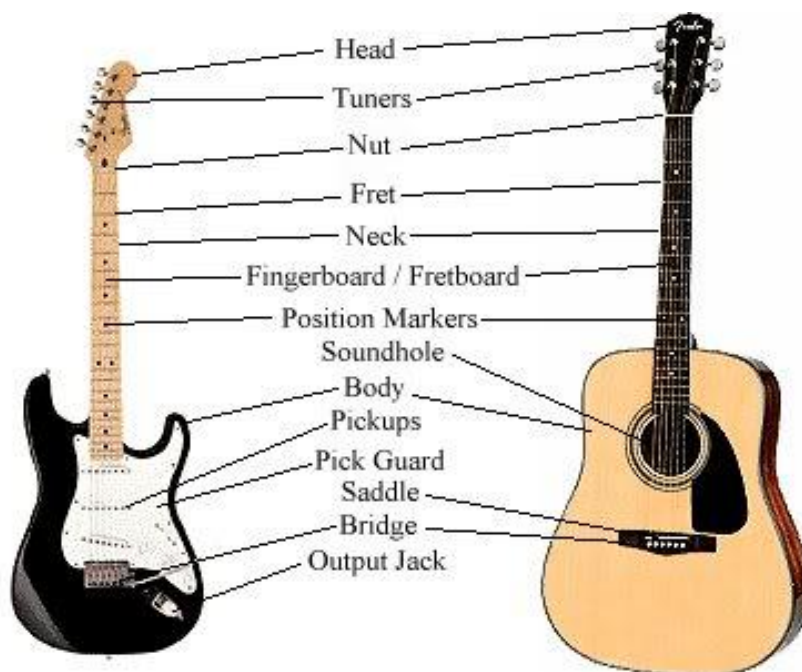
Before we discuss string tension, tuning, and fret placement, let's discuss briefly some basic music theory as it relates to physics.

### Relating Tension to Pitch

The pitch (or tone you hear) generated by a vibrating string is related to its mass, length, and tension. Changing one or more of these factors will affect the frequency at which the string vibrates, thereby changing the pitch of the tone you hear. The Equation 1 describes the relationship between these properties.

$$f = \frac{\sqrt{T}}{2L} \sqrt{\frac{1}{\rho}} \quad \text{Eq. 1}$$

where,  $f$  = frequency (Hz),  $T$  = tension in the string (N),  $\rho$  = linear density (kg/m), and  $L$  = length of vibrating string (m). It is difficult to change the mass of the string on the fly so that leaves us with either changing the tension or the length of the string in order to control the pitch. Surely, you have stretched a rubber band and plucked it. As you stretch the band farther, what happens? The pitch increases. In this case you are changing both the length of the "string" and the tension in the string. A guitar works in a similar way. Most guitars work by allowing the guitarist to change the length of the string. There are guitars that allow you to change the tension in the string on the fly as well - these guitars have a special bridge that is movable. Since we have started using specific guitar terms, now is a good time to label a few parts of a guitar.



<http://media.photobucket.com/image/guitar+diagram/dmeerwebmaster/GuitarGuru/GuitarsDiagram.jpg>



Our guitar will have frets that are raised above the “fretboard.” When the player presses the string down, it comes in contact with the fret effectively changing the length of the vibrating portion of the string. At this point, Equation 1 says that a shorter string will vibrate at a higher frequency and the pitch you hear will therefore be higher as well.



In order for our guitar to make music and not just random noise, these frets need to be placed in precise locations on the fretboard. Otherwise, the frequencies generated by the vibrating strings would not coincide with musical notes. Since we have an equation that relates frequency to string length and linear density we should be able to calculate exact positions for the frets assuming we know something about the musical notes we want to create.

## Music Scale and Note Frequencies

In western music, there are 12 notes (C, C<sup>#</sup>, D, D<sup>#</sup>, E, F, F<sup>#</sup>, G, G<sup>#</sup>, A, A<sup>#</sup>, B) or (C, D<sup>b</sup>, D, E<sup>b</sup>, E, F, G<sup>b</sup>, G, A<sup>b</sup>, A, B<sup>b</sup>, B). Don't be confused by the two different lists of notes. There are musical reasons why one would use C<sup>#</sup> in one case and in another case use D<sup>b</sup>, but for our purposes they are the same note – i.e. both have the same frequency. The interval (or the distance between the pitches of two notes) between adjacent notes is called a semi-tone or a half-step. The chart below shows the frequencies for one octave of notes. For the complete chart refer to <http://www.phy.mtu.edu/~suits/notefreqs.html>.

Note	Frequency (Hz)
D <sub>2</sub>	73.42
D <sup>#</sup> <sub>2</sub> /E <sup>b</sup> <sub>2</sub>	77.78
E <sub>2</sub>	82.41
F <sub>2</sub>	87.31
F <sup>#</sup> <sub>2</sub> /G <sup>b</sup> <sub>2</sub>	92.5
G <sub>2</sub>	98
G <sup>#</sup> <sub>2</sub> /A <sup>b</sup> <sub>2</sub>	103.83
A <sub>2</sub>	110
A <sup>#</sup> <sub>2</sub> /B <sup>b</sup> <sub>2</sub>	116.54
B <sub>2</sub>	123.47
C <sub>3</sub>	130.81
C <sup>#</sup> <sub>3</sub> /D <sup>b</sup> <sub>3</sub>	138.59
D <sub>3</sub>	146.83

Notice the frequency of  $D_2$  and of  $D_3$ .  $D_3$  is the same note as  $D_2$  (both are a D), but presented an octave higher. The frequency of  $D_3$  is twice that of  $D_2$ , this pattern hold true for all notes of the same name.  $B_4$  has twice the frequency of  $B_3$  and three times the frequency of  $B_2$ . Using the information from this chart, we can determine how long the strings need to be in order to create different notes, and therefore we can figure out where to put the frets on our guitar.



