Innovative STEM Education

through

Guitar Design Manufacture

Faculty Professional Development
In Design, Construction, Assembly and Analysis of a Solid Body Guitar Design
NSF ATE DUE Grant 0903336

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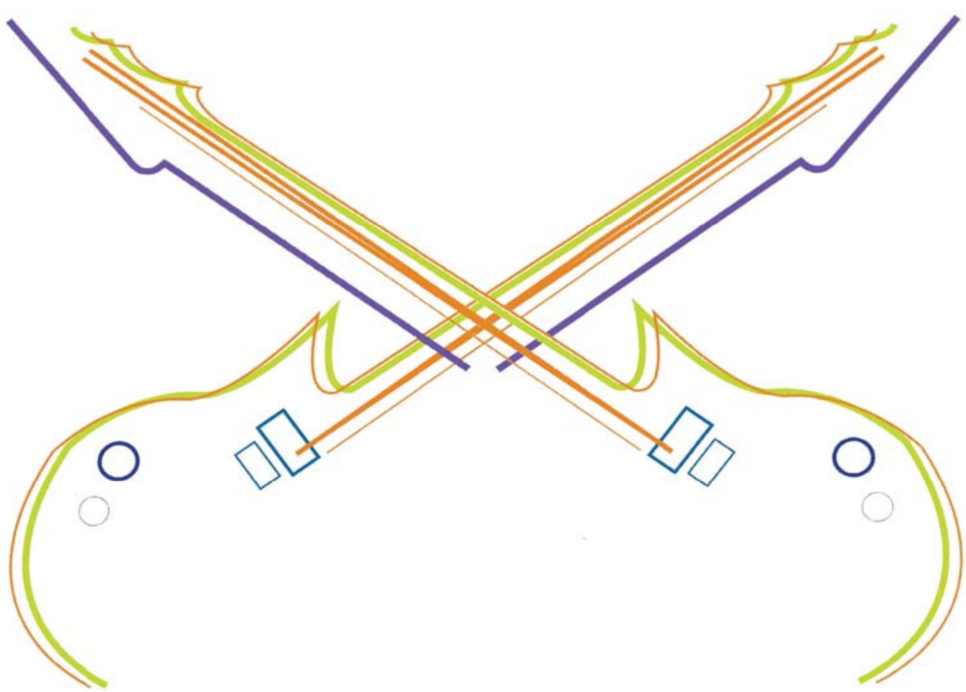
Exploring Innovative
STEM Education
Through

Guitar Design and Manufacture

Workbook

(Version 1006.1)



About Us

Guitars in the Classroom?

Absolutely.

This National Science Foundation STEM Guitar Project provides innovative professional development to high school and community college faculty in collaborative design and rapid manufacturing.

Faculty teams take part in an intense five day guitar design/build project. Each faculty member builds his/her own custom electric guitar and will engage in student centered learning activities that relate the guitar design to specific math, science and engineering topics. Participants leave this weeklong experience with their custom-made guitars, curriculum modules that can be immediately integrated into the faculty teams school curriculum, and much more.

Morning classroom sessions include the following:

- STEM Learning Activities in the following disciplines: Physical Science, Math, Engineering, CADD, CNC, RPT, Reverse Engineering, etc.
- Lab time for practical application
- Develop and share a STEM learning activity
- Remote design team exercise

Afternoon sessions include the following guitar build/hands-on activities:

- Guitar Body, neck, fret board selection and preparation
- Headstock design
- Fretting
- Electronic installation
- Neck installation and setup
- Intonation
- Rock Star Friday

Table of Contents

Science Learning Activity 1

The Decibel Scale

Students will practice calculating decibels based on the intensity of sounds.

Learning Objectives:

1. Students will calculate the sound level in decibels using logarithms.
2. Students will calculate the pressure of sound waves based on their intensity with respect to the threshold of hearing.
3. Students will extrapolate data from a chart to use in a mathematical analysis.

Materials Required:

- Calculator that can do logarithms and exponents.

References:

- http://www.coolmath.com/decibels1.htm. Accessed April 2010.
- http://physics.info/intensity/. Accessed April 2010.
- http://web.cvcaroyals.org/~rheckathorn/ (PPT on the Decibel Scale). Accessed April 2010.
- Serway, R. and Beichner, R. Physics for Scientists and Engineers. 5th Edition. pg. 526

Science Exercise 1

Notes

Sound is a longitudinal or a compression wave. As energy travels through the air, the gas is compressed and rarefied. This transfer of energy exerts pressure on our ear drum. While humans are rather average when it comes to sound detection, we still can hear a range of intensities from 10^{-12} to 10^{4} W/m^2 (well, at least until our eardrum bursts). If we compare this to light, it would be like being able to see from radio waves (10^{4}m) to x-rays (10^{-12}m)

The unit of intensity level was originally the *bel*, coined by Bell Labs in honor of Alexander Graham Bell. However, that proved to be too large a unit, so the decibel (dB), defined to be one tenth of the *bel*, is used. The equation for the decibel is given by the following:

$$(dB) = 10\log_{10}\frac{I}{I_0}$$

Below is a table with common sounds and their intensity level[1]:

Source of Sound	B (dB)	Intensity W/m^2
Nearby Jet Airplane	140	1×10^{2}
Jackhammer, threshold of pain	130	1×10^{1}
Rock concert	120	1×10^{0}
Lawn mower	100	1×10^{-2}
Busy traffic	80	1×10^{-4}
Vacuum cleaner	70	1×10^{-5}
Normal conversation	50	1×10^{-7}
Mosquito buzzing	40	1×10^{-8}
Whisper	30	1×10^{-9}
Tustling Leaves	10	1×10^{-11}
Threshold of hearing	0	1×10^{-12}

Taken and adapted from *Physics for Scientists and Engineers*. 7th Edition. Serway. pg. 481, ppt. from Dick Heckathorn's website: http://web.cvcaroyals.org/~rheckathorn/HONORS/web%20pages/Honors9.htm, and http://physics.info/intensity/.

A Fender guitar amp can produce a sound with an intensity of $1 \cdot 10^{-1}$ W/m^2 (at 10 inches away). Calculate the sound level (in dB) produced by the amp:

Calculate the sound level (in dB) perceived by someone standing ten inches away from two Fender guitar amps.

Increasing the intensity by a factor of two corresponds to a sound level increase of only __________ dB.

A rocket launch is capable of producing a sound intensity of $1 \cdot 10^6$W/m^2. Calculate the sound level in dB.

A sound level of 160 dB will instantly break an ear drum. As you remember, sound is produced by a vibrating object causing pressure differences in a medium such as air. As the vibrating object moves towards the ear, the gas molecules in the air move with a higher velocity. As the vibrating object moves away from the ear, the gas molecules in the air move with a smaller velocity. These moving gas molecules exert a pressure on the ear drum. The pressure on the ear is given by the following equation:

$$\Delta P_{\max} = \sqrt{2\rho v I}$$

Where v is the speed of sound in air (v = 343 m/s), and ρ is the density of air (1.2 kg/m^3).

Calculate the pressure exerted by a sound of that level.

If the area of the inner ear is 0.52 cm^2, what is the force exerted on the ear by a 160 dB sound?

Science Exercise 1 Solutions

A Fender guitar amp can produce a sound with an intensity of $1{\cdot}10^{-1}$ W/m^2 (at 10 inches away). Calculate the sound level (in dB) produced by the amp:

$$(dB) = 10\log_{10}\frac{I}{I_0} \qquad (dB) = 10\log_{10}\frac{(1\cdot10^{-1}W/m^2)}{(1\cdot10^{-12}W/m^2)} = 110dB$$

Calculate the sound level (in dB) perceived by someone standing ten inches away from two Fender guitar amps.

$$(dB) = 10\log_{10}\frac{I}{I_0} \qquad (dB) = 10\log_{10}\frac{2(1\cdot10^{-1}W/m^2)}{(1\cdot10^{-12}W/m^2)} = 113dB$$

Increasing the intensity by a factor of two corresponds to a sound level increase of only ____3______ dB.

A rocket launch is capable of producing a sound intensity of $1{\cdot}10^6$W/m^2. Calculate the sound level in dB.

$$(dB) = 10\log_{10}\frac{I}{I_0} \qquad (dB) = 10\log_{10}\frac{(1\cdot10^{6}W/m^2)}{(1\cdot10^{-12}W/m^2)} = 180dB$$

A sound level of 160 dB will instantly break an ear drum. As you remember, sound is produced by a vibrating object causing pressure differences in a medium such as air. As the vibrating object moves towards the ear, the gas molecules in the air move with a higher velocity. As the vibrating object moves away from the ear, the gas molecules in the air move with a smaller velocity. These moving gas molecules exert a pressure on the ear drum. The pressure on the ear is given by the following equation:

$$\Delta P_{\max} = \sqrt{2\rho v I}$$

Where v is the speed of sound in air (v = 343 m/s), and ρ is the density of air (1.2 kg/m^3).

Calculate the pressure exerted by a sound of that level.

Hint: Students can look on the chart on the first page and infer that since a noise of 130 db corresponds to an intensity of $1\text{x}10^1$, a noise of 140 corresponds to an intensity of $1\text{x}10^2$, a noise of 150 should correspond with an intensity of $1\text{x}10^3$, and a noise of 160 should correspond with an intensity of $1\text{x}10^4$.

Students can use the definition of a logarithm to confirm this since $\log_{10}(1\text{x}10^4/1\text{x}10^{-12})$ is 16. 16x10=160.

$$\Delta P_{\max} = \sqrt{2(1.2kg/m^3)(343m/s)(1\cdot10^4W/m^2)} = 2869.15Pa$$

If the area of the inner ear is 0.52 cm^2, what is the force exerted on the ear by a 160 dB sound?

$$P = \frac{F}{A} \qquad F = P\cdot A$$

Changing the area from cm^2 to m^2: $\dfrac{0.52cm^2}{1}\cdot\left(\dfrac{(1m)}{(100cm)}\right)^2 = 5.2\cdot10^{-5}m^2$

$$F = (5.2\cdot10^{-5}m^2)\cdot(2869.15Pa) = 0.15N$$

Science Learning Activity 2

Big Ben Sound Demonstration

This demonstration illustrates two ways for sound waves to travel and relates these to the parts on an electric guitar. It is designed to engage students in a discussion of sound production and types of sound waves. Students are then asked to relate how transverse waves on a string can then be converted to longitudinal/compression waves via a speaker or other similar device

Learning Objectives:

1. Students will identify the regions where sound is transmitted using transverse and longitudinal waves.
2. Students will relate these regions to parts on an electric guitar and amplifier.

Materials Required:

1 Wire coat hanger
2 ~30cm pieces of string (kite string works well, but any thick string will do)
2 Waxed paper drinking cups (e.g., Dixie cups)
2 paper clips

References:

Addison, Pam. "Improving Ohio's Physical Science Proficiency" class at Miami University, Middletown. June 2007.

Science Exercise 2

Tie one end of each piece of string to the metal coat hanger. Poke a hole in the bottom of each paper cup. Feed the loose end of one string up through the hole of the cup, tie around a large paperclip to secure. Repeat with the other string and paper cup.

To use:

Hold paper cups to both ears and let the hanger fall loose. Swing the hanger so it hits something hard, such as a desk. When the hanger strikes another hard surface, you will hear a sound like a clock chime. The audience will not hear anything, however.

I encourage you to make a class set; I have one hanger for each lab table for my students to try.

Possible Discussion Topics:

This would be a great activity to start a discussion of sound waves.

Q1: What type of waves traveled up the string to the bottom of the cup?

Q2: What is this analogous to on the electric guitar?

Q3: What type of waves traveled from the bottom of the cup to your ears?

Q4: How are the sound waves transferred from the bottom of the cup to your ears?

Q5: What is this analogous to on an electric guitar?

Science Exercise 2 Solutions

Q1: What type of waves traveled up the string to the bottom of the cup?
Transverse

Q2: What is this analogous to on the electric guitar?
Guitar strings

Q3: What type of waves traveled from the bottom of the cup to your ears?
Longitudinal/compression

Q4: How are the sound waves transferred from the bottom of the cup to your ears?
Transverse waves carry energy from the colliding hanger up through the string to the bottom of the cup. This causes the bottom of the cup to vibrate, which causes regions of compression and rarefaction in the air between the bottom of the cup and your ear.

Q5: What is this analogous to on an electric guitar?
Amplifier/Speakers

Notes

Science Learning Activity 3

Dancing Laser Demo

This lesson demonstrates how sound is produced by a speaker and how sound is a longitudinal/compression wave. Many students have difficulty in understanding how a speaker produces sound. This demo should illustrate how the speaker diaphragm moves in order to create compression waves in air.

Learning Objectives:

At the end of this demo, students should be able to describe how the diaphragm of a speaker moves to create a longitudinal/compression wave in the air and interpreted by the ear as sound.

Materials Required:

- Old speaker(s) (nothing fancy, they just have to work)
- Radio, computer, etc. that speakers hook up to
- Small mirror (1" is fine)—these can be found at craft stores
- Tape
- String
- Laser pointer (one from the dollar store is fine)

References:

- Addison, Pam. "Improving Ohio's Physical Science Proficiency" class at Miami University, Middletown. June 2007.
- http://www.soundonmind.com/files/speaker%20diagram%201%20-%20lables%20%28flat%29.png . Accessed April 2010.
- http://mypages.iit.edu/~smile/ph93jl.html
- http://www.exploratorium.edu/square_wheels/modulated_led.pdf
- http://www.xprt.net/~rcrowley/AVclass/Aud-Dcon.htm

Science Exercise 3

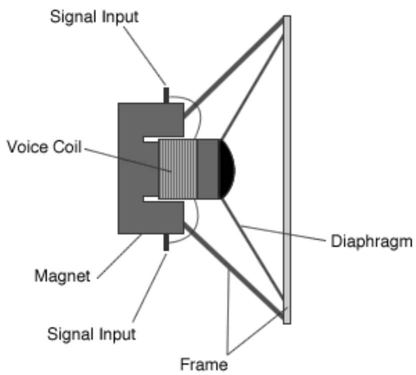


Image source: http://www.soundonmind.com/

Safety precautions:

- ✓ Take care to ensure that the laser never is shown in anyone's eyes.
- ✓ Test out the sound system before doing this demo in class. While use of bargain equipment is encouraged, please make sure the equipment is in good working order.
- ✓ Make sure the volume is set to a reasonable level before beginning.

Set-up:

If possible, remove speaker casing to reveal its internal structure. Hook up speakers to radio (or other device). Tape one end of the string to the back of the mirror. Tape the other end of the string to the top of the speaker so the mirror dangles in front of the diaphragm. Make sure the reflective side of the mirror is facing outward.

Fix the laser pointer so that it shines into the center of the mirror when the sound is off. The laser can be held stationary or can be taped down to a rigid surface.

Any music will work. Music that has a lot of bass will work the best (have students bring in their favorite bass CDs that they like to have blaring in their $750 car with a $2500 stereo system with car parts vibrating off as they go down the road).

Turn lights off and the laser and music on. Watch the reflected laser "dance!"

Possible Discussion Topics:

- Have students identify parts of a speaker and describe what their function is (see diagram under the "Goals" heading).
- Have students explain why the reflected laser light is moving.
- Have students explain how the speaker produces sound.

Explanation:

The diaphragm creates regions of compression and rarefaction in the air; thus propagating a sound wave. The mirror moves in response to these vibrations. The stationary laser light is moved due to the moving mirror. This demo illustrates that sound is a longitudinal/compression wave.

Extension—Speak into the Speaker:

Show students how the speaker's function can be reversed. Connect speaker to an oscilloscope (the soundcard oscilloscope presented at the end of this Workbook by Christian Zeitnitz will work fine). If using a soundcard oscilloscope, it will need to be connected to a 1/8" jack. Have a student speak into a speaker and watch the electronic signal as it is displayed on the screen (this would work best if the computer was hooked up to a projector or to the TV via an AVerKey). Swap out the speaker and connect a microphone to the computer. Have a student repeat what was said into the speaker. Ask the class to consider why the signal display was similar. Explain that a dynamic microphone works in a similar way. For the speaker, an electronic signal triggers the diaphragm to move which causes compression waves in the air interpreted by the ear as sound. The dynamic microphone is the reverse of this process. The diaphragm on a dynamic microphone moves in response to sound (compression) waves in air. This causes the magnets to move which sends a current through the coil.

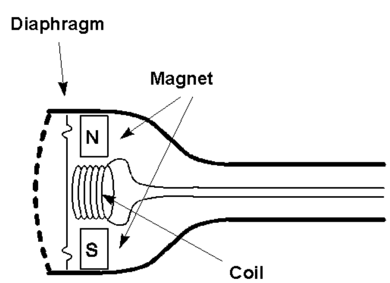


Image source: http://www.xprt.net/~rcrowley/AVclass/Aud-Dcon.htm

Science Learning Activity 4

Introductory Wave Behavior

Students will produce transverse and longitudinal waves using a Slinky or small, loose spring. Students will experiment with changing wave speed, frequency, and wavelength. Students will also determine what happens to the frequency of the wave when string tension is changed.

Learning Objectives:

By the end of this lesson, students should be able to:

1. Describe the difference between a transverse and a longitudinal (compression) wave
2. Identify areas of compression and rarefaction in longitudinal/compression waves
3. Identify the amplitude, wavelength, crest, and trough in a transverse wave
4. Explain boundary behavior of transverse waves
5. To understand the difference between transverse and longitudinal (compression) waves and to examine the wave characteristics of frequency and wavelength.

Materials Required:

- Regular-sized Slinky or similar small, lose spring

Caution: Do not stretch the Slinky to its maximum limit. This could cause permanent damage to the Slinky. Take care in keeping the Slinky in good condition.

References:

Mrs. Aker's Science Class archived files: http://www.fifeschools.com/cjh/staff/laker/filesarchive.htm. Accessed April 2010.

Physics Principles and Problems. Glencoe/McGraw-Hill. 2009.

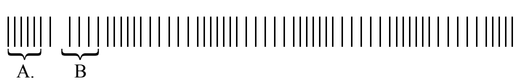
Science Exercise 4

The two basic classes of waves are transverse and longitudinal (also known as compression waves). Both of these wave types play a role in producing sound from the electric guitar. Sound waves are longitudinal waves. Our ears detect the pressure differences in the air caused by the compression wave which is produced by the speaker. When a player plucks the strings of a guitar, a transverse wave is produced. In this activity, you will use a Slinky to model both types of waves.

Caution: Do not stretch the Slinky to its maximum limit. This could cause permanent damage to the Slinky. Take care in keeping the Slinky in good condition.

Longitudinal/Compression Waves:

Take one end of the Slinky and have a lab partner hold onto the other end of the Slinky. Spread the Slinky out about 2-3 meters (do not stretch the Slinky out completely!). Grab about 0.5 meters of Slinky coils and compress them in your hand. Quickly let go. Observe the compressions and rarefactions in the Slinky. You may have to try this a couple of times to get the hang of it. Your Slinky should look like this, where A is the compression and B is the rarefaction:



Which direction was energy transferred along the Slinky?

Did the Slinky coils move parallel or perpendicular to the way the wave/energy was moving?

Transverse Waves:

Again, have one person hold the Slinky at the opposite end. Move the Slinky to one side, then back quickly to produce a wave pulse.

Notes

[1] To start the wave, you moved the Slinky left or right. Which way is the energy being transferred?

Sketch a diagram of the wave traveling on the Slinky and label the direction of the wave and the direction of the transferred energy:

[2] What does the word *transverse* mean? Why are these waves labeled as such?

[3] Flick the Slinky again with a quick left or right motion. Pay attention to how the wave travels along the Slinky. When the wave reaches your lab partner at the other end, how is the wave reflected? Does the wave return on the same side as it traveled down or on the opposite side?

[4] Stretch the Slinky out without damaging it so it is fairly taught. Give one end a good "karate chop," either vertically or horizontally. Note how the wave behaves. Now move in closer to your lab partner so the Slinky is lose. Give the Slinky another good "karate chop" either vertically or horizontally. Note how the wave behaves. How does tension affect the wave?

Predict how a guitar string would sound if it were under too much tension and if it was not wound tight enough:

[5] Have one person hold the Slinky taught at one end. The other person needs to move the Slinky up and down quickly in order to create a wave train. Count how many wavelengths you are able to get. What do you have to do to increase the number of wavelengths? Decrease the number of wavelengths?

[6] Have one lab partner hold one end and another partner hold the Slinky at the opposite end. Try to flick the Slinky so that you both create a wave at the same time. Record what happens to the Slinky when both wave crests reach the center at the same time:

[7] Next, try to do the same thing, but instead, have one wave crest meet with a trough in the center. What happens to the Slinky when a crest and trough meet at the same point?

[8] Which type of waves travel along guitar strings?

[9] Which type of waves travel out of the amplifier and into a listener's ear?

Science Exercise 4 Solutions

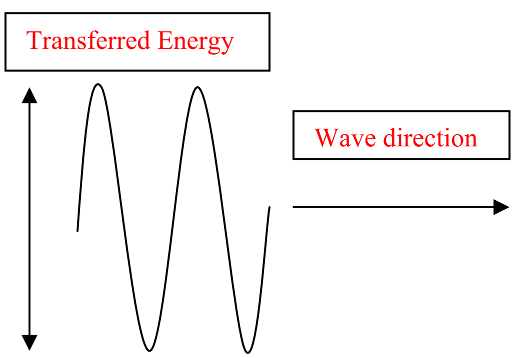
[1] Which direction was energy transferred along the Slinky?
Energy was transferred in the direction of the Slinky.

[2] Did the Slinky coils move parallel or perpendicular to the way the wave/energy was moving? Parallel to the energy.

II. Transverse Waves:
Again, have one person hold the Slinky at the opposite end. Move the Slinky to one side, then back quickly to produce a wave pulse.

[1] To start the wave, you moved the Slinky left or right. Which way is the energy being transferred?
Perpendicular to the Slinky.

Sketch a diagram of the wave traveling on the Slinky and label the direction of the wave and the direction of the transferred energy:



[2] What does the word *transverse* mean? Why are these waves labeled as such?
Transverse means perpendicular. (Ask students to consider what *transverse* means in geometry.) These waves are labeled as such because the energy is being transferred perpendicular to the direction of the wave.

[3] Flick the Slinky again with a quick left or right motion. Pay attention to how the wave travels along the Slinky. When the wave reaches your lab partner at the other end, how is the wave reflected? Does the wave return on the same side as it traveled down or on the opposite side?
When the wave strikes a boundary (the partner's hand), it will travel back on the opposite side. For example, if the wave crest was to the left of the person before it reflected off of her hand, the reflected wave crest would be to the right of the person's hand.

[4] Stretch the Slinky out without damaging it so it is fairly taught. Give one end a good "karate chop," either vertically or horizontally. Note how the wave behaves. Now move in closer to your lab partner so the Slinky is lose.

Give the Slinky another good "karate chop" either vertically or horizontally. Note how the wave behaves. How does tension affect the wave?
As tension increases, so should the speed of the wave.
Predict how a guitar string would sound if it were under too much tension and if it was not wound tight enough:
If a guitar string were under too much tension, it will have a higher pitch. If a guitar string were too loose, it will have a lower pitch.

[5] Have one person hold the Slinky taught at one end. The other person needs to move the Slinky up and down quickly in order to create a wave train. Count how many wavelengths you are able to get. What do you have to do to increase the number of wavelengths? Decrease the number of wavelengths?
Number of wavelengths will vary. To increase the number of wavelengths, the person should move her hand more frequently. To decrease the number of wavelengths, the person should move her hand less frequently.

[6] Have one lab partner hold one end and another partner hold the Slinky at the opposite end. Try to flick the Slinky so that you both create a wave at the same time. Record what happens to the Slinky when both wave crests reach the center at the same time:
When two crests collide, the amplitude should be twice as large as the two initial waves (constructive interference).

[7] Next, try to do the same thing, but instead, have one wave crest meet with a trough in the center. What happens to the Slinky when a crest and trough meet at the same point?
There should be a point of no disturbance in the center where the crest and trough meet. They should cancel each other out (destructive interference).

[8] Which type of waves travel along guitar strings?
Transverse waves

[9] Which type of waves travel out of the amplifier and into a listener's ear?
Longitudinal/compression waves

Science Learning Activity 5

Standing Waves on a String

To understand how the frequency of waves on a string depends on factors such as the length of the string and harmonic number.

A guitar produces tones because of standing waves on a string. In this exercise, students will work in groups of three or more to study waves on a large piece of rope. While it is harder to see waves on a guitar string, they vibrate in a similar manner.

By the end of this lesson, students should be able to:

- Explain what is meant by the frequency of a standing wave
- Explain that the frequencies of harmonics are multiples of the fundamental frequency
- Explain that a shorter string has standing waves of a higher frequency

Learning Objectives:

In this lab, students will get to use their prior knowledge of transverse waves (velocity, wavelength, and frequency) and apply it to the electric guitar.

1. Measure the length, mass, and peak frequency for each guitar string
2. Calculate the velocity on the six guitar strings based on their data
3. Use the basic equation for the speed of a wave, $v=f\lambda$
4. Use the fact that the wavelength of the first harmonic is twice as long as the guitar string

Materials Required:

Clothesline or similar rope roughly 15 feet long, stopwatch
Guitar, Meter stick, Guitar Tuner
Fourier Synthesis Java Applet
http://homepages.gac.edu/~huber/fourier/

References:

"Physics", Douglas Giancoli, 6th ed., Prentice Hall, 2005.
http://davide.gipibird.net/A_folders/Theory/t1.html
Tom Huber, Physics Department, Gustavus Adolphus College, huber@gac.edu Revised: June 6, 2010
http://www.betterguitar.com/instruction/essentials/guitar_parts.html
"Engineering the Guitar: Theory and Practice", R. Mark French, Springer, 2009

Science Exercise 5

National Science Standards:

- **Motion and Forces:** Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship F=ma, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object. {pg. 179-180}
- **Interactions of Energy and Matter:** Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter. {pg. 180s}

Note: There are two different naming conventions for names of the standing waves – this can easily lead to confusion! Almost all textbooks for both physics or music will call the lowest mode, Figure 1(a), the Fundamental. Some texts, particularly physics texts, will also call Figure (a) the First Harmonic.

The second mode, Figure 1(b), might be called the Second Harmonic in some texts, but it might also be called the First Harmonic in other texts! Another name for this would be the First Overtone.

The third mode, Figure 1(c), again might be called either the Second or Third Harmonic, depending on the convention used.

Figure 1: Standing waves on a string

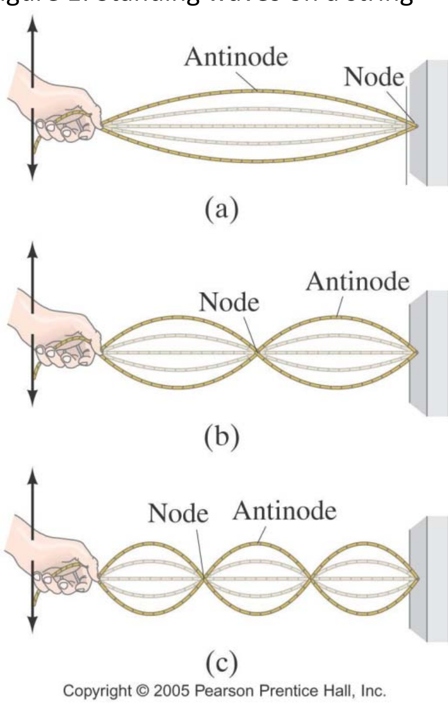


Figure 1(a): Fundamental Mode, Frequency f_1
Also sometimes called First Harmonic

Figure 1(b): Second Mode, Frequency $f_2 = 2f_1$
Some texts call this the First Overtone,
Or the 2^{nd} Harmonic (or sometimes the 1^{st} Harmonic)

Figure 1(c): Third Mode, Frequency $f_3 = 3f_1$

For standing waves on a string, the two ends of the string are nodes (where the string is essentially motionless), and there are one or more antinodes (where the displacement is large) between the nodes.

The frequency, *f*, of a wave is defined as the number of times each second it goes through a full cycle. The units for frequency are "Hertz" or "Hz", which is the number of cycles per second. For example, if a string is vibrating at 440 Hz, it means that it moves an entire cycle (wave up, to wave down, back to wave up) 440 times each second.

I. Fundamental Mode of Standing Waves on a String:
(a) Two lab partners should hold onto the ends of a rope about 10-15 feet apart. Back up until the rope is sagging only a few inches in the middle of the rope. One partner should hold the rope so that it doesn't move (for example, hold your elbows close to your body and your hands with the rope right next to your chest). The other partner will move the rope up and down. Increase or decrease the frequency (how fast you vibrate the rope) until you get stable, large amplitude of the First Mode, as shown in Figure 1(a).

How many antinodes are there on the string for the fundamental mode _________

How many nodes are there for the fundamental mode ___________

(b) Once you have a large amplitude for the First Mode, use a stopwatch to time 10 seconds, and count the number of cycles of the wave. Divide the number of cycles in 10 seconds by 10 to get the frequency, which is the number of cycles per second.

_____________ Number of cycles in 10 seconds

_____________ Number of cycles in 1 second

_____________ Frequency of the Fundamental Mode in Hz

II. Second Mode of the String:
Now, without moving forward or backwards, speed up the rate that you are vibrating the rope until you form a stable pattern of the Second Mode, as shown in Figure 1(b). Again, count the number of cycles that occur in 10 seconds, and determine the frequency by dividing by 10.

How many antinodes are there on the string for the Second Mode _________

How many nodes are there for the Second Mode ___________

_____________ Number of cycles in 10 seconds

_____________ Frequency of the Second Mode in Hz

III. Third Mode of the String:

Finally, speed up the rate that you are vibrating the rope until you form a stable pattern of the Third Mode, as shown in Figure 1(c).

How many antinodes are there on the string for the Third Mode _________

How many nodes are there for the Third Mode ___________

_____________ Number of cycles in 10 seconds

_____________ Frequency of the Third Mode in Hz

Discuss: According to theory, the second mode should have twice the frequency of the fundamental, and the third mode should be about three times the frequency of the fundamental. Do your results agree with this prediction?

IV. Length of String

If the length of the string is shortened, the frequency of the standing wave will increase. Instead of holding the ends of the rope, move so that you are about half the distance apart from each other that you were originally. Shake the rope until you get it vibrating in its first mode. Use the same technique to measure the frequency of the standing wave.

_____________ Number of cycles in 10 seconds

_____________ Frequency of the Third Mode in Hz

Explain what happens to the frequency of the standing wave on a string when the length of the string is shortened. Explain how this relates to making notes on a guitar.

Problems:

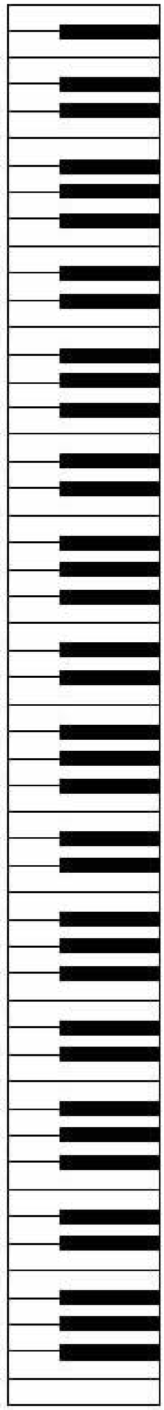
[1] Sketch the standing wave when the string is vibrating in its 2nd mode. If a 64.8 cm long guitar string is vibrating in its 2nd mode, how far from the end is one of the nodes?

[2] Sketch the standing wave when the string is vibrating in its 3rd mode. If a 64.8 cm long guitar string is vibrating in its 3rd mode, how far from the end is one of the nodes?

[3] The fundamental frequency of the low E string on a guitar is 82.4 Hz. What is the frequency of the second and third modes of this string?

[4] The diagram on the following page shows the notes on a piano and the corresponding frequencies. The low E string on a guitar (82.4 Hz) is called E2 because it is the note corresponding to the 2nd E key on a piano. What notes do the second and third modes of this string correspond to?

Middle C



A0	27.5	A#0	29.135
B0	30.868		
C1	32.703	C1#	34.648
D1	36.708	D1#	38.891
E1	41.203		
F1	43.654	F1#	46.249
G1	48.999	G1#	51.913
A1	55.000	A1#	58.270
B1	61.735		
C2	65.406	C2#	69.296
D2	73.416	D2#	77.782
E2	82.407		
F2	87.307	F2#	92.499
G2	97.999	G2#	103.83
A2	110.00	A2#	116.54
B2	123.47		
C3	130.81	C3#	138.59
D3	146.83	D3#	155.56
E3	164.81		
F3	174.61	F3#	185.00
G3	196.00	G3#	207.65
A3	220.00	A3#	233.08
B3	246.94		
C4	261.63	C4#	277.18
D4	293.66	D4#	311.13
E4	329.63		
F4	349.23	F4#	369.99
G4	392.00	G4#	415.30
A4	440.00	A4#	466.16
B4	493.88		
C5	523.25	C5#	554.37
D5	587.33	D5#	622.25
E5	659.25		
F5	698.46	F5#	739.99
G5	783.99	G5#	830.61
A5	880.00	A5#	932.33
B5	987.77		
C6	1046.5	C6#	1108.7
D6	1174.7	D6#	1244.5
E6	1318.5		
F6	1396.9	F6#	1480.0
G6	1568.0	G6#	1661.2
A6	1760.0	A6#	1864.7
B6	1979.5		
C7	2093.0	C7#	2217.5
D7	2349.3	D7#	2489.0
E7	2637.0		
F7	2793.8	F7#	2960.0
G7	3136.0	G7#	3322.4
A7	3520.0	A7#	3729.3
B7	3951.1		
C8	4186.0		

Science Learning Activity 6

Standing Waves on a Guitar String

One purpose of this learning activity is to investigate the relationship between the length of strings on a guitar and the frequency. Another is to investigate harmonics of strings

Learning Objectives

In a previous learning activity, you studied the shapes for the different modes of vibration of strings. You noticed that there were nodes (motionless points) at the two ends of the string. For the 2^{nd} Harmonic, with twice the frequency of the fundamental, there was also a node at the center of the string.

Materials Required:

Guitar
Meter stick
Guitar Tuner

References:

"Physics", Douglas Giancoli, 6th ed., Prentice Hall, 2005.
http://www.betterguitar.com/instruction/essentials/guitar_parts.html
"Engineering the Guitar: Theory and Practice", R. Mark French, Springer, 2009
Written By: Tom Huber, Physics Department, Gustavus Adolphus College, huber@gac.edu
Revised: July 11, 2010

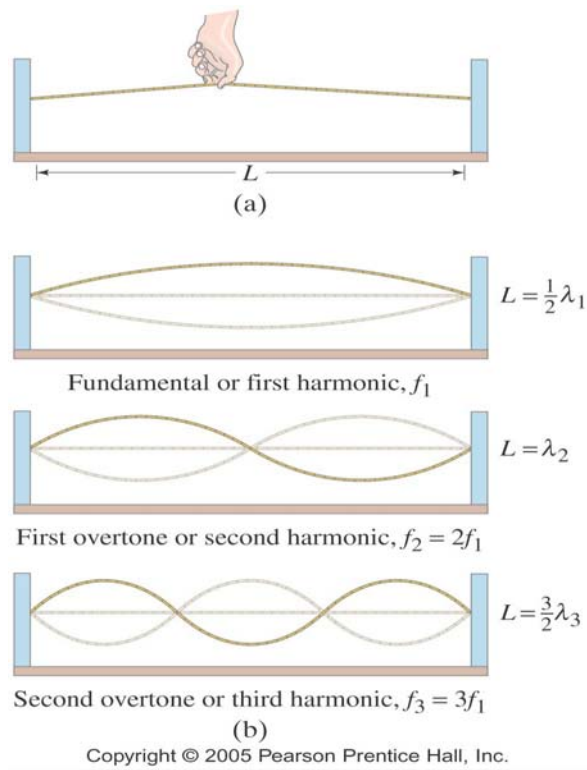
Science Exercise 6

There are a couple of key concepts to understand when discussing waves on a string:

Frequency (*f*) is the number of cycles of the string each second. This is measured in units of Hertz (Hz), which is another name for cycles per second.

Wavelength (λ, which is the Greek letter lambda) is the length of one full cycle of a wave. The wavelength of the fundamental standing wave λ_1 is twice the length of the string L, or $\lambda_1=2L$

Velocity (v) is the speed of the wave on the string. As we will find out in a subsequent learning activity, the speed of the wave increases as the tension in the string increases, and the speed decreases as the mass per unit length of the string increases (which is why the lower strings on the guitar are thicker – they can have a lower tone because there is more mass in the same length of string).



These three quantities are interrelated in the following equation:

$$v = f\lambda \qquad (1)$$

Namely, the product of the wavelength times the frequency is equal to the speed of the wave. We can write this another way. Namely, by solving for the frequency, and noting that for the fundamental, the wavelength is given by $\lambda_1=2L$, the frequency of the fundamental can be written as

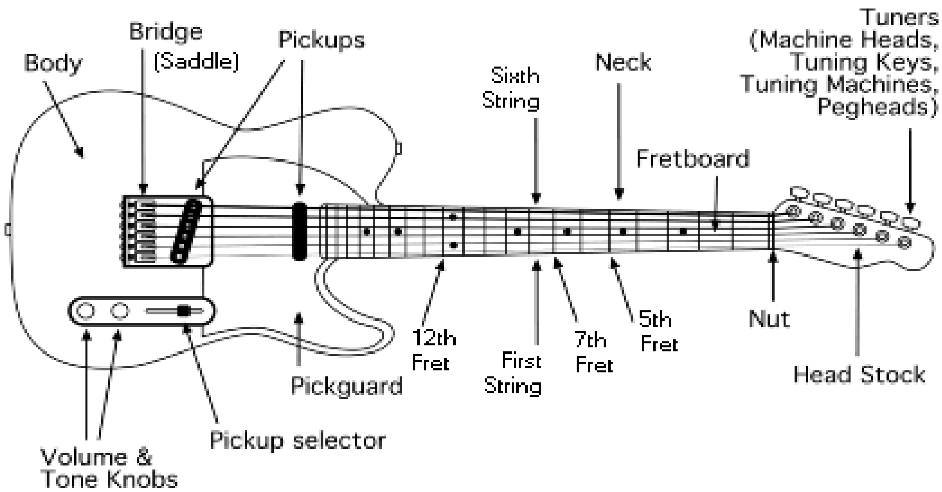
$$f_1 = v / 2L. \qquad (2)$$

The frequencies of different harmonic are multiples of the fundamental frequency. For the n^{th} harmonic is

$$f_n = n\,(v / 2L) = n\,f_1\,. \qquad (3)$$

where n=1,2,3,…

When you pluck a string, it will vibrate in many different harmonics at the same time. For example, if you pluck it near the center of the string, it will mainly vibrate in its fundamental harmonic, whereas if a string is plucked near the end, it will vibrate in many of the upper harmonics. As we will see in later learning activities, the combination of harmonics that are present in a sound wave is critical in determining what the tone will sound like.



I. Tuning the Guitar.

For the 6th string on the guitar (the thickest string), measure the length of the string between the nut and the saddle, which is the part of the bridge that the string passes over.

Length of String from Nut to Saddle _________ inches __________ cm

Is the length of each string the same? ________________________________

Use an electronic tuner to tune your guitar. Starting with the 6th string on the guitar, pluck a note, and then turn the tuners until the note is in tune. The notes and their frequencies are listed in the table below

String	Note	Frequency
6th (Thick wound string)	E2	82.4 Hz
5th	A2	110.0 Hz
4th	D3	146.8 Hz
3rd	G3	196.0 Hz
2nd	B3	246.9 Hz
1st (Thin steel string)	E4	329.6 Hz

II. Varying frequency by changing length

As you observed in a previous learning activity, as the length of a string is decreased, the frequency gets larger. This can also be seen in Equation 2 – if the length L gets smaller, the frequency f will get larger. On a guitar, the length of the string can be changed by pressing a string against the neck with your finger. The string will touch a fret, so the effective length of the string would then be the distance from the fret to the saddle.

Locate the 5th fret on the guitar. Frets are numbered starting from the nut. On most guitars, there will be a dot on the neck between the 4th and 5th fret. Press your finger firmly on the 6th string between the 4th and 5th fret, so that the string is touching on the 5th fret. Play the note. It may take a little practice to get a clear tone from the guitar.

What do you observe about this note (5th fret on the 6th string)? Is it higher or lower in pitch? Compare this note to the note that you get when you play the open note on the 5th string.

Now we can use Equation 2 to investigate how the fret board is laid out to properly make notes on the guitar.

First, calculate the speed of waves on the string. Using algebra, solve Equation 2 so that the speed v is on one side of the equation, and the frequency f_1 and length L are on the other side. (HINT: Multiply both sides of the equation by $2L$).

$$f_1 = v / 2L.$$

v =________________

Using the length L (in cm) that you found in Part I, and the fundamental frequency f_1 of an E2 (82.4 Hz), calculate the speed of waves on the string.

L = _________ cm f_1 = ____________ Hz

v =________________ cm/second

This speed (in cm/seconds) is for the 6th string. In a later learning activity we will investigate how this speed changes when the tension in the string changes.

Now, measure the distance from the saddle to the 5th fret on the 6th string.

$L_{5th\ Fret}$ = ___________ cm (from saddle to the 5th fret)

Plug this length and the speed of the wave above into Equation 2 to calculate the frequency of the note that you get when you play the note that is the 5th fret on the 6th string.

$f_1 = v / 2L_{5th\ Fret}$ = ___________ Hz

Compare this frequency to the frequency that you would expect for an A2. On the last page of this handout, you will find a table that has frequencies and corresponding notes. Discuss your results

In order to play a note that has twice the frequency, the string would need to be half as long as the open string.

Divide the total string length by two to find the midpoint of the string.

$L_{Midpoint}$ = ___________ cm

Measure this distance from the saddle. Is this midpoint of the string just about exactly above the 12th fret? ______________________________

Play the note corresponding to the 12th fret on the 6th string. Discuss your results. In particular, for those of you with musical background, is this note an octave higher?

The frequency of an E2 is 82.4 Hz. What frequency is twice the frequency of an E2? According to the table at the end of this learning activity, what note is this? Look at other notes in this table. What do you observe about the frequency of notes that are an octave apart from each other?

One could actually use the table to calculate the fret position that would be needed for any note! We will investigate how to calculate fret spacing's in a later learning activity.

III. Harmonics of Waves on a Guitar String

Position the ball of your thumb near the midpoint (12th fret) of the 6th string; play the string by gently deflecting the string with the broad part of your thumb and releasing the string. This should be a very "round" tone. Compare this tone to the tone that you get when you pluck the same string with a stiff pick near the saddle; this should sound much more metallic. Experiment with plucking the string in different ways in different positions on the neck.

Describe your observations when you pluck the string in different positions

In your previous learning activity, you observed different harmonics for waves on a string. When you pluck the string with a broad thumb near the midpoint of the string, you are exciting mainly the fundamental harmonic.

To excite the 2nd harmonic, you need to make the midpoint of the string a node. To create a node at the midpoint of the guitar string, very gently set a finger on the string directly above the 12th fret; do not press down on the string. Gently pluck the string near the middle of the remaining section of the string. You should get a clear, ringing tone that will persist even after you gently remove your finger. Practice this until you can get a clear tone. Compare the pitch to what you get if you pluck the open string.

Is there an octave difference between the tones? __________________ Also compare the tone that you get by exciting this harmonic to the tone that you get if you conventionally play the note on the 12th fret by pressing the string all the way to the fingerboard and plucking. Discuss your results

To get the 3rd harmonic, you will need to create a node one third of the way along the string.

First, calculate the length of one third of the string _____________ cm.

Measure this distance from the nut of the guitar. Which fret is this _______________

Play this harmonic by very gently placing your finger on the string above the 7th fret, and gently plucking the string. You should be able to get a clear tone.

Does this correspond to any other open note on the guitar? Determine the frequency of this 3rd harmonic and look up this frequency in the table. Discuss your results

Problems:
The first string on a electric guitar is 64.8 cm long, and is tuned to an E4. Using the table at the end of this learning activity, what is the frequency of this string? Using the equation you derived in Problem 3, what is the velocity of the wave on this string?

For the E string described in the previous problem, you want to play a concert A (440 Hz). Use the velocity that you determined from Problem 1 to determine how long you would want to make the string.

Science Learning Activity 7

Determining String Tension Using Measured Frequencies

The purpose of this lab is to determine the tension of a guitar string using measured frequencies. Tension gauges are commercially available but are cost prohibitive for most high school and community college labs. This lab makes use of a free on-line oscilloscope or a hand-held tuner that displays frequency. Students measure the frequency, compare it to the theoretical (in-tune) frequency, calculate the tension on each string, and then calculate the total tension on the guitar due to the strings.

Learning Objectives:

In this lab, students will get to use their prior knowledge of transverse waves (velocity, wavelength, and frequency) and apply it to the electric guitar.

1. Measure the length, mass, and peak frequency for each guitar string
2. Calculate the velocity on the six guitar strings based on their data
3. Use the basic equation for the speed of a wave, $v=f\lambda$
4. Use the fact that the wavelength of the first harmonic is twice as long as the guitar string

Materials Required:

- Oscilloscope (may be accessed on-line) or hand-held tuner that displays frequency
- Electric guitar that is more or less in-tune

On-line oscilloscope may be downloaded from: http://www.zeitnitz.de/Christian/scope_en

References:

- http://www.noyceguitars.com/Technotes/Articles/T3.html {Feb. 9, 2010}
- Serway. *Physics for Scientists and Engineers*.
- Zitzewitz, *et al.* Physics *Principles and Problems.* Glencoe. Pg. 428
- http://www.physicsclassroom.com/Class/sound/u11l5b.cfm {March 25, 2010}
- http://www.sciencebuddies.org/science-fair-projects/project_ideas/Music_p010.shtml {March 29, 2010}
- http://www.harmony-central.com/articles/tips/pitch_vs_frequency/ {April 1, 2010}
- http://www.noyceguitars.com/Technotes/Articles/T3.html {April 1, 2010}
- 1 – French, M., A Pop Bottle and a Helmholz Resonator, *Experimental Techniques*, May/June 2005.
- 2 – Fletcher, N. and Rossing, T., The Physics of Musical Instruments, 2nd ed., Springer 1998, ISBN 0387983740

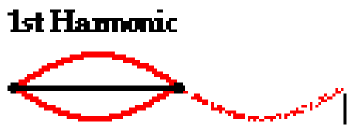


Image Source: http://www.physicsclassroom.com

- **Motion and Forces:** Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship F=ma, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object. {pg. 179-180}

- **Interactions of Energy and Matter:** Waves, including sound and seismic waves, waves on water, and light waves, have energy and can transfer energy when they interact with matter. {pg. 180s}

Notes

Notes

Science Exercise 7

If a guitar string under tension ($\vec{F}_T$) is pulled to the side, then released, the tension causes the string to accelerate back toward the equilibrium position. According to Newton's second law, as the tension on the string increases, the acceleration increases. If the acceleration of the string increases, so should the velocity of the string. It is more difficult to accelerate a more massive string than a lighter one. The wave speed should also decrease as the mass per unit length (μ) increases.

The velocity of a string segment under tension is given by the following formula:

$$v = \sqrt{\frac{\vec{F}_T}{\mu}}$$

One can measure the tension directly using a tension gauge, however, these can be quite expensive. The velocity of a string is also given by:

$$v = \lambda f$$

where λ = 2L. Substituting 2Lf for *v,*

$$2Lf = \sqrt{\frac{F_T}{\mu}}$$

$$4L^2 f^2 \mu = F_T$$

Instead of *measuring* string tension, string length and frequency will be measured in order to calculate the tension on each string.

Measure the mass and length of each string. Record your answers in the table below:

String #	Mass (kg)	Length (m)	μ (kg/m)
1 (E)			
2 (B)			
3 (G)			
4 (D)			
5 (A)			
6 (E)			

Next, measure the peak frequency using an on-line oscilloscope or a hand-held guitar tuner that displays the correct frequency and the actual frequency on the guitar string.

String #	Measured Frequency (Hz)	Ideal Frequency (Hz)
1 (E)		329.63
2 (B)		246.94
3 (G)		196
4 (D)		146.82
5 (A)		110
6 (E)		82.4

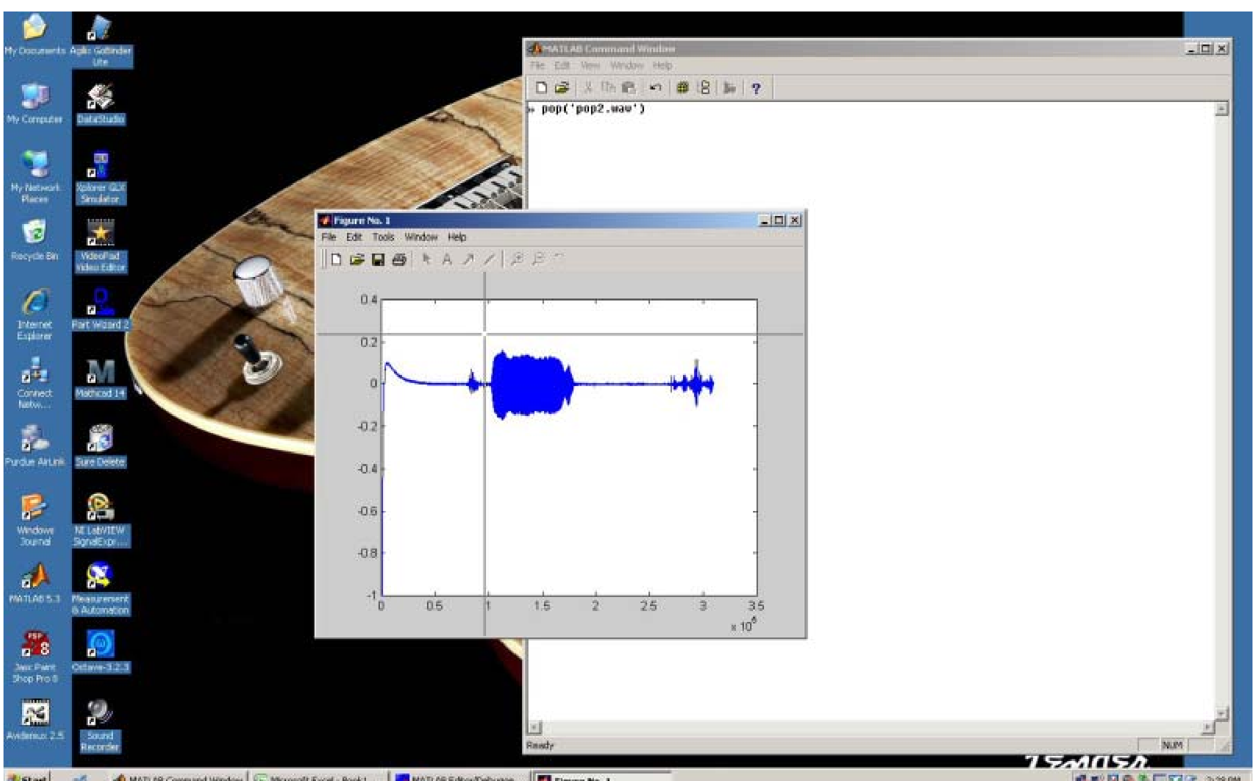
Using the equations from page 1, calculate the tension on each string. Then calculate the ideal string tension in Newton's using the ideal tension in kg and multiplying by $9.8 m/s^2$. Add up the total tensions in each column for the guitar.

String #	Calculated Tension (N)	Ideal Tension (kg)	Ideal Tension (N)
1 (E)		7.35	
2 (B)		6.98	
3 (G)		7.53	
4 (D)		8.34	
5 (A)		8.84	
6 (E)		7.94	
Total Tension:			

[1] Show using dimensional analysis that the units for the square root of the quantity tension divided by the mass per unit length are equal to the units for velocity.

[2] Dean Markley guitar strings have a length of 640mm. The first E string has a diameter of 0.254mm and a μ of $4.01 \cdot 10^{-4}$ kg/m. The tension on the string is 71.3N. Find the frequency of the fundamental note produced by plucking this string.


Sound - Sound Recorder
Position: 5.79 sec.
Length: 5.79 sec.
Save As
Save in: Data
pop1
test
test 2
test 3
Sound Selection
Name:
[untitled]
Save As...
Remove
Format:
PCM
Attributes:
48.000 kHz, 16 Bit, Mono 93 kb/sec
44.100 kHz, 16 Bit, Stereo 172 kb/sec
48.000 kHz, 8 Bit, Mono 46 kb/sec
48.000 kHz, 8 Bit, Stereo 93 kb/sec
48.000 kHz, 16 Bit, Mono 93 kb/sec
48.000 kHz, 16 Bit, Stereo 187 kb/sec
File name: pop1
Save as type: Sounds (*.wav)
Save
Cancel
Format: PCM 44.100 kHz, 16 Bit, Stereo
Change...
Start
2010 Proposal
MATLAB Command Window
Sound - Sound Recor...
1:51 PM


MATLAB Command Window
File Edit View Window Help
» pop('pop2.wav')
Figure No. 1
File Edit Tools Window Help
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0 0.5 1 1.5 2 2.5 3 3.5
x 10^5
Ready
Start
MATLAB Command Window
Microsoft Excel - Book1
MATLAB Editor/Debugge...
Figure No. 1
2:28 PM

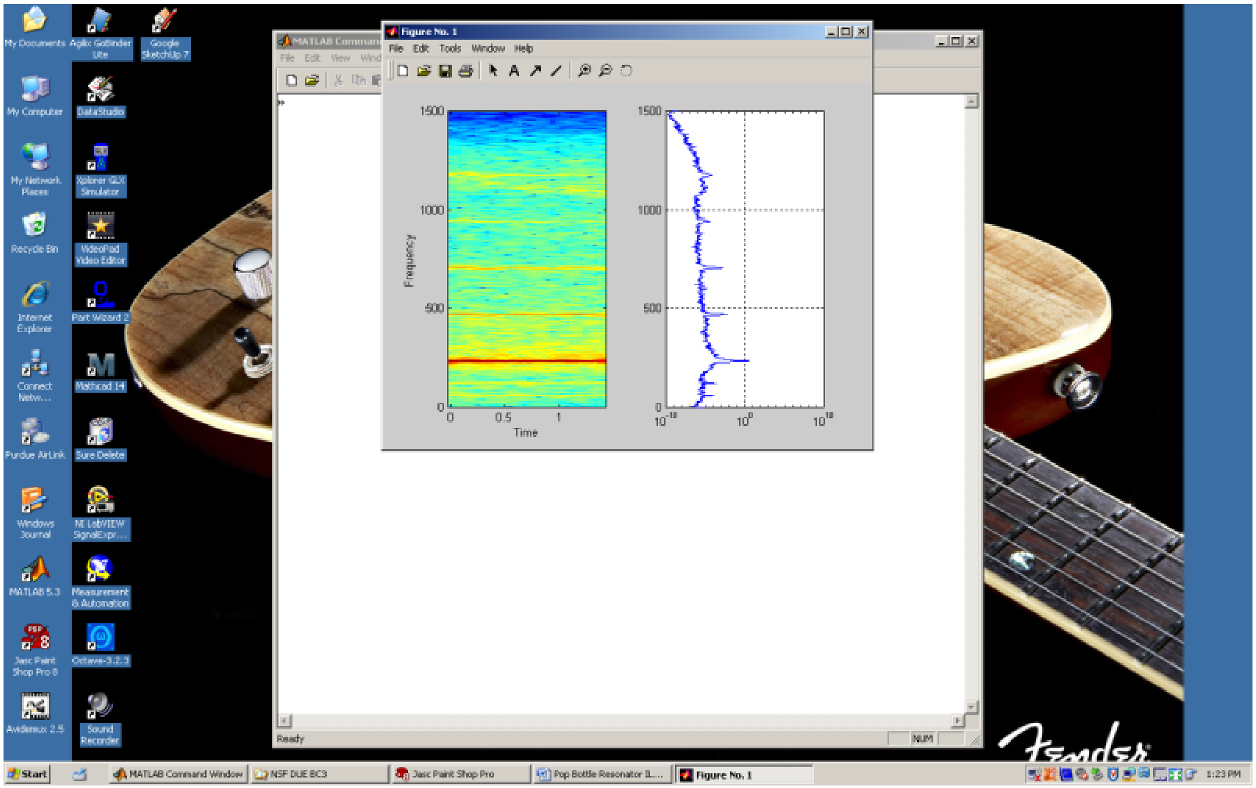
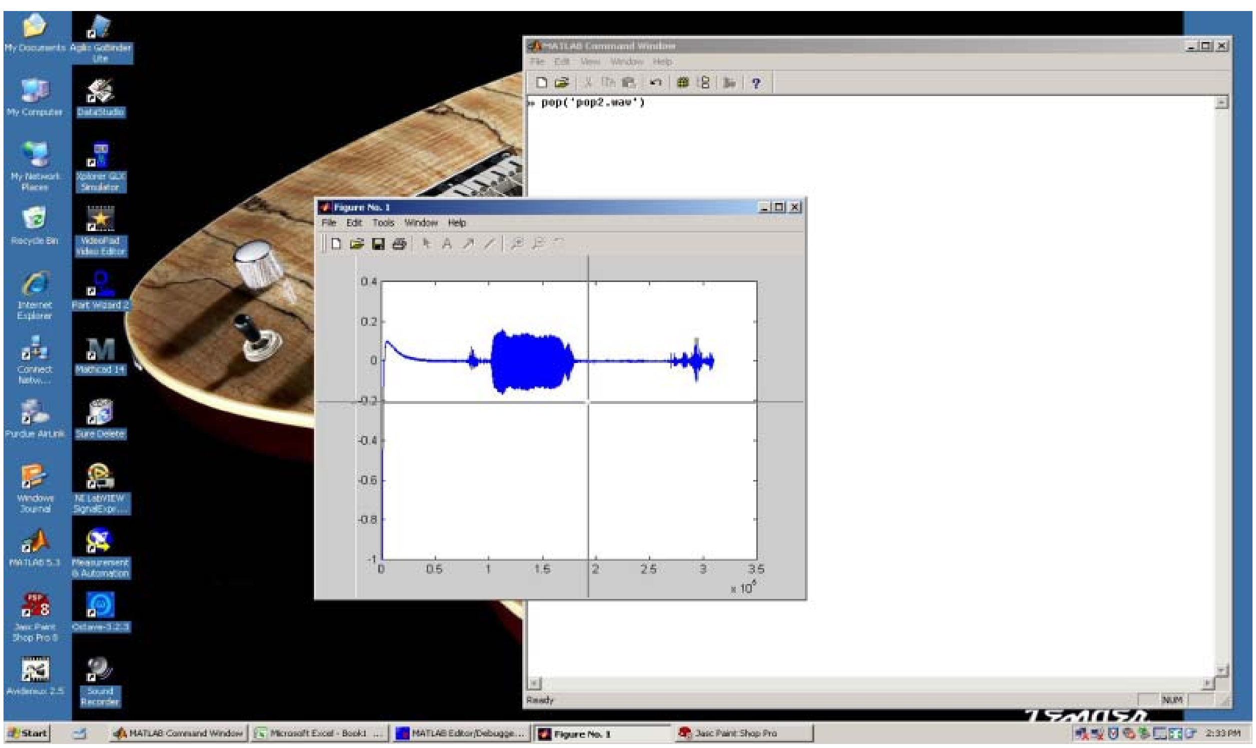


Figure No. 1
Frequency
Time
1500
1000
500
0
0.5
1
Ready


MATLAB Command Window
pop('pop2.wav')
Figure No. 1
Ready

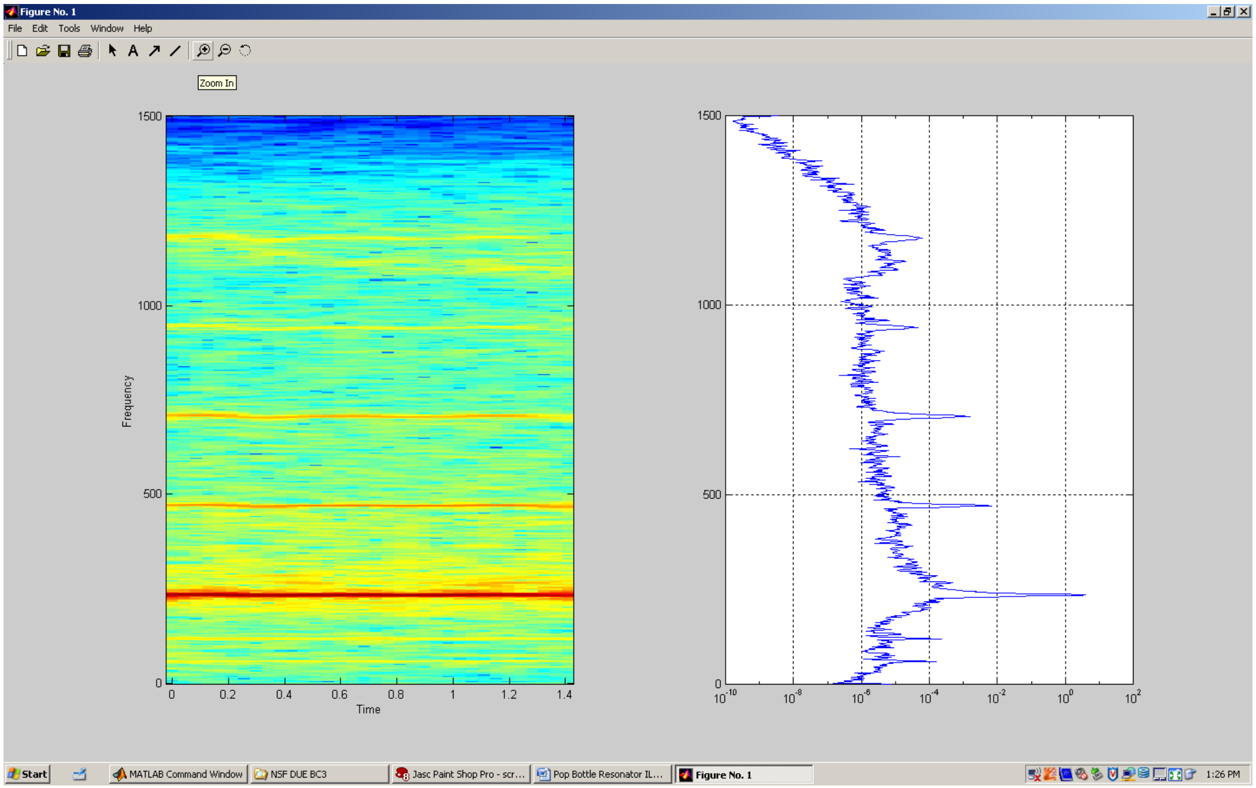


Figure No. 1
File Edit Tools Window Help
Zoom In
Frequency
Time
Start
MATLAB Command Window
NSF DUE BC3
Jasc Paint Shop Pro - scr...
Pop Bottle Resonator Il...
Figure No. 1
1:26 PM

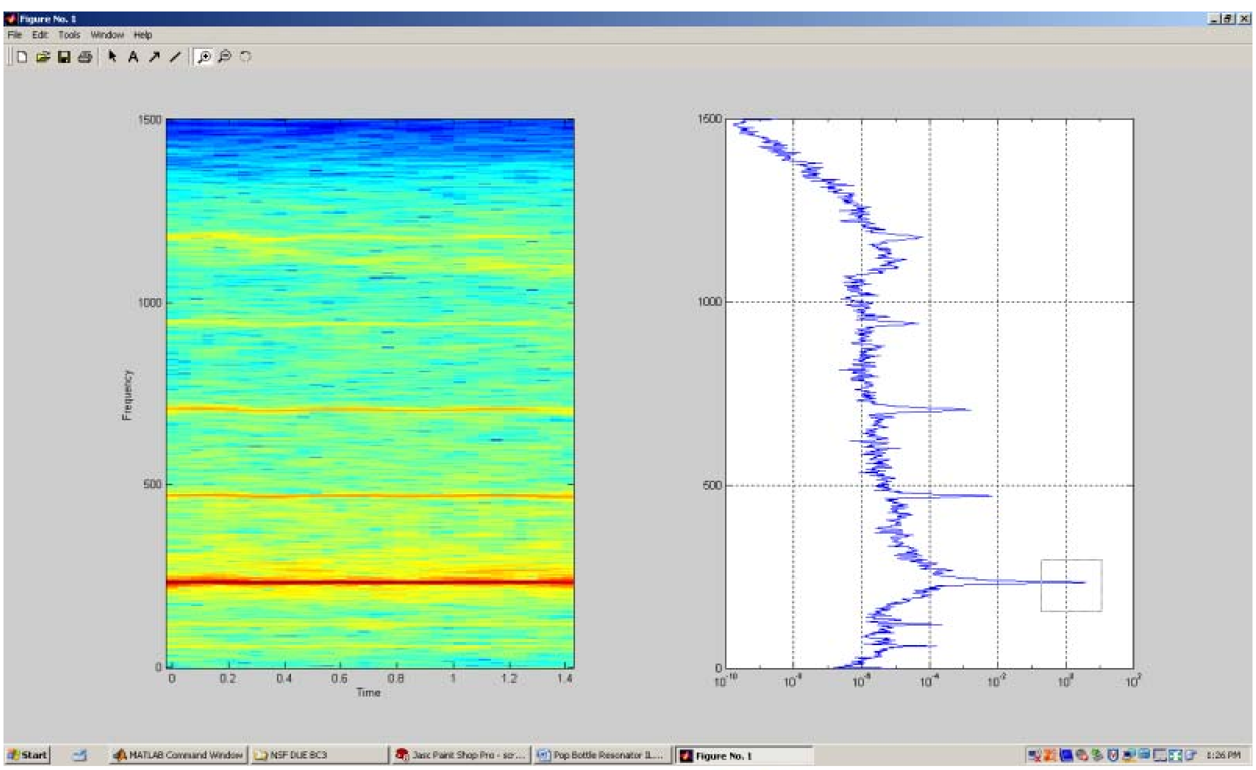


Figure No. 1
File Edit Tools Window Help
Frequency
Time
Start
MATLAB Command Window
NSF DUE BC3
Jasc Paint Shop Pro - scr...
Pop Bottle Resonator Il...
Figure No. 1
1:26 PM

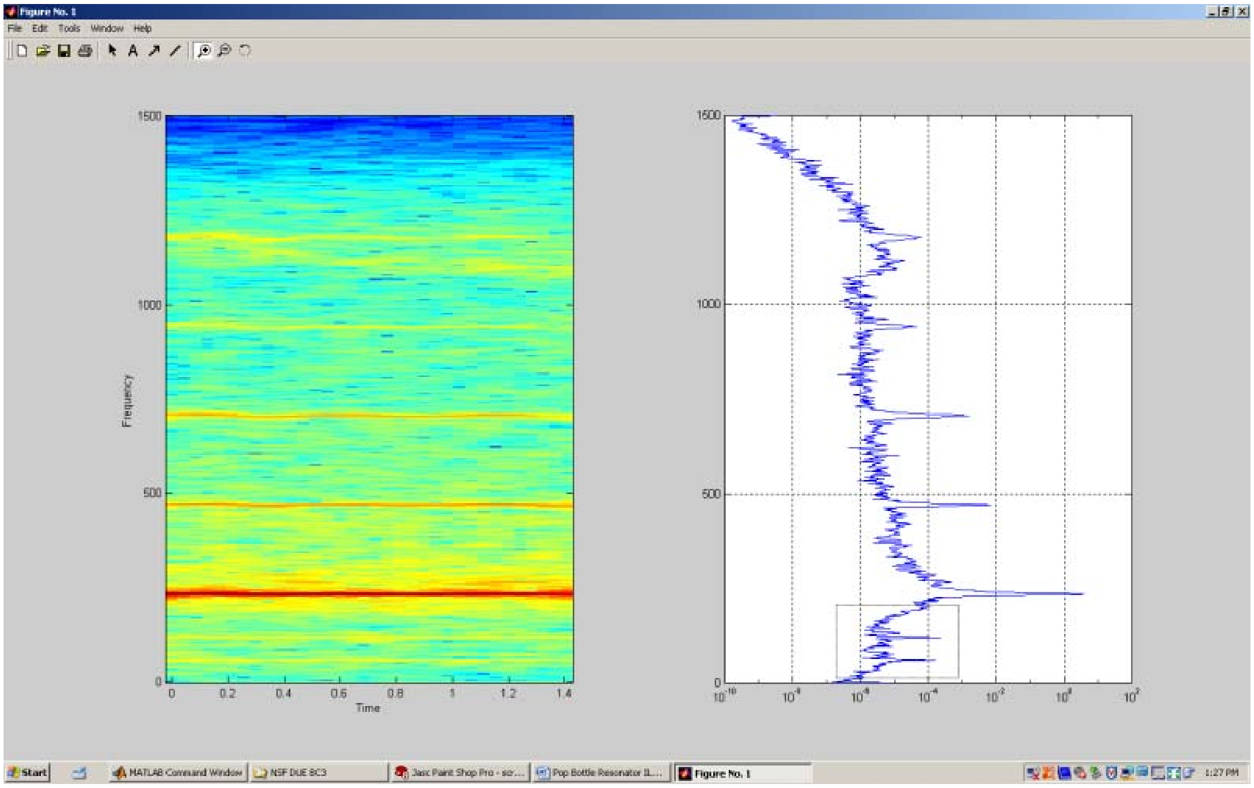


Figure No. 1
File Edit Tools Window Help
1500
1000
500
0
Frequency
0 0.2 0.4 0.6 0.8 1 1.2 1.4
Time
Start
MATLAB Command Window
NSF DUE 8C3
Jasc Paint Shop Pro - scr...
Pop Bottle Resonator I...
Figure No. 1
1:27 PM

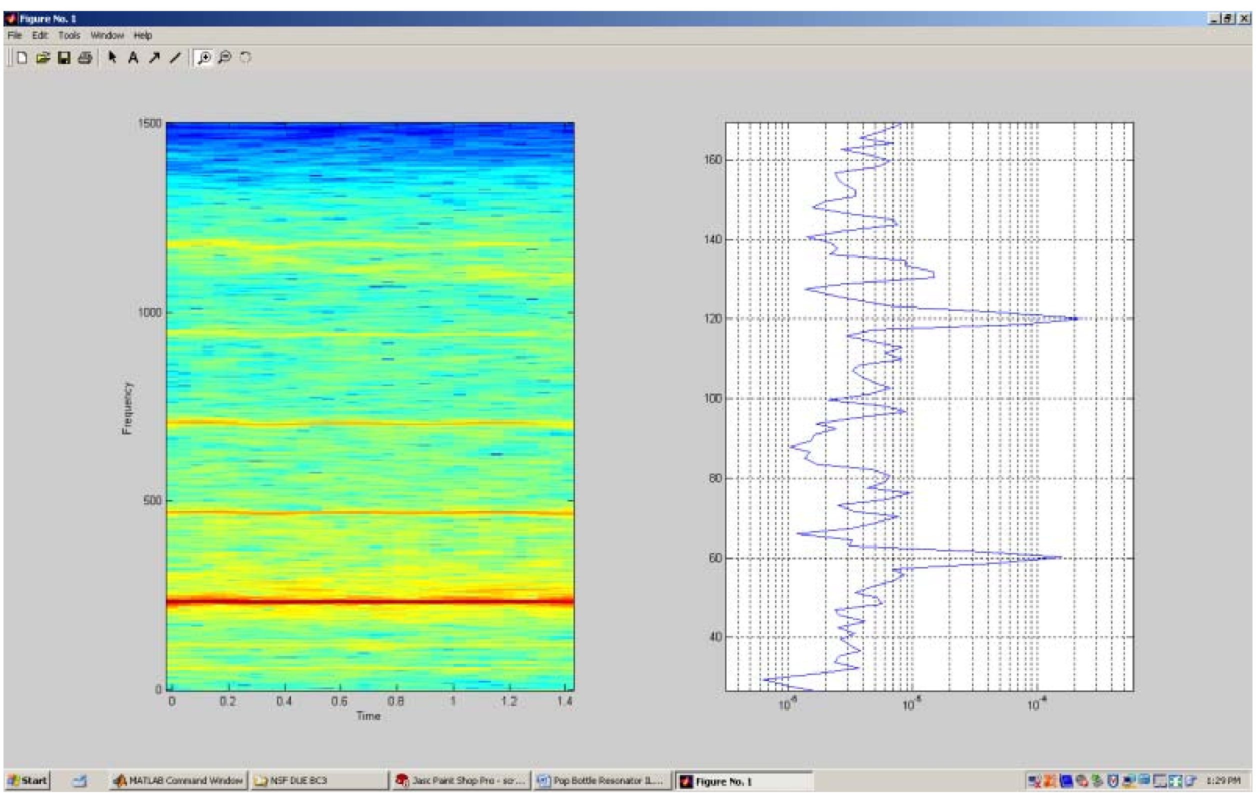


Figure No. 1
File Edit Tools Window Help
1500
1000
500
0
Frequency
0 0.2 0.4 0.6 0.8 1 1.2 1.4
Time
160
140
120
100
80
60
40
Start
MATLAB Command Window
NSF DUE 8C3
Jasc Paint Shop Pro - scr...
Pop Bottle Resonator I...
Figure No. 1
1:29 PM

Science Exercise 8

Any periodic wave can be built up from a combination of sine and cosine waves of different frequencies. The different tone quality (timbre) of sound waves from a musical instrument like a guitar comes from the amount of each of these harmonics.

Materials:
Fourier Synthesis Java Applet
http://homepages.gac.edu/~huber/fourier/

We have seen in previous labs that there are certain fixed frequencies that occur for standing waves on a string, like a guitar. In particular, the frequencies of the standing waves are integer multiples of the fundamental. For the n^{th} harmonic is

$$f_n = n\, f_1 \, . \qquad (3)$$

where n=1,2,3,…

We also noted that depending on how we plucked the string, the pitch (note of the scale) could remain the same, but the tone quality could change from very “smooth” to very “metallic”. Even more changes result from running the output of an electric guitar through filters that modify the tone quality. Musicians use the word “timbre” to refer to the tone quality – the timbre is one of the main qualities that differentiates one musical instrument like a trumpet from another instrument such as a flute playing the same note. (Interesting note: The word “timbre” is generally pronounced with an “a” sound rather than an “i” sound, so the phonetic pronunciation is \□tam-bər)

The mathematician Joseph Fourier proved in the 1800’s that any wave can be built up from combinations of sines and cosines, so the technical term for this procedure is Fourier Synthesis.