## Calculations

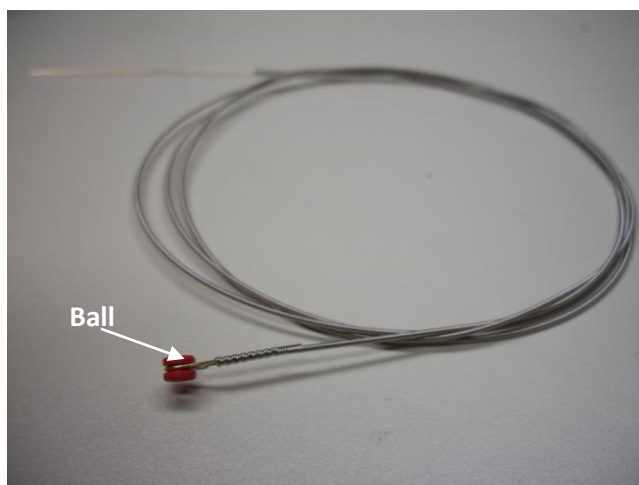
### Linear Density of a String

Guitar strings (and instrument strings in general) are gaged by their diameter. You will often hear guitarists talk about playing with 9's or 10's etc . . .they are referring to the diameter of the string measured in thousandths of an inch. So a "9" would be a string that has a diameter of 0.009 inches.

Normally strings come in packs of 6 six separate strings. These strings will vary in diameter anywhere from 0.009in to 0.050in (maybe more in some cases). For our guitar we will use three of the 6 strings, more specifically the 36, 26, and 17 string or also known as the A, D, and G strings, respectively. The reasoning behind choosing these three is that the diameters are not too small and will have less tendency to break. When completing the project in the classroom environment, it is up to your discretion to choose the three strings.

Back to the calculations, density is normally measured in mass per volume, but in the case of a vibrating string we are assuming that the cross section of the string remains constant throughout the length of the string. Therefore, we are going to measure what we are calling the "linear" density. The units for this linear density are kg/m. Each string will have a different linear density, and it will be necessary to determine this property for each string (or at least for each string weight).

When measuring the mass of the strings, be sure to account for the ball at the end of the string. Also notice that the string is wound back on itself at the end. You may want to take one set of strings and cut the end off and either use this set to calculate linear density or use the cut ends to subtract their mass from the students measurements of their own strings.



For time sake, at this workshop we will provide you with the various string masses and are shown in the following table. Also Appendix B contains spreadsheets showing the calculations performed in Excel.

String	Mass (with Ball) (g)	Ball Mass (g)
<b>0.017"</b>	1.4	0.2
<b>0.026"</b>	2.5	0.2
<b>0.036"</b>	4.4	0.2

To calculate the linear density of the string in question, simply divide the mass of the string in kilograms by its length (L) in meters as shown in Equation 2.

$$\rho = \frac{mass_{string} - mass_{ball}}{L} \quad \text{Eq. 2}$$

### Tension for Given Pitch

Now that we have the linear density of the strings we are going to use, we need to determine the tension required for the string to create the note we are after. For our guitars, we will use an “open D” tuning. This means that strumming all three open (or unfretted) strings at the same time will create a D chord. In order to do this, we will tune the strings of our guitar to D for the largest string (Note: Although this string is the A string we are tuning to a D, a similar situation for the remaining strings), A for the middle string, and D for the smallest string. These three strings would have diameters close to 0.036”, 0.026”, and 0.017” respectively.

The length of the open string is determined by the “scale length”; the distance between the nut and the bridge. For our example calculations, we are going to use a scale length of 21.5 inches. You can actually use any scale that you wish, it just depends on where you place the nut and the bridge. You will see that shorter scales require less tension in the strings to produce the same notes. In practice, shorter scales produce a more “tiny” sound while longer scales tend to produce a “fatter” sound.

Going back to equation 1, and solving for the tension we get equation 2 shown below.

$$T = 4\rho L^2 f^2 \quad \text{Eq. 3}$$

If we are talking about the smallest of our strings (0.017”), we know the linear density from our measurements from is 0.00115 kg/m (refer to Appendix B). We also know the length, L is equal to our scale length which we set at 21.5 inches. Finally, we know that we want this string to produce a D<sub>2</sub> which corresponds to a frequency of 73.42 Hz. Calculating Equation 3 using these values, we find that the tension in the string should be 26.0 Newtons. To change the tension in your string, you will turn the eyebolt.

Later in the workbook we will discuss how to tune the guitars by determining the tension using concurrent forces, frequency analyzer, or using a chromatic tuning.

## Fret Location

Assuming that the act of fretting the string does not change the tension in the string, we can calculate where to put the first fret to make the next note in the series. Speaking of the next note, what would it be? The progression of notes is alphabetical, but when you get to “D<sup>#</sup>”, you start over at “E” again. Our open string plays a “D<sub>2</sub>”, so the next note would be “D<sup>#</sup><sub>2</sub>”. The frequency of this note is 77.78 Hz. So we go back to Equation 1 and solve for the Length which results in Equation 4 shown below.

$$L = \frac{\sqrt{\frac{T}{\rho}}}{2f} \quad \text{Eq. 4}$$

We set the frequency equal to 77.78 Hz, the Tension to 7.4 Newtons, and the linear density to 0.00115 kg/m. Solving for L we find that the string needs to be shortened to 20.3 inches. Therefore, our first fret needs to be placed 1.2 inches from the nut (refer to Appendix B for calculations). We continue this process until we have as many notes as we would like. We would recommend a minimum of 7 frets.