There are a variety of tools that can be used to demonstrate how a periodic waveform can be built up from different combinations of sines and cosines. We will be using the applet

http://homepages.gac.edu/~huber/fourier/

to illustrate this technique. This applet will allow you to modify the amounts of different harmonics, and it will draw the resulting waveform and play this through the computer speaker. This will allow you to see how changing the amounts of different harmonics changes the shape and sound of the wave.

I. Basic Operation of Fourier Synthesis Applet

Begin by loading the applet

http://homepages.gac.edu/~huber/fourier/

in your browser. Scroll down until you can see the applet as shown in Figure 1.

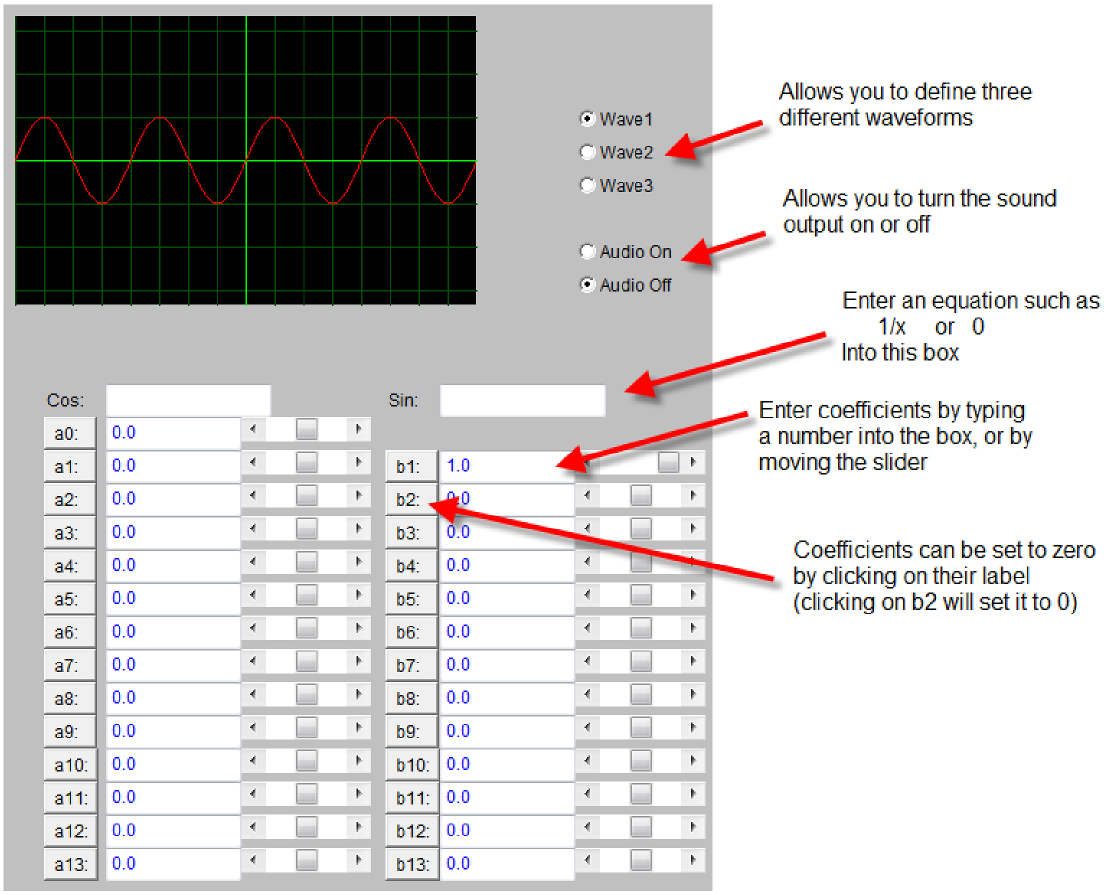


Figure 1: Fourier Synthesis Applet Screen

Begin by typing the 1 into the box for coefficient b1 and pressing the Enter key. The graph should display a sine wave, and the speaker should play a simple tone.

Move the b1 slider back and forth to change the amount of this tone. Notice that this can be either positive or negative, and the wave will flip over. Then click on the b1 button and this coefficient will go to zero.

Next move the a1 slider back and forth. The a1 coefficient adjusts the amount of the cosine wave, and the b1 coefficient adjusts the amount of the sine wave. Next, clear out both the a1 and b1, and adjust the b2 coefficient.

Try other coefficients one at a time and describe your observations

II. Combining harmonics to make different tones

Start by clearing out all of the coefficients.
First, in the box for b1, type in the value 1.0 and press the Enter key.

Next, in the box for b2, type in the value 0.5 and press the Enter key.
Notice what happens to both the wave displayed on the screen, and the sound of the wave

As you type in the coefficients below, observe what happens to the shape of the wave, as well as the sound of the wave. Note: the wave will get louder as more harmonics are added – we are mainly interested in the tone quality (or timbre) rather than the volume. You may also want to turn the audio off and then back on after you change harmonics to help you hear the entire waveform instead of the individual pitches.
Next, in the box for b3, type in the value 0.333
Next, in the box for b4, type in the value 0.25
Next, in the box for b5, type in the value 0.2

Describe your observations about both the sound and shape of the waveform as you add more harmonics. Does this sound almost a little like a clarinet?

Make a sketch of the waveform below – this waveform is sometimes called a sawtooth wave

Now work backwards by eliminating harmonics, starting with b5 and working back to b1. Describe what you observe

Another way of understanding the waveform is to make a spectrum plot. This plot shows the amplitude of each harmonic as a function of the harmonic number. Figure 2 shows what this looks like.

Figure 2: Spectrum plot for sawtooth wave

Instead of continuing to enter coefficients, the Fourier Series Applet allows you to enter an equation and it will calculate all of the coefficients. If you look at Figure 1, there is a box to the right of the word Sine:. Type the equation `1/x` into this Sine box and press the Enter key. The applet should calculate all of the coefficients.

Describe how the waveform changes when there are now 13 coefficients for this wave.

On the Spectrum Plot above, fill in the rest of the coefficients for the first 9 harmonics.

Next, select Wave 2. Clear all of the coefficients by putting a 0 into the Sine box. Then, enter in the same values from your graph above for the odd numbered coefficients
(b1 = 1.0, b3=0.333, b5=0.20, …).

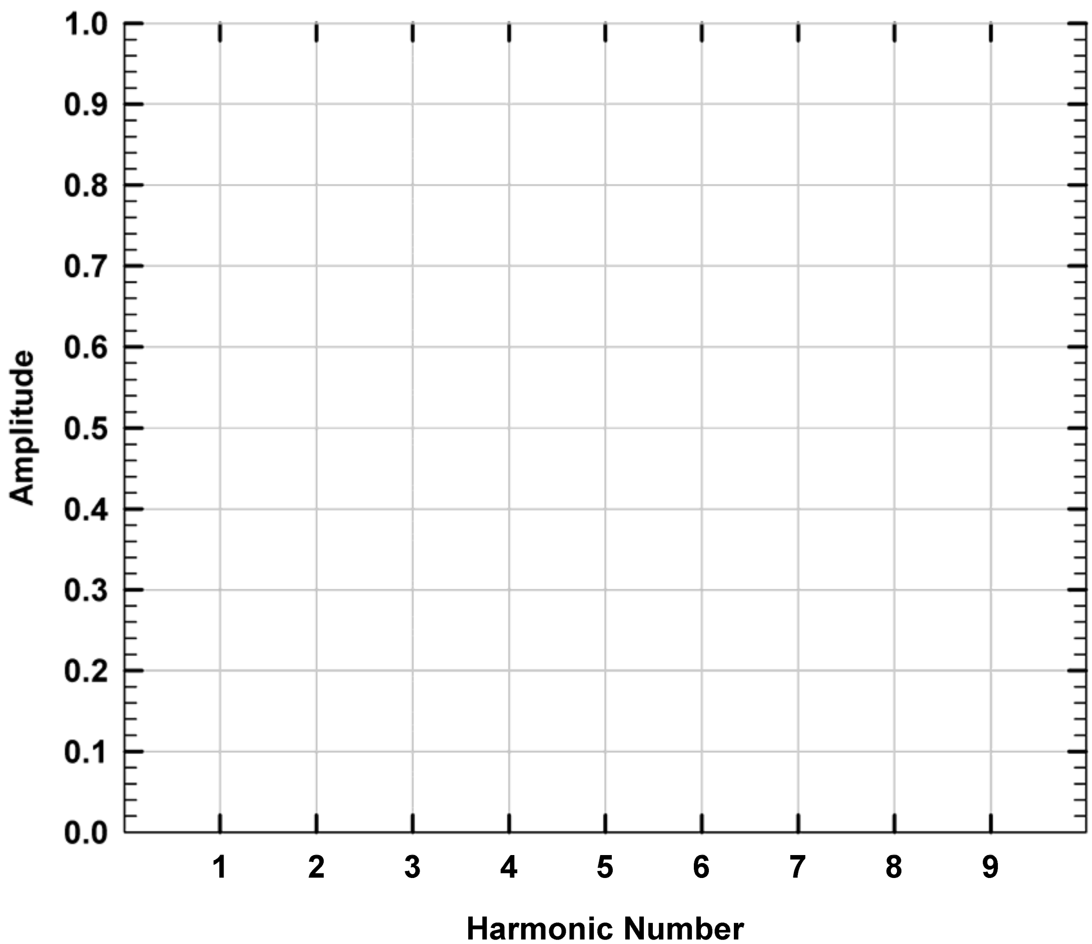
Sketch the waveform and describe what you think it would look like if you entered enough coefficients. Compare both the shape of the waveforms as well as the timbre of the sound produced.

Select Wave 3, and try changing some of the coefficients from positive to negative or putting some of them into the coefficients for the cosine (such as letting b3 = -0.333, a1=1.0). Try several different combinations. Obviously, the waveform has very different shape. However, with your eyes closed, have your lab partner switch between the two waveforms.
Can you tell the difference?

Clear all the coefficients. Build a waveform where the odd numbered harmonics of cosine go as $1/x^2$. In other words, a1=1, a3=1/9, a5=1/25, … You can either do this by calculating the coefficients, or you can enter `1/(x^2)` in the Cosine box and then set all the even numbered coefficients to zero.

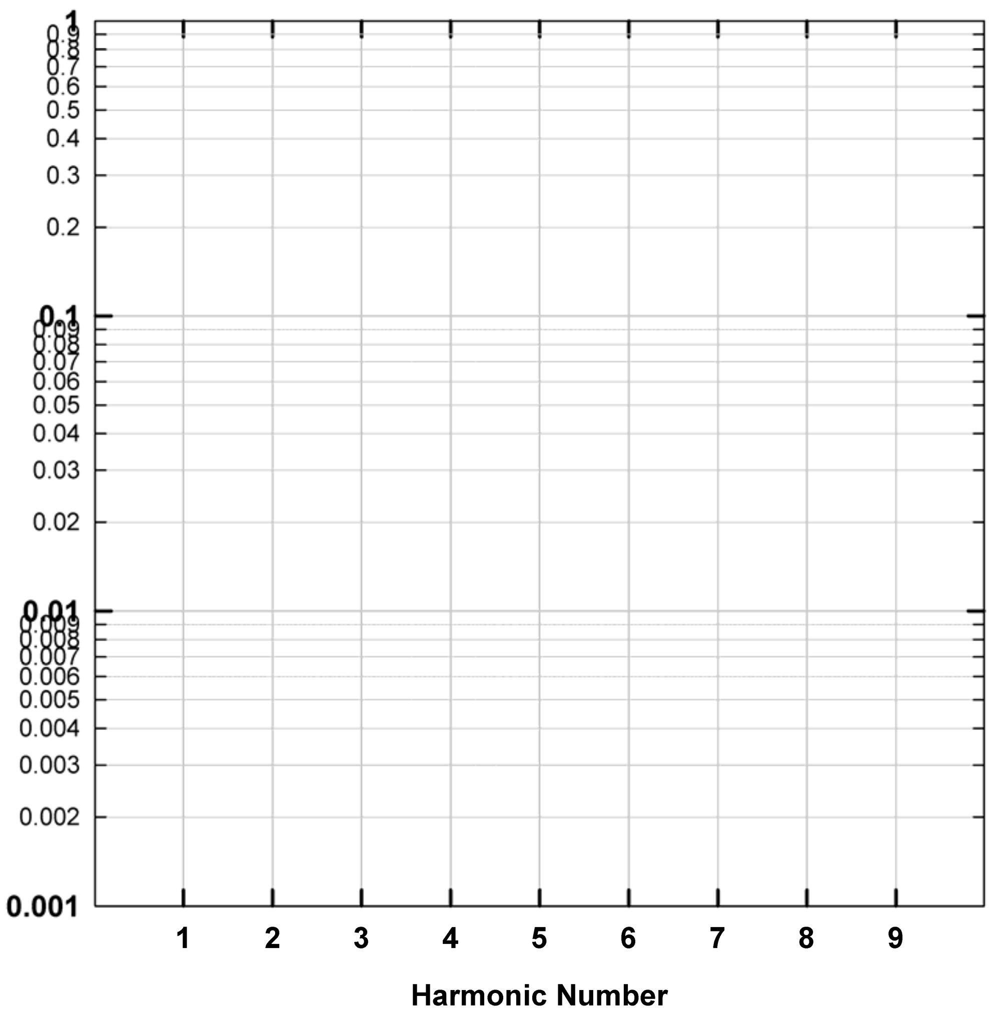
Sketch the resulting waveform and discuss your results.

Make a spectrum plot of this wave.

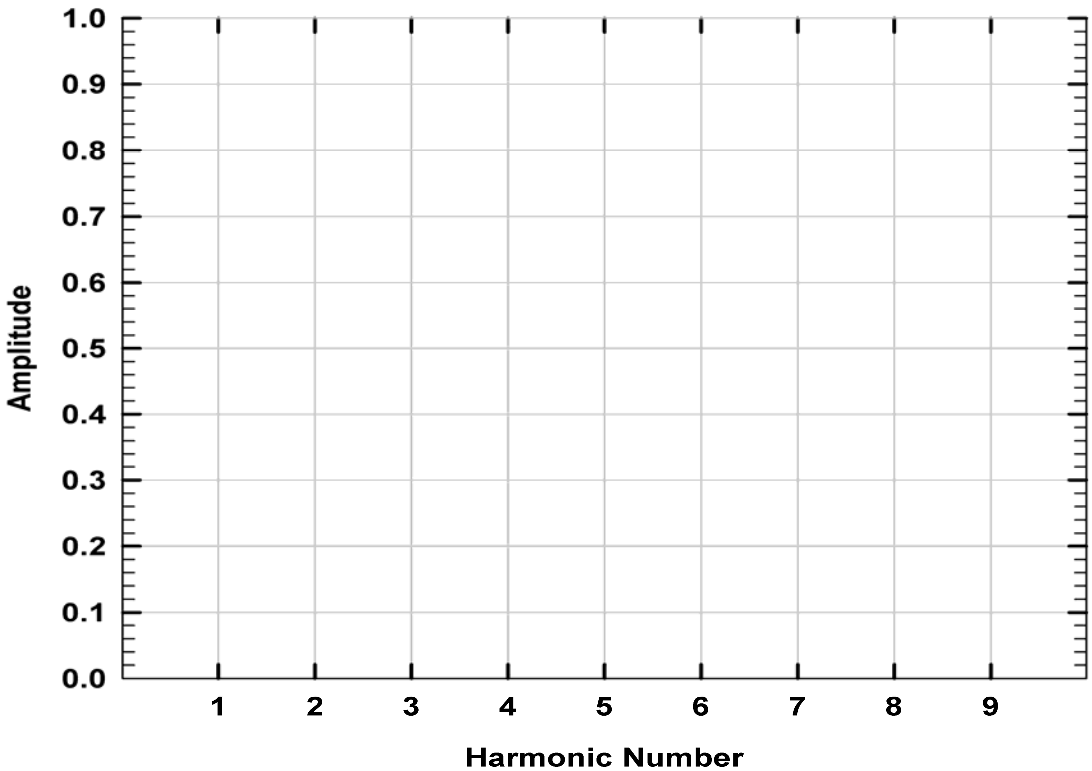


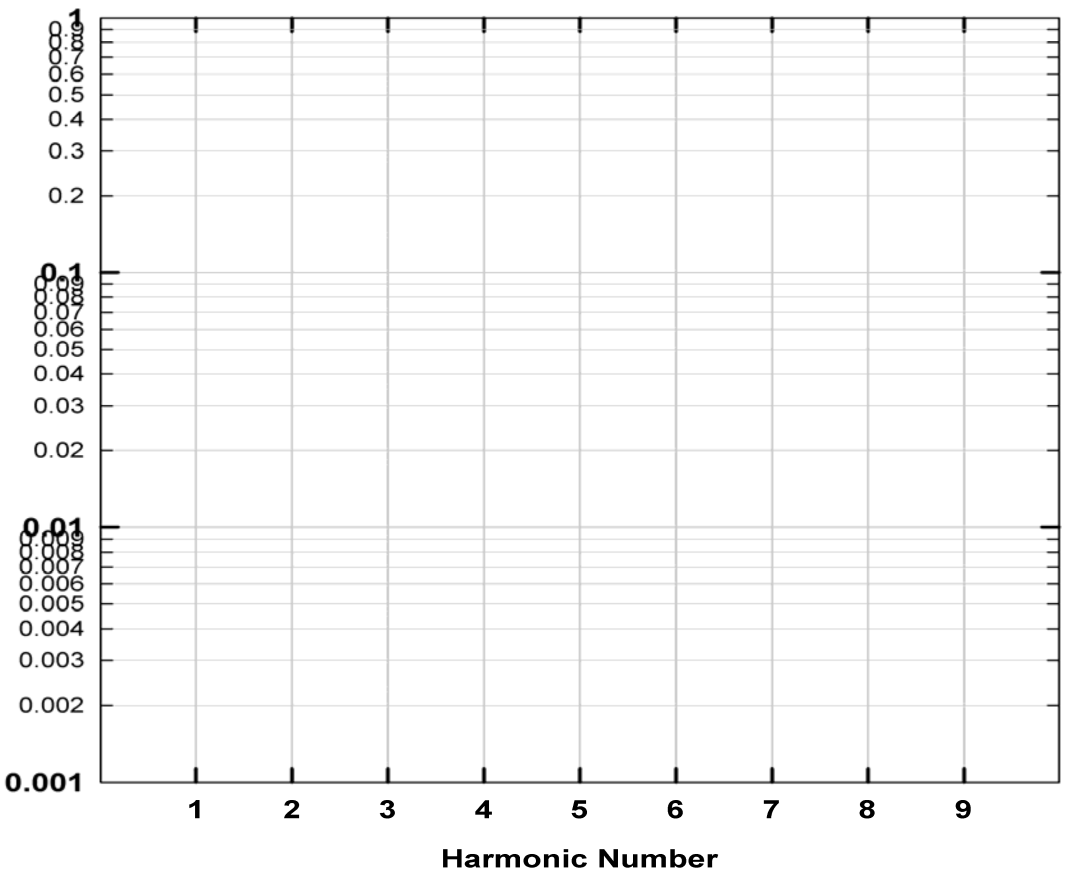
A you will note, the coefficients for the higher harmonics quickly become very small and difficult to see. To make it easier to visualize these upper harmonics, it is easier to use a logarithmic scale for the vertical axis. As you will note the spacing between each division is not uniform. Instead, the scale repeats for each power of ten. This means that the upper harmonics, even though they are over 100 times smaller than the fundamental, still show up on the graph.

Sketch the spectrum plot on this logarithmic scale

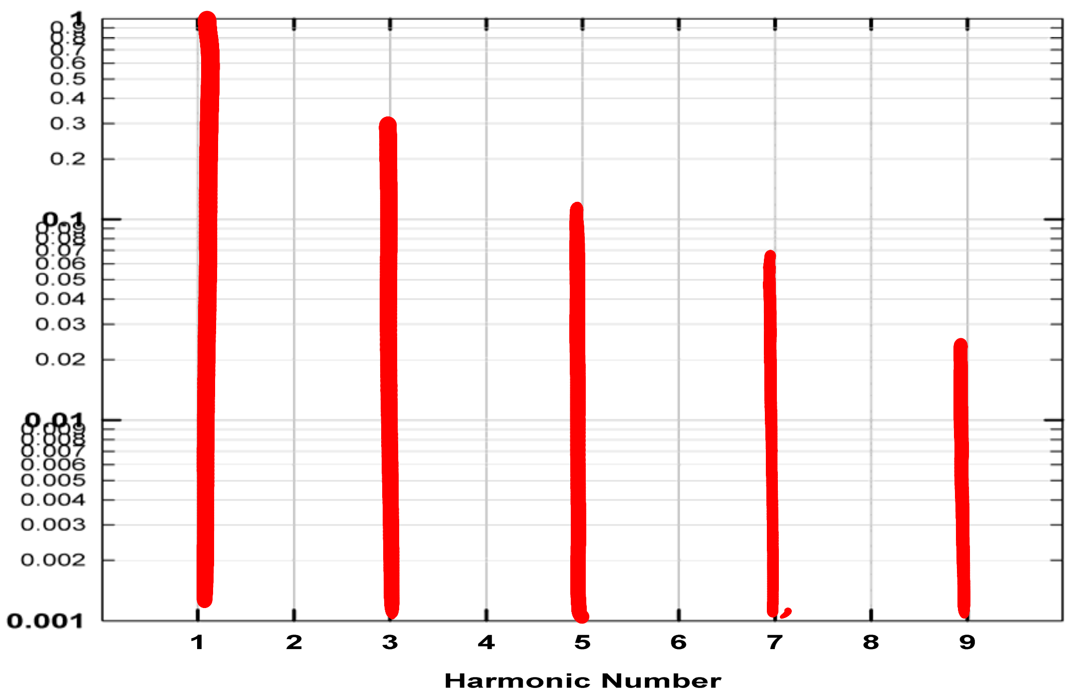


Now that you are familiar with running the program, experiment with different combinations of waves. For example, try comparing the timbre and wave shape for waves that have primarily low harmonics with almost no amplitude of high harmonics, to waves that have almost all high harmonics and almost no low harmonics. On the following pages sketch some of your results, both the wave graph, as well as the spectrum plot with either a linear or logarithmic scaled y axis. Feel free to make more copies of the spectrum plot page.
Include sketches and discuss the results of your studies.



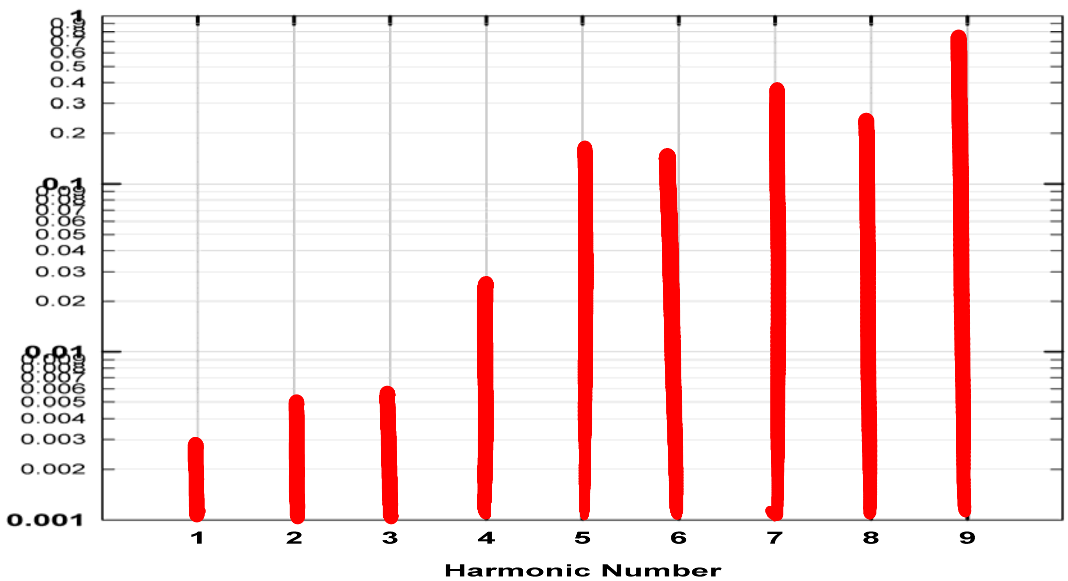

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
1
2
3
4
5
6
7
8
9
Harmonic Number

Questions:
For a guitar that is plucked with a broad thumb towards the center of the string, the spectrum plot might look like this.



Based on your previous observations of standing waves on strings, why do you think that the even numbered harmonics would all be zero if you pluck the string near the middle?
HINT: Think about where nodes and antinodes are for even and odd numbered harmonics.

Now consider a string that is plucked with a hard pick right next to the saddle. The spectrum plot for this might look like the following.



Why do you think that the lower harmonics are so much smaller than the upper harmonics when the string is plucked near the saddle? How would the timbre of this wave compare to the timbre of the wave from Problem 11? Explain why.

Synthesis of Waves Using Harmonics Answer Key

Try other coefficients one at a time and describe your observations

The higher harmonics have a higher pitched tone. Increasing the amount of the slider increases both the volume and the amplitude on the graph

Describe your observations about both the sound and shape of the waveform as you add more harmonics. Does this sound almost a little like a clarinet?

The waveform starts to have a steep rise and a slower fall off on the right, but is a little wiggly. It sounds a little like a clarinet

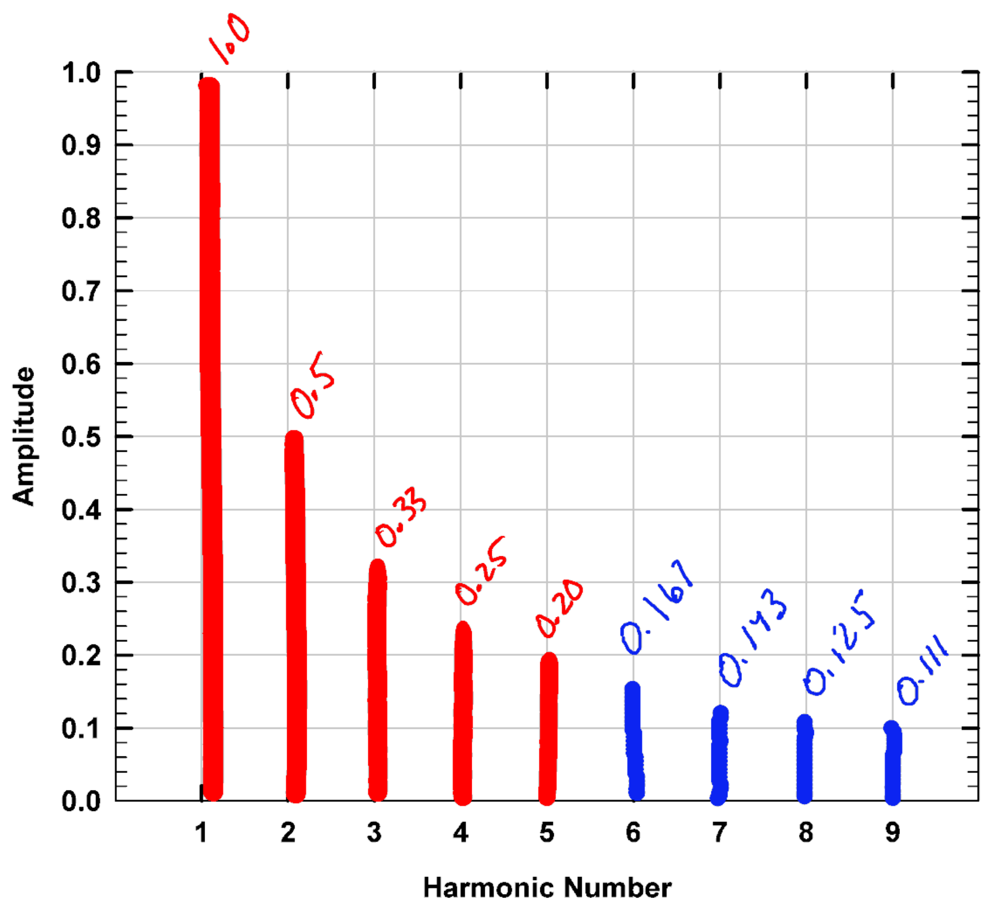
Make a sketch of the waveform below – this waveform is sometimes called a sawtooth wave

Now work backwards by eliminating harmonics, starting with b5 and working back to b1. Describe what you observe

As the harmonics are eliminated, the tone gets simpler, and approaches a sine wave.

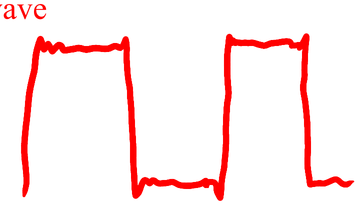
Describe how the waveform changes when there are now 13 coefficients for this wave.
The sides of the wave get more straight and less wiggly

On the Spectrum Plot above, fill in the rest of the coefficients for the first 9 harmonics.



Sketch the waveform and describe what you think it would look like if you entered enough coefficients. Compare both the shape of the waveforms as well as the timbre of the sound produced.

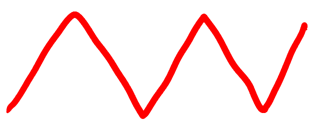
This approaches a square wave with flat top and bottom. It sounds a little less "harsh" than the sawtooth wave



Can you tell the difference?

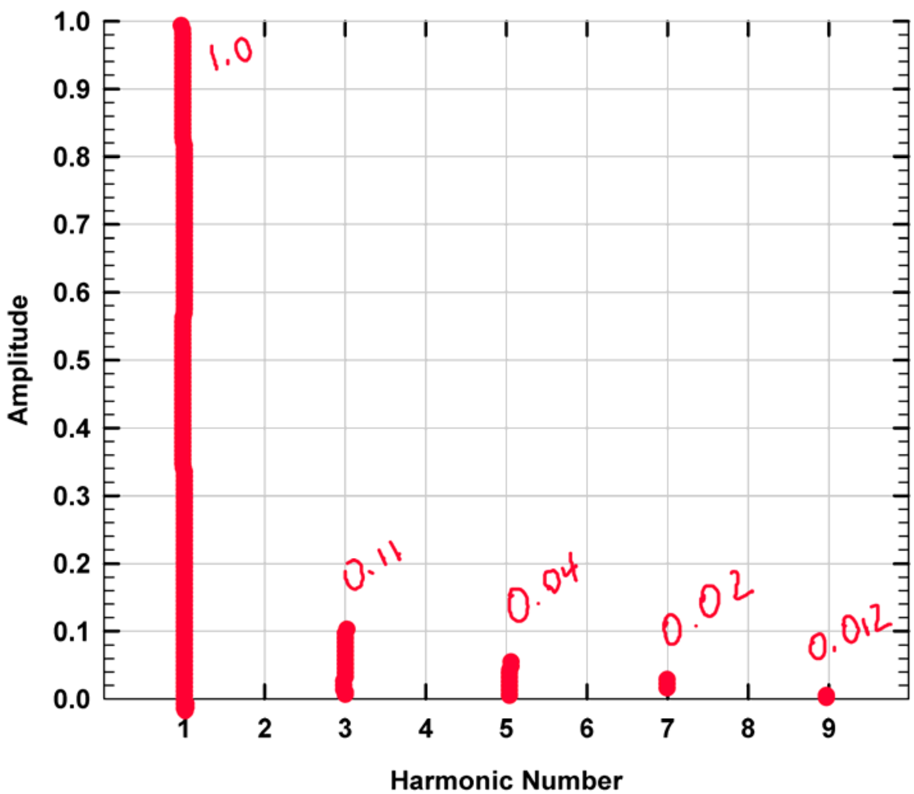
The waves look very different in shape, but the sound of the waveform depends only on the amount of each of the harmonics, and not whether they are positive, negative or sines or cosines. The ear can't hear the phase difference of these waves.

Sketch the resulting waveform and discuss your results.

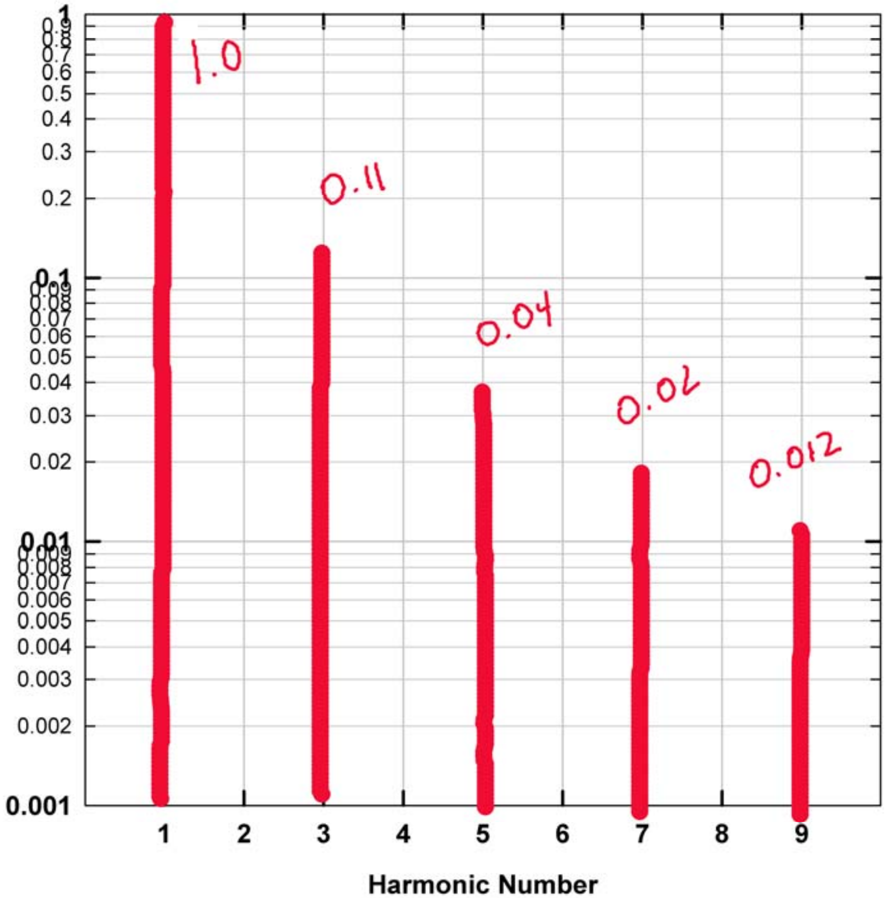


The wave is a triangle wave

Make a spectrum plot of this wave.



Sketch the spectrum plot on this logarithmic scale

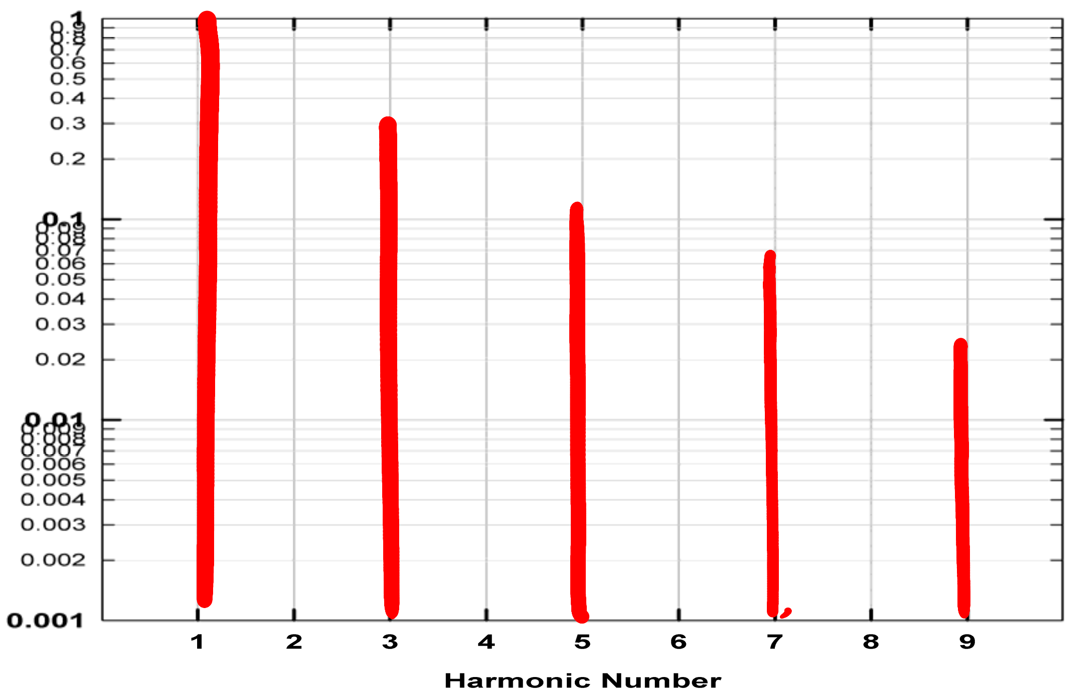


Include sketches and discuss the results of your studies.

Results may vary with different students

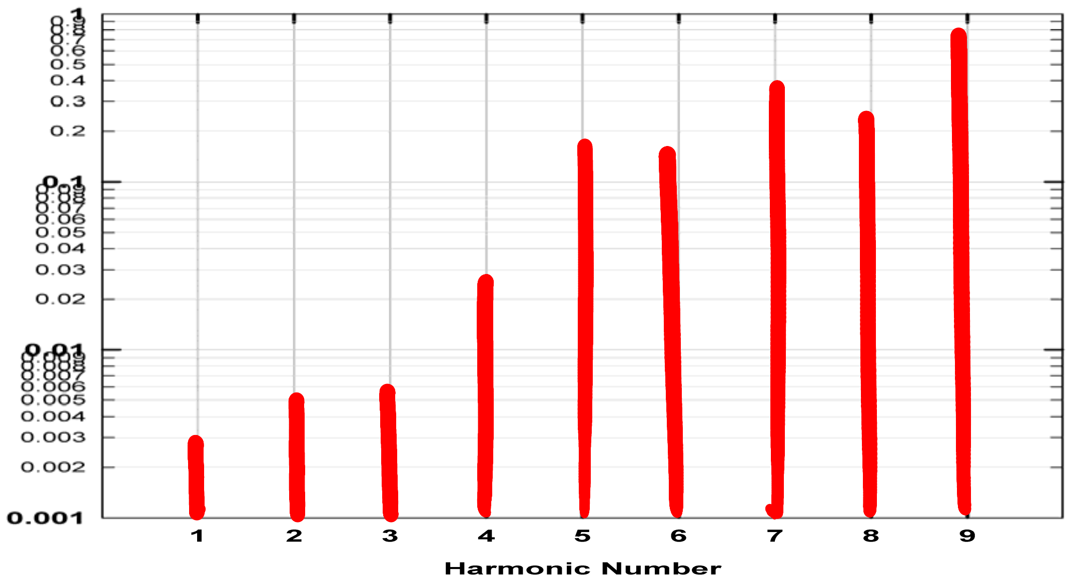
Questions:

For a guitar that is plucked with a broad thumb towards the center of the string, the spectrum plot might look like this.



The even numbered harmonics have nodes near the center of the string. Therefore if you pluck the string at the center, so the string has a large amplitude at the center, these even numbered harmonics won't show up as shown above.

Now consider a string that is plucked with a hard pick right next to the saddle. The spectrum plot for this might look like the following.



Why do you think that the lower harmonics are so much smaller than the upper harmonics when the string is plucked near the saddle? How would the timbre of this wave compare to the timbre of the wave from Problem 11? Explain why.

In this case, the lower harmonics don't show up because the lowest harmonics have almost no amplitude right near the saddle. Therefore, since the largest motion of the string is near the saddle since that is where it was plucked, the upper harmonics will dominate.

Since this has a lot of high harmonics, the tone will be more "metallic" than Problem 11 when there are more low harmonics that give a "richer" tone.

Science Learning Activity 9

Using a Pop Bottle as a Helmholz Resonator

Students will record and analyze audio files to determine the natural frequency of the pop-bottle system.

Learning Objectives:

1. Students will be able to describe the three mechanisms for sound production on a hollow-body acoustic guitar (strings, body, and air in cavity).
2. Students will be able to describe what a Helmholz resonator is and how one works.
3. Students will gain practice recording audio files on a computer and using the Octave program to obtain graphs of their recording.

Materials needed:

- Microphone
- Computer with audio recording capabilities
- Pop or water bottle filled
- Thirsty students (or if beverages are not able to be consumed, a cup to transfer water out of the pop bottle)
- Electronic balance
- Calipers (optional—can use a ruler to measure diameter of bottle opening)
- Ruler
- pop1.wav (unless recording a new audio file)
- pop.m (This is a program written in Octave, which is similar to MathLab)
- Computer sound recorder
- Octave (can be downloaded from Sourceforge.net)

References:

French, R. M., "A Pop Bottle as a Helmholz Resonator." Experimental Techniques. May/June 2006.

http://www.phys.unsw.edu.au/jw/Helmholtz.html. Accessed July 10, 2010.

Pre-lab discussion:

Hold up or show an image of a hollow-body acoustic guitar. Ask students what three things on the guitar are responsible for sound production. Students should respond by noting the strings, the guitar body (especially the top, or soundboard) and the air inside the guitar cavity are all responsible for sound production. A discussion on how different woods used for guitars produce different tones may be appropriate here.

Ask students if they have ever blown across a pop bottle before. What did they observe? Ask students to predict what would happen to the frequency or pitch of the sound if the level of the liquid decreased. The frequency of the sound should decrease as well. In this situation, the pop bottle was acting as a Helmholz resonator. A Helmholz resonator is a system where gas is enclosed by the rigid walls of a container. The neck and opening of a Helmholz resonator should be relatively small when compared to the container. When someone blows across the bottle, it shoves the air in the neck downward which increases the pressure in the container. The air above the bottle top is now less dense and has slightly less pressure which causes the air inside the container to rise up slightly out of the bottle.

Getting the Data…

Measure the following quantities on the pop bottle and record your answers here:

Cross-sectional area of bottle, *A*	
Length of air column, *t*	

Science Exercise 9

You will be blowing across the neck of the bottle at four different levels of liquid (see image below).

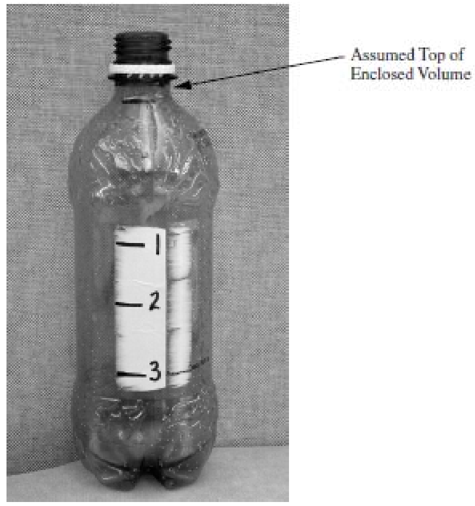


Figure 1: Image of pop bottle used for experimental data {1}.

In order to measure the volume, you will need to obtain the mass of the beverage container at each condition and empty. You will also need to know the density of the liquid. If you are using water, the density, ρ = 1g/mL. If you are using a soft drink, you will need to look up its density.

✋Caution—You will need to measure the mass of the liquid + bottle at Condition 1 (full), then record the audio file, then do the Octave analysis. Once you are finished, then you may proceed to Condition 2 (drink or pour out liquid), record audio file, do the Octave analysis, etc.

Condition	Mass of liquid + bottle (g)	Mass of Bottle (g)	Mass of Liquid (g)	Density of Liquid g/mL	Volume of air (L)
1					
2					
3					
4					

To save new audio file:

- Record at 4k or 8k settings with 16 bits (lowest setting for frequency domain with most number of bits)
- Save audio file as .wav (mono)

Make sure your audio file is in the same folder as pop.m. May want to put in C drive so it is easy to find and recall. Saving the file to the desktop will not work.

In Octave,

At command prompt, type in

- cd c:\
  - This changes the directory to the c drive. Type in other drive if saved elsewhere.
- dir
  - This shows the file directory so you can check to see you are in the right place.
- cd pop
  - calls up the "pop.wav" file to get a frequency spectrogram
- dir
  - This shows the file directory so you can check to see you are in the right place.
- pop(´pop1.wav´);
- Click on graph in desired regions. Program may take a few seconds to display/change graphs.

Condition	Air Volume (L)	Frequency (Hz)
1		
2		
3		
4		

Post-lab questions:

[1] Explain (in your own words) what a Helmholtz Resonator is and how it works.

[2] Explain how the frequency changed as the level of the liquid decreased.

[3] Assuming that the speed of sound in air is 343m/s, calculate the wavelength that corresponds to each of the peak frequencies.

Condition	Frequency	Wavelength
1		
2		
3		
4		

[4] Using your initial measurements, calculate the ideal frequency based on each condition:

Condition	Calculated Frequency
1	
2	
3	
4	

[5] Calculate the percent difference of the measured frequency and the calculated frequency.

Condition	Frequency (Hz)	Calculated Frequency (Hz)	% Difference
1			
2			
3			
4			

[6] Show, using dimensional analysis, that the units in the equation below are consistent:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{tV}}$$

Anticipated Answers to Post-lab Questions:

A sample data set may look like this…

Condition	Air Volume (L)	Frequency (Hz)
1	0.195	330.0
2	0.296	260.3
3	0.411	220.1
4	0.616	175.9

Post-lab questions:
[1] Explain (in your own words) what a Helmholtz Resonator is and how it works.

A Helmholtz resonator is a rigid container of gas where the opening is relatively small compared to the container. When air is blown across the container, the air acts like a spring and oscillates, producing a natural frequency.

[2] Explain how the frequency changed as the level of the liquid decreased.

The frequency should decrease as the liquid level decreases.

[3] Assuming that the speed of sound in air is 343m/s, calculate the wavelength that corresponds to each of the peak frequencies.
Using $c = f\lambda$

Condition	Frequency (Hz)	Wavelength (m)
1	330.0	1.04m
2	260.3	1.32m
3	220.1	1.56m
4	175.9	1.95m

[4] Using your initial measurements, calculate the ideal frequency based on each condition:

Condition	Calculated Frequency (Hz)
1	321.8
2	261.5
3	221.9
4	181.2

[5] Calculate the percent difference of the measured frequency and the calculated frequency.

Condition	Frequency (Hz)	Calculated Frequency (Hz)	% Difference
1	330.0	321.8	-2.48
2	260.3	261.5	0.46
3	220.1	221.9	0.82
4	175.9	181.2	3.01

[6] Show, using dimensional analysis, that the units in the equation below are consistent:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{tV}}$$

$$\frac{1}{s} = \frac{m}{s}\sqrt{\frac{m^2}{m \cdot m^3}} \Rightarrow \frac{m}{s}\sqrt{\frac{m^2}{m^4}} \Rightarrow \frac{m}{s}\sqrt{\frac{1}{m^2}}$$

$$\frac{1}{s} = \frac{\cancel{m}}{s} \cdot \frac{1}{\cancel{m}}$$

$$\frac{1}{s} = \frac{1}{s} \checkmark$$

Science Learning Activity 10

Spectrum Analysis: Overtone Analyzer

The goal of this experiment is to demonstrate how a waveform can be broken into a sequence of harmonics. The different tone quality (timbre) of sound waves from a musical instrument like a guitar comes from the amount of each of these harmonics.

Learning Objectives:

In a previous learning activity, you saw that complex waveforms can be built up from combination of sines and cosines where the frequencies of these harmonics are multiples of a fundamental frequency. For the n^{th} harmonic is

$$f_n = n\, f_1 . \qquad (1)$$

where the frequency of the fundamental is f_1, and n=1,2,3,…

The process of building up a wave from fundamentals is called Fourier Synthesis. In the current activity, we will do the opposite – we will take a complex waveform and use a program to break this into its harmonic components; the graph of the amount of each harmonic is called the spectrum.

Materials Required:

Windows Computer
Overtone Analyzer Program
http://www.sygyt.com/en/overtone-analyzer-editions
Download and install the Free edition
Microphone and Speakers for computer

References:

Tom Huber, Physics Department, Gustavus Adolphus College, huber@gac.edu
Revised: July 10, 2010

Science Exercise 10

The process of determining the spectrum is sometimes called Fourier Analysis, Harmonic Analysis or Spectral Analysis. Another name that you may see for this type of software is FFT – this stands for "Fast Fourier Transform", which is the numerical technique that is generally used to determine the spectrum.

In this activity, you will learn to use the free version of the spectrum analyzer program called Overtone Analyzer (www.sygyt.com). This program will take the sound measured by the microphone on your computer and determine the amount of every frequency that makes up the sound wave. The text below is a modified version of the tutorial that comes with Overtone Analyzer.

Table of Contents [-]

This guide will show you how to record and visualize a sound with Overtone Analyzer. The quickstart guide focuses on how to use the main elements of the program, and not so much what they mean. You can find more detailed explanations of everything in the Program Reference.

1. Prerequisites

You have installed Overtone Analyzer on your computer. You have a working microphone connected to the microphone input of your soundcard.

2. Configuration

Start the program. The splash screen will briefly appear, and then you should see something like this:

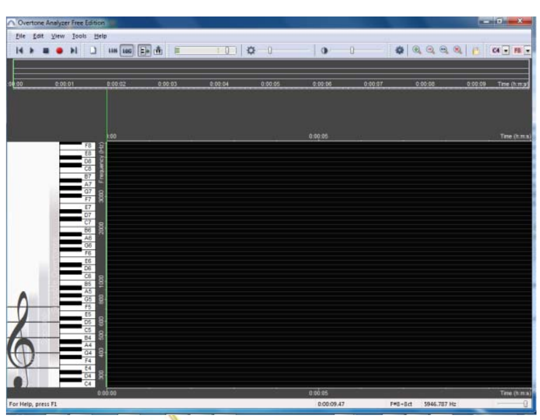


Figure 3: Startup screen showing vertical piano

When you start the program, it will likely start up in the "Vertical Piano" mode with a piano keyboard along the left side of the screen. For the remainder of this tutorial, we will use the other screen organization with the piano along the bottom of the screen. You get to this mode by clicking on the Horizontal Piano icon. In this view, you will see the Piano on the bottom, and the Analyzer View in the main section.

Configure the initial setup of the screen by selecting the Options Button from the tool bar at the top of the screen, and make sure that the following major options are set up:

Options -> Audio Settings -> Playback -> Overtone Instrument -> Pure Sine wave

Under the Display Settings tab:

Analyzer View -> Spectrogram + Spectrum, and click Spectrum Type to blue lines
Scale -> From A1 to A6 ; Frequency Display -> log ; Notation System -> Scientific
Colormap Editor -> Selected Colormap -> Spectral2
Note Sliders -> Show Notename, Show Frequency ; Snapping -> No Snapping

After pressing OK, select the View selection on the main menu, and make sure that the following items are selected: Staff View, Piano, Status Bar, Waveform Time Scale, Frequency Scale, Spectrogram Time Scale, Display Staff Lines and Clef.
When you have done this, the screen should look similar to Figure 2.

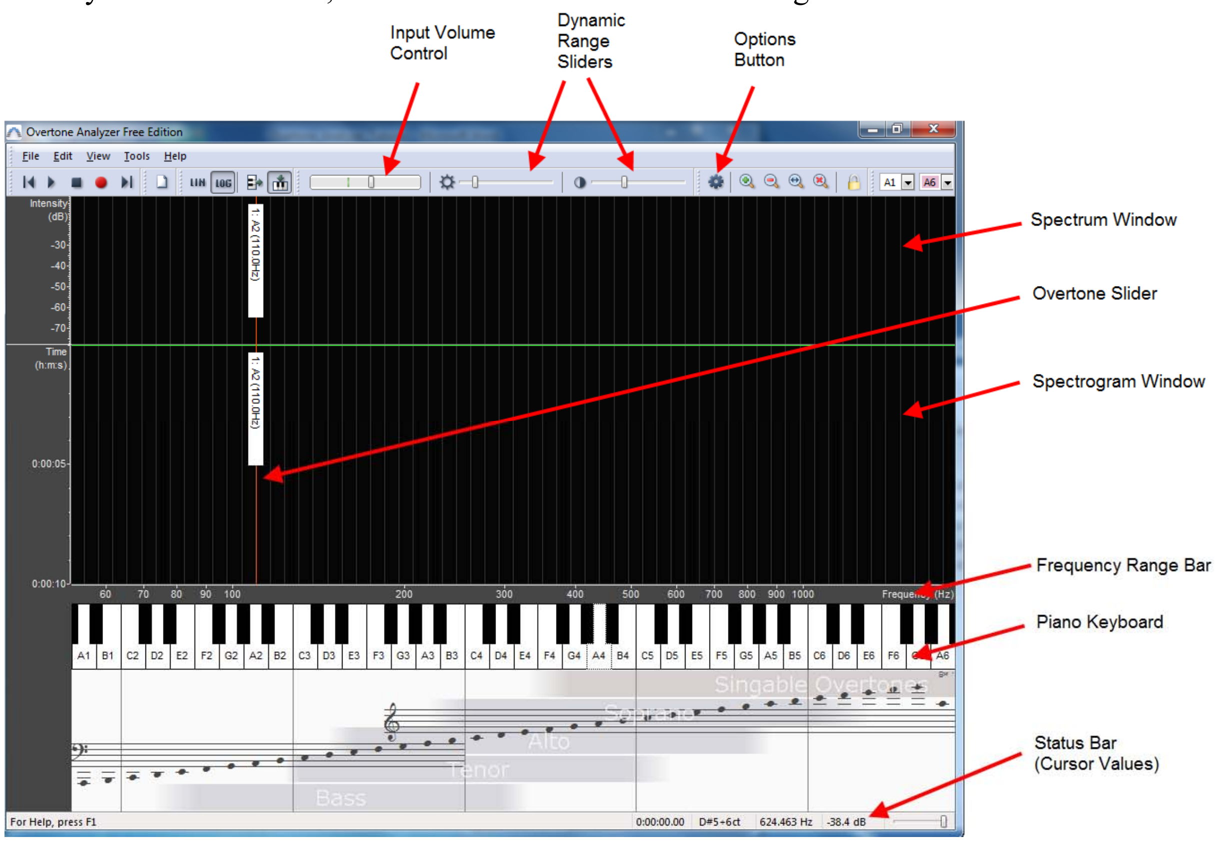


Figure 4: Overtone Analyzer Screen

3. Select Recording Source

In the Tools Menu, click on Options. This will open the Options Dialog as shown in Figure 3. On the left side, select the entry Audio Settings. Here you should make sure that the Microphone is selected as your Recording Source.

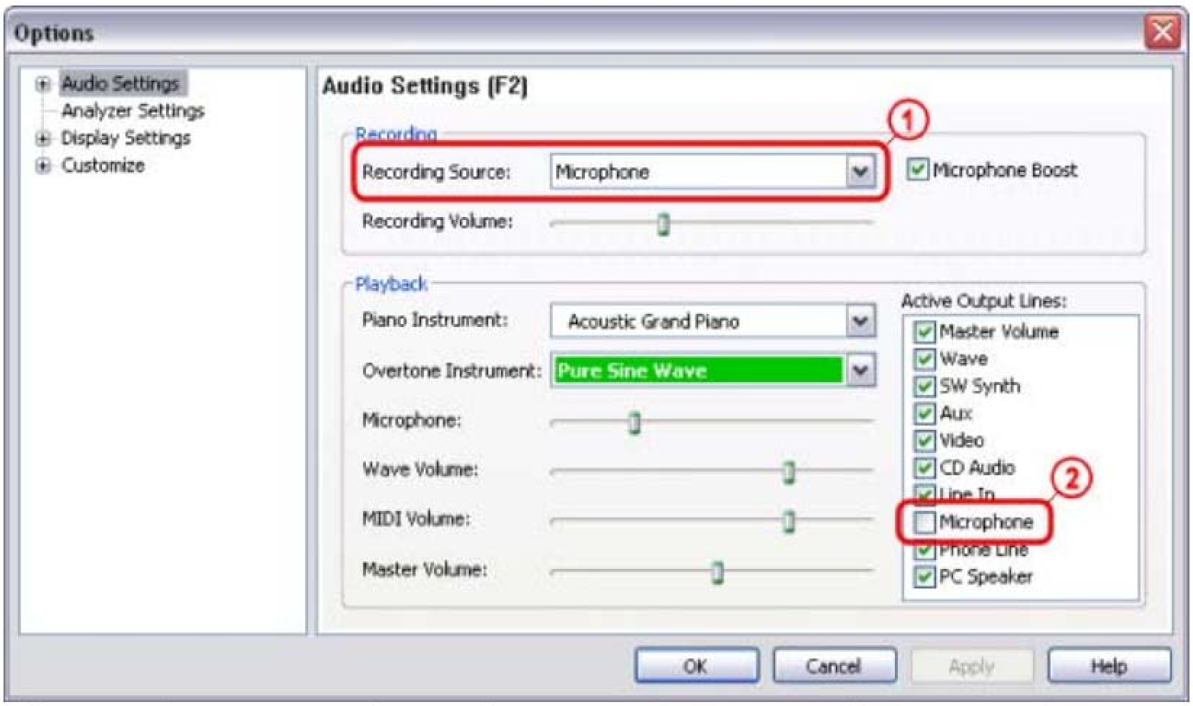


Figure 5: Audio Settings: 1. Select microphone as recording source, 2: Disable mic as output line, and 3: the Overtone Instrument should be set to Pure Sine Wave

Depending on your soundcard, you may or may not see a "Microphone Boost" checkbox, and there might be slightly different playback and slider adjustments shown. This checkbox and the recording volume require some experimentation. With a standard PC Microphone, it is probably good to check it. Adjust the recording volume slider to be in the middle. Now look at the box "Active Output Lines" and disable the Microphone there. This tells your computer to record the sound received by the microphone, but to not play this sound back through the speakers to prevent feedback. Finally, make sure that you set the Overtone Instrument to be Pure Sine Wave.

4. Analyzer Settings

We won't worry about the Analyzer Settings for now, as the default settings that are active after installing the program should be fine to get started.

5. Input Level Meter

Click on OK to close the Options Dialog and look at the toolbar. On the toolbar are three sliders. The left one is the Input Level Meter. Here you can monitor and adjust the volume of the recorded sound. The slider that you can move is the same slider as the "Recording Volume" slider on the Audio Settings Dialog. The colored stripes in the background show the strength of the current signal. If you make a noise into your microphone, you should see some activity there.

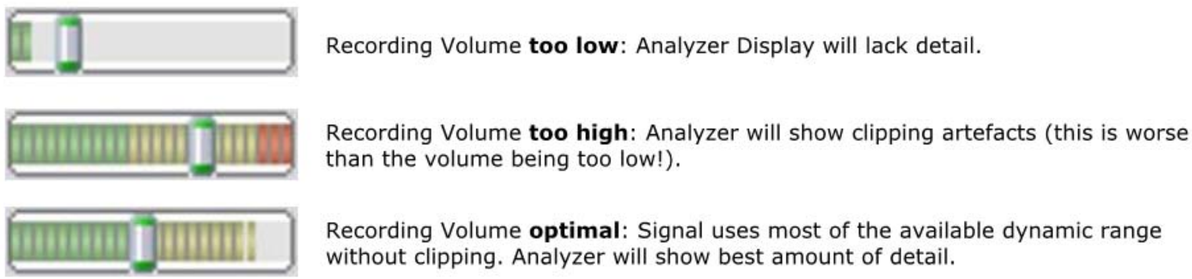


Figure 6: Setting recording level

It is very important to adjust the recording volume correctly to prevent clipping as shown in Figure 4. If the input volume reaches the the red area, reduce the input level, or increase the distance to your microphone. You should aim to keep the maximum volume of the recorded sound just at the upper end of the yellow area:

Make some test sounds (talking, clapping, humming, whistling, etc.) into your microphone and adjust the recording level until it is getting a strong signal without clipping.

6. Recording

Now you are ready to record some sound. Click the "Record" button on the toolbar, or press "Ctrl-Space". The computer will record any sounds picked up by your computer microphone. During the recording you should keep monitoring the Input Level and make adjustments if necessary. You can use the piano keyboard on the screen to make sounds - position your mouse above the A4 piano key on the screen and press and hold the left mouse button. The computer should make a sound like a piano. If you cannot hear a tone, check that the sound on your computer is working, and that the volume is loud enough. Fill up one screen and then press "Space" to stop recording. This should look something like Figure 5

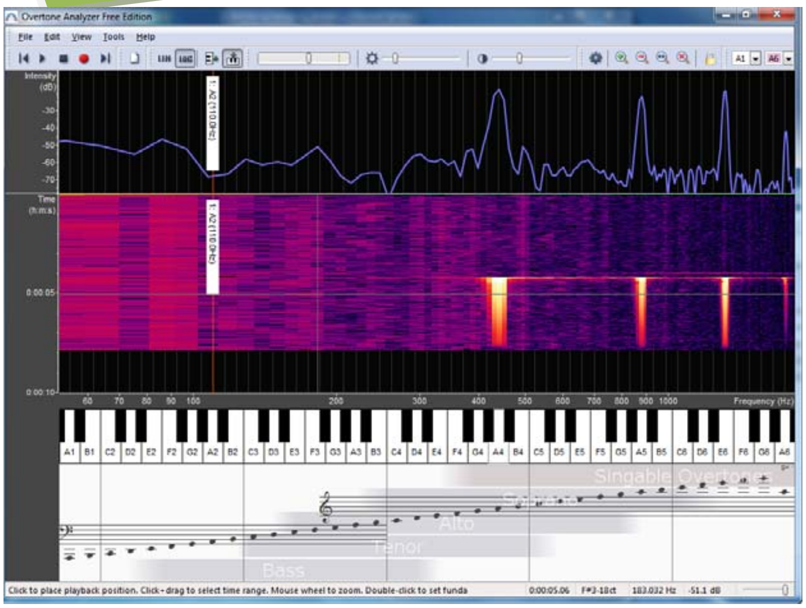


Figure 7: Sample recording using Overtone Analyzer showing spectrum (top line graph) and spectrogram (sliding colored graph showing intensity of frequencies as function of time)

The bottom region of the analyzer view contains the spectrogram, which shows the intensity level of the various frequencies of the sound over time. On top section of the analyzer view is the spectrum. The spectrum is the amount of each harmonic of the spectrogram at a specific point in time. If you move the mouse over the spectrogram, the spectrum will always show the intensities at the time where the mouse cursor is located.

7. Adjusting Displayed Dynamic Range (Brightness and Contrast) and Frequency Range

You have already adjusted the input volume through the leftmost slider on the toolbar. The other two sliders on the toolbar control the displayed dynamic range. Move both sliders and observe what happens. Notice that the brightness slider shifts the spectrum along the intensity scale, while the contrast slider compresses or expands the intensity range of the spectrum. Experiment with the dynamic range sliders until you are comfortable with the settings.

You can scroll the frequency by positioning the mouse on the frequency bar (below the spectrogram) and holding the left-mouse button and moving the mouse from side to side; the range of frequencies can be zoomed in or out by using the scroll wheel when the mouse is in the frequency bar. With suitable adjustments of these controls, you may be able to get a display that looks roughly similar to Figure 6, where the display shown below where the peaks in the spectrum and spectrogram show up clearly above a small background. (NOTE: If there are background sounds such as noise from other sources or computer fans, these will also be detected by the microphone and displayed in the spectrogram. You might not be able to obtain a spectrum as clean as Figure 6 – as long as you can clearly see the peaks, don't worry about the background)

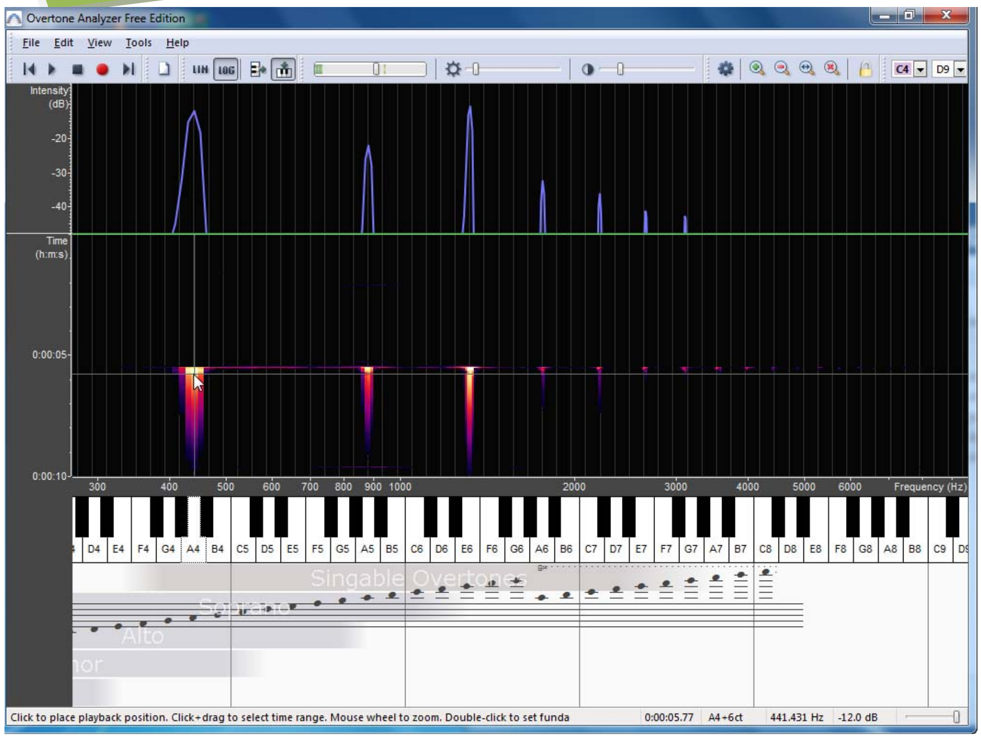


Figure 8: Spectrogram and Spectrum observed after shifting frequency range and scaling the dynamic range

The spectrogram window shows the intensity of each frequency (as a color that goes from black for a weak signal to whitish yellow for high intensity) as a function of time (for a 10-second period of time starting at the top of the window and going down)

To produce the graph of Figure 6, the recording was started and the A4 key was pressed a little after 5 seconds. When the key was pressed, the tone initially has many that very quickly disappear. The lowest three harmonics (A4, A5 and D6) decay away more slowly (getting dimmer as time progresses down the screen).

As you move the cursor on the screen, the spectrum window, above the spectrogram, displays a blue line drawing of the spectrum at the instant represented by the cursor. For example, if you place the cursor to the time just after the A4 key was pressed, there will be many harmonics displayed as shown in Figure 6. If you move the cursor such that it is about 1 second or more after the start of the A4 key, the spectrum will essentially only show the lowest three harmonics.

8. Using the Overtone Slider

One of the most powerful features of this program is the Overtone Slide. This vertical cursor can be used to measure the frequency of a waveform, and also to determine the harmonics of the tone. If the overtone slider is not visible on the screen, you may need to zoom out or scroll the frequency scale (as described earlier) until you can see the overtone slider. Position the cursor so that is over the overtone slider – the cursor shape will change to be a horizontal double arrow. Hold your left mouse button and move the mouse. The overtone slider should change position. Move this so that it overlaps with the lowest bright fringe (fundamental harmonic) that shows up on the screen. To do fine movements of the overtone slider, hold down the shift key and then move the mouse. The label on the overtone slider shows the note, and may show a number of Cents. In parenthesis, it will have the frequency. (As will be discussed in a future activity, the musical term Cents refers to the fraction of the difference between notes. In the equal tempered scale, there are exactly 100 cents between each note in the scale.) By using the mouse and possibly fine-adjusting with the shift key, you should be able to position the slider until the display reads 1: A4 (440 Hz).

By default, the overtone slider might only show the fundamental (1st harmonic). To display more harmonics, position the cursor near the fundamental and it will show red triangles to the left and right of the slider. Position the cursor on the triangle on the right, hold down the left mouse button and drag the mouse to the right. As you progress to the right, it will draw vertical lines at each harmonic of the fundamental frequency (f_1, $2f_1$, $3f_1$, etc.). This allows you to easily see the frequencies of all the harmonics. You will note that the peaks in the spectrum should match up nearly exactly with the overtone sliders, similar to Figure 7. By using the overtone slider, you can determine the frequency of a note, or any harmonic, and the spectrum at any instant.

Hold down the left mouse button when pointing at the white label of any of the overtone sliders. The label will turn red and will play a sine wave represented by that slider.

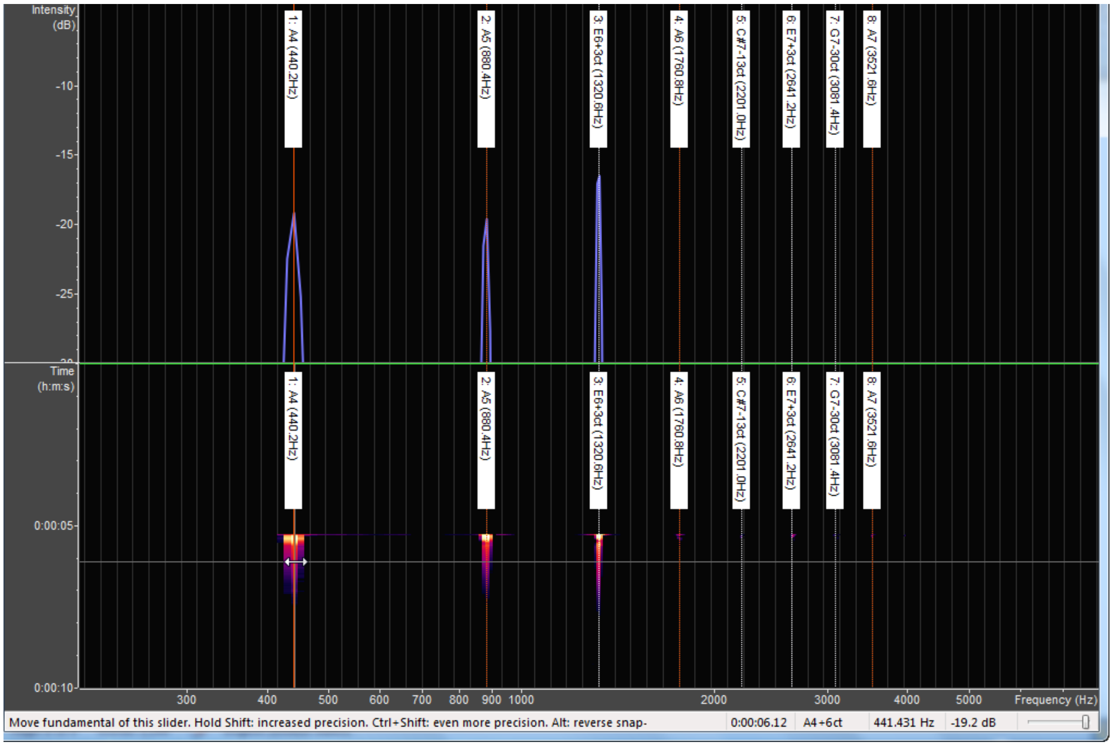


Figure 9: Spectrum and spectrogram showing the Overtone Slider adjusted to 440 Hz

Linear/Logarithmic Frequency Scaling

Select the LIN button instead of LOG button on toolbar. Note that with this display, since harmonics are integer multiples of the fundamental frequency, the harmonics will be equally spaced on the display. However, the notes on the piano become non-uniformly spaced. Switch back to the LOG setting, and the piano notes will be uniformly spaced, but the harmonics will be nonuniformly spaced on the screen as shown in Figure 7. In a future activity, you will study more about how the musical scale works using many of these features of the Overtone Analyzer program.

Other Features to try

There are many more features that you can experiment with using this program. In particular:

- In the Options -> Note Sliders menu, change the Snapping option to “Snap to Nearest Note”. In this case, the sliders will always be centered exactly on a note of the scale. This is convenient for looking at notes that are exactly tuned, whereas turning the snap feature off allows more flexibility in positioning the cursor to allow frequency measurements.
- On the Options -> Audio Settings, you can change the Piano and Overtone instruments to be other than the default Acoustic Grand Piano. For example, if you use the Violin device, you can investigate vibrato (slight shifting of pitches with time)
- Use the zoom commands to zoom into specific harmonics or time intervals
- The View menu also has Timeline and Waveform options – you may want to experiment with what these do

Features of Commercial Versions of the Overtone Analyzer program

In this activity, we have been using the free version of the Overtone Analyzer program; the authors of this program have been helpful in implementing features into the free version that enable the type of qualitative and quantitative measurements needed for teaching about acoustics and musical instruments. On the website http://www.sygyt.com/en/overtone-analyzer-editions they compare the free version to extended versions of the program that have many exciting additional features. Among the features of the commercial versions are

- Higher resolution to allow more precise measurements of frequency or timing
- Ability to store waves to a file or analyze waves from a file instead of the 10 second loop of the free version
- Multiple overtone sliders
- Editing of files and MIDI support

You may want to check out these commercial versions if you have an interest in recording or musical instruments. They offer a 30% discount for educational institutions, and a 50% discount for students.