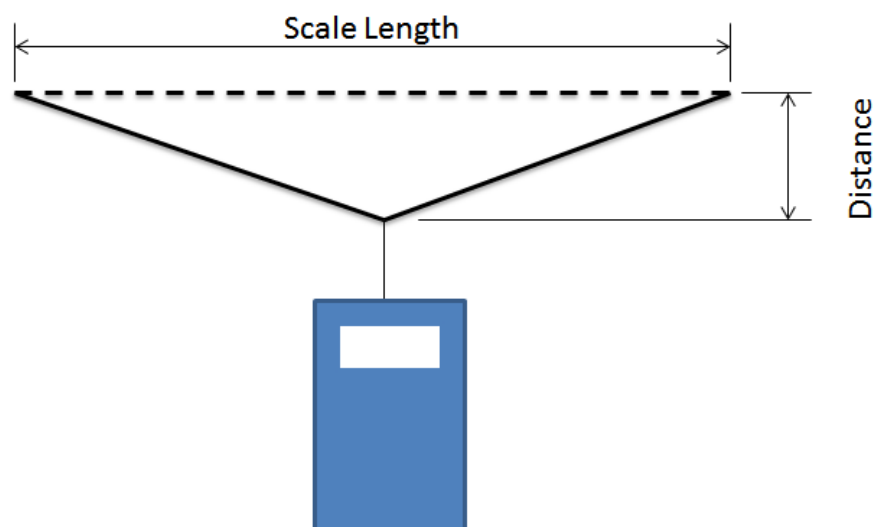
The fret position for all three strings could be handled in this manner, but an interesting thing happens when you go to calculate the fret positions for the middle string. You will notice that the fret positions as measured as distance from the nut will be the same as they were for the first string we calculated. This makes it much easier for us to place our frets since they can lie straight across the fretboard, instead of being at an angle, or worse, having to place individual frets for each string. This spacing of the frets occurs because of the way we defined the intervals between each pair of notes.

## Tuning

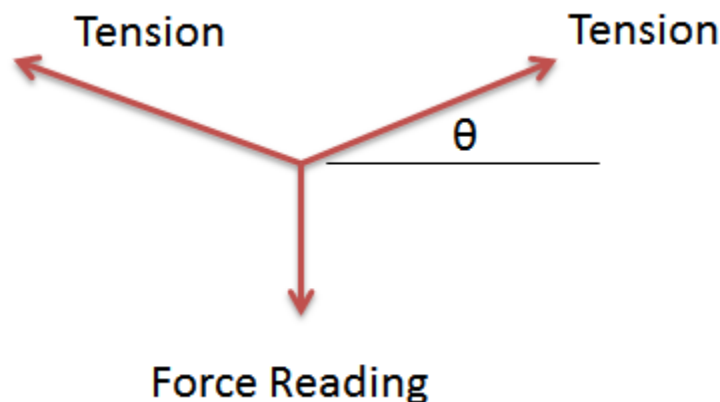
### Tuning using Concurrent Forces

We have already calculated the required tension for a given size string to produce a particular note. How are we going to measure the tension in the string to confirm our calculations? Most methods for measuring tension require the measuring instrument to be in line with the object in which the tension is being measured. This is not possible in our guitar. Instead, we will do some simple calculations using the concept of static equilibrium, a concurrent force system, and a force scale (Note: the force scale is not listed in the original materials list since it is for an optional component of the lesson).

Since we can't put our force scale in line with the string and measure tension directly, we will pull the string to the side a given distance ( $d$ ), and based on the reading on the force scale, we will be able to calculate the tension in the string. An overhead view of the setup is shown below, where the dotted line represents the original position of the string. Remember the scale length is the distance from the nut to the bridge. It is important to pull the string sideways, and not up (pulling the string up will pull it away from the nut and bridge and change the scale length).



Next we will draw a free body diagram of the system. It will be easiest to draw the free body with an origin located at the point where the force scale is attached to the string. This free body diagram will look like the one shown.



In the free body diagram above, the tension on either side of the force scale should be the same. The angle theta can be calculated by taking the inverse tangent of the distance (d) pulled divided by half the scale length as shown in Equation 5.

$$\theta = \tan^{-1} \left( \frac{d}{\frac{1}{2}(\text{scale length})} \right) \quad \text{Eq. 5}$$

By summing the forces in the y-direction we can calculate the tension in the string. Or, given a desired string tension, we can calculate what the force on the scale should read for a certain displacement. Equation 6 can be used to calculate the tension in the string.

$$T = \frac{\text{Force Reading}}{2 \sin \theta} \quad \text{Eq. 6}$$

Alternatively, Equation 7 below can be used to find the Force Reading on the scale for a given string tension.

$$\text{Force Reading} = 2T \sin \theta \quad \text{Eq. 7}$$

### **Tuning using a Frequency (or spectrum) Analyzer**

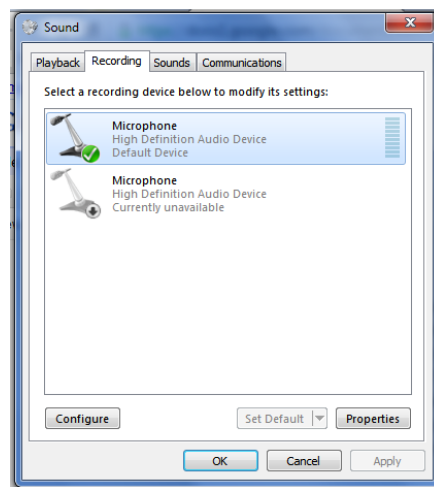
Another method for tuning the guitar is to use a spectrum or frequency analyzer. There is a free software program called "Spectrogram" for download at: <http://www.w5big.com/spectrogram.htm>

This software uses your computer's built in microphone to display a chart of the frequency of whatever it hears. In order to use the software, simply download it and extract the files - there is no installation process required. Once the program is running you may want to select File>Scan Input and change the "Display Type" from "Scroll" to "Line". This will give a cleaner looking plot. You may be able to see the overtones generated by the guitar using this method. For example, a guitar string tuned to vibrate at

440 Hz will also produce overtones as multiples of the fundamental frequency (880Hz, 1320 Hz, 1760 Hz ...)

If you notice a large spike at the far left side of the screen, you may need to reduce the gain on your microphone. To reduce the gain on a Windows machine, right click the speaker in the bottom right corner of your screen and select “recording devices.” A window should appear with your selected recording device shown. If you are using the built in microphone, it will be listed as “microphone.” In the lower right hand corner, click on “Properties.”

See the picture below for a screenshot of the recording devices pop-up window. After clicking on properties, another window will appear with the details for the selected recording device. Click on the Levels tab in this new window and adjust the “Microphone Boost” to a lower level (you may need to lower it all the way to 0).



## Chromatic Tuner

A third option for tuning your guitar is to use a chromatic tuner. You can download an app for your smartphone, install a piece of software, or purchase a tuner from a music supply store. Having an instrument tuner on hand is recommended as it will give the most reliable results.