This concludes this quickstart guide. You have learned the basics of how to record and visualize sounds with Overtone Analyzer. The main steps to remember are:

- Select the desired input source (such as the microphone) in the Audio Settings
- Always monitor the input volume meter during recording to prevent clipping
- Adjust the displayed dynamic range to show the desired amount of detail
- Use the Overtone Slider to play sounds and to measure frequencies and harmonics

Science Learning Activity 11

Understanding Musical Scales

Learning Objectives:

The goal of this experiment is to understand the Equal Tempered musical scale that is commonly used in western music. This can be done using the Overtone Analyzer program

Materials Required:

Windows Computer
Overtone Analyzer Program
http://www.sygyt.com/en/overtone-analyzer-editions
Download and install the Free edition
Microphone and Speakers for computer

References:

http://en.wikipedia.org/wiki/History_of_pitch_standards_in_Western_music
http://en.wikipedia.org/wiki/Musical_tuning
http://en.wikipedia.org/wiki/History_of_pitch_standards_in_Western_music
http://en.wikipedia.org/wiki/Musical_tuning

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Science Exercise 11

In a previous learning activity, you have studied how Overtone Analyzer allows you to break down a complex tone into its harmonics, and also how the Overtone Sliders allow you to display the expected harmonic frequencies of the fundamental. In this activity, you will investigate the structure of the Equal Tempered musical scale that is used for essentially all western music.

In music, there are a couple of intervals that are particularly "consonant" or pleasant. One of the first people to study the relationships between these consonant tones mathematically is the Greek mathematician Pythagoras. As described below, he developed a method for tuning that was based on very simple mathematical ratios, but there was a problem when applying this to a 12-tone scale. There was a fundamental compromise made in the 1700's about whether instruments would be perfectly in tune for a few key signatures (called Just Tuning or Pythagorean Tuning), or whether they would be easy to play in any key signature, but that every note would be slightly "wrong" (called Equal Tempered Tuning). Unfortunately, the equal tempered tuning method won out, so now all musical instruments are always a little bit out of tune. (For more details on some other tuning methods, see http://en.wikipedia.org/wiki/Musical_tuning)

The most common convention that is currently used is that the A4 key on the piano, which musicians sometimes call a concert A, will have a frequency of exactly 440 Hz. The table reproduced at the end of this activity shows the frequency of notes in the Equal Tempered scale using a convention of concert A, A4=440 Hz.

Throughout history, there have been wide variations in this reference tone – in some cases it has been significantly higher or lower than the current convention of 440 Hz. Even today, there are some groups that play baroque music on period instruments using about 415 Hz as the reference, whereas some symphony orchestras like the more brilliant tone produced by higher frequencies such as 442 Hz (See http://en.wikipedia.org/wiki/History_of_pitch_standards_in_Western_music)

The most important interval in music is the Octave; this is represented by the "same" key on the piano that are 12 keys apart. Two notes that are an octave apart have frequencies that differ by exactly a factor of 2.

To illustrate this, start up Overtone Analyzer. As discovered in previous activities, complex waveforms are a combination of many different harmonics. To eliminate the complications introduced by listening to tones with many harmonics, we will use pure sine waves. In Overtone Analyzer, select:

Options -> Audio Settings -> Playback -> Overtone Instrument -> Pure Sine wave

Also select

Options -> Display Settings -> Note Slider -> Snap to Nearest Musical Note

so that the Overtone Slider will automatically point at a note of the musical scale rather than an arbitrary frequency.

Adjust the Overtone Slider position until it points at A4=440 Hz. Point the mouse at the white slider label for 440 Hz and hold down the left mouse button. The slider label will turn red, and it will play a sine wave that is 440 Hz. As described in the Overtone Analyzer tutorial, pull the triangle setting to the right of the Overtone Slider so that at least the first five harmonics are displayed.
The frequency that is twice the fundamental will be an octave higher. This is the 2nd harmonic, and you can hear this by pressing the "2: A5 (880 Hz)" label on the overtone slider.

Next, play the tone for the 3rd harmonic (3*440 Hz = 1320 Hz) and 4th harmonic (4*440 Hz =1760 Hz). You will note that the 2nd harmonic is an octave higher than the fundamental, and the 4th harmonic is 2 octaves higher, since it is 4x the frequency of the fundamental.
The notes on a piano are arranged so that going up one octave doubles the frequency. Because of this, the spacing between the harmonics bands does not appear to be uniform. To better see the relationship between harmonics, press the LIN (instead of the LOG) key on the menu bar. In this case, the frequency scale is made to be uniform, and the spacing between each harmonic is uniform. You will note that the space between each harmonic is exactly the same since they are just integer multiples of the fundamental. Note, however, that the piano keyboard looks very unusual on a linear scale. While the display is in LIN mode, use a ruler to measure the distance between the A4 and A5 piano keys on your computer screen, and the distance from the A5 to A6 keys. You will notice that the distance from A5 to A6 on the screen is exactly twice as large as the distance from A4 to A5. This is because the difference in frequency (in Hz) between A5 and A6 is twice as large as the frequency difference between A4 and A5. When you are done, you might want to switch back to LOG mode. As you proceed with your studies of acoustics, there are different advantages of both LIN and LOG scaling, so feel free to toggle between them.
In ancient Greece, Pythagoras also demonstrated that other intervals are particularly consonant, or pleasant to listen to. One of these is what is called the "Musical Fifth" which corresponds to a ratio of 1.5 times the fundamental.

Calculate the frequency of the musical tone that is exactly a musical fifth (1.5 times the frequency) for the notes A4=440Hz and A5=880Hz.

You will note that the tone that is exactly a perfect 5th above an A5 will be the 1320 Hz tone that you played earlier. Since, as Pythagoras demonstrated, this interval sounds so good together, one might want to put a tone of the scale at that position. In musical terms, the note that is a musical 5th above the A4 is E5, and the note that is a musical 5th above the A5 is E6. If one uses this "Pythagorean tuning", the frequency of E5 would be 660 Hz and E6 would be 1320 Hz.
Pythagorean tuning would continue by using a musical 5th above the E's to tune the B note on the piano, and so on. Unfortunately, when one goes around what is called the "circle of 5ths" through the 12-tones that are commonly used on western musical instruments, the result will be that the frequency of octave notes will not be exact – there is an "error". Therefore, various tuning methods were proposed and developed to fix this problem. One method was to tune an instrument such that certain intervals were perfect, but that other intervals were significantly wrong; this is sometimes known as Pythagorean or Just tuning.

The problem is that these results in certain musical keys that have notes that are so far from their "exact" frequencies that the resulting tones are basically musically unplayable together – in these keys, the instrument will sound grossly out of tune. Another alternative is to use "Equal Tempered" tuning, whereby the octave notes are precisely tuned to be correct, but the musical interval for every other is slightly different from the frequency of the Pythagorean tuning. The "tuning error" that would result from Pythagorean tuning is spread out among all the notes of the scale such that no interval is exactly what it should be. This Equal Tempered tuning is much easier for musical instrument builders and players, since the instrument can play in any key without being retuned. The downside is that every note in the scale is a little off. (Note: there are some synthesizers that allow one to change the intonation from Equal Tempered tuning to another system such as Pythagorean tuning in a particular key – if you are a keyboard player, you might want to play around with this and see if you can notice the difference when you play some musical passage or chords)

In the table at the end of the activity handout, look up the frequency of the E5 and E6 notes in the Equal Tempered scale, and compare to the frequencies that you calculated in Problem 1 by using Pythagorean tuning of 1.5 times the fundamental. As an alternative to using the table, you can use the Overtone Slider - position the fundamental on E5, and you can read off the frequency of the E5 and E6 from the slider.

You will note that the frequencies that you calculated in Problem 1 (based on Pythagorean Tuning) are slightly different than the frequencies from the Equal Tempered scale.
Two other intervals that Pythagoras found to be "musically" and "mathematically" consonant are what are called the Pythagorean Perfect Third (ratio of 5/4 of the fundamental) and Pythagorean Perfect Fourth (ratio of 4/3 of the fundamental). In musical terms the Perfect Third above an A4 would be C#5, and the Perfect Fourth would be D5.
Calculate the frequencies of the Pythagorean Perfect Third and Perfect Fourth above an A4, and compare to the Equal Tempered C#5 and D5.

We will now go into more detail on how the notes of the Equal Tempered scale are generated. In the equal tempered scale, each octave is divided into 12 semitones (keys on the piano), and each octave is exactly a factor of 2 higher in frequency. If we call ratio of the frequency between two successive tones to be r, then if there are 12 tones needed to double the frequency, then $r^{12}=2$. This means that r is the 12th root of 2, or

$$r = 2^{1/12} = 1.05946309436$$

To calculate the frequency of any note in the Equal Tempered scale, start with a reference frequency (such as A4=440 Hz), and multiply by r for each semitone (note on the piano keyboard) higher. So, according to this method, the Equal Tempered frequency of a C#5, since it is 4 piano keys higher than an A4 is

$$f_{C\#5} = 440 \text{ Hz x } r^4 = 440 \text{ Hz x } (1.05946309436)^4$$

Use your calculator to show that the frequency is 554.37 Hz, which is the frequency that is listed in the table of Equal Tempered tones or if you point at C#5 using the Overtone Slider.
An orchestra tunes to a concert A frequency of A4=442 Hz. Calculate the Equal Tempered frequency of a D5 (which is 5 semitones higher) than this A4=442 Hz?

Compare this frequency to the frequency of a D5 when Concert A is A4=440 Hz (from the table or Overtone Slider). Is the tone sharp (higher frequency) or flat (lower frequency) when A4=442 Hz is used as the reference instead of A4=440 Hz?

Since an A5 is 12 semitones above an A4, use your calculator to calculate the frequency of an A5, based on A4=440 Hz. Is this what you would expect?

Musicians have another way of expressing intervals, and that is in terms of Cents. A cent is defined as 1/100 of the difference between two successive notes. This is analogous to money where 100 cents makes up one dollar; in music 100 cents makes up the musical interval between two notes on a piano. Mathematically, you can calculate the number of cents, *n*, between two notes with frequency *a* and *b* by using the equation

$$n = 3986 \log_{10}\left(\frac{a}{b}\right)$$

where $\log_{10}$ is the Base-10 logarithm function; this might be the "Log" key on your calculator. On your calculator, calculate the difference in cents between 440 Hz and 442 Hz by entering

$$3986 \log_{10}\left(\frac{442}{440}\right)$$

Your calculator should give a value of about 7.85. As with money, values are generally rounded to the nearest cent, so one would say that 442 Hz is about 8 cents above 440 Hz.
In Problem 3, you calculated the C#5 in the Pythagorean Tuning, and we calculated that the C#5 is given as 554.37 Hz in Equal Tempered tuning. How many Cents different are these two values. Is the tone in the Pythagorean Tuning sharp or flat relative to the Equal Tempered tuning?

One of the convenient features of the Overtone Analyzer program is that the labels in the Overtone Slider and also the Cursor Status Bar show not only frequency but also the difference in cents to the nearest note of the musical scale.

Position the Overtone slider to the note E2, which is the note that the Low E string (6^{th} string) on the guitar is tuned to. List the frequencies and notes for the first 4 harmonics including the number of cents (if displayed)

1^{st} Harmonic	E2__________	82.4 Hz______
2^{nd} Harmonic	____________	____________
3^{rd} Harmonic	____________	____________
4^{th} Harmonic	____________	____________

The 2^{nd} string on the guitar is a B3. Adjust the Overtone Slider until the fundamental is a B3. What is the frequency of a B3?

What would happen if you carefully tuned the lowest string on the guitar to exactly the right frequency for E2. Then using your carefully tuned E2 string, you pluck the string such that you can hear the 3^{rd} harmonic, and carefully tune your 2^{nd} string so that it matches the 3^{rd} harmonic of the lowest string. Will your guitar be in tune? Why or why not?

Problems:

Some suppliers (Such as Sargent Welch Scientific Instruments, or you can find these on Amazon.com) sell tuning forks based on a "Scientific" scaling of C4=256 Hz (this is used since 256 is exactly a power of 2). This leads to frequencies that are significantly different from the standard A4=440 Hz.

[10] How many cents different (sharp or flat) is C4=256 from the C4 listed in Table 1 (based on A4=440 Hz).

The note A4 is 9 semitones higher than C4. Calculate the frequency of an A4 based on this "scientific scaling" of C4=256 Hz. Compute the number of cents that this is sharp or flat from A4=440 Hz.

Table 1: Frequencies (in Hz) of Equal Tempered Tones based on A4 =440 Hz. The frequencies for the standard tuning of a guitar are highlighted.

E_0	20.602	E_3	164.81	E_6	1318.5	E_9	10548
F_0	21.827	F_3	174.61	F_6	1396.9	F_9	11175
	23.125		185.00		1480.0		11840
G_0	24.500	G_3	196.00	G_6	1568.0	G_9	12544
	25.957		207.65		1661.2		13290
A_0	27.500	A_3	220.00	A_6	1760.0	A_9	14080
	29.135		233.08		1864.7		14917
B_0	30.868	B_3	246.94	B_6	1975.5	B_9	15804
C_1	32.703	C_4	261.63	C_7	2093.0	C_{10}	16744
	34.648		277.18		2217.5		17740
D_1	36.708	D_4	293.66	D_7	2349.3	D_{10}	18795
	38.891		311.13		2489.0		19912
E_1	41.203	E_4	329.63	E_7	2637.0	E_{10}	21096
F_1	43.654	F_4	349.23	F_7	2793.8		
	46.249		369.99		2960.0		
G_1	48.999	G_4	392.00	G_7	3136.0		
	51.913		415.30		3322.4		
A_1	55.000	A_4	440.00	A_7	3520.0		
	58.270		466.16		3729.3		
B_1	61.735	B_4	493.88	B_7	3951.1		
C_2	65.406	C_5	523.25	C_8	4186.0		
	69.296		554.37		4434.9		
D_2	73.416	D_5	587.33	D_8	4698.6		
	77.782		622.25		4978.0		
E_2	82.407	E_5	659.26	E_8	5274.0		
F_2	87.307	F_5	698.46	F_8	5587.7		
	92.499		739.99		5919.9		
G_2	97.999	G_5	783.99	G_8	6271.9		
	103.83		830.61		6644.9		
A_2	110.00	A_5	880.00	A_8	7040.0		
	116.54		932.33		7458.6		
B_2	123.47	B_5	987.77	B_8	7902.1		
C_3	130.81	C_6	1046.5	C_9	8372.0		
	138.59		1108.7		8869.8		
D_3	146.83	D_6	1174.7	D_9	9397.3		
	155.56		1244.5		9956.0		

Understanding Musical Scales Answer Key

Calculate the frequency of the musical tone that is exactly a musical fifth (1.5 times the frequency) for the notes A4=440Hz and A5=880Hz.

1.5 x 440 Hz = 660 Hz

1.5 x 880 Hz = 1320 Hz

In the table at the end of the activity handout, look up the frequency of the E5 and E6 notes in the Equal Tempered scale, and compare to the frequencies that you calculated in Problem 1 by using Pythagorean tuning of 1.5 times the fundamental. As an alternative to using the table, you can use the Overtone Slider - position the fundamental on E5, and you can read off the frequency of the E5 and E6 from the slider.

E5 = 659.26 Hz

E6 = 1328.5 Hz

Calculate the frequencies of the Pythagorean Perfect Third and Perfect Fourth above an A4, and compare to the Equal Tempered C#5 and D5.

C#5 (Pythagorean) = (5/4)x440 Hz = 550 Hz : Equal Tempered = 554.37 Hz

D5 (Pythagorean) = (4/3)x440 Hz = 586.67 Hz : Equal Tempered = 587.33 Hz

An orchestra tunes to a concert A frequency of A4=442 Hz. Calculate the Equal Tempered frequency of a D5 (which is 5 semitones higher) than this A4=442 Hz? Compare this frequency to the frequency of a D5 when Concert A is A4=440 Hz (from the table or Overtone Slider). Is the tone sharp (higher frequency) or flat (lower frequency) when A4=442 Hz is used as the reference instead of A4=440 Hz?

f_{D5} = 442 Hz x r^5 = 442 Hz x $(1.05946309436)^5$ = 589.99 Hz

which is sharp relative to the 587.33 Hz when using an A4=440 Hz reference

Since an A5 is 12 semitones above an A4, use your calculator to calculate the frequency of an A5, based on A4=440 Hz. Is this what you would expect?

f_{A5} = 440 Hz x r^{12} = 440 Hz x $(1.05946309436)^{12}$ = 880 Hz

This is what you would expect since it is an octave above A4=440, it should have twice the frequency

In Problem 3, you calculated the C#5 in the Pythagorean Tuning, and we calculated that the C#5 is given as 554.37 Hz in Equal Tempered tuning. How many Cents different are these two values. Is the tone in the Pythagorean Tuning sharp or flat relative to the Equal Tempered tuning?

3986 x log(550/554.37) = -13.7, so we would say that the C#5 in Pythagorean tuning is about 14 cents flat from the C#5 in the Equal Tempered tuning

Position the Overtone slider to the note E2, which is the note that the Low E string (6^{th} string) on the guitar is tuned to. List the frequencies and notes for the first 4 harmonics including the number of cents (if displayed)

1^{st} Harmonic	E2	82.4 Hz
2^{nd} Harmonic	E3	164.8 Hz
3^{rd} Harmonic	B3+2cents	247.2 Hz
4^{th} Harmonic	E4	329.6 Hz

The 2^{nd} string on the guitar is a B3. Adjust the Overtone Slider until the fundamental is a B3. What is the frequency of a B3?

246.9 Hz

What would happen if you carefully tuned the lowest string on the guitar to exactly the right frequency for E2.

Then using your carefully tuned E2 string, you pluck the string such that you can hear the 3rd harmonic, and carefully tune your 2nd string so that it matches the 3rd harmonic of the lowest string. Will your guitar be in tune? Why or why not?
No, your guitar will not be in tune with other musical instruments. If you tuned the guitar so that the B3 string matched the third harmonic of the E2 string, the B3 string would be 2 cents sharp (247.2 Hz) relative to other instruments that are tuned to 246.9 Hz.

Problems:
Some suppliers (Such as Sargent Welch Scientific Instruments, or you can find these on Amazon.com) sell tuning forks based on a "Scientific" scaling of C4=256 Hz (this is used since 256 is exactly a power of 2). This leads to frequencies that are significantly different from the standard A4=440 Hz.
How many cents different (sharp or flat) is C4=256 from the C4 listed in Table 1 (based on A4=440 Hz).
3986 x log(256/261.63) = -37.65, so we would say that this "Scientific C4" tuning fork is about 38 cents flat from the standard C4 with A4=440 Hz tuning.
The note A4 is 9 semitones higher than C4. Calculate the frequency of an A4 based on this "scientific scaling" of C4=256 Hz. Compute the number of cents that this is sharp or flat from A4=440 Hz.
256 Hz x $(1.05946309436)^9$ = 430.54 Hz
3986 x log(430.54/440) = -37.8 Hz
or about 38 cents flat from a standard A4=440 Hz

Science Learning Activity 12

Investigation of Guitars using a Spectrum Analyzer

The goal of this experiment is to better understand the sounds produced by a guitar by using a spectrum analyzer.

Learning Objectives:

In previous activities, you have looked at waves on a string, waves on a guitar string, and have used a spectrum analyzer to better understand the musical scale. You are now in a position to combine all of these tools to better understand how guitars make sounds.

Materials Required:

Windows Computer
Overtone Analyzer Program
http://www.sygyt.com/en/overtone-analyzer-editions
Download and install the Free edition
Microphone and Speakers for computer
Guitar
For electric guitar: Input jack (1/4" to 1/8" adapter)
For acoustic guitar: Microphone
Electronic Guitar Tuner

Science Exercise 12

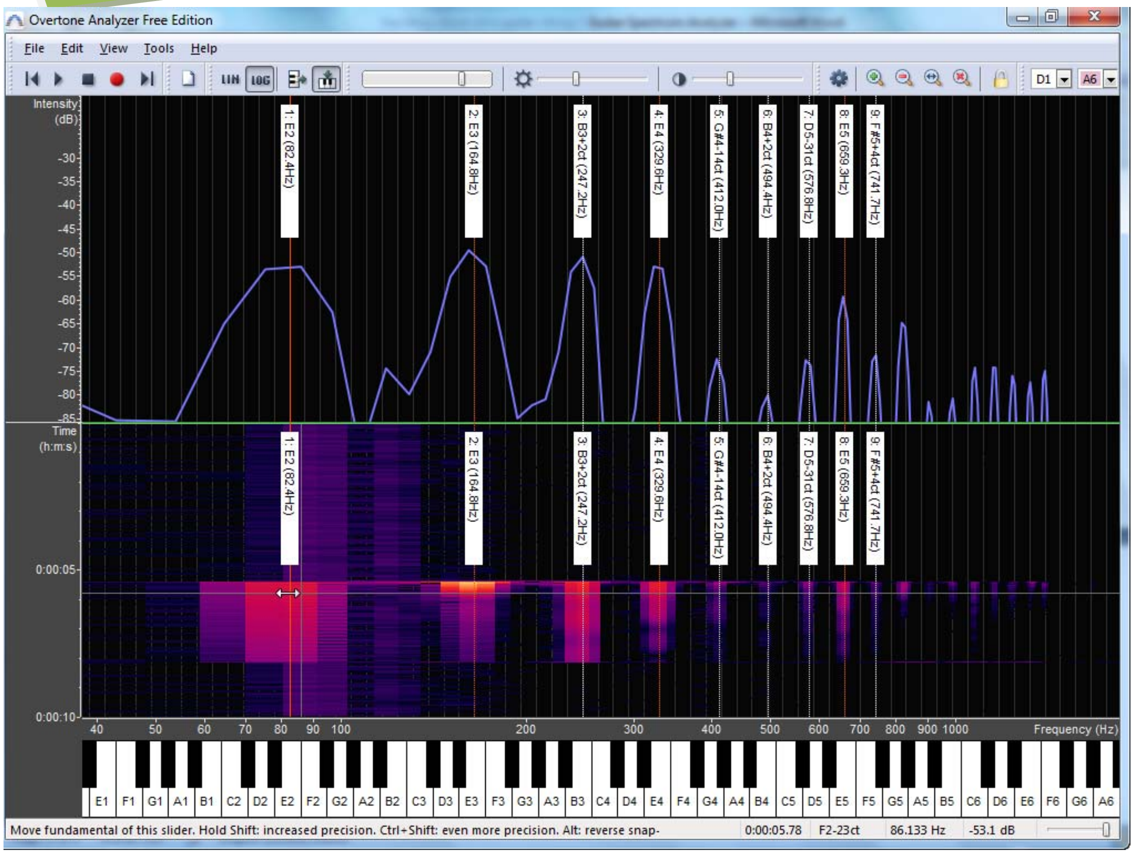
Begin by carefully tuning your guitar using an electronic guitar tuner. The notes and their frequencies are listed in the table below

String	Note	Frequency
6^{th} (Thick wound string)	E2	82.4 Hz
5^{th}	A2	110.0 Hz
4^{th}	D3	146.8 Hz
3^{rd}	G3	196.0 Hz
2^{nd}	B3	246.9 Hz
1^{st} (Thin steel string)	E4	329.6 Hz

Part I: Investigating Guitar using a Spectrum Analyzer

Now you will want to get the sounds from your guitar into the computer. If you are using an acoustic guitar, you can just pluck notes on the guitar so the microphone can detect these. If you are using an electric guitar, you can play the guitar through an amplifier (use a "clean" setting on your amp with as little distortion as possible). Alternately, you can use a ¼" to 1/8" adapter to allow you to plug the output of the electric guitar directly into the microphone input on the computer.

Next, play the 6^{th} string on the guitar (the lowest note). Adjust the recording level and the dynamic range sliders. After some adjustment, you should be able to obtain a spectrum that clearly shows up on the screen. After stopping the recording, set the Overtone Slider to have the fundamental frequency E2, and display the first several harmonics. When you have adjusted this suitably, the display should look something like this



There are a couple interesting things to note about the display shown above. First, you will notice that the note was plucked at about 5 seconds. Even before the note is played, there is a dim blue/purple band on the spectrogram display that shows up near the notes F2 and B2. This tone is present even when the guitar is not being played – it actually comes from the microphone picking up the fan on the computer that was used for this experiment! When the microphone is moved closer to the computer, this band gets brighter. This demonstrates that a spectrum analyzer can be used to analyze and diagnose "noise" in a room.

Another thing that is quite apparent is that the lowest peaks in the spectrum are very "fat", and they get narrower as they go up. The freeware version of the Overtone Analyzer program that we are using has a frequency resolution of 10.8 Hz. For a low-frequency tone such as E2=82.4 Hz, a frequency range of 10.8 Hz is actually several semitones wide. Thus, the lowest band in this spectrum is very fat. For much higher frequency, a difference of 10.8 Hz is a very small fraction of the width of one semitone, so these peaks appear to be much narrower. (If you are interested in higher resolution, the commercial version of the Overtone Analyzer program can have a frequency resolution as small at 0.17 Hz instead of the 10.8 Hz resolution of the freeware version)

To see more clearly that each peak has the same width, change the display to a Linear scaling on the frequency axis by pressing the Lin button. If you look at this linear display, the harmonics will be uniformly spaced, and all of them will have the same width. When you are done with this test, change back to the Log scaling by pressing the Log button.

Next, you can start to understand the difference in waveforms by plucking the same note in different ways with and without a pick and at different positions on the string. For example, start the Overtone Analyzer program recording then play the 6th string by plucking it "gently" towards the middle of the string, then use a hard pick to pluck the note right next to the bridge.

Carefully compare the two spectra. In particular, comment on the following:

[1] Are all of the harmonics present in both cases? In which case are low frequency harmonics more present? In which case are high frequency harmonics more present? Describe why this might be the case.

[2] Does the frequency of the harmonics shift when you play the note in different ways? Why or why not?

[3] Which harmonics sustain longer, and which die out faster?

[4] Why do you think that a hard pick pluck next to the bridge sounds more "tinny" than a broad pluck near the center of the string.

[5] Please record any other observations you have about the spectra.

Part II: Investigating the spectrum when plucking guitar harmonics

In a previous activity, you demonstrated that you can excite the 2nd harmonic of the string by lightly placing your finger on the midpoint of the string (do not press the string down at all, just lightly touch the string) and plucking the string. Practice this until you can get a clear tone that is an octave above the fundamental. When you have this down, make a recording where you first pluck this 2nd harmonic, and then you pluck the string in the regular way. Keep your Overtone Slider centered on E2.

[6] For the tone where you plucked the 2nd harmonic, what do you notice about the amplitude of the even harmonics versus the odd harmonics? Why do you think this is the case? You may want to include a rough sketch of the amplitude of spectrum.

[7] Repeat this procedure by plucking the 3rd harmonic where you lightly place your finger on the 7th fret and pluck the note. What do you notice about harmonics that are multiples of 3 versus other harmonics? Why? Include a rough sketch.

[8] Finally, you can excite the 4th harmonic by lightly placing your finger directly above the 5th fret and plucking. Before you look at the spectrum for this note, what do you expect?

[9] Now, record the spectrum and describe the results. Are they what you would expect? Why or why not?

Part III: Investigation of spectra using different pickup positions (for electric guitars)

If you are using an electric guitar, investigate the spectra obtained by using different pickups and/or tone controls. The best way to do this is by doing direct comparisions of two spectra on the same recording; you may want one person to just be responsible for plucking notes, and another for changing controls and running the program. For example, start a recording and pluck a note using one pickup, then change pickups and pluck the note again as close to the same position on the string and with the same amount of force. Or pluck the string with a tone control rotated all the way one direction and then all the way the other direction.

[10] Describe your observations. Do you notice any difference between a pickup closer to the neck of the guitar versus one that is close to the saddle? Why? Describe what the tone controls do to the spectrum.

Part IV: Harmonic Tuning

If you are a guitar player, you may have been taught how to do "harmonic tuning" to tune a guitar. With your understanding of how the Equal Tempered scale works, as well as your experience with Overtone Analyzer, you will be able to see why this technique will result in your guitar being tuned incorrectly. Begin by recording a plucked note of the 6th string and 5th string (E2 and A2) on the same screen. You will notice that the 4th harmonic of the 6th string and the 3rd harmonic of the 5th string appear to overlap on the note E4. Put the Overtone Slider onto the E2, and note that the 4th harmonic is exactly an E4. Now move the Overtone Slider such that the fundamental is A2.

[11] What is the frequency of the 3rd Harmonic? Is this exactly an E4?

With harmonic tuning, one first tunes the 6th string (E2). Then the player plays the 4th harmonic of the 6th string, and adjusts the 5th string until its third harmonic is in tune with the 4th harmonic of the 6th string. This process is repeated to tune the next couple of strings. We can use the Overtone Slider to see what happens when we do this process. Point your mouse cursor at the 3rd harmonic of the A2 string (the E4 that is a couple cents off).

Now hold the left mouse button and move this third harmonic is exactly on E4 instead of being a few cents off (you may want to enable the "snap to nearest note" feature in the Options -> Analyzer Settings -> Note Slider menu).

[12] Now look at the fundamental – what frequency is it listing? How many cents different is the A2 from the desired frequency in the Equal Tempered scale (110 Hz)?

The reason that this note is off is that this harmonic tuning results in strings that will be perfectly adjusted for Pythagorean Tuning of the E scale. However, every other musical instrument uses the Equal Tempered tuning, so the A2 is "wrong" relative to all other instruments. With harmonic tuning, this incorrectly tuned A2 would become the reference by which the D3 would be tuned (with the result that it will be even further off), and repeated with the G3.

[13] Do you think that these strings will be closer or further from the "correct" tuning if you continue this harmonic tuning technique.

Investigation of Guitars using a Spectrum Analyzer Answer Key

[1] Are all of the harmonics present in both cases? In which case are low frequency harmonics more present? In which case are high frequency harmonics more present? Describe why this might be the case.
When the guitar is plucked towards the middle, the most prominent harmonics are the 1st, 3rd and other odd harmonics. This is because the odd harmonics have maxima near the center, whereas the even harmonics are zero near the center. Therefore plucking the string near the middle won't excite these harmonics.
When the guitar is plucked near the bridge, the fundamental will be much smaller than the upper harmonics. This is because the fundamental has an amplitude of almost zero near the end of the string. Therefore, when you pluck the string this way, there will be very little of this harmonic excited.

[2] Does the frequency of the harmonics shift when you play the note in different ways? Why or why not?
No, the frequencies of the harmonics depend on the length of the string and the tension. Therefore it doesn't matter how you pluck the string, the frequencies of the harmonics will remain the same. The only difference is which harmonics are excited.

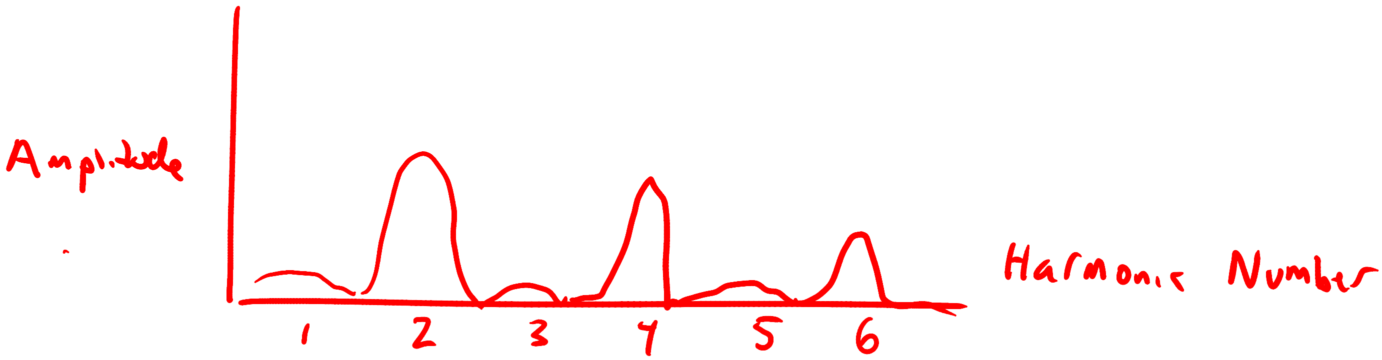
[3] Which harmonics sustain longer, and which die out faster?
The lower harmonics sustain longer, and the higher harmonics die out faster.

[4] Why do you think that a hard pick pluck next to the bridge sounds more "tinny" than a broad pluck near the center of the string.
The sound is more "tinny" because there is very little of the fundamental and lower harmonics, and a lot more of the upper harmonics that have higher frequency. Therefore, plucking towards the center gives a more "rich" tone and plucking near the end gives a "tinny" tone.

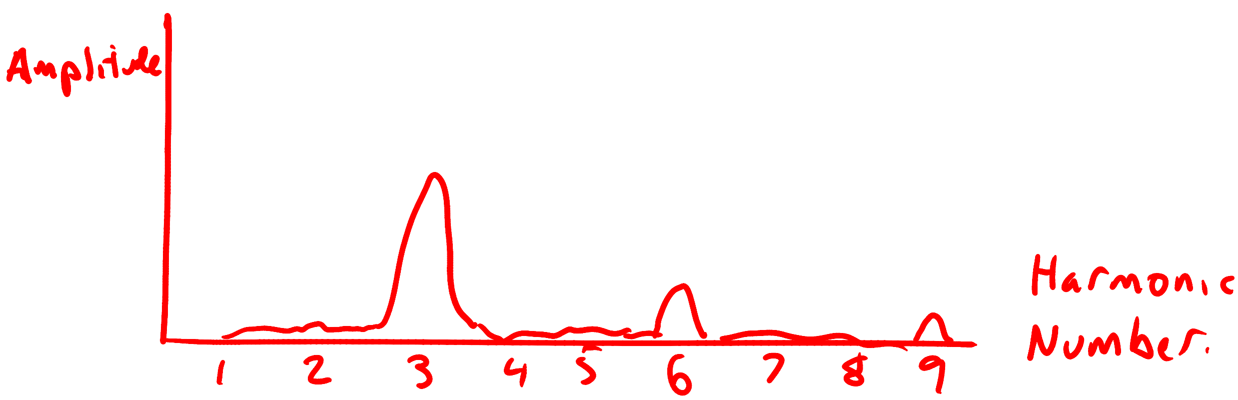
[5] Please record any other observations you have about the spectra.
They might have other observations such as

- The sound lasts longer when played near the middle than near the bridge
- We didn't see the first two harmonics at all
- If we plucked at different places near the bridge, the amount of different harmonics changed a lot

[6] For the tone where you plucked the 2nd harmonic, what do you notice about the amplitude of the even harmonics versus the odd harmonics? Why do you think this is the case? You may want to include a rough sketch of the amplitude of spectrum.
The even numbered harmonics are large, and the odd harmonics are small. This is because your finger forced a node at the center of the string, so the odd harmonics (that have antinodes at the center) will be eliminated.



[7] Repeat this procedure by plucking the 3rd harmonic where you lightly place your finger on the 7th fret and pluck the note. What do you notice about harmonics that are multiples of 3 versus other harmonics? Why? Include a rough sketch.
The amplitude of harmonics that are multiples of 3x times the fundamental are much larger than the others. This is because there is a node 1/3 of the way along the string, so others are suppressed to some extent. There may be a small amount present since other harmonics still have some amplitude at 1/3 the way along the string



[8] Finally, you can excite the 4th harmonic by lightly placing your finger directly above the 5th fret and plucking. Before you look at the spectrum for this note, what do you expect?
Expect to see harmonics that are multiples of 4x the fundamental

[9] Now, record the spectrum and describe the results. Are they what you would expect? Why or why not?
See some of other harmonics, but the largest is the 4th harmonic. The others are present to some extent because there is still a little amplitude at ¼ of the way along the string. However, the finger tends to damp these, so the 4th will likely be the largest.

[10] Describe your observations. Do you notice any difference between a pickup closer to the neck of the guitar versus one that is close to the saddle? Why? Describe what the tone controls do to the spectrum.

Observations may vary. In general, you will observe that pickups closer to the neck (middle of the string) will have more lower harmonics than pickups closer to the saddle which will have more higher harmonics. Since the pickup samples the motion of the string at different position, the closer the pickup is to the middle of the string, the larger the fundamental will be, and the closer it is to the saddle, the smaller the fundamental (and low harmonics) will be.

The tone controls will tend to filter out harmonics – increasing the bass control will reduce the amount of high-frequency harmonics, and increasing the treble control will reduce the amount of low-frequency harmonics.

[11] What is the frequency of the 3rd Harmonic? Is this exactly an E4?

The 3rd harmonic of A2 has a frequency 330 Hz, which is 2 cents sharp from E4.

[12] Now look at the fundamental – what frequency is it listing? How many cents different is the A2 from the desired frequency in the Equal Tempered scale (110 Hz)?

The frequency after doing this "harmonic tuning" is 109.9 Hz, which is about 2 cents flat from the desired 110 Hz.

[13] Do you think that these strings will be closer or further from the "correct" tuning if you continue this harmonic tuning technique.

If you continue the harmonic tuning technique, the next string (D3) will be about another 2 cents flat, so it will be a total of about 4 cents flat. The G3 will be another 2 cents flat, so about 6 cents flat.

Science Learning Activity 13

Independent Project

Learning Objective:

The objective of this experiment is to use everything that you have learned to date about standing waves, musical scales and using the Overtone Analyzer program to perform an independent project.

Materials Required:

Windows Computer
Overtone Analyzer Program
http://www.sygyt.com/en/overtone-analyzer-editions
Download and install the Free edition
Microphone and Speakers for computer
Guitar, other musical instrument or noise source

Science Exercise 13

For this independent project, you are to use all of the things you have learned to date to do an independent project.

First, choose a system for which you want to study the sound waves: this might be a guitar, another musical instrument, or just about any other system where it makes a "tone" (a pop bottle being blown, the "ping" of a tennis racket, the whir of a computer fan, the pattern of tones generated when you press keys for dialing a telephone, etc.). Be creative in coming up with an interesting idea.

Second, make some preliminary observations using Overtone Analyzer to see the resulting spectrogram and spectrum. Record some of your observations below.

Now that you have made some preliminary observations, state below some aspect of the system that you want to study in more detail, as well as a tentative plan of study.

Next, do your experiment and record your observations. You should record both quantitative and qualitative observations (such as which tones and harmonics are present, what happens when you "change" something in the system, etc.) You should make tables, sketches, etc. to document your results.

Finally, make some conclusions. What did you learn from your experiments?

Independent Project

Additional Ideas for Independent Projects

Depending on your class, there can be a tradeoff when listing too many ideas for student projects. If there are too many ideas listed in the writeup, the students may not think of their own ideas. However, it is also helpful as an instructor to have some additional ideas to throw out. Therefore, listed below are some other ideas. If you or your students come up with other ideas, contact Tom Huber (Huber@gac.edu) to add them to this list

- Just about any musical instrument can be analyzed (our students have looked at everything from conventional musical instruments to different pop-bottle resonators to a Didgeridoo from Australia. Wind and string instruments will have a very regular set of harmonics, whereas drums and some other percussion instruments often have non-uniformly spaced harmonics. Are all harmonics present, or are some more dominant? Does the spectrum have primarily odd harmonics? Make some "changes" to how the instrument is played, and see whether you can see the resulting changes in timbre.
- An interesting problem is to look at the frequencies that are emitted by a touch-tone phone when dialing. Each key emits a pair of frequencies as described below – some of my students have had fun figuring out for themselves what the pattern is
  - The contemporary keypad is laid out in a 4×3 grid, although the original DTMF system in the new keypad had an additional column for four now-defunct menu selector keys. When used to dial a telephone number, pressing a single key will produce a pitch consisting of two simultaneouspure tone sinusoidal frequencies. The row in which the key appears determines the low frequency, and the column determines the high frequency. For example, pressing the '1' key will result in a sound composed of both a 697 and a 1209 hertz (Hz) tone..

DTMF Keypad Frequencies (with sound clips)

1	2	3	**697 Hz**
4	5	6	**770 Hz**
7	8	9	**852 Hz**
*	0	#	**941 Hz**
1209 Hz	**1336 Hz**	**1477 Hz**	

(from http://en.wikipedia.org/wiki/Telephone_keypad)

- Analyze the changes that are caused by various guitar effects boxes.
- Compare the duration and frequency of the "ping" of a tennis racket with and without the string dampener

- Hold an electric guitar such that the pickup is somewhat close to a "wall wart" transformer. You should be able to hear and see (in the Overtone Analyzer) the 60 Hz hum being picked up, as well as multiples such as 120 Hz and 180 Hz.
- You may also be able to detect the hum from florescent lights, or the speed of a fan by looking at the spectrum obtained.
- If you can find a train whistle, it emits a pair of tones instead of a single tone.
- Another interesting topic is "helium talking or singing". Here is how I do this with students:
    - First fill a very small balloon (don't fill it more than about the size of a baseball) with helium and pinch off the end (it is easier if you don't tie it shut)
    - Start the Overtone analyzer program and have a student hum or sing a note and record in for a few seconds (they might want to listen to a tuning fork before they sing so they "lock in" the pitch) and then stop the recording
    - Then have the student gradually let the helium out of the balloon and breathe it in (it might take two breaths)
    - Start recording again and have the student sing the same note and stop the program. The student can then carefully compare the spectrum before and after the helium.
    - Have the student breathe normally for several minutes to make sure that all of the helium is out of their lungs before breathing in helium again.
    - ***Warning: Never have a student breath directly from a helium tank, since the pressure may be too large and also as an instructor you cannot regulate how much the student is going to breathe in.***
    - As noted in http://en.wikipedia.org/wiki/Helium

      "Inhaling helium can be dangerous if done to excess, since helium is a simple asphyxiant and so displaces oxygen needed for normal respiration. Breathing pure helium continuously causes death by asphyxiation within minutes. Inhaling helium directly from pressurized cylinders is extremely dangerous, as the high flow rate can result in barotrauma, fatally rupturing lung tissue. However, death caused by helium is quite rare, with only two fatalities reported between 2000 and 2004 in the United States."

      "The speed of sound in helium is nearly three times the speed of sound in air. Because the fundamental frequency of a gas-filled cavity is proportional to the speed of sound in the gas, when helium is inhaled there is a corresponding increase in the pitches of the resonant frequencies of the vocal tract. This causes a reedy, duck-like vocal quality which some people find amusing. ***Instructors Note: The Wikipedia page also states the following:***

"(The opposite effect, lowering frequencies, can be obtained by inhaling a dense gas such as sulfur hexafluoride.)" ***Warning: Never perform this experiment with a gas more dense than air!*** ***For a gas less dense than air (such as helium), it will naturally rise out of the lungs, so the lungs will clear themselves after breathing several breaths. For a gas that is more dense than air (such as sulfur hexafluoride) the gas will naturally fall to the "bottom" of the lungs and cannot be simply exhaled without standing on ones head.***

  - Helium talking (or singing) is interesting – the fundamental tone that is produced by the human voice comes from the frequency of the vocal cords. The vibration of the vocal cords is essentially unaffected by helium or air. Therefore, the tone of your voice is essentially unaffected by the helium. The reason that your voice sounds so odd is not because the tone that you are singing is higher, but a change in the timbre because the resonance frequencies of the vocal tract are shifted higher because of the higher speed of sound in helium.

- When an experienced student/instructor is playing a musical instrument or singing, analyze their vibrato. Using the spectrogram display, determine the amount of frequency shift and how fast the variation is that seems "pleasant" as compared to a "warbling" sound when vibrato is too fast or has too large of a pitch shift.

Math Learning Activity 1

Fret Spacing Calculation

Learning Objectives:

Student will demonstrate understanding of the concepts of string instrument scale length and how fret locations are determined by calculating the exact fret locations for the first five fret positions when given the scale length of the string instrument. The precise locations of frets on a fret board are essential to creating an instrument that plays in tune.

References:

- From http://www.cybozone.com/luthier/instruments/fretscale.html

Notes

“Pythagoras was first to experiment with determining scalar intervals... and later, in the 16th century, Vicenzo Gallelei was credited with developing the "rule of 18". . . used for centuries by instrument makers to determine the fret scale of their instruments. For any given vibrating string length they would simply divide the length of the string by 18... Yielding the distance from the nut to the first fret. By subtracting that figure from the original string length they arrived at a new shorter scale measurement which was then divided once again by 18 and resulted in the distance between the first and second frets. They continued in this manner until the entire scale was determined. Over the years several variations on this theme have been developed... The divisor has been refined, (based on a complex mathematical formula that utilizes the 12th root of 2) resulting in more accurate scales

$$X_n = L\left(1 - \frac{1}{r^n}\right)$$

Or written on one line, looks like

Xn = L (1 – 1 / r ^ n)

Where:

Xn is the distance of the fret n to the string nut at the end of the fretboard

n is the current fret

L is the scale length

$r = 2^{(1/12)}$ = 1.059463

Problems 1-5: Determine the first 5 fret locations for a stringed instrument with a 25.5 inch scale length

Problems 6-10: Determine the first 5 fret locations for a stringed instrument with a 32.125 inch scale length.

You must show all your work neatly, so that it flows in a straight line. Formulas, substitution, calculation, answer.

Math Exercise 1

Fret Spacing Calculation

Determine the first 3 fret locations for a stringed instrument with a 24” scale length.

Fret Spacing Example calculation

Fret position #1

Xn = L (1 – 1 / r ^ n)

= 24” (1 – 1 / 1.059643 ^ 1)
= 24” (1 – 1 / 1.059643)
= 24” (1 – 0.943714)
= 24” (0.056286)
=1.350”

Fret position #2

Xn = L (1 – 1 / r ^ n)

= 24” (1 – 1 / 1.059643 ^ 2) = 24” (1 – 1 / 1.122843)
= 24” (1 – 0.890596) = 24” (0.109404) = 2.625”

Fret position #3

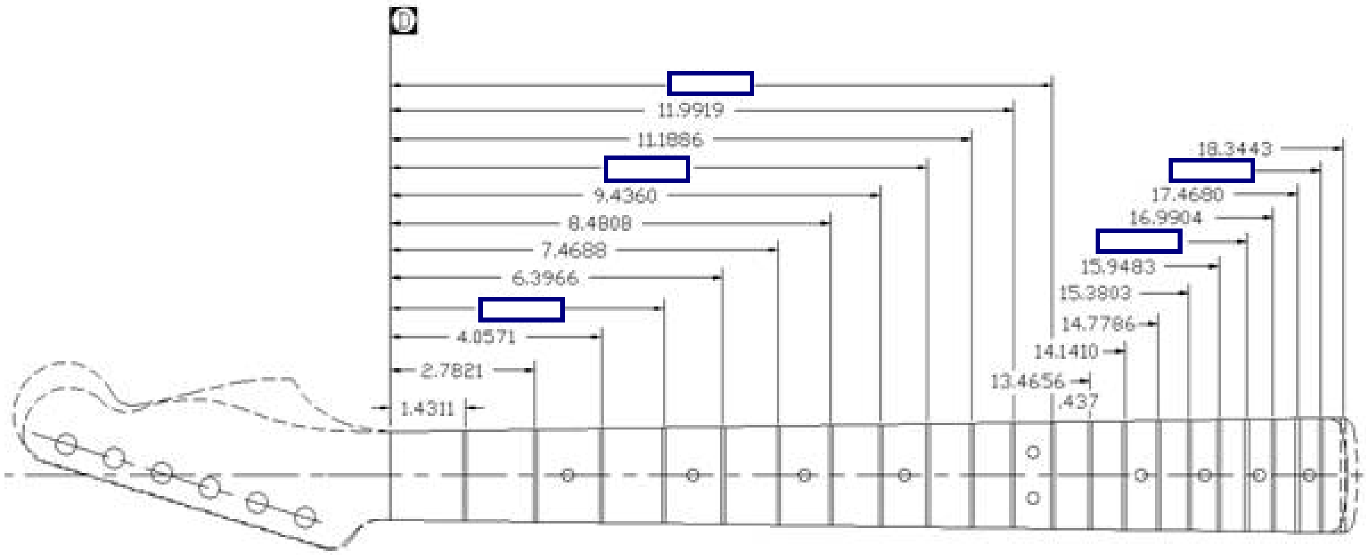
Xn = L (1 – 1 / r ^ n)

= 24” (1 – 1 / 1.059643 ^ 3) = 24” (1 – 1 / 1.18981)
= 24” (1 – 0.840468) = 24” (0.159532) = 3.828”

Problems 1-5: Determine the first 5 fret locations for a stringed instrument with a 25.5 inch scale length

Problems 6-10: Determine the first 5 fret locations for a stringed instrument with a 32.125 inch scale length.
You must show all your work neatly, so that it flows in a straight line. Formula, substitution, calculation, answer.

Problem 11



Fill in the missing fret positions as indicated on the neck. Use the existing fret spacing numbers to help determine the distance.

Fret Spacing Calculation Answers

Solution for Fret Spacing Calculation **for 25.5” scale length**

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5” (1 – 1 / 1.059643 ^ 1) = 25.5” (1 – 1 / 1.059)
= 25.5” (1 – 0.944) = 25.5” (0.056) = 1.431”

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5” (1 – 1 / 1.059643 ^ 2) = 25.5” (1 – 1 / 1.122)
= 25.5” (1 – 0.891) = 25.5” (0.109) = 2.782”

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5” (1 – 1 / 1.059643 ^ 3) = 25.5” (1 – 1 / 1.189)
= 25.5” (1 – .841) = 25.5” (0.159) = 4.057”

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5” (1 – 1 / 1.059643 ^ 4) = 25.5” (1 – 1 / 1.260)
= 25.5” (1 – .794) = 25.5” (0.206) = 5.261”

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5” (1 – 1 / 1.059643 ^ 5) = 25.5” (1 – 1 / 1.335)
= 25.5” (1 – 0.749) = 25.5” (0.251) = 6.397”

Solution for Fret Spacing Calculation **for 32.125” scale length**

$X_n = L\,(1 - 1 / r \wedge n)$

= 32.125” (1 – 1 / 1.059643 ^ 1) = 32.125” (1 – 1 / 1.059)
= 32.125” (1 – 0.944) = 32.125” (0.056) = 1.803”

$X_n = L\,(1 - 1 / r \wedge n)$

= 32.125” (1 – 1 / 1.059643 ^ 2) = 32.125” (1 – 1 / 1.122)
= 32.125” (1 – 0.891) = 32.125” (0.109) = 3.505”

$X_n = L\,(1 - 1 / r \wedge n)$

= 32.125” (1 – 1 / 1.059643 ^ 3) = 32.125” (1 – 1 / 1.189)

= 32.125" (1 – .841) = 32.125" (0.159) = 5.111"

$X_n = L\,(1 - 1 / r \wedge n)$

= 32.125" (1 – 1 / 1.059643 ^ 4) = 32.125" (1 – 1 / 1.260)
= 32.125" (1 – .794) = 32.125" (0.206) =6.627"

$X_n = L\,(1 - 1 / r \wedge n)$

= 32.125" (1 – 1 / 1.059643 ^ 5) = 32.125" (1 – 1 / 1.335)
= 32.125" (1 – 0.749) = 32.125" (0.251) = 8.058"

Solution for necks shown, frets 4,9,12,18,21

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5" (1 – 1 / 1.059643 ^ 4) = 25.5" (1 – 1 / 1.335)
= 25.5" (1 – 0.749) = 25.5" (0.251) = 6.397"

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5" (1 – 1 / 1.059643 ^ 9) = 25.5" (1 – 1 / 1.414)
= 25.5" (1 – 0.707) = 25.5" (0.293) = 7.469"

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5" (1 – 1 / 1.059643 ^ 12) = 25.5" (1 – 1 / 2.0)
= 25.5" (1 – .500) = 25.5" (0.500) = 12.750"

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5" (1 – 1 / 1.059643 ^ 18) = 25.5" (1 – 1 / 2.828)
= 25.5" (1 – .354) = 25.5" (0.646) = 16.484"

$X_n = L\,(1 - 1 / r \wedge n)$

= 25.5" (1 – 1 / 1.059643 ^ 21) = 25.5" (1 – 1 / 3.364)
= 25.5" (1 – 0.297) = 25.5" (0.703) = 17.919"

Math Learning Activity 2

Tuners and Gear ratios

Reinforce concepts of ratios and pi by solving problems that deal with gear ratios and linear distances of rotational movement. This exercise applies the concepts of rotation translational movement and gearing ratios that are used in a guitar tuner.

Learning objectives:

1. Student will be able to explain how gear ratio can translate a small amount of effort into a greater force.
2. Student will be able to explain the difference between linear and rotational movement.
3. Student will be able to identify a worm gear and a spur gear and explain how they interact with one another
4. Student will be able to calculate how much string post has turned based on knob turn amount expressed as degrees or fractional turns.
5. Student will be able to calculate the linear distance of a string movement the post diameter, gearing ratio, and number of knob turns.
6. Student will be able to compare calculated prediction to real-world application.

References:

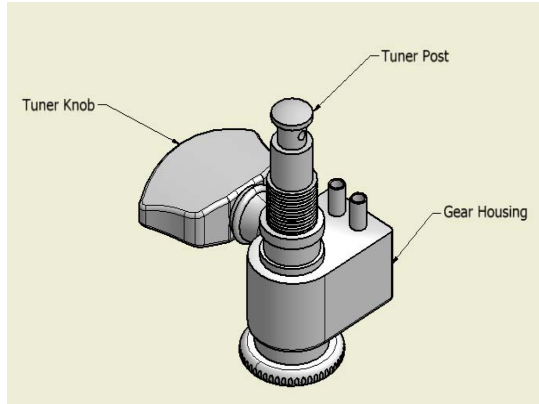
http://www.allparts.com/HB5-Bass-Tuners-Nickel-p/tk-7754-001.htm

Worm Gear connected to Tuning post

Worm connected to Tuning Knob

Bass Guitar Tuner

Image Source: http://www.allparts.com/HB5-Bass-Tuners-Nickel-p/tk-7754-001.htm



Math Principles covered:

Linear distance of string per turns of knob using given gear ratio:

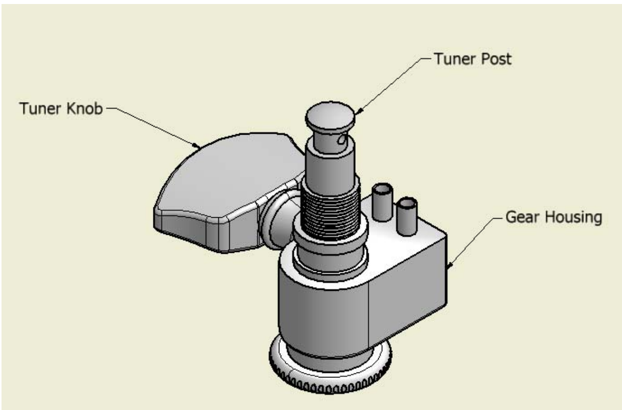
$$L = \frac{T_k T_o C}{T_i}$$

L = linear movement
T_k = knob turns
T_o = output shaft turns (from gear ratio)
T_i = input shaft turns (from gear ratio)
C = circumference of output shaft (where $C = 2\pi r$)

$L = (T_k \cdot T_o \cdot 2\pi r) \div T_i$
L = 3 knob turns * 1 output turn * 2 π .25inches / 14 input turns
L = 3 * 1 * 2 * 3.14 * .25" / 14
L = 4.71 inches / 14
L = 0.336 inches

Activity or class demonstration: Verify on a guitar by placing a black mark on a string at the nut position. Turn the knob the indicated number of turns in the calculation and measure the linear distance with a set of calipers to determine whether the calculation is reasonable.
If the measured amount is different than the equation calculation; students provide explanations for the difference. (i.e., string stretches; gear ratio is not exactly as printed, etc.)

Math Exercise 2



Gear ratios -- tuner gear ratio refers to the effect of how many turns of the tuner knob to have 1 complete turn of the post that has the guitar spring winds around

Equations: Circumference = 2 π r

Problem 1: The guitar tuner has a gear ratio of fourteen to one, what does that mean?

Problem 2: If there are 6 guitar tuners on a headstock with a 14 to one gear ratio a person attempts to tune a guitar. They first turn the knob 13 times to the left and then turn 5 times to the right. How many full turns and partial turns of the post were made after all the knob turns?

Problem 3: The post of the guitar tuner is .25" in diameter with a gear ratio of 15 to 1 how many turns will it take to wind 1 linear inch of guitar sting on the post?

For Problems 4-6: Tuner gear ratio 14 to 1, post diameter 3/16", Solve the following problems using the above information.

Problem 4: if the tuner knob is turned 28 complete turns to the left how much guitar sting was wrapped on the post.

Problem 5 - if the tuner knob is turned 32 ½ turns to the left how much guitar sting was wrapped on the post.

Problem 6 - if the tuner knob is turned 18 complete turns to the right how much guitar sting was un-wrapped from the post.

Problem 7 - The gear tuner was turned 5 3/4 turns, the gear ratio is 14 to 1, how much has the tension changed if each 1/8" linear movement of guitar string the string tension changes by 1/2 lb.

Problem 8 - A tuner knob was turned 35 degrees to the left to bring the guitar into tune. With a gear ratio of 15 to 1 and a post diameter of .25" how much linear movement occurred to the guitar string?

Solutions for Gear Ratios and Tuners

Problem 1: The guitar tuner has a gear ratio of fourteen to one, what does that mean?
Variously, answers mention every 14 turns of knob, string post turns one full turn.

Problem 2: A person attempts to tune a guitar on a headstock with a 14 to one gear ratio. They first turn the knob 13 times to the left and then turn 5 times to the right. How many full turns and partial turns of the post were made after all the knob turns?

Tk = 8 = 13 – 5

Problem 3: The post of the guitar tuner is .25" in diameter with a gear ratio of 15 to 1 how many turns will it take to wind 1 linear inch of guitar sting on the post?

Tk = ?
L = 1
To = 1
Ti = 15
r = .125 = 0.5 * D = 0.5 * .25

Tk = L * Ti ÷ (To * 2πr)
Tk = 1" * 15 ÷ (1 * 2 * 3.14 * 0.125")
= 15" ÷ (7.85")
= 19.1 turns

Problem 4: if the tuner knob is turned 28 complete turns to the left how much guitar string was wrapped on the post.

Tk = 28
To = 1
Ti = 14
r = .09375 = 3/32 = (1/2)(D) = ½ * 3/16

L = (Tk · To ·2πr) ÷ Ti
L = (28 * 1 * 6.28 * .09375") ÷ 14
L = 1.1775"

Problem 5: - if the tuner knob is turned 32 ½ turns to the left how much guitar sting was wrapped on the post.

Tk = 32.5
To = 1
Ti = 14
r = .09375"
L = (Tk · To ·2πr) ÷ Ti
L = 32.5 * 1 * 6.28 * .09375" ÷ 14
L = 1.3667"

Problem 6: - if the tuner knob is turned 18 complete turns to the right how much guitar sting was un-wrapped from the post.

Tk = 18
To = 1
Ti = 14
r = .09375"
$L = (Tk \cdot To \cdot 2\pi r) \div Ti$
L = 18 * 1 * 6.28 * .09375" ÷ 14
L = 0.757"

Problem 7: - The gear tuner was turned 5 3/4 turns, the gear ratio is 14 to 1, how much has the tension changed if each 1/8" linear movement of guitar string the string tension changes by 1/2 lb.

Tk = 5.75
To = 1
Ti = 14
r = .09375"
$L = (Tk \cdot To \cdot 2\pi r) \div Ti$
L = 5.75 * 1 * 6.28 * .09375 ÷ 14
L = .2418"

$$\frac{.125''}{0.5 \text{ lbs.}} = \frac{.2418''}{n}$$

(0.125") (n) = (0.5lb) (0.2418")
n = (0.5lbs.)(0.2418") ÷ 0.125"
n = .9672 lbs.

Problem 8: - A tuner knob was turned 90 degrees to bring the guitar into tune. With a gear ratio of 15 to 1 and a post diameter of .25" how much linear movement occurred to the guitar string?

Tk = 0.25 (90 degrees/360 degrees = ¼ = 0.25)
To = 1
Ti = 14
r = 0.125" = (1/2)(D) = (1/2)(0.25")
$L = (Tk \cdot To \cdot 2\pi r) \div Ti$
L = 0.25 * 1 * 6.28 * .125" ÷ 14
L = .014"

Math Exercise 3

Area of the headstock

Create drawing of a headstock.

Break the headstock into geometric shapes and calculate the surface are of the headstock.

How many Gallons of paint will be needed to cover the headstock surface area, if the paint covers 150 square feet per gallon?

Measurements – develop a diagram where the items get measured

Pickup spacing as a percentage of scale length – measure bridge location to bridge pickup and express as percentage -- sound quality / tonality of pickup movement.

String spread bridge and nut, any 2 strings

Distance from nut to bridge – scale length pre-cursor

Width or neck at heel and nut

Body thickness

Metric English conversions – drill bits, fret dots etc

Fret Dots Sizing

Modulus of elasticity of high E string.

Centroid of guitar body –

Measure resistance on the potentiometers (image) minimum and max from the 4 pots (teams of 2) and chart the results

Nut – string force with the break angle on the nut. Develop a free body diagram of forces of a sting on the nut – simplified

Math Exercise 4

Problem 4.1 Calculate

With the equation s- (s/ 2^ n/12) = d, find the distance from nut to the 9th and 11th fret.

s= scale length
n= fret #
d= distance from nut

Problem 4.2 Calculate the following

With the frequency equation- f = (t/u)^1/2/ 2L

f = frequency
t = tension force
u = mass per length
L = string length

a. What is the frequency of a note on a string, with a mass per length = 0.0002132 kg/ m, and pulled at force of 72.03N. The scale length is 26in or 0.6604m.

b. What is the tension force of a string with a frequency of 220hertz, a mass per length of 0.0002132 and a scale length of .6604m?

Problem 4.3

Research the number of frets found on an electric and acoustic guitar. Provide fret spacing formulas

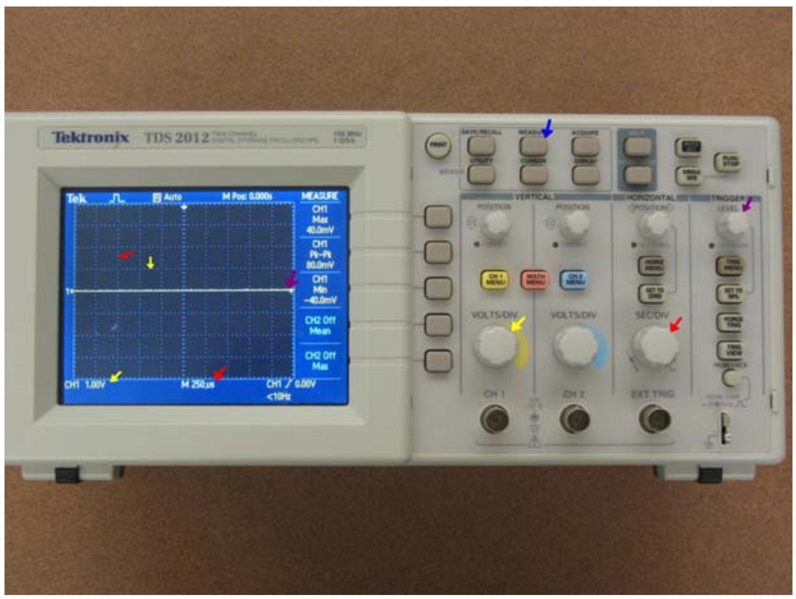
Electronics Exercise 1

Use an oscilloscope to measure frequency of the all six strings

Materials: Oscilloscope, oscilloscope probe, and a ¼” jack adapter (provided).

Deliverable: Excel spread sheet showing frequencies of all six strings.

The basics of the oscilloscope will be described so that the output wave from the guitar can be easily seen. Please read before you attempt the ILA.



- The yellow arrow will change your volts per a division
- The red arrow will change your time per a division
- Pushing the yellow or blue channel buttons will turn off and on the respective channels and give you a menu for each channel
- In the menu on the top box it should have AC coupling this is changed by pushing the gray button directly to the right of the box
- After the menu is set up push the measure button (blue arrow) and you will get your current screen.
- The position knobs will change the position where the wave is on the graph (this can make the wave go off of the graph and not be seen)
- The trigger level knob (purple arrow) should be tuned (little arrow) to the middle of the wave form.
- The period (time for one cycle) is how much time it takes the string to go up down and back up again or one revolution. **The reciprocal of that is the frequency.** Each note is assigned to a certain frequency which can be seen easily on an oscilloscope.

Connect the guitar to the oscilloscope. To do this plug the oscilloscope probe into CH. 1 slot at the bottom below the CH. 1 VOLTS/DIV knob. Once the probe is connected to the ¼" jack adapter (attach alligator clip of the probe to the black wire- ground) you can strum the guitar to see the waveform. If the VOLTS/DIV or SEC/DIV settings are not set properly the output will not be seen. Typically a guitar has about a $150mV_{pk\text{-}pk}$ to $300mV_{pk\text{-}pk}$ output therefore set the knob by setting the VOLTS/DIV to approx. 100mV (if strummed or plucked hard the string output peaks at about $600mV_{pk\text{-}pk}$ to $800mV_{pk\text{-}pk}$). The SEC/DIV setting will have to be calculated from the desired frequency.

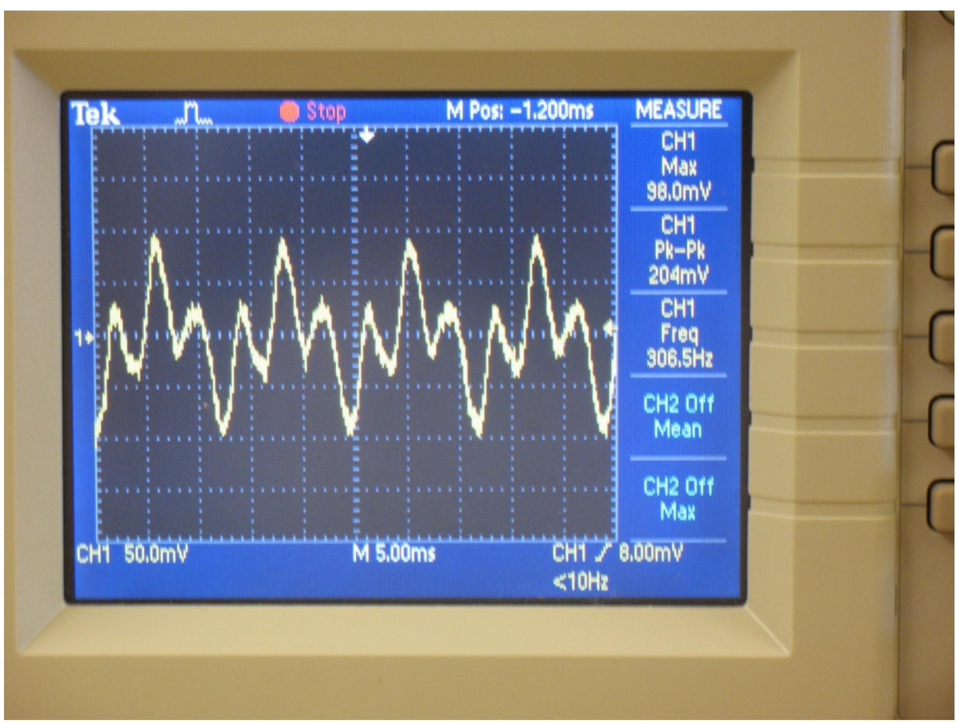
Period is found from the inverse of the frequency.

f = frequency T = period

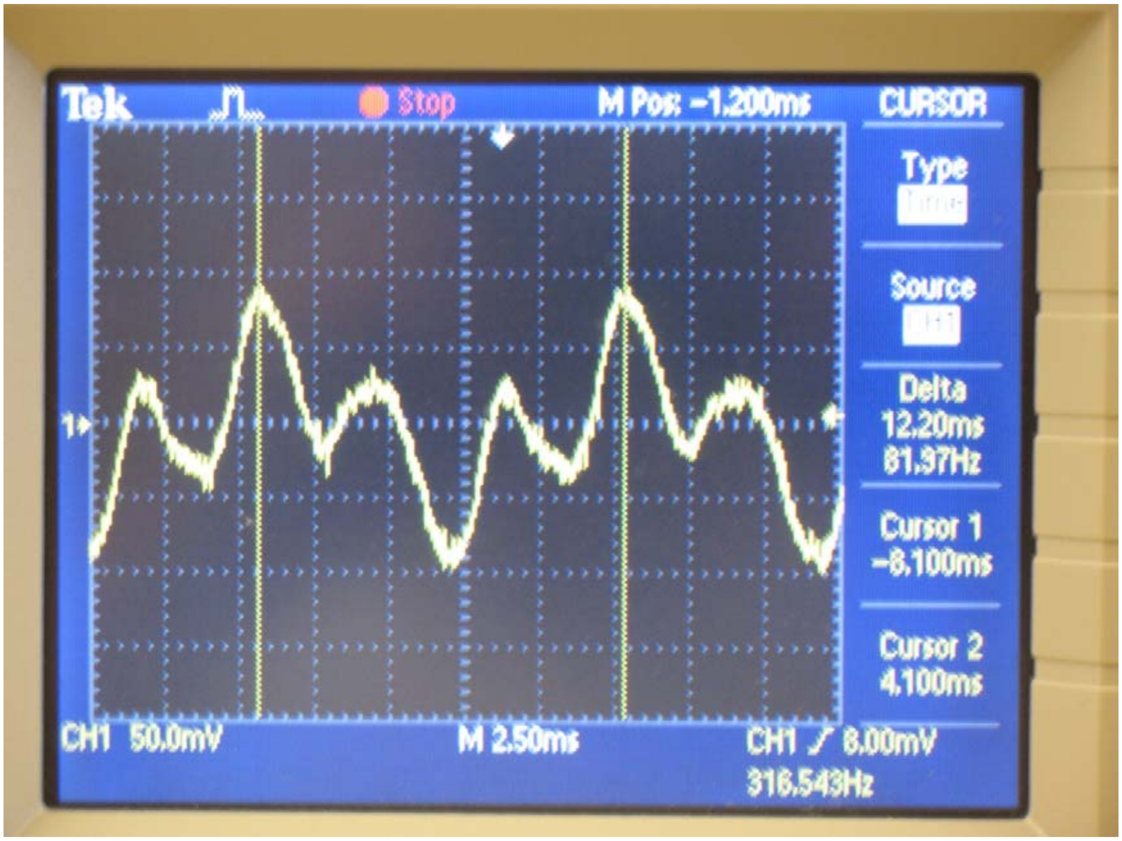
$$T = \frac{1}{f}$$

Once the period is found divide it by two and that should be about where the SEC/DIV should be set. If necessary adjust knob up or down to get the desired view.

NOTE: To freeze the waveform there is a button at the top right corner of the oscilloscope that reads "run/stop" push this button to freeze the current output.



Count the boxes on the graph or use the cursor button to determine the string's frequency.



The yellow vertical lines that are seen are accessed by the cursor button which is just below the measure button used earlier.

- Push cursor button to get a new menu to pop up on the right side of the graph.
- Push the button across from the "Type" and change it until it reads "Time"
- Push the button across from the "Source" and change it till it reads "CH1"
- The two position knobs for CH.1 and CH.2 control the vertical lines.
- Move the yellow vertical lines from one peak to the next as shown in the picture (be careful harmonics are sometimes pretty strong on the low strings and can be deceiving)
- "Delta" will indicate the period and frequency for the spacing between the yellow vertical lines.

Each note is assigned a certain frequency. Complete the list of string frequencies.

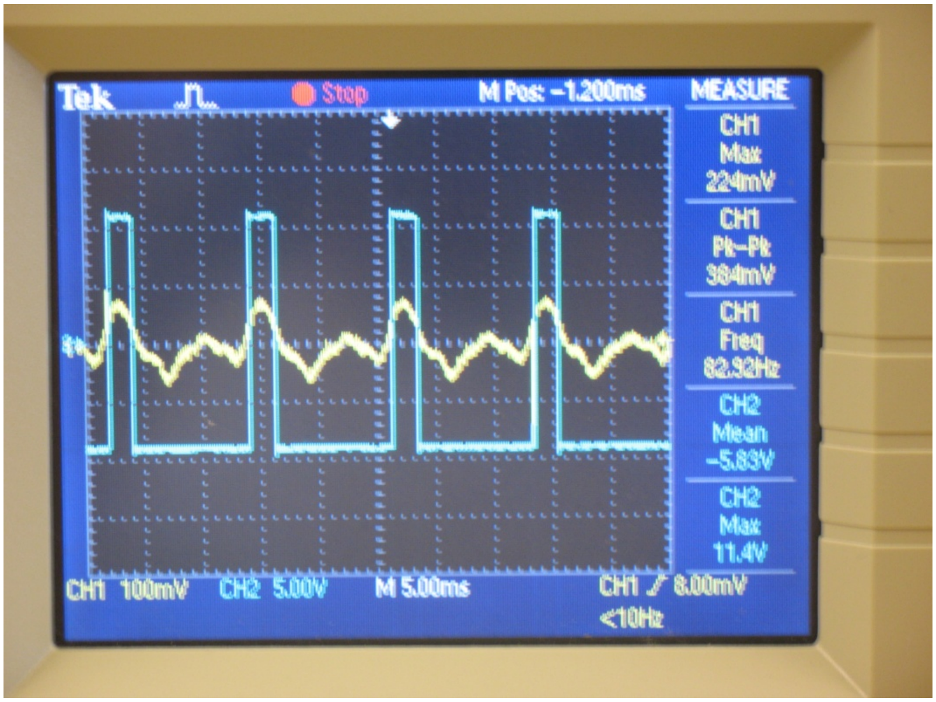
Low E - ___________
A - ___________
D - ___________
G - ___________
B - ___________
High E - ___________

A guitar's intonated by strumming the string open (no frets) then strumming it holding down the twelfth fret (usually denoted by two fret dots). Intonation is more than just tuning it is changing the length of the string. The open string should be the given frequency above. The frequency should be doubled while pressing the string down at twelfth fret. If the frequency is higher, then increase the length of the string at the bridge, and if the frequency is lower, then shorten the length of the string.

Standard guitar tuning frequencies per string

1 (Highest)	**e'**	329.6 Hz
2	**b**	246.9 Hz
3	**g**	196.0 Hz
4	**d**	146.8 Hz
5	**A**	110.0 Hz
6 (Lowest)	**E**	82.4 Hz

A guitar tuner uses the same principles as an oscilloscope but needs to change those waves into computer language (pulses or high and low)



Here the yellow wave form is the output of the guitar and the blue wave form is almost like computer language. If measured from the positive edge to the next positive edge it should be the same period as the yellow wave form as it is from one peak to the next.