## Glossary

Below you will find a glossary of terms that will be used throughout the Waves, Light, and Frequency section of the NASA-Threads curriculum. Many of these terms are directly applicable to the guitar project.

### Waves

Transverse Wave – each point moves *perpendicular* to the direction of wave motion

Longitudinal Wave – points along the medium move back and forth parallel to the motion of the pulse

Wavelength ( $\lambda$ ) – length (m) of repeating wave shape

Period (T) – time (s) for one wave to pass a given point

Frequency ( $f$ ) – number of waves passing a given point in a unit of time (s)  $f = \frac{1}{T}$

Speed of a wave –  $v = \lambda f$  or  $v = \frac{\lambda}{T}$

Incident Wave – wave that strikes a boundary from one medium to another

Reflected Wave – wave that is reflected backward from a boundary

Superposition Principle – resultant wave formed by the simultaneous influence of two or more waves is the vector sum of the displacements

Constructive Interference – pulses add to form a larger pulse

Destructive Interference – pulses cancel each other out

Standing Waves – wave produced by superposition of similar but inverted pulses, which appears to be standing still

Nodal Points – point where one wave is cancelled by equal and opposite displacement from reflected pulse. Distance between nodes is  $\lambda/2$

Antinodes – points of maximum displacement (halfway between nodal points)

Law of Reflection – waves striking a barrier follow the Law of Reflection whereby the angle of incidence is equal to the angle of reflection

Refraction – the change of direction waves at a boundary

Diffraction – the spreading of waves around the edge of a barrier



## Sound

Sound Wave – a pressure variation transmitted through matter (as a longitudinal wave)

Speed of Sound Waves – in air depends on air temperature and pressure. At sea level and 20°C, sound travels at 343 m/s. In general, the speed of sound is greater in solids and liquids than in gases. Sound cannot travel in a vacuum because there are not particles to move and collide.

Intensity (W/m<sup>2</sup>) – amount of energy crossing a unit area in a unit of time. The intensity threshold of hearing ( $I_0$ ) is about  $10^{-12}$  W/m<sup>2</sup>.

$$I = \frac{P}{4\pi r^2}$$

The relation between loudness and intensity is nearly logarithmic.

$$\beta = 10 \log I/I_0$$

The intensity level of sound is measured in decibels. ~10dB (barely audible) to ~110dB (painful)

Doppler Effect – change in observed frequency ( $f'$ ) due to relative motion. Where  $v$  is the speed of sound in air and  $v_s$  is the speed of the source. A siren moving toward an observer will have an increased frequency and decreased wavelength.

$$f' = f \left( \frac{v}{v \pm v_s} \right)$$

Resonance (Sympathetic Vibration) – occurs when the natural vibration rates of two objects are the same or when one is a multiple of the other.

Beats – Occur when two waves have slightly different frequencies. The resultant waves have alternating constructive and destructive interference which is heard as alternating loudness.

Beat Frequency – number of beats per second which equals the difference between the frequencies of the two individual waves.

Resonance Frequencies in a Closed Pipe – resonates when its length is an odd number of quarter wavelengths:  $L = \lambda/4, 3\lambda/4, 5\lambda/4, 7\lambda/4...$

Resonance Frequencies in an Open Pipe – resonates when its length is an even number of quarter wavelengths:  $L = \lambda/2, \lambda, 3\lambda/2, 2\lambda...$

Fundamental – lowest frequency an object will resonate.

Harmonics – multiples of the fundamental frequency at which an object resonates.

Musical notes represent different frequencies. 2 notes with frequencies in a 1:2 ratio are said to differ by an octave.

The fundamental (frequency) and its harmonics are related by octaves. The 1<sup>st</sup> harmonic is 1 octave higher, the 2<sup>nd</sup> is 2 octaves higher...

The notes in a musical scale are divided into octaves. Major Scale: C D E F G A B C ...

Scales are based on harmonic ratios (2:1, 3:1, 4:1...). Harmonics are wavelengths in simple ratios with fundamental frequencies. For example, the ratio of  $C_3/C_2$  or  $C_4/C_3$  or  $A_4/A_3$  is 2:1.

Chord - Two or more pitches played together.

Consonance – when a combination of pitches has a pleasant sound.

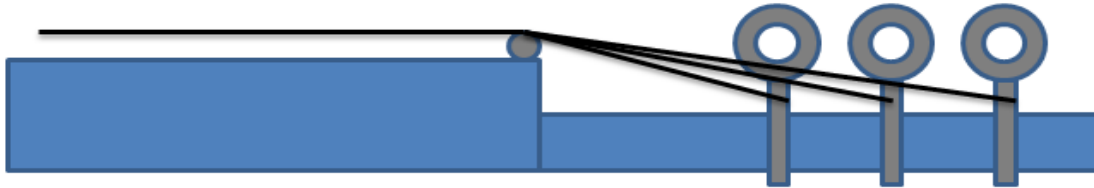
Dissonance – when a combination of pitches has an unpleasant sound.

Sounds from different instruments can have the same pitch (frequency) but different timbre (tone color, tone quality)

## Appendix A – Alternative Neck Designs

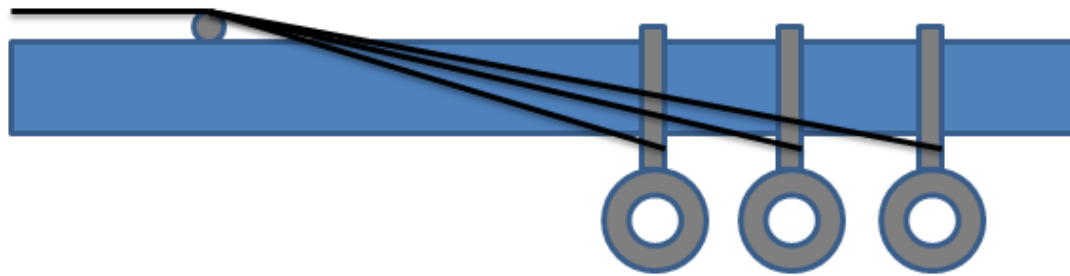
Some other optional neck designs are as:

### Recessed Neck Construction



The recessed neck is an option if you do not have time to glue the bent neck. For this design simply cut an approximately 1/4 inch slice from the top of the 1 x 2 to create a recess that will allow the strings to angle down past the nut. This will weaken the headstock so it is recommended that you use the lighter gage strings with this design.

### String Through Neck Construction



One alternative to the previous headstock variations is to run the strings through to the other side of the neck, this does have the problem of allowing the strings to eat into the soft wood of the headstock and makes staying in tune difficult. This method is the simplest as far as the amount of construction time required.

## Appendix B – Calculations Spreadsheets

The following are the three Excel spreadsheets used to calculate the tension needed for each string as well as the location of the frets.

0.017" Diameter String (tuned to a D)						
			Equations being used:			
			$f = \frac{1}{2L} \cdot \sqrt{\frac{T}{\rho}}$	$L = \frac{\sqrt{T}}{2 \cdot f}$		
			$T = 4 \cdot \rho \cdot L^2 \cdot f^2$			
<b>Note</b>	<b>Frequency (Hz)</b>		<b>mass of string (g)</b>	1.4		
D <sub>2</sub>	73.42		<b>ball (g)</b>	0.2		
D <sup>#</sup> <sub>2</sub> /E <sup>b</sup> <sub>2</sub>	77.78		<b>length of string (mm)</b>	1040		
E <sub>2</sub>	82.41		<b>linear density (kg/m)</b>	0.00115		
F <sub>2</sub>	87.31					
F <sup>#</sup> <sub>2</sub> /G <sup>b</sup> <sub>2</sub>	92.5					
G <sub>2</sub>	98					
G <sup>#</sup> <sub>2</sub> /A <sup>b</sup> <sub>2</sub>	103.83					
A <sub>2</sub>	110					
A <sup>#</sup> <sub>2</sub> /B <sup>b</sup> <sub>2</sub>	116.54					
B <sub>2</sub>	123.47					
C <sub>3</sub>	130.81					
C <sup>#</sup> <sub>3</sub> /D <sup>b</sup> <sub>3</sub>	138.59		<b>length of scale (mm, in)</b>	546.1	21.50	
D <sub>3</sub>	146.83					
<b>FRET</b>	<b>NOTE</b>	<b>FREQ (Hz)</b>	<b>TENSION (N)</b>	<b>Length From Bridge (mm)</b>	<b>Distance from Nut (mm)</b>	
open	D <sub>2</sub>	73.42	7.4	546.1	0.0	
1st fret	D <sup>#</sup> <sub>2</sub> /E <sup>b</sup> <sub>2</sub>	77.78	7.4	515.5	30.6	
2nd fret	E <sub>2</sub>	82.41	7.4	486.5	59.6	
3rd fret	F <sub>2</sub>	87.31	7.4	459.2	86.9	
4th fret	F <sup>#</sup> <sub>2</sub> /G <sup>b</sup> <sub>2</sub>	92.5	7.4	433.5	112.6	
5th fret	G <sub>2</sub>	98	7.4	409.1	137.0	
6th fret	G <sup>#</sup> <sub>2</sub> /A <sup>b</sup> <sub>2</sub>	103.83	7.4	386.2	159.9	
7th fret	A <sub>2</sub>	110	7.4	364.5	181.6	
8th fret	A <sup>#</sup> <sub>2</sub> /B <sup>b</sup> <sub>2</sub>	116.54	7.4	344.0	202.1	

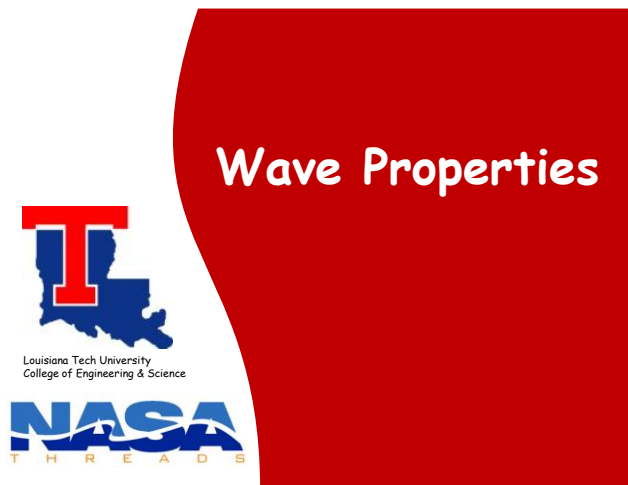
0.026" Diameter String (Tuned to an A)			Equations Being Used:		
<b>Note</b>	<b>Frequency (Hz)</b>		$f = \frac{1}{2L} \cdot \sqrt{\frac{T}{\rho}}$	$L = \frac{\sqrt{\frac{T}{\rho}}}{2 \cdot f}$	
A <sub>2</sub>	110		$T = 4 \cdot \rho \cdot L^2 \cdot f^2$		
A <sup>#</sup> <sub>2</sub> /B <sup>b</sup> <sub>2</sub>	116.54				
B <sub>2</sub>	123.47				
C <sub>3</sub>	130.81				
C <sup>#</sup> <sub>3</sub> /D <sup>b</sup> <sub>3</sub>	138.59				
D <sub>3</sub>	146.83				
D <sup>#</sup> <sub>3</sub> /E <sup>b</sup> <sub>3</sub>	155.56		mass of string (g)	2.5	
E <sub>3</sub>	164.81		ball (g)	0.2	
F <sub>3</sub>	174.61		length of string (mm)	1040	
F <sup>#</sup> <sub>3</sub> /G <sup>b</sup> <sub>3</sub>	185		linear density (kg/m)	0.00221	
G <sub>3</sub>	196				
G <sup>#</sup> <sub>3</sub> /A <sup>b</sup> <sub>3</sub>	207.65		length of scale (mm, in)	546.1	21.50
A <sub>3</sub>	220				
FRET	NOTE	FREQ (Hz)	TENSION (N)	Length of Scale (mm)	Distance from Nut (mm)
open	A <sub>2</sub>	110	31.9	546.1	0.0
1st fret	A <sup>#</sup> <sub>2</sub> /B <sup>b</sup> <sub>2</sub>	116.54	31.9	515.5	30.6
2nd fret	B <sub>2</sub>	123.47	31.9	486.5	59.6
3rd fret	C <sub>3</sub>	130.81	31.9	459.2	86.9
4th fret	C <sup>#</sup> <sub>3</sub> /D <sup>b</sup> <sub>3</sub>	138.59	31.9	433.4	112.7
5th fret	D <sub>3</sub>	146.83	31.9	409.1	137.0
6th fret	D <sup>#</sup> <sub>3</sub> /E <sup>b</sup> <sub>3</sub>	155.56	31.9	386.2	159.9
7th fret	E <sub>3</sub>	164.81	31.9	364.5	181.6
8th fret	F <sub>3</sub>	174.61	31.9	344.0	202.1