Technology Learning Activity 1

Reverse Engineering to Design a Mechanical Part (Neck Plate) for Electric Guitar Manufacture

In this lab, students will design a mechanical part (Neck Plate) for manufacture and apply it to the electric guitar. Students are to develop the dimension of size for the length, width and thickness of the neck Cover Plate for an electric guitar. Using these measurements the students will plan the detail drawings and prepare the design data for manufacture. Finally they are to use these data to then select and calculate the cutting tools, speeds and feeds required for the manufacture of the Neck Plate.

Learning Objectives:

1. The student will determine the measurements of size of the electric guitar Neck Plate.
2. Design through a technical sketch the size and location of the mounting holes of the guitar neck.
3. The students will develop the hole and countersink geometry with the intent of manufacturing the neck plate.
4. The students will devise a design/manufacturing plan.
5. The student will write a tool list listing calculated speed and feed requirements for the tools used in manufacture of the plate.

Materials Required:

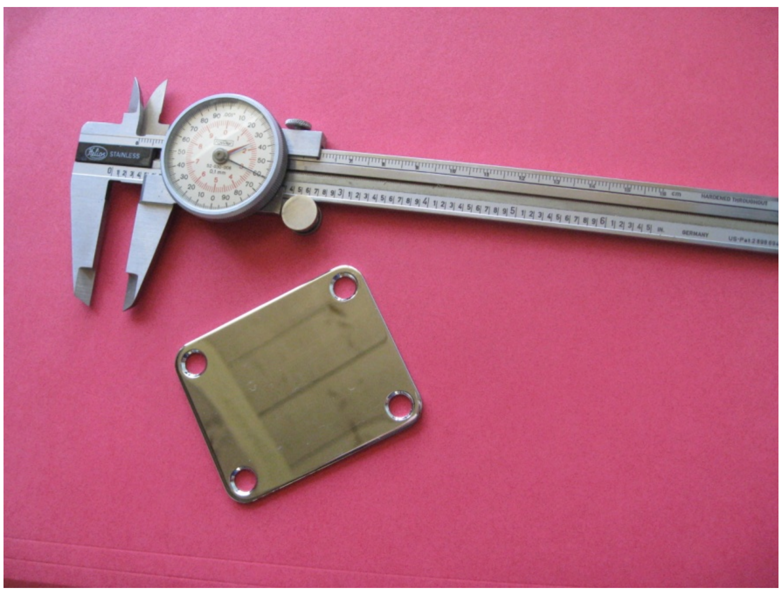
Safety instruction as required, sketch pad and pencil, measuring tools such as rulers, dial calipers, calculator, CAD Software, electric guitar and or data of design and application intent of the neck plate.

References:

http://new.industrialpress.com/products/category_feature/MH - Machinery's Handbook
http://safety.seas.harvard.edu/services/shopsafety.html - Machine Shop Safety
http://www.engineeringtoolbox.com/machinability-metals-d_1450.html - Machinability of Metals
http://www.unbf.ca/ME/undergrad/Safe%20Operating%20Procedures/Function,_Safety,_and_Operation_of_the_Drill%20Press.pdf - Drill Press Operation

Technology Exercise 1

Using a measuring tool, such as a dial caliper, metal scale or other appropriate tool, inspect the neck plate. (See the attached drawing for precise measurements.)
Sketch the neck plate with dimensions. Be sure to include on the orthographic drawing the important datum edges for later layout of the hole locations. See example figure of design sketch page and process planning.

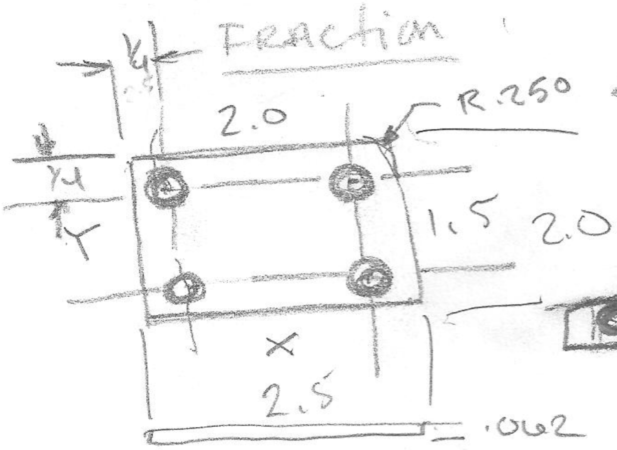


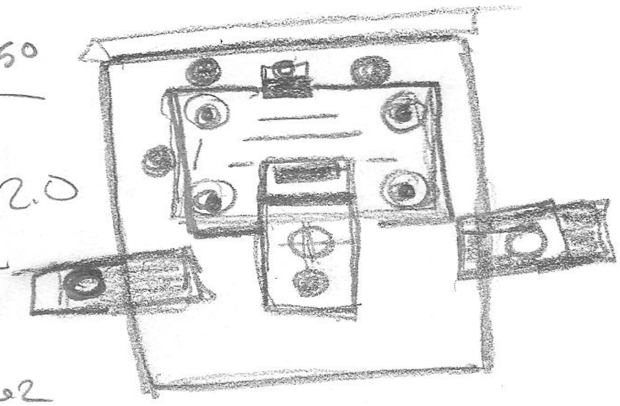
Notes

CNC

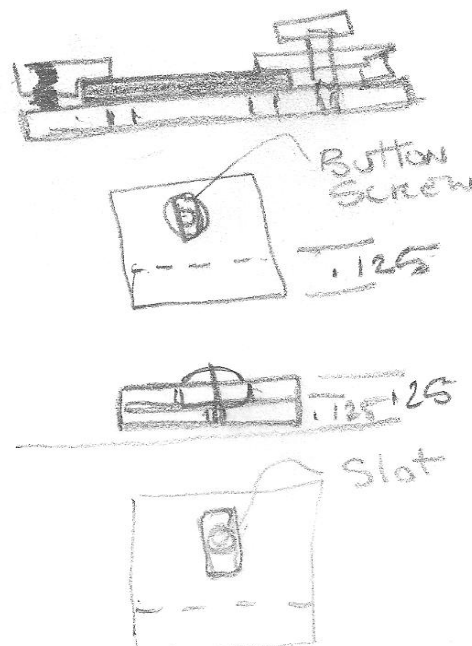
DRill FIXTURE

NECK PLATE

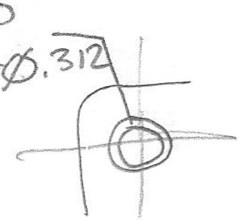


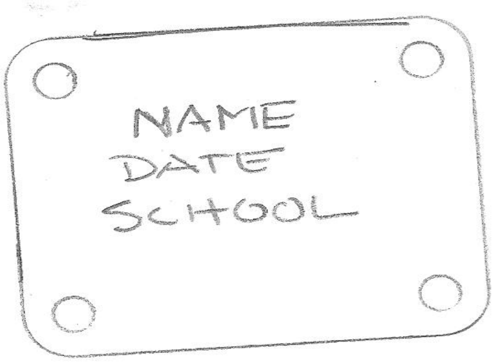


- PRODUCTION Plan
  CNC

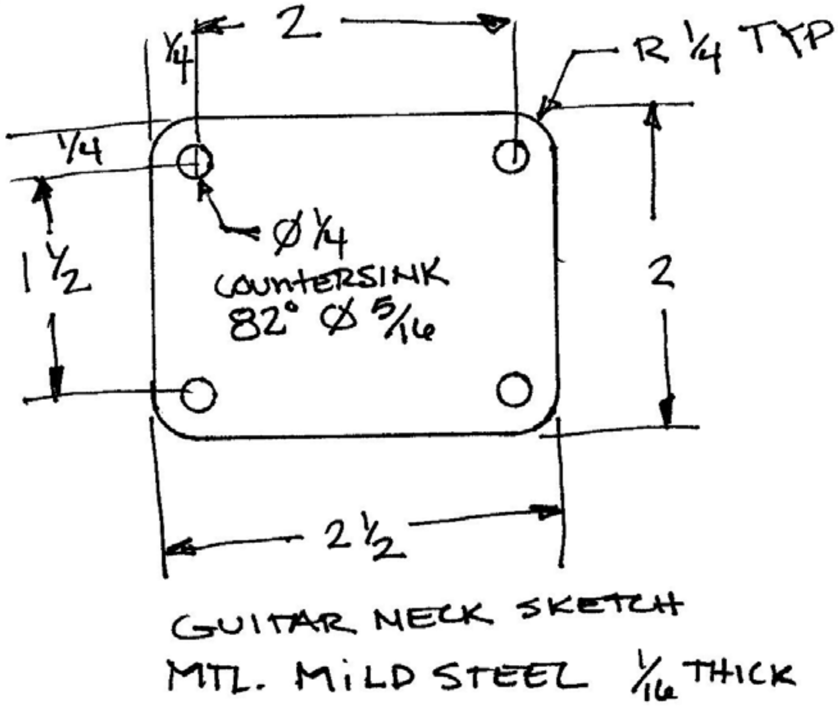


- DRill/c'sink G81
- DEBURR G82
- ENGRAVE ?
  - NAME
  - DATE
  - CLASS/School





.062 THK



Design sketch example:

Change all fraction dimensions to their decimal equivalents using the attached chart.

Outside dimensions, length and width are fractional while the locations of the holes are identified by a three place decimal which increases the accuracy by limiting the tolerance.

The tolerance block from the CAD drawing shows tolerances as:
FRACTIONS ± (plus or minus) 1/16, This calculates to 1/8 total tolerance
.X ± .1 total tolerances of .2 inches
.XX ± .01 total tolerance of .02
.XXX ± .005 total tolerance of .010

As the number of decimal places increases a smaller total tolerance is allowed. This controls quality and allows for problem free assembly.

Starrett PRECISION TOOLS

DECIMAL EQUIVALENTS and TAP DRILL SIZES

THE L. S. STARRETT COMPANY · World's Greatest Toolmakers · ATHOL, MASSACHUSETTS, U.S.A.

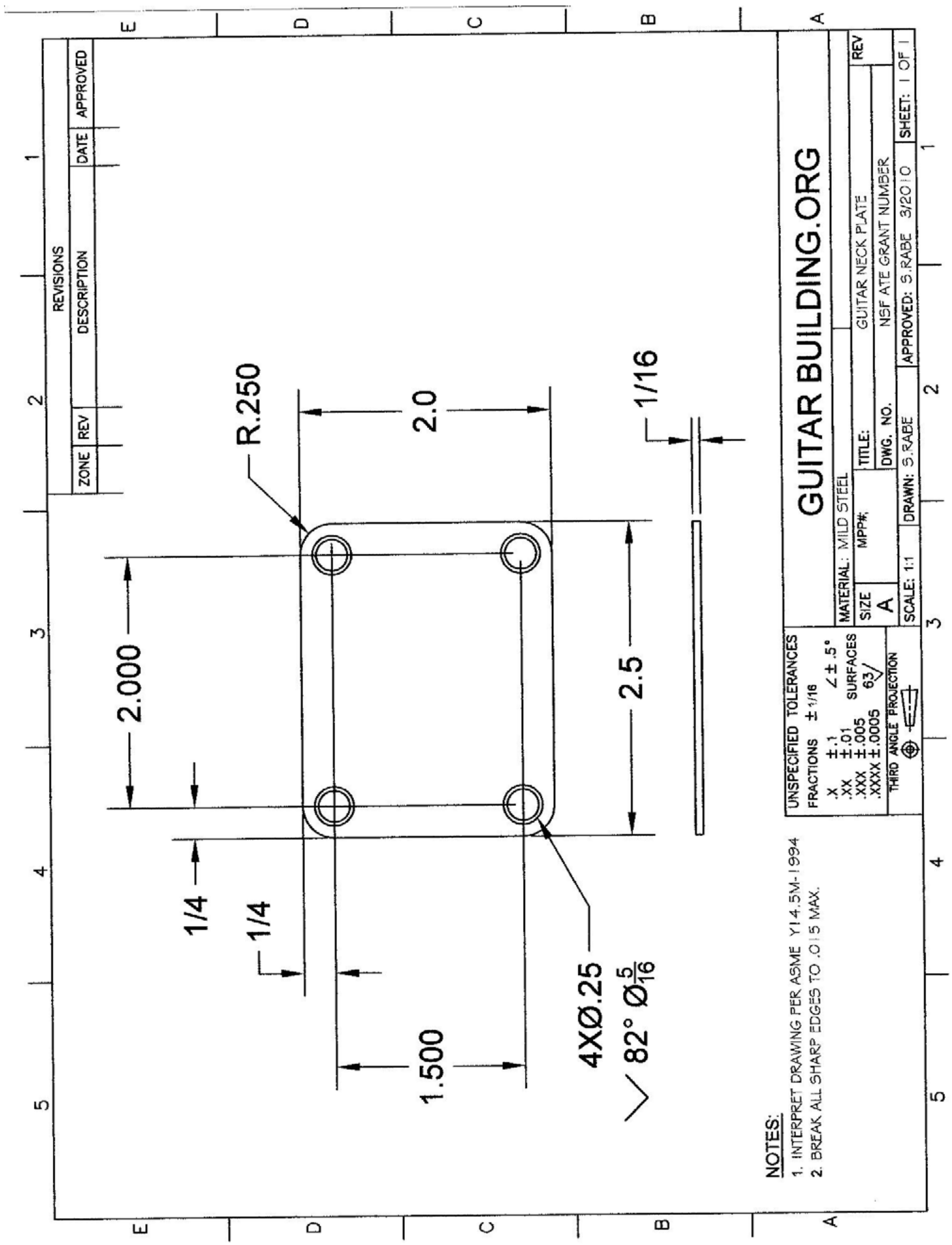
Fraction	Number Size Drills	Decimal Equivalent	Tap Size
	80	.0135	
	79	.0145	
1/64		.0156	
	78	.0160	
	77	.0180	
	76	.0200	
	75	.0210	
	74	.0225	
	73	.0240	
	72	.0250	
	71	.0260	
	70	.0280	
	69	.0292	
	68	.0310	
1/32		.0312	
	67	.0320	
	66	.0330	
	65	.0350	
	64	.0360	
	63	.0370	
	62	.0380	
	61	.0390	
	60	.0400	
	59	.0410	
	58	.0420	
	57	.0430	
	56	.0465	
3/64		.0469	0-80
	55	.0520	
	54	.0550	1-56
	53	.0595	1-64, 72
1/16		.0625	
	52	.0635	
	51	.0670	
	50	.0700	2-56, 64
	49	.0730	
	48	.0760	
5/64		.0781	
	47	.0785	3-48
	46	.0810	
	45	.0820	3-56, 4-32
	44	.0860	4-36
	43	.0890	4-40
	42	.0935	4-48
3/32		.0937	
	41	.0960	
	40	.0980	
	39	.0995	
	38	.1015	5-40
	37	.1040	5-44
	36	.1065	6-32
7/64		.1093	
	35	.1100	
	34	.1110	6-36
	33	.1130	6-40
	32	.1160	
	31	.1200	
1/8		.1250	
	30	.1285	
	29	.1360	8-32, 36
	28	.1405	8-40
9/64		.1406	
	27	.1440	

Fraction	Drill Size (Number / Letter Size Drills)	Decimal Equivalent	Tap Size
	26	.1470	
	25	.1495	10-24
	24	.1520	
	23	.1540	
5/32		.1562	
	22	.1570	10-30
	21	.1590	10-32
	20	.1610	
	19	.1660	
	18	.1695	
11/64		.1719	
	17	.1730	
	16	.1770	12-24
	15	.1800	
	14	.1820	12-28
	13	.1850	12-32
3/16		.1875	
	12	.1890	
	11	.1910	
	10	.1935	
	9	.1960	
	8	.1990	
	7	.2010	1/4-20
13/64		.2031	
	6	.2040	
	5	.2055	
	4	.2090	
	3	.2130	1/4-28
7/32		.2187	
	2	.2210	
	1	.2280	
	A	.2340	
15/64		.2344	
	B	.2380	
	C	.2420	
	D	.2460	
1/4	E	.2500	
	F	.2570	5/16-18
	G	.2610	
17/64		.2656	
	H	.2660	
	I	.2720	5/16-24
	J	.2770	
	K	.2810	
9/32		.2812	
	L	.2900	
	M	.2950	
19/64		.2968	
	N	.3020	
5/16		.3125	3/8-16
	O	.3160	
	P	.3230	
21/64		.3281	
	Q	.3320	3/8-24
	R	.3390	
11/32		.3437	
	S	.3480	
	T	.3580	
23/64		.3594	
	U	.3680	7/16-14
3/8		.3750	
	V	.3770	
	W	.3860	

Fraction or Drill Size	Decimal Equivalent	Tap Size
25/64	.3906	7/16-20
X	.3970	
Y	.4040	
13/32	.4062	
Z	.4130	
27/64	.4219	1/2-13
7/16	.4375	
29/64	.4531	1/2-20
15/32	.4687	
31/64	.4844	9/16-12
1/2	.5000	
33/64	.5156	9/16-18
17/32	.5312	5/8-11
35/64	.5469	
9/16	.5625	
37/64	.5781	5/8-18
19/32	.5937	11/16-11
39/64	.6094	
5/8	.6250	11/16-16
41/64	.6406	
21/32	.6562	3/4-10
43/64	.6719	
11/16	.6875	3/4-16
45/64	.7031	
23/32	.7187	
47/64	.7344	
3/4	.7500	
49/64	.7656	7/8-9
25/32	.7812	
51/64	.7969	
13/16	.8125	7/8-14
53/64	.8281	
27/32	.8437	
55/64	.8594	
7/8	.8750	1-8
57/64	.8906	
29/32	.9062	
59/64	.9219	
15/16	.9375	1-12, 14
61/64	.9531	
31/32	.9687	
63/64	.9844	1 1/8-7
1	1.0000	
1 3/64	1.0469	1 1/8-12
1 7/64	1.1093	1 1/4-7
1 1/8	1.1250	
1 11/64	1.1719	1 1/4-12
1 7/32	1.2187	1 3/8-6
1 1/4	1.2500	
1 19/64	1.2968	1 3/8-12
1 11/32	1.3437	1 1/2-6
1 3/8	1.3750	
1 27/64	1.4219	1 1/2-12
1 1/2	1.5000	

PIPE THREAD SIZES

Thread	Drill	Thread	Drill
1/8-27	R	1 1/2-11 1/2	1 47/64
1/4-18	7/16	2-11 1/2	2 7/32
3/8-18	37/64	2 1/2-8	2 5/8
1/2-14	23/32	3-8	3 1/4
3/4-14	59/64	3 1/2-8	3 3/4
1-11 1/2	1 5/32	4-8	4 1/4
1 1/4-11 1/2	1 1/2		


REVISIONS
ZONE
REV
DESCRIPTION
DATE
APPROVED
R.250
2.0
1/16
2.000
2.5
1/4
1/4
1.500
4XØ.25
82° Ø5/16
NOTES:
1. INTERPRET DRAWING PER ASME Y14.5M-1994
2. BREAK ALL SHARP EDGES TO .015 MAX.
UNSPECIFIED TOLERANCES
FRACTIONS ± 1/16
.X ±.1
.XX ±.01
.XXX ±.005
.XXXX ±.0005
∠ ± .5°
SURFACES 63
THIRD ANGLE PROJECTION
GUITAR BUILDING.ORG
MATERIAL: MILD STEEL
MPP#:
SIZE A
TITLE: GUITAR NECK PLATE
DWG. NO. NSF ATE GRANT NUMBER
REV
SCALE: 1:1
DRAWN: S.RABE
APPROVED: S.RABE 3/2010
SHEET: 1 OF 1

Notes

Technology Exercise 2

The students will develop a plan for the manufacture of the neck plate.

1. List the tools required to layout the hole positions.
2. List the tools required for the drilling and counter sinking process.
3. Calculate a safe recommended spindle speed to drill and countersink the screw holes.
4. Show a safe material clamping plan for the drilling operation.

Accurate layout requires a few tools including a flat work surface clear of obstacles, layout fluid or other marking liquid to allow clear visibility of layout lines, a sharp scribe or awl or at least a paperclip opened to allow scratching the surface with one end of the wire.

1. Cover the mild steel part with a thin coat of layout fluid or colored marking pen.
2. Locate with a scale or dial caliper the center of the first hole of the four hole pattern. Scratch the surface color to show this location.
3. Using the caliper or scale measure from this point the remaining holes locations.
4. Check the locations to insure correct placement.

Drilling the holes can be done in several ways.
First if using a drill motor (electric hand drill) you should lightly center punch the hole locations.

1. Lay the part on the flat table or other secure work surface. Align the center punch over the hole location. Strike sharply the center punch with a Ball Peen or machinist hammer. This will place a small dent or starting point for the twist drill to follow.

2. Electric hand drill motors come in many sizes and spindle speed ratings. The speed at which a twist drill should spin (RPM) depends on several factors:

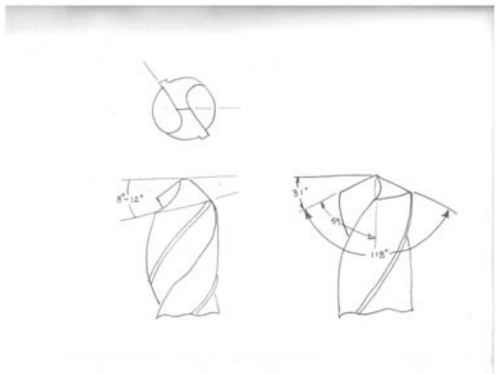
   Part material must be determined to find the correct material cutting speed (CS), this is a number representing surface feet per minute orSFM. This value is developed from tests done to determine the mach inability of a material against a known standard.

Knowing this value is important to control the heat at the cutting point which will protect the part and the cutting tool from overheating. Cutting speeds for various materials can be found in chart form in text books and Machinist handbooks. For mild steel we will use the value of 100 SFM.

The size (DIA) of the cutting tool or drill will next be used to correctly calculate the correct RPM for our drilling operation. The drawing shows a ¼ diameter drill hole this we change to its decimal equivalent .25 inches. The formula for converting this information to RPM or spindle speed is the following:

RPM = 4 X CS ÷ DIA

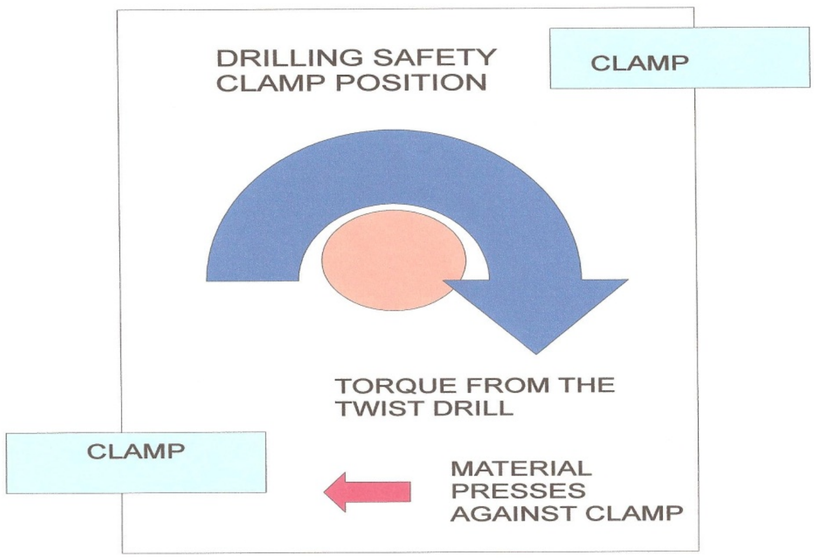
Example: Drilling a .5 (1/2 inch) diameter hole in mild steel with a CS of 100 RPM = 4 X 100 ÷ 1/2" works out to 400 ÷ .5 = 800 RPM



Drill point geometry

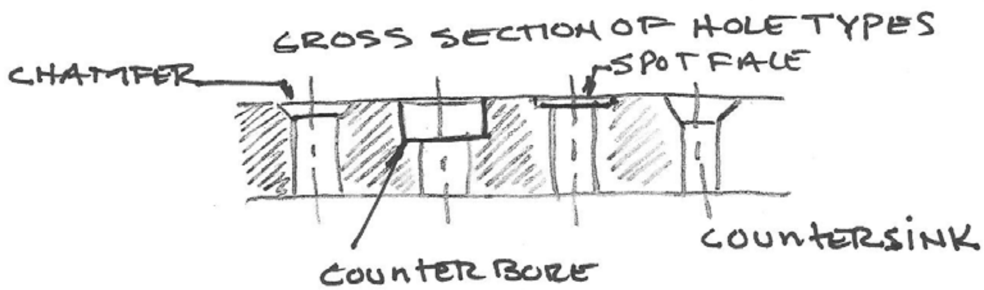
Safe clamping requires understanding the operation of the electric drill motor and the torque created by the cutting tool:

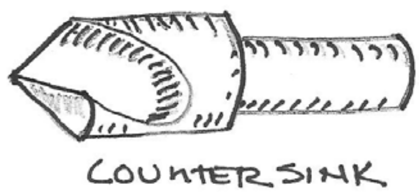
1. Never hold any work piece with your hands while drilling or cutting.
2. Use a back up piece of material when drilling through holes in thin material.
3. Know the direction of spin the cutting tool will produce as this is the direction the material will naturally spin.
4. Set up your clamps to hold against the spin, not to be pulled out of the clamp. See the attached example.
5. Ease up on feed pressure when the drill breaks through back surface.
6. Keep the correct RPM throughout the drilling process.
7. Watch for sharp edges and burrs on drilled holes.
8. Deburr all cut edges and surfaces with a flat file or sand paper.

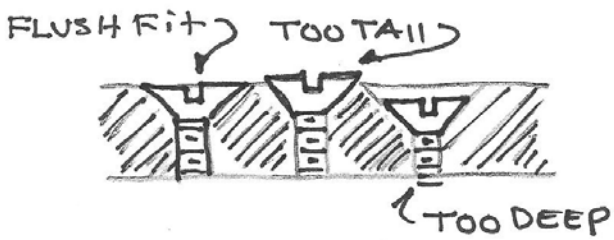


Secondary hole cutting operations such as the counter sink provides special shapes for locating the head of a screw or bolt. This is to protect you from rubbing or touching the screw head or catching the screw head on passing materials or objects.

The attached figure shows the Countersink tool and hole types:







Countersinks are made in various standard angles. This provides options for the designer on the types of hole shapes required. The angle most commonly used for flat head or pan head screws is 82°. The standard screw head should be flush with the surface or slightly below, depending on the application. Countersinks are also used to deburr and chamfer holes.

The countersink operation follows the drilling of the holes. The countersink will locate in the drilled hole and its size may be dimensioned by the depth of the chamfer or the diameter of the chamfer. The neck plate countersink callout is 5/16 or .312 diameter. The spindle speed for the countersink tool is much slower than that of the twist drill and can be simply calculated at 1/3 that of the twist drill. This works out to 800÷3 = 233 RPM. Deburr all sharp edges and radius corners with smooth mill file.

The setup and spindle speed calculations should be discussed when drilling any feature of the guitar body or metal parts. When calculating for larger forstner bit and connecting holes for electrical wires one should revisit this section to review the safety and planning of the operations.

Drill point geometry

Countersink and hole geometry

Forstner bit

Technology Exercise 3

Problem 3.1

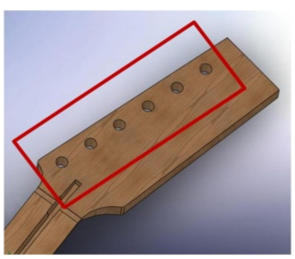
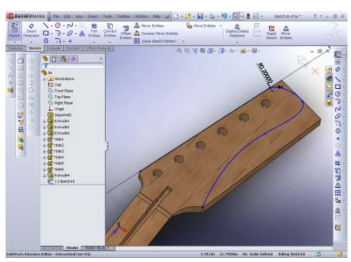
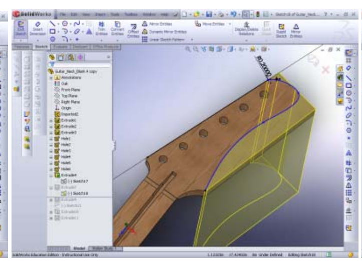
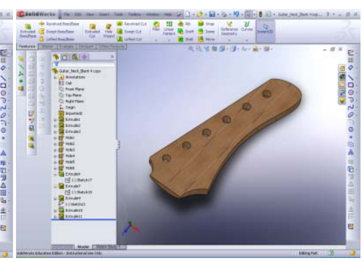
Research and report on a unique patented guitar headstock design. What are the unique characteristics of the design? Who owns the patent and when was it granted? Provide an image of the patented design.

Materials: Internet

Deliverable: One page report with image(s) and contribution to group discussion regarding unique and innovative headstock designs.

Project 3.2

Custom Headstock Design Using a 3D modeling program, design three custom headstocks. You will be provided with a 3D model of an in-line six head stock with tuner holes already located. The design of the headstock cannot go beyond the red rectangle shown in the diagram below. Although the headstock design is important for marketing, this is one of the few places on the guitar where you can customize your own designs. This activity can be enhanced by incorporating remote design teams and collaborative tools (for example: Skype, Adobe Connect, Streamline)

Red rectangle represents the “No Fly” zone. The new design should avoid this zone.

Materials: 3D CAD software, internet, sample guitar neck (optional), CAD file of neck/headstock

Deliverable: Provide a minimum of three headstock designs for an in line 6 style peg head. Using Streamline as our ftp storage site and post all designs in the appropriate folder.

Project 3.3

Create a physical model of the new custom headstock design using a rapid prototyping (RPT) system. As necessary, create the appropriate output file required by the rapid prototyping system (for example: SLA, STL).

Materials: 3D CAD software, RPT system

Deliverable: A scaled down RPT model (33%) of the new headstock design.

Project 3.4

Using a computer assisted manufacturing program (for example: CamWorks, MasterCam) create a CNC file to produce the customized headstock. If available run a tool path simulation.

Materials: CAM software, 3D model of new headstock design, machineable wax or desired stock.

Deliverable: The new headstock designed machined from 3D model.

Notes

Technology Learning Activity 2

3D Virtual Modeling

Sharing 3D files between different software programs is a common occurrence in industry. Therefore it becomes necessary to translate files from one program to another. CADD file formats that are commonly used are: DXF, IGES, STL, DWG, etc. When a file is not in the native file format the file must be translated or re-created. Use the provided 3D CAD files of the electric guitar along with a parametric 3D modeling program to create a virtual assembly using all the individual guitar components. Students will be able to properly assemble and print a virtual parametric assembly of the solid body electric guitar.

Demonstrate to the class how to operate the 3D modeling software to create an assembly file. Students should be shown how to open the software, save, print, place text, import parts and convert them to a compatible format.

Learning objectives:

1. Become more familiar with the components of the guitar and their relationship to one another
2. Use non-native file formats
3. Access necessary files to assemble the guitar
4. Create and save an assembly file in a 3D modeling software program
5. Use feature recognition to break model into individual features.
6. Define all constraints needed to create the assembly
7. Print exploded assembly drawing on a B (11x17) size sheet

Materials Required:

- 3D CAD files
- 3D parametric software (i.e. SolidWorks, Inventor, etc.)
- Printer

References:

http://en.wikipedia.org/wiki/solid_modeling

Technology Learning Activity 3

Capturing Design Intent in Guitar Design

Using the 3D CADD files for the body of the electric guitar, design a new guitar body style. Do not alter the neck pocket, pick-up pockets, bridge locations or electronics pocket. Keep the design within the overall dimensions of the 14 x 22 inch body blanks. Use the internet and the Guitar Primer to explore different body styles.

Learning objectives:

1. Define design intent.
2. Apply design intent to 3D CAD models of guitar components.
3. Differentiate between "built in intelligence" and "random design".
4. Use spreadsheets and equations to capture design intent.
5. Analyze the effects that capturing design intent has downstream manufacturing processes and machine-ability.

Materials Required:

3D CADD software, CADD file of body blank including no-fly zones.

References:

Design with Intent – Dan Lockton
http://architectures.danlockton.co.uk/2009/04/06/the-design-with-intent-toolkit/
http://www.allegromusic.ca/gtr_choose_EL_style.htm
http://en.wikipedia.org/wiki/Electric_guitar

Technology Learning Activity 4

Innovation Report

Each guitar manufacturer uses a unique feature, materials, processes, or innovation in their product to make their guitar stand out from the rest. These features, materials, processes, or innovations influence consumers to purchase these guitars by making them believe that the manufacturer makes the best guitar on the market. Students will select one guitar manufacturer and present, in writing and in speech form, one innovation, material or process that they believe is unique to that manufacturer (consider visiting your local music store). Students will submit a well written 2-3 page report with images, sketches or drawings if appropriate of the unique process, material, or innovation used by the specific manufacturer. Students will also prepare a presentation 3-5 minutes in length explaining the unique process, material, or innovation. The presentation should include a minimum of 3 visual aids.

Give students examples of brand name guitar manufacturers and sample design differences. Students should pick their own material, process or innovations, and not pick one that was used in the introduction to the lesson. You may also show students how to use any software they need for creating the presentation or report. Students may also be supplied with a list of some manufacturers to get them started.

Learning objectives:

1. Distinguish between materials and processes.
2. Find creditable resources on the internet
3. Create a presentation of materials or processes unique to companies.

Materials Required:

- Computer
- Internet
- Other publications

References:

www.gibson.com
www.fender.com
www.prsguitars.com
www.schecterguitars.com
www.washburn.com

Technology Learning Activity 5

Weight Calculation

Description: The weights and sizes of guitars vary from manufacturer to manufacturer. The weight depends on many things such as size shape and type of material. Material changes weight because materials have different densities. Today's software packages allow us to calculate mass properties.

Students will produce a chart or table that shows the overall length width and height of a guitar body. In addition provide the weight of three different body styles of electric guitars made from 3 different materials. Students will also show on the chart the mean calculation for each category.

Students will be given a CADD file of a typical electric solid body guitar and shown how to import it into your given software system. Use the software to do area calculations and density weight calculations. Students will use a spreadsheet program to create the chart. Lastly, students will be told the 3 materials they will use for calculations of their 3 body designs. These 3 materials can be Mahogany, Maple and Aluminum. Students will use CADD software to do the calculations and Spreadsheet software to create a neat, easy-to-read chart.

Learning objectives:

1. Calculate the weight of 3 solid bodies by using the mass properties provided by the CADD software
2. Create a chart that shows overall length, width and height of bodies as well as their weights.
3. Determine the mean weight and size of the 3 solid bodies.

Materials Required:

- Internet
- CADD files of electric guitar bodies
- Identify woods and other material to be used
- Spreadsheet program for creating chart or table

References:

www.tcc.edu/faculty/webpages/pgordy/Egr110/N110IL8.pdf

Technology Learning Activity 6

Package Design

You are employed at STEM guitars. Your responsibility is package design. Due to the high quality of your guitars many famous musicians have been drawn to your product. It is your task to design a package to hold 3 guitars, or 3 guitars in cases. If you are using cases you must specify all needed information about these cases. In the end you will present your design to your boss (the teacher) and sell your idea to them.

Students will do a 3 to 5 minute presentation using visual aids to explain their package design, how it functions, cost, and materials used. Students will also turn in all required drawings and research to teacher.

Students will be told what information they should have for you. This information will be organized using a spreadsheet program creating an easy to read chart with all necessary information. Students will also turn in a set of working drawings that follow engineering conventions. The following information should be included in the 3-5 minutes presentation cost of package, drawings of package, weight of package and guitars, what makes their package the best.

Learning objectives:

1. Design a shipping package
2. Create detailed engineering drawings for the package design
3. Create a parts list for all components needed and include in the Bill of Materials of the drawing
4. Calculate the cost of construction
5. Calculate the weight of the package design

Materials Required:

- Computer
- CAD software
- Spreadsheet software

Technology Learning Activity 7

Product shipping cost

The weights and sizes of material have a dramatic effect on product costs including the cost to ship products throughout the United States and the world. You are the owner of STEM guitar Inc. Customer needs 3 of your guitars shipped to them over night to the following address. Compare 3 companies shipping costs to get your customer the most economic shipping.
Students will print out a spreadsheet comparing three companies' estimates of shipping the package. The shipping estimate will including total weight, shipping method, and cost if using each carrier.
Students will use a guitar and their previously designed package designed in the previous problem and determine the cost to ship three (3) of these guitars over night from Pittsburgh Pennsylvania to Corona California.

Learning objectives:

Calculate the cost to ship 3 guitars in the student's previous package design between two locations.

Materials Required:

- Computer
- Internet
- Guitars

References:

www.ups.com
www.fedex.com
www.usps.com
www.dhl.com

Technology Learning Activity 8

Collaborative Project- Remote Design Teams

This project is a joint project that will emulate the challenges that occur when design teams are located in different parts of the country using different software tools. The file format that will be used between the groups when sharing files is the native files created by the particular CAD software (SolidWorks or Inventor). A STEP file format may also be used. Design teams will use online collaboration tools like Skype (skype.com), Autodesk Streamline, WIMBA and Adobe Connect and email to share ideas.

Learning Objectives:

1. Identify on-line collaboration tools such as; Adobe Connect, Wimba, Skype, Blackboard, etc.
2. Determine best file format to use for file sharing between remote design teams
3. Define Rapid Prototyping Technology (RPT)
4. Provide a scaled physical prototype of design.

Materials Required:

CADD software ie; SolidWorks, Inventor, etc., CADD files for necessary guitar components, RPT technology if prototypes are required and headsets with mics.

References:

http://dspace.mit.edu/handle/1721.1/12957, http://www.iasdr2009.org/ap/Papers/Orally%20Presented%20Papers/Co-Design/Representing%20Reflective%20Practice%20in%20a%20Remote%20Design%20Collaboration%20Process.pdf , http://sixrevisions.com/project-management/the-remote-designer-how-to-work-while-on-the-road/, http://www.eetimes.com/showArticle.jhtml?articleID=18401607

Collaborative Project- Remote Design Teams

Phase I

Create a new set of sound holes based on a specific theme that the guitar will have. The sound hole cannot exceed the current sound hole design (tribal) surface area by more than 10%. A sample solid model in Solid Works, Inventor and or a DXF or IGES file will be provided to each group.

Phase II

Create a new bridge based on a specific theme to compliment the new sound hole design. The bridge has a "no fly zone" that will be discussed during the bridge project introduction. A sample solid model in both Solid Works and Inventor will be provided to each group.

Phase III

Create a new design for the peg head portion of the guitar neck. Again, there is a "no fly zone" area on the model that will be provided. Teams are encouraged to consider themes. When considering the design of the peg head, more is not better.

Deliverables:

- All members must agree and sign off on the theme
- Each team member will generate a sketch of their application of the theme for the guitar body sound hole.
- 2 solid model variations (in Solid Works or Inventor format) will be submitted from each team.
- Printed copies of the 2 design options submitted to the instructor.
- Outstanding themes and designs will be prototyped for the students on that team.

Wood Learning Activity 1

Moisture content of Wood Species

The moisture content of wood can change the weight, flexibility, and dimension of wood. These variables impact the characteristic sound and intonation as well as structural stability of a wooden instrument. Some wood species are more sensitive to moisture content changes than others. Therefore, instrument makers must be aware of how different wood species will behave to changes in moisture content; for instance, when moving an instrument from a humid climate to an arid climate.

Professional moisture meters are available to measure the approximate moisture content of wood. One common type of moisture meter measures the electrical resistance of the wood fibers. The electrical resistance within the wood fibers becomes increasingly lower as the moisture content of the wood rises. Two electrodes are driven into the wood fibers and the electrical resistance is translated into moisture content on the device's electronic or dial output.

In this lab you will compare the relative moisture content of different species of wood. In Method A, you will measure the piece of wood before and after placing it in a microwave for 30 seconds, then measure the change in dimensions with calipers. In Method B you will weigh the piece of wood before and after placing it in a microwave for 30 second and then note the change in the weight to see how much how much water was lost during the microwaving process.

Learning Objectives:

1. Use calipers or steel rule to accurately measure the size dimensions of wood before and after microwaving the wood for 30 seconds.
2. Compare wood species based on the dimensional change resulting from lower moisture content.
3. Use a balance to record weight change of wood before and after microwaving the wood for 30 seconds.
4. Compare woods species based on weight change resulting from lower moisture content.

Materials Required:

- Balance
- Steel metric rule (calipers)
- Set of rectangular samples of several wood species (labeled) small enough to fit in microwave

References:

http://guitarnotes.com/guitar/notes2/humidity
http://blog.customguitars.com/scotts_guitar_blog/2006/12/index.html
http://en.wikipedia.org/wiki/Tonewood
http://www.pawless.com/care.html
http://en.wikipedia.org/wiki/Moisture_meter

Wood Exercise 1

1. Prepare samples of different species of wood with the same dimensions then record the length, width, and height of each sample.
2. Submerge the wood samples in water for at least 2 hours.
3. Record the length, width, height and weight of each piece of wet wood.
4. Microwave the pieces of wood for 30 seconds then record the change in length, width, height, and weight.
5. Create a table showing the percent change in size and weight for each species of wood (before and after soaking, and after microwaving).

Discussion:

1. Which wood species is most sensitive to moisture content change?
2. Why was it important to know the moisture content of wood when building guitars?
3. Which part of a guitar would be most sensitive to wood content - the body, neck, or fret board?
4. How can you determine the amount of water that was lost during the microwave process by weighing the piece of wood?
5. Which method (size v. weight) do you think is more accurate? Why?
6. How do you think the relative humidity in the environment can affect a guitar?

Notes

Wood Learning Activity 2

Density of Wood Species

Density is a physical property of matter, as each element and compound has a unique density associated with it. Density defined in a qualitative manner is the measure of the relative "heaviness" of objects with constant volume. The equation used to calculate density is: density = mass/volume

The density of wood used in the manufacturing of a string instrument will contribute to the tonal quality of the instrument. High density woods will tend to reflect sound and lower density woods will absorb sound. Different combinations of woods used on the sides and backs of stringed instruments will provide variation in the resulting tone of the instrument.

Two methods that may be used to quantitatively compare the relative densities of wood are:

- Relative buoyancies
- Measurements of actual volume
-

In this lab you will compare the densities of different species of wood. In Method A, you will be simply comparing and ranking the woods from most dense to least dense. In Method B you will make actual measurements and calculate numerical values for the density of each wood. Record all results and answer all discussion questions in your lab report.

Learning Objectives:

1. Determine the relative density of wood species using the measurement of buoyancy
2. Calculate the density of wood species using weight and volume measurements
3. Measure object sizes using the metric system

Materials Required:

- Graduated cylinder
- Balance
- Steel metric rule (optional dial calipers)
- Set of rectangular samples of several species (labeled) small enough to fit in graduated cylinder
- Additional set of labeled rectangular wood species (to remain dry).

References:

http://en.wikipedia.org/wiki/Density
http://www.engineeringtoolbox.com/wood-density-d_40.html
http://www.physics.ucla.edu/k-6connection/Mass,w,d.htm
http://www.physorg.com/news134193065.html

Wood Exercise 2

Procedure: Method A (Buoyancy)

1. Fill the graduated cylinder with water to a depth of 7 inches. Place a wood sample into the cylinder (zero-end down) and immediately record the depth to which each sample sinks (the deeper it sinks, the more dense the sample).
2. Repeat for each species of wood supplied.
3. Use your results to rank the woods from most dense (#1) to least dense.
4. Why was it important to measure immediately after placing the wood in the water? (What would probably happen if you waited a while?)
5. Test your hypothesis in question #4 and record the result.

Method B (Measurement)

1. Get a new set of dry samples.
2. Measure the mass of each sample on the balance and record it.
3. With the metric rule or dial caliper, measure the length, width and height in millimeters for each sample and record.
4. Calculate the volume of each sample with the formula: Volume = length x width x height. Record these values with appropriate units.
5. Now calculate the density of each sample with the formula: Density = mass/volume.
Record these values with appropriate units.
6. Do these values agree with your rankings from Method A?

Discussion:

1. Why was it important to get a whole new set of samples when beginning Method B? Explain.
2. Suppose the samples were not perfect rectangles. Try to describe a way to determine the volume of a sample if it were an odd shape.
3. Which method do you think is more accurate? Why?
4. Why would you care about wood density when considering the species for your guitar?

Notes

Board feet calculations of lumber

Rough Lumber information:

Rough lumber is sold in a unit of measure called board/foot (bd/ft). The thickness of the boards is always expressed as a fraction in quarters, ex 3/4, 4/4, 5/4, 6/4, 8/4, and so on, even if the thickness is an improper fraction.

4/4 = 1" thick		144 cu inches = 1 board foot
8/4 = 2" thick		A board foot = a 12" wide board 1" thick by 12" long

Calculate the following amounts of board feet using bd/ft = cu in / 144 where cu in = t x w x l. Hint: Be sure to observe proper units! Show all work on separate paper.

Height	Width	Length	Cu In	Board Feet
4/4	6"	12'		
4/4	8"	10'		
5/4	14"	8'		
6/4	12"	10'		
8/4	8"	12'		
4/4	7.5"	10'8"		
8/4	13-3/4"	45"		
12/4	14"	22"		
4/4	14"	22"		
3/4	6"	24"		
2/4	10"	66"		
8/4	5-1/2"	87"		
10/4	8-3/8"	12'		
5/4	6-5/8"	79-1/2"		
7/4	9-1/4"	56"		

Sample

8/4" x 10" x 4'-6" board

$$bf = \frac{(t)(w)(l)}{144in^3}$$

bf = (2") (10") (54") ÷ 144in3

bf = 1080 in3 ÷ 144in3

bf = 7.5 bd/ft

Board feet calculations of lumber Answers

thickness	width	length	cu in	bd/ft
1.00	6	144	864	6.00
1.00	8	120	960	6.67
1.25	14	96	1680	11.67
1.50	12	120	2160	15.00
2.00	8	144	2304	16.00
1.00	7.5	128	960	6.67
2.00	13.75	45	1238	8.59
3.00	14	22	924	6.42
1.00	14	22	308	2.14
0.75	6	24	108	0.75
0.50	10	88	440	3.06
2.00	5.5	87	957	6.65
2.50	8.38	144	3017	20.95
1.25	6.63	79.5	659	4.58
1.75	9.25	56	907	6.30

Learner-Centered Learning Objectives

A

by Mark Ferrer

We have spoken in other sections of your need to check with your Dean and/or Department Chair concerning college-defined objectives for your course. Some institutions state that course learning objectives --what students will be able to do upon completion of the course-- must remain the same no matter who teaches the course. If that is the case, then your academic freedom means you decide *how* you'll help students achieve those outcomes. You will decide the **enabling objectives** [some institutions use the phrase "enabling objectives" to mean those things students learn to do along the way toward reaching learning objectives]. Teachers should identify and order these objectives as part of the course planning process. In any case, your best first step as you plan the course is to determine ***what students will be able to do upon successful completion of the course***.

Here are some general guidelines for the wording, organization, and tone to use as you craft objectives (adapted from Columbia College's website):

- Goals and objectives should be stated as student **outcomes** ("The student will…", or "You will be able to …").
- They may be **organized** according to the units of the course; if appropriate, include projects and options.
- They should correspond to the **professional standards** of the discipline and work environment the student is preparing to enter.

Describe your learning objectives using **active verbs** that indicate what students will need to do as the semester progresses. For example, in a course on history, one instructor told students they would acquire the "basic skills used by historians," which included the ability to:

- critically analyze primary documents
- identify an author's thesis and evaluate how well it is supported
- write a logical and coherent argument of your own.

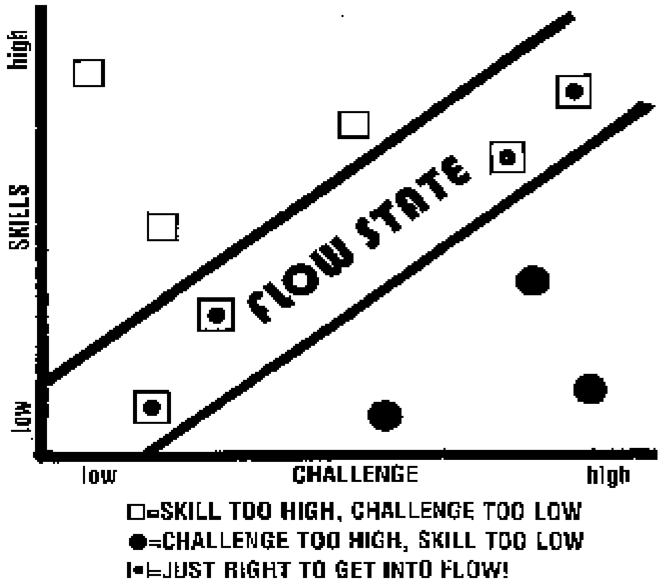
The tone of a learning-centered syllabus should be informal and accessible. Personally, I recommend the phrase "you will be able to . . ." instead of "the student will be able to . . .". One other consideration is the decision to use "will" or "should." Check with your institution; in this litigious society, some educational institutions have decided that objectives should be stated as, "You should be able to . . ." because using "will" implies successful accomplishment merely due to attendance.

We refer many times to Bloom's Taxonomy. Visit the following website to help clarify how to define and phrase objectives so that you are requiring students to work at the higher levels of the Taxonomy: . The authors provide active verbs related to each of the levels in the Taxonomy. It is clear that "cite," "list," and "pronounce" verbs associated with Bloom's Knowledge level differ markedly from "diagram," "integrate," and "assess" verbs characteristic of Application, Analysis, Synthesis, and Evaluation.

"Integrating" as an activity clearly requires students to ***do something*** with the material. "List," on the other hand, requires only successful memorization and ability to say or write what has been memorized. Use the following table to locate your objectives on Bloom's scale. The level of demand on students' abilities to think critically, solve problems, make connections rises as the chart moves from knowledge (lowest demand) up to evaluation (highest demand). Keeping the level required to complete your objective commensurate with your students' readiness to accomplish it means that you have set realistic, positive objectives -- ones that will result in success rather than frustration and loss of engagement.

There is no bad or good level in Bloom's Taxonomy, but there is appropriate vs. inappropriate. Knowledge-level learning activity and assessment are quite appropriate at the right times. For instance, learning the names of the parts of the digestive system and listing them on a test may be the right task at the right place in your physiology course. A student who missed this step might be forced into an inappropriate phrase in a real-world scenario. Assure that students know the basic vocabulary by employing a Knowledge-Level activity before moving to assignments that require students to do something with that knowledge.

It is important to give students the right challenge at the appropriate moment. If you ask too little, they lose interest. If you ask too much, they hit overload and can't process the information or complete the task. One way to set the cognitive load of a learning task is to select the verbs appropriate to student readiness. Choose the verbs from the list below that match what students are ready to do with the learning task you want to assign. For example, using the verb "name" (as in, "Name the parts of the digestive system"), means the cognitive load required of students will be lower than if the verb, "determine" (as in, "Determine potential causes for the peptic ulcer given the patient's medical history") is used. You want to manage the ***flow state*** to maintain momentum in the learning process:



The higher levels in Bloom correspond to higher levels of cognitive load. Students have to be skilled and prepared to handle demands made of them at the higher levels. Staged preparation, scaffolding, incremental familiarization, and graduated practice make the move upward possible. Abrupt shifts and inconsistent levels within an assignment or presentation will leave most students stranded. (For more see *Tests and Testing* in Module Seven).

Knowledge-Remembering previously learned materials

cite	label	name	reproduce
define	list	quote	pronounce
identify	match	recite	state

Comprehension-ability to grasp the meaning of material. Answers: who? what? when? where?

alter	discover	manage	relate
change	explain	rephrase	substitute
convert	give examples	represent	summarize
depict	give main idea	restate	translate
describe	illustrate	reword	vary
interpret	paraphrase	tell why	express

Application-ability to use learned material in new and concrete situations

apply	discover	manage	relate
classify	employ	predict	show
compute	evidence	prepare	solve
demonstrate	manifest	present	utilize
direct			

Analysis-ability to break down material into its component parts. Answers: how many? which? what is?

ascertain	diagnose	distinguish	outline
analyze	diagram	divide	point out
associate	differentiate	examine	reduce
conclude	discriminate	find	separate
designate	dissect	infer	determine

Synthesis-ablity to put parts together to form a new whole. Answers why?

combine	devise	originate	revise
compile	expand	plan	rewrite
compose	extend	pose	synthesize
conceive	generalize	propose	theorize
create	integrate	project	write
design	invent	rearrange	
develop	modify		

Evaluation-ability to judge the value of material for a given purpose. Answers how can we improve? what would happen if?

appraise	conclude	critique	judge
assess	contrast	deduce	weigh
compare	criticize	evaluate	

The importance of keeping Bloom in mind as you create/define your learning objectives for the course and unit is clear. The added benefit is that our process of syllabus-making/course planning and its order of activities help you:

1. determine objectives in terms of student-doing
2. create assessments to measure achievement of objectives
3. create assignments and activities to facilitate student achievement of objectives.

Working in this way guides you constantly along the learning-centered path. Planning the order of the steps keeps your focus on student learning and not solely on the presentation of material:

“. . . one reason students do not learn may be related to the failure of many faculty to consider, articulate, and specify their expectations and objectives. Outcomes assessment forces academics to become student-centered.”

from *Successful College Teaching* by Baiocco & DeWaters, p. 158

B

Lesson #_____

Title_____________________________

Synopsis of lesson:

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Learning Objectives:

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Materials Required:

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References:

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C

FEATURE *My Favorite Experiment Series*
by R.M. French

NEW SERIES

A POP BOTTLE AS A HELMHOLZ RESONATOR

The Helmholz resonator is perhaps the simplest acoustic resonant system. The ideal Helmholz resonator consists of an air volume enclosed with rigid walls and vented through a neck whose cross-sectional area is small compared to the dimensions of the volume (see Figure 1). It is assumed that the air volume acts as a mechanical spring and the air in the neck acts as a moving mass. The expression for the natural frequency of the system is[1]

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{tV}} \qquad (1)$$

Where c is the speed of sound,[2] A is the cross-sectional area of the port, t is the length of the neck and V is the volume. A familiar approximation to the ideal resonator is a 20 oz plastic pop bottle. Blowing over the top of the bottle makes a whistle whose frequency should be described by this expression.

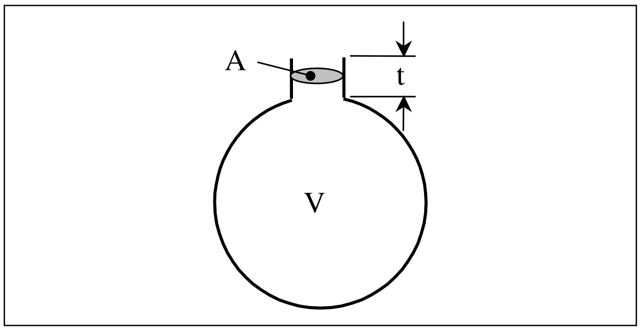


Fig. 1: Ideal Helmholz resonator

EXPERIMENT

As an experiment, the frequency of the sound made by blowing over the top of a bottle was measured with different liquid levels in the bottle. Figure 2 shows the bottle with the label removed and marks showing the different fill levels. The frequencies and corresponding air volumes are shown in Table 1. The measured acoustic resonance frequencies from the different fluid levels can be used to identify unknown terms in Equation 1 using a least squares approach.

Table 1—Experimental results

CONDITION	AIR VOLUME (Liters)	FREQUENCY (Hz)
1	0.195	330.0
2	0.296	260.3
3	0.411	220.1
4 (Empty)	0.616	175.9

The volume of the enclosed air was determined by weighing the bottle empty and filled with water. By subtracting the empty weight (tare weight), the weight of the water filling the bottle is found. The density of water is assumed to be 1 gm/cm^3. By weighing the bottle at the different fill levels, it is a simple task to find the resulting air volumes.

The sound recordings clearly showed the resonant frequencies and several harmonics for each fill level as seen in Fig. 3.

Equation 1 assumes an ideal system that isn't completely realized in the pop bottle, so at least one of the parameters must be tuned using experimental data. The neck of the bottle is approximately 21.5 mm in diameter, giving a cross-sectional area, A, of 363 mm^2. If all parameters except t are assigned, t can be selected to give the best correlation

Fig. 2: Bottle used for experimental data

Editor's Note: *ET is creating a new feature series to focus on short, educational/teaching related articles under the title "My Favorite Experiment." The short articles demonstrate experimental techniques that can be applied directly to the classroom and laboratory to enhance both the teaching process and conveyance of various apparatus and measurement methods to the students.*

This month, we are featuring an article titled "A Pop Bottle as a Helmholz Resonator" by Prof. Mark French (SEM Member) of Purdue University, West Lafayette, IN, formerly with Robert Bosch Corporation. Series Editor: Kristin B. Zimmerman, General Motors Corporation.

N

MY FAVORITE EXPERIMENT

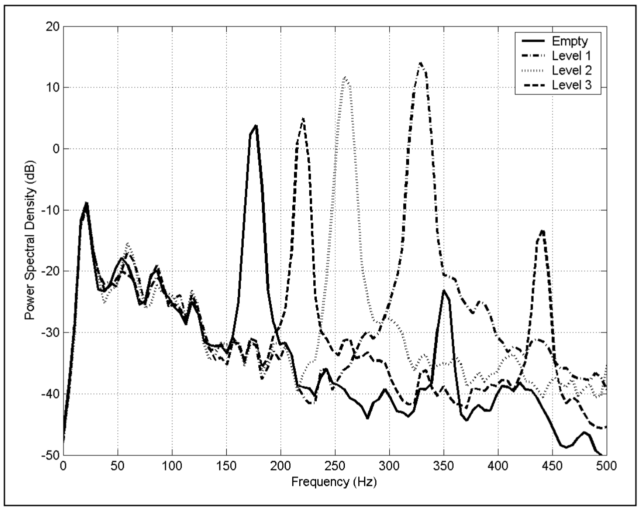


Fig. 3: Frequency domain representation of sound data

between measured and calculated frequencies. The assigned values are: $A = 363\ \text{mm}^2$, $c = 338.3$ m/sec and volumes as shown in Table 1. A value of $t = 52$ mm minimized the squared error function for measured and calculated frequencies as defined in Eq. 2. The results are shown in Table 2.

$$E = \sum_{i=1}^{4} (f_i^{\text{exp}} - f_i^{calc})^2 \qquad (2)$$

SUMMARY

The Helmholz resonator is both a simple introduction to acoustic resonance and a useful model of many physical systems. These include such diverse examples as engine intake manifolds and the bodies of stringed musical instruments. A pop bottle with a roughly cylindrical body and a short cylindrical neck is a good example since it is readily available and its acoustic response is intuitively familiar. Using several different fluid levels to vary the enclosed air volume, the parameters in the Helmholz equation can be identified so that the calculated frequencies are within a few percent of the measured ones.

Table 2—Calculated and measured resonant frequencies

CONDITION	MEASURED FREQUENCY, f_i^{exp} (Hz)	CALCULATED FREQUENCY, f_i^{calc} (Hz)	% DIFFERENCE
1	330.0	321.8	−2.48
2	260.3	261.5	0.46
3	220.1	221.9	0.82
4 (empty)	175.9	181.2	3.01

References

1. Rossing, T.D. “The Science of Sound, 2nd Edition”, Addison-Wesley, 1990.

2. Anderson, J.D. “Introduction to Flight”, McGraw-Hill, 1978. ■

N

D

Guitar Notes - Musical Frequencies Table												
Chromatic Scale 12 half-notes per octave			-			**Diatonic Scales (Major) (8 notes per octave)**					**Note Frequency Hz.**	1.999999901 (12 times root 2 below)
Piano Octaves	**Guitar Octaves**	**Note # Key of E**	-	**Guitar String**	-	**Key of E**	**Key of G**	**Key of A**	**Key of C**	**Key of D**	Piano Octaves	12th Root of 2
-	-	-		-		-	-	-	-	-	-	-
E2	E	1		**# 6**		do (1)	-	so (5)	-	re (2)	**82.407**	1.05946309
F2	F	2					ti (7)	la (6)	fa (4)	mi (3)	87.31	1.05946309
F#	F#	3				re (2)	-	-	-	-	92.50	1.05946309
G2	G	4				mi (3)	do (1)	ti (7)	so (5)	fa (4)	98.00	1.05946309
G#	G#	5				-	-	-	la (6)	-	103.83	1.05946309
A2	A	6		**# 5**		fa (4)	re (2)	do (1)	-	so (5)	**110.00**	1.05946309
A#	A#	7				-	mi (3)	-	ti (7)	la (6)	116.54	1.05946309
B2	B	8				so (5)	-	re (2)	-	-	123.47	1.05946309
C3	C	9				la (6)	fa (4)	mi (3)	do (1)	ti (7)	130.81	1.05946309
C#	C#	10				-	-	-	-	-	138.59	1.05946309
D3	D	11		**# 4**		ti (7)	so (5)	fa (4)	re (2)	do (1)	**146.83**	1.05946309
D#	D#	12				-	la (6)	-	mi (3)	-	155.56	1.05946309
E3	E	1				do (1)	-	so (5)		re (2)	164.81	1.05946309
F3	F	2				-	ti (7)	la (6)	fa (4)	mi (3)	174.61	1.05946309
F#	F#	3				re (2)	-	-	-	-	185.00	1.05946309
G3	G	4		**# 3**		mi (3)	do (1)	ti (7)	so (5)	fa (4)	**196.00**	1.05946309
G#	G#	5				-	-	-	la (6)	-	207.65	1.05946309
A3	A	6				fa (4)	re (2)	do (1)	-	so (5)	220.00	1.05946309
A#	A#	7				-	mi (3)	-	ti (7)	la (6)	233.08	1.05946309
B3	B	8		**# 2**		so (5)	-	re (2)	-	-	**246.94**	1.05946309
C4	C	9				la (6)	fa (4)	mi (3)	do (1)	ti (7)	**261.63**	1.05946309
C#	C#	10				-	-	-	-	-	277.18	1.05946309
D4	D	11				ti (7)	so (5)	fa (4)	re (2)	do (1)	293.67	1.05946309
D#	D#	12				-	la (6)	-	mi (3)	-	311.13	1.05946309
E4	E	1	-	**# 1**	-	do (1)	-	so (5)	-	re (2)	**329.63**	1.05946309
F4	F	2		1st fret		-	ti (7)	la (6)	fa (4)	mi (3)	349.23	1.05946309
F#	F#	3		2nd fret		re (2)	-	-	-	-	369.99	1.05946309
G4	G	4		3rd fret		mi (3)	do (1)	ti (7)	so (5)	fa (4)	392.00	1.05946309
G#	G#	5		4th fret		-	-	-	la (6)	-	415.30	1.05946309
A4	A	6		5th fret		fa (4)	re (2)	do (1)	-	so (5)	**440**	1.05946309
A#	A#	7		6th fret		-	mi (3)	-	ti (7)	la (6)	466.16	1.05946309
B4	B	8		7th fret		so (5)	-	re (2)	-	-	493.88	1.05946309
C5	C5	9		8th fret		la (6)	fa (4)	mi (3)	do (1)	ti (7)	523.25	1.05946309
C#	C#	10		9th fret		-	-	-	-	-	554.37	1.05946309
D5	D	11		10th fret		ti (7)	so (5)	fa (4)	re (2)	do (1)	587.33	1.05946309
D#	D#	12		11th fret		-	la (6)	-	mi (3)	-	622.25	1.05946309
E5	E	1		12th fret		do (1)	-	so (5)	-	re (2)	659.26	1.05946309
F5	F	2		13th fret		-	ti (7)	la (6)	fa (4)	mi (3)	698.46	1.05946309
F#	F#	3		14th fret		re (2)	-	-	-	-	739.99	1.05946309
G5	G	4		15th fret		mi (3)	do (1)	ti (7)	so (5)	fa (4)	783.99	1.05946309
G#	G#	5		16th fret		-	-	-	la (6)	-	830.61	1.05946309
A5	A	6		17th fret		fa (4)	re (2)	do (1)	-	so (5)	**880.00**	1.05946309
A#	A#	7		18th fret		-	mi (3)	-	ti (7)	la (6)	932.33	1.05946309
B5	B	8		19th fret		so (5)	-	re (2)	-	-	987.77	1.05946309
C6	C	9		20th fret		la (6)	fa (4)	mi (3)	do (1)	ti (7)	1,046.50	1.05946309
C#	C#	10		21st fret		-	-	-	-	-	1,108.73	1.05946309
D6	D	11		22nd fret		ti (7)	so (5)	fa (4)	re (2)	do (1)	1,174.66	1.05946309
D#	D#	12		23rd fret		-	la (6)	-	mi (3)	-	1,244.51	1.05946309
E6	E	1		24th fret		do (1)	-	so (5)	-	re (2)	1,318.51	1.05946309
F6	F	2		25th fret		-	ti (7)	la (6)	fa (4)	mi (3)	1,396.91	1.05946309
F#	F#	3				re (2)	-	-	-	-	1,479.98	1.05946309

						(1)= Tonic (4)= Sub-dominant			(5)= Dominant (7)= Seventh		**261.63 = Middle C**		
	Each horizontal line = 1 half-note = 1 fret Chromatic Scale = Each half-note is 5.95% higher in frequency than the previous note. 1 octave = 12 half-notes = doubling of frequency												
50	50	50	10	80	10	60	60	60	60	60	65	75	

Custom Guitar Tools

2/2010

Stewart Macdonald	stewmac.com	10% off possible
Luthiers Mercantile	http://www.lmii.com/	10% off for Educaiton

Specialty Tools

Part name	Rank	Part number	Supplier	MIN QTY	Cost	total	class of 15 qty
Fretting Kit	1	5345	Stewart Macdonald	2	$170.90	$341.80	3
neck support caul	3	4479	Stewart Macdonald	4	$10.44	$41.76	7
Precision straight edge	2	3850	Stewart Macdonald	1	$47.40	$47.40	2
Notched Straight Edge	1	3814	Stewart Macdonald	1	$72.21	$72.21	1
Optional 18" Radius Sanding Block	?		Stewart Macdonald	1	$125.00	$125.00	1
Radius sanding blocks	1	0417	Stewart Macdonald	4	$15.95	$63.80	7
Fret Leveler 6"	3	0862	Stewart Macdonald	3	$39.74	$119.22	4
Arbor Press	3	4483	Stewart Macdonald	1	$164.72	$164.72	1
fret file crowning	1	4455	Stewart Macdonald	1	$55.98	$55.98	2
Fret hammer	2	4895	Stewart Macdonald	1	$19.60	$19.60	
nut file 012/016	1	4541	Stewart Macdonald	1	$25.45	$25.45	3
nutfile 026/032	1	4542	Stewart Macdonald	1	$25.45	$25.45	3
nut file 036/042	1	4543	Stewart Macdonald	1	$25.45	$25.45	3
nut vise	3	1816	Stewart Macdonald	1	$34.95	$34.95	1
string spacing rule	1	0673	Stewart Macdonald	1	$20.95	$20.95	2
nut shaping file	1	4556	Stewart Macdonald	1	$25.25	$25.25	2
metal ruler - centering	1	37188	Rockler	1	$5.99	$5.99	3
Fret wire bender	2	FWB	LMI	1	$69.95	$69.95	1
Fret Saw	1	SWB	LMI	1	$28.25	$28.25	2
String Height Guage	1		Stewart Macdonald	1			2
						$1,313.18	

E

Standard tools		HF= Harbor Freight		
Small hammer	HF			
open end wrench set Eng + Metric	HF			
Screwdrivers -- Variety (many)	craftsman			
pliers variety - soldering	HF			
wire strippers	HF			
flush cut saw	HF			
jig saw? Or small hand saw	HF			
wood chisels	HF			
Drill Bits - Variety	woodcraft set			
Drill bits - micro - for T-pins	HF			
T-Pins - craft store				
multimeter - electronic	HF			
Shelf liner		protect guitar		
rubber sanding blocks				
clamps quick release 12"	10-16	irwin or bessy		
clamps quick release 18"	8	irwin or bessy		
Rubberbands 1/4" X17"	2 boxes	grainger		
Extra Strings	Amazon	D adarrio 25 packs		
Guitar Tuner	??			
Bona Finish		online floor store		
Bona sealer		online floor store		
Gun stock finish tru-oil (higher VOC + exothermic)		rifle magizine wolfe publishing		
concentrated stains or minwax				
Fret Dots and side markers	allparts.com	6mm dots =~1/4"		
Fret Dot plug cutter and wood		LT-0474-023 - Black Inlay Dots	50	$13.00
		LT-0474-025 - White Inlay Dots	50	$13.00
		LT-0483-055 - Pearloid Inlay Dots	50	$13.00
		LT-0496-025 - White Side Dots	10	$6.50
		LT-0496-023 - Black Side Dots	10	$6.50

Solid Body Electric Guitar Design & Fabrication
Guitar Making Tools, Equipment, Supplies, & Consumables
Preliminary Budget

	Min. Startup Cost	Total: Class 12-15	Total: Class 16-22
"Must Have" Specialty Tools	$907.47	$1,839.32	$2,999.94
"Really Need" Specialty Tools	$756.83	$974.37	$1,363.78
Power and Hand Tools	$3,596.71	$4,222.07	$4,976.92
Supplies & Consumables	$3,043.79	$5,260.94	$7,345.70
Totals:	$8,304.80	$12,296.70	$16,686.34

Part name	Rank	Part No.	Potential Supplier	Min. Cost	Reqd Qty for Start up	Min. Startup Cost	Qty for Class Size of 12-15	Total: Class 12-15	Qty for Class Size of 16-22	Total: Class 16-22
"Must Have" Specialty Tools										
Fretting Kit	1	5345	Stewart Macdonald	$170.90	2	$341.80	3	$512.70	4	$683.60
12" Radius sanding blocks (8")	1	0417	Stewart Macdonald	$15.95	4	$63.80	7	$111.65	12	$191.40
12" Aluminum Radius-sanding Beam (18")	1	5643	Stewart Macdonald	$125.84	1	$125.84	3	$377.52	6	$755.04
Notched Straightedge (for guitars)	1	3814	Stewart Macdonald	$72.21	1	$72.21	2	$144.42	2	$144.42
Dual-grit Diamond Fret File (medium fretwire)	1	4455	Stewart Macdonald	$55.98	1	$55.98	3	$167.94	5	$279.90
Essential Nut Making Tool Kit	1	5350	Stewart Macdonald	$194.74	1	$194.74	1	$194.74	2	$389.48
Double-edge Nut Files (0.012" & 0.016")	1	4541	Stewart Macdonald	$25.45	0	$0.00	2	$50.90	3	$76.35
Double-edge Nut Files (0.026" & 0.032")	1	4542	Stewart Macdonald	$25.45	0	$0.00	2	$50.90	3	$76.35
Double-edge Nut Files (0.036" & 0.042")	1	4543	Stewart Macdonald	$25.45	0	$0.00	2	$50.90	3	$76.35
Nut & Saddle Shaping Files, Set of 2	1	4556	Stewart Macdonald	$25.25	0	$0.00	2	$50.50	4	$101.00
String Spacing Rule	1	0673	Stewart Macdonald	$20.95	0	$0.00	1	$20.95	2	$41.90
String Action Gauge (string/fretboard height gauge)	1	0670	Stewart Macdonald	$18.95	1	$18.95	2	$37.90	4	$75.80
Fairgate Center-finding Rule, 6" x 3/4"	1	23-106	Fashion Designers Place	$2.95	2	$5.90	4	$11.80	8	$23.60
Fret Saw, 20 TPI, 0.023 kerf, Pull ("Backsaw")	1	SWB	LMI	$28.25	1	$28.25	2	$56.50	3	$84.75
"Really Need" Specialty Tools										
Fret wire bender (3 roller type)	2	FWB	LMI	$69.95	1	$69.95	1	$69.95	1	$69.95
Precision Straightedge (18")	2	3850	Stewart Macdonald	$47.40	1	$47.40	2	$94.80	2	$94.80
Fret hammer	2	4895	Stewart Macdonald	$19.60	1	$19.60	2	$39.20	4	$78.40
7/8" Replacement plastic face (for fret hammer)	3	4896	Stewart Macdonald	$1.79	2	$3.58	2	$3.58	2	$3.58
7/8" Replacement brass convex face (for fret hammer)	3	4897	Stewart Macdonald	$7.83	2	$15.66	2	$15.66	2	$15.66
Fret Press System (caul, arbor press, support, 5 inserts)	2	4483	Stewart Macdonald	$164.72	1	$164.72	1	$164.72	2	$329.44
Fret/Fingerboard Leveling Files (Set of 3)	2	0860	Stewart Macdonald	$108.49	2	$216.98	2	$216.98	2	$216.98
Fret Leveler (6")	2	0862	Stewart Macdonald	$39.74	0	$0.00	3	$119.22	6	$238.44
Nut Vise	3	1816	Stewart Macdonald	$34.95	0	$0.00	0	$0.00	1	$34.95
Neck Support Caul	2	4479	Stewart Macdonald	$10.44	3	$31.32	6	$62.64	9	$93.96
Fret/Fingerboard Leveler (16")	2	4578	Stewart Macdonald	$43.67	1	$43.67	1	$43.67	1	$43.67
Amana In-Groove CNC Insert Engraving Tool (8 pc. Set)	4	AMS-209	toolstoday.com	$143.95	1	$143.95	1	$143.95	1	$143.95
								$0.00		$0.00
								$0.00		$0.00
Standard Tools (Power and Hand)										
Hand-Held Pneumatic Drum Sander (7-1/2" x 2-1/4")	1	H2882	Grizzly	$99.95	1	$99.95	2	$199.90	4	$399.80
Hand-Held Pneumatic Drum Sander (4" x 1-1/8")	2	H2881	Grizzly	$69.95	1	$69.95	2	$139.90	2	$139.90
1/2" HD Var Speed Reversible Drill (w/ handle)	1	3273-0VGA	Harbor Freight	$39.99	3	$119.97	5	$199.95	8	$319.92
3/8" Var Speed Reversible Drill (w/ handle)	2	3670-2VGA	Harbor Freight	$19.99	2	$39.98	4	$79.96	6	$119.94
5" Random