0.036" Diameter String (Tuned to a D)					
		Equations Being Used:			
<b>Note</b>	<b>Frequency (Hz)</b>	$f = \frac{1}{2L} \cdot \sqrt{\frac{T}{\rho}}$	$L = \frac{\sqrt{T}}{2 \cdot f}$		
D <sub>2</sub>	73.42	$T = 4 \cdot \rho \cdot L^2 \cdot f^2$			
D <sup>#</sup> <sub>2</sub> /E <sup>b</sup> <sub>2</sub>	77.78				
E <sub>2</sub>	82.41				
F <sub>2</sub>	87.31				
F <sup>#</sup> <sub>2</sub> /G <sup>b</sup> <sub>2</sub>	92.5				
G <sub>2</sub>	98				
G <sup>#</sup> <sub>2</sub> /A <sup>b</sup> <sub>2</sub>	103.83	mass of string (g)	4.4		
A <sub>2</sub>	110	ball (g)	0.2		
A <sup>#</sup> <sub>2</sub> /B <sup>b</sup> <sub>2</sub>	116.54	length of string (mm)	1040		
B <sub>2</sub>	123.47	linear density (kg/mm)	0.00404		
C <sub>3</sub>	130.81				
C <sup>#</sup> <sub>3</sub> /D <sup>b</sup> <sub>3</sub>	138.59	length of scale (mm, in)	546.1 21.50		
D <sub>3</sub>	146.83				
FRET	NOTE	FREQ (Hz)	TENSION (N)	Length of Scale (mm)	Distance from Nut (mm)
open	D <sub>2</sub>	73.42	26.0	546.1	0.0
1st fret	D <sup>#</sup> <sub>2</sub> /E <sup>b</sup> <sub>2</sub>	77.78	26.0	515.5	30.6
2nd fret	E <sub>2</sub>	82.41	26.0	486.5	59.6
3rd fret	F <sub>2</sub>	87.31	26.0	459.2	86.9
4th fret	F <sup>#</sup> <sub>2</sub> /G <sup>b</sup> <sub>2</sub>	92.5	26.0	433.5	112.6
5th fret	G <sub>2</sub>	98	26.0	409.1	137.0
6th fret	G <sup>#</sup> <sub>2</sub> /A <sup>b</sup> <sub>2</sub>	103.83	26.0	386.2	159.9
7th fret	A <sub>2</sub>	110	26.0	364.5	181.6
8th fret	A <sup>#</sup> <sub>2</sub> /B <sup>b</sup> <sub>2</sub>	116.54	26.0	344.0	202.1

## Appendix C – Supplemental PowerPoint Presentations

The following PowerPoint presentations are supplemental to the guitar lesson and the sounds/waves unit in the curriculum. They were developed by Marvin Nelson from Benton High School, Benton, Louisiana. Benton High is one of our partner high schools for both NASA-Threads and TechSTEP.

### PowerPoint 1 – Wave Properties



The slide features a large red background with the title "Wave Properties" in white text. On the left side, there is a logo for Louisiana Tech University College of Engineering & Science, which includes a stylized "L" and "T" in red and blue, and the NASA Threads logo below it.



### Objectives

- Identify Transverse and Longitudinal waves .
- Define speed (velocity), amplitude, wavelength, period, and frequency.
- Solve problems involving frequency, period, wavelength, and velocity.

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### Types of Waves

- **Transverse Wave** - each point moves perpendicular to the direction of wave motion.
- **Longitudinal Wave** - points along the medium move back and forth parallel to the motion of the pulse.

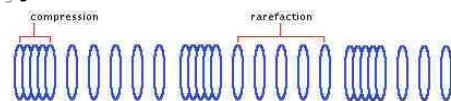
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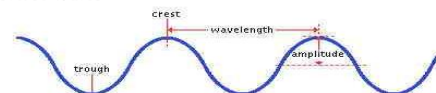


### Types of Waves

#### Longitudinal Waves



#### Transverse Waves



<http://jasonw.wcpinfo.net/ncs/mpl/wopds/2010/12/waves.js>

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## Measuring Waves

- Wavelength ( $\lambda$ ) - length (m) of repeating wave shape.
- Period (T) -time (s) for one wave to pass a given point.
- Frequency (f) - number of waves passing a given point in a unit of time (s).

$$f = \frac{1}{T}$$



## Speed of a Wave

In the time interval of one period, moves one wave length.

$$v = \frac{\lambda}{T}$$

$$v = \lambda f$$



## Class Problem

A sound wave has a frequency of 262 wavelength of 1.29m.

- What is the period of the wave?
- What is the speed of the wave?
- How long will it take the wave to travel the length of a football field? (100 yards)



## Properties of Sound



### Objectives

- Describe how sound waves are generated and transmitted.
- Discuss the speed of sound in various media.
- Find the wavelength of sound given frequency and velocity.
- Describe how the loudness/intensity of sound is measured.
- Describe the Doppler Effect and compute observed frequency.

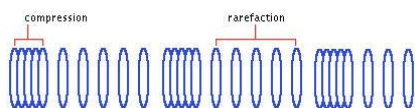
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### Sound Waves

**Sound Wave** - a pressure variation transmitted through matter (as a longitudinal wave).



<http://jasonwupilly.com/wp-content/uploads/2010/12/waves.jpg>

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### Speed of Sound

- **Speed of Sound Waves** - in air depends on air temperature and pressure. At sea level and 20°C, sound travels at 343 m/s.
- In general, the speed of sound is greater in solids and liquids than in gases.
- Can sound travel in a vacuum?

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### Class Problem

A tuning fork produces a sound wave in air with a frequency of 262 Hz. What is the wavelength? (assume speed of sound is 343 m/s).

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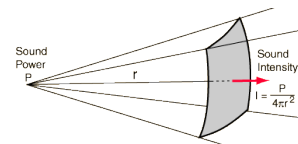
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### Sound Intensity

**Intensity (W/m<sup>2</sup>)** - amount of energy crossing a unit area in a unit of time. The intensity threshold of hearing (I<sub>0</sub>) is about 10-12 W/m<sup>2</sup>.

$$I = \frac{P}{4\pi r^2}$$



<http://hyperphysics.phy-astr.gsu.edu/hbase/acoustic/invsgs.html>

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## Measuring Sound Intensity

The relation between loudness and intensity is nearly logarithmic. The intensity level of sound is measured in decibels. ~10dB (barely audible) to ~110dB (painful)

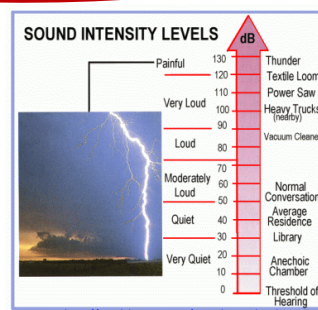
$$\beta = 10 \log I/I_0$$

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## Sound Intensity Levels



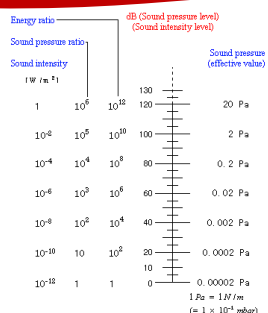
<http://windchimes.co.za/soundnotes.html>

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## Intensity, Energy, & Pressure



<http://www.sengpielaudio.com/calculator-soundlevel.htm>

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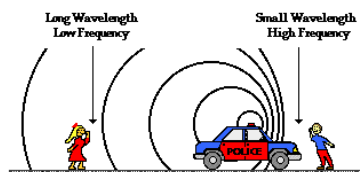
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## Doppler Shift

A siren moving toward an observer will have an increased frequency and decreased wavelength.

The Doppler Effect for a Moving Sound Source



<http://www.physicsclassroom.com/class/waves/u103d.cfm>

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## Doppler Effect

Doppler Effect - change in observed frequency ( $f'$ ) due to relative motion. Where  $v$  is the speed of sound in air and  $v_s$  is the speed of the source.

$$f' = f \left( \frac{v}{v \pm v_s} \right)$$

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## Physics of Music



## Objectives

- Describe Resonance in air columns.
- Discuss open and closed-pipe resonators/resonance frequencies.
- Define Beats and Beat Frequencies.
- Compute the speed of sound using resonance.
- Find a Beat between 2 known frequencies.

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## Resonance

- **Resonance (Sympathetic Vibration)** - occurs when the natural vibration rates of two objects are the same or when one is a multiple of the other...resulting in an increase in amplitude
- **Fundamental** - lowest frequency an object will resonate.
- **Harmonics** - multiples of the fundamental frequency at which an object resonates.

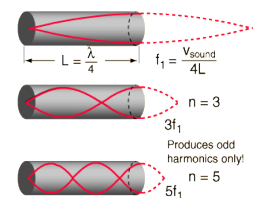
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## Closed Pipe Resonance

- A closed pipe will resonate when its length corresponds to odd multiples of a  $\frac{1}{4}$  wavelength.
- Standing waves in a pipe can be represented as a sine wave.
- When the wave hits the end of the pipe, it is reflected back to the source.
- The reflected wave reaches the source at the same time another pressure wave is generated.



<http://hyperphysics.phy-astr.gsu.edu/hbase/Waves/clocl.html>

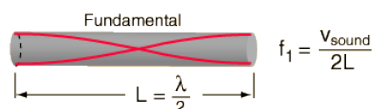
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## Open Pipe Resonance

- An open pipe will resonate when its length corresponds to multiples of a  $\frac{1}{2}$  wavelength.
- When the wave hits the open end of the pipe, it is inverted and reflected back.
- Again, the reflected wave reaches the source at the same time another pressure wave is generated.



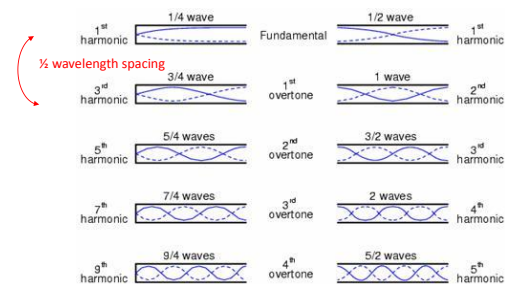
<http://hyperphysics.phy-astr.gsu.edu/hbase/Waves/clocl.html>

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## Closed Pipe & Open Pipe Resonance



<http://www.mrfizix.com/home/sound.htm>

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## Class Problem

A tuning fork with a frequency of 392 Hz is used with a closed pipe resonator. The loudest sound is heard when the air column is 21.0 cm and 65.3 cm long. The air temperature is 27°C. What is the speed of sound at this temperature?

$$v = \lambda f$$

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## Beat Frequency

- **Beats** - Occur when two waves have slightly different frequencies. The resultant waves have alternating constructive and destructive interference which is heard as alternating loudness.
- **Beat Frequency** - number of beats per second which equals the difference between the frequencies of the two individual waves.

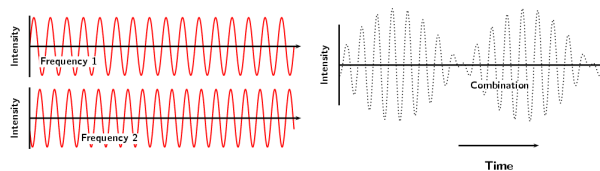
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## Beat Frequency

$$f_{beat} = |f_A - f_B|$$



<http://www.gta.lgs.net/~bcbauer/hrentweb/366W04/>

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## Musical Notes & Sound Quality



### Objectives

- Discuss musical notes and scales.
- Compute musical note frequencies using a geometric sequence.
- Define Fundamental Harmonics.
- Define Dissonance and Consonance.

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### Musical Scale

- The notes in a musical scale are divided into octaves
  - Major Scale: C D E F G A B C ...
- Scales are based on harmonic ratios (2:1, 3:1, 4:1...)
  - Harmonics are wavelengths in simple ratios with fundamental frequencies.
  - For example, the ratio of  $C_3/C_2$  or  $C_4/C_3$  or  $A_4/A_3$  is 2:1

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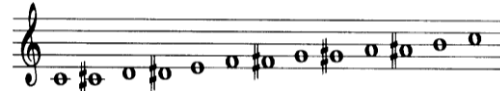
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### Musical Scale

The "Equally Tempered Scale" (Chromatic Scale) is based on 12 equal ratios within an octave.

C C# D D# E F F# G G# A A# B C



<http://www.music-mind.com/Music/mpage4.HTM>

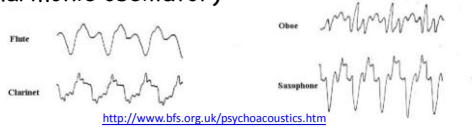
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## Sound Quality

- Sounds from different instruments can have the same pitch (frequency) but different timbre (tone color, tone quality)
- Superposition in the instrument produces more complex waves than a simple sine wave (harmonic oscillator)



<http://www.bfs.org.uk/psychoacoustics.htm>

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## Chords

- **Chord** - Two or more pitches played together.
- **Consonance** - when a combination of pitches has a pleasant sound.
- **Dissonance** - when a combination of pitches has an unpleasant sound.

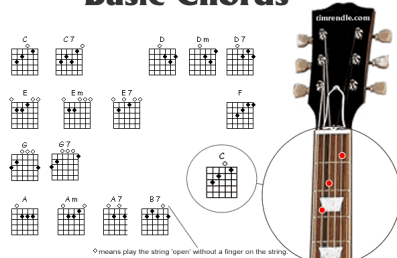
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## Basic Chords

### Basic Chords



<http://the-area51.blogspot.com/2010/11/basic-guitar-chords.html>

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# Guitar Project



## Introduction

- Describe the Doppler Effect and compute observed frequency. The Physics of a Vibrating String
- Parts of a Guitar
- Finding the Linear Density of a String
- Cigar Box Tuning
- Finding String Tension and Length

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## Vibrating String

The pitch (frequency) generated by a vibrating string is related to its mass (linear density), length, and tension.

$$f = \frac{\sqrt{T}}{2L} \sqrt{\rho}$$

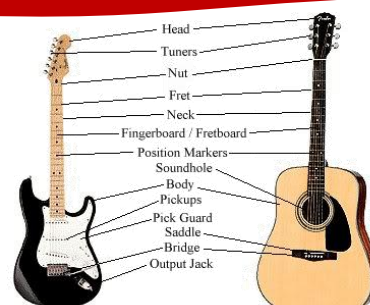
$T = \text{tension (N)}$   
 $\rho = \text{linear density (kg/m)}$   
 $L = \text{length (m)}$

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## Parts of a Guitar



<http://media.photobucket.com/image/guitar+diagram/dmeerwebmaster/GuitarGuru/GuitarsDiagram.jpg>

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## String Frequencies & Fret Locations

Frequencies for 1 octave:

Note	Frequency (Hz)
D <sub>2</sub>	73.42
D <sub>2</sub> /E <sup>b</sup> <sub>2</sub>	77.78
E <sub>2</sub>	82.41
F <sub>2</sub>	87.31
F <sub>2</sub> /G <sup>b</sup> <sub>2</sub>	92.5
G <sub>2</sub>	98
G <sub>2</sub> /A <sup>b</sup> <sub>2</sub>	103.83
A <sub>2</sub>	110
A <sub>2</sub> /B <sup>b</sup> <sub>2</sub>	116.54
B <sub>2</sub>	123.47
C <sub>3</sub>	130.81
C <sub>3</sub> /D <sup>b</sup> <sub>3</sub>	138.59
D <sub>3</sub>	146.83

<http://www.phy.mtu.edu/~suits/notefreqs.html>

### Frets

- Frets need to be placed in exact locations to coincide with specific musical notes.
- Using this equation, we can determine the spacing between frets.

$$f = \frac{\sqrt{T}}{2L} \sqrt{\rho}$$

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## Linear Density

- Guitar strings are gauged by their diameter.
  - A "9" would be a string that has a diameter of 0.009 inches.
  - A pack of strings will vary in diameter from about 0.009in to about 0.050in.
- We will assume that this diameter remains constant.
- To find  $\rho$ , divide mass (kg) by length (m)

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## Guitar Tuning

- We will use an "open D" tuning.
  - Strumming all three open strings at the same time will create a D chord.
- In order to do this, we will tune the strings of our guitar to:
  - D for the largest string (.036")
  - A for the middle string (.026")
  - D for the smallest string (.017")
- The length of the open string is determined by the "scale length"; the distance between the nut and the bridge.
  - 21.5 inches is the scale length for the class project

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## Class Problem

### Tension to Produce a G3 Note

For our smallest string, assume the linear density from our measurements is 0.00115 kg/m. With a scale length set at 21.5 inches -

- Solve this equation for tension (T).
- Find the tension to produce a D2 (73.42Hz).

$$f = \frac{\sqrt{T}}{2L} \sqrt{\frac{\rho}{T}}$$

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## Class Problem

### Locating the First Fret

Our open string plays a "D2", so the next note would be "D#2" (77.78 Hz). Find L to produce this note and determine the location of the next fret relative to the Nut.

$$f = \frac{\sqrt{T}}{2L} \sqrt{\frac{\rho}{T}}$$

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## Assignment

Find songs with chords/fingering for 3- string guitars.

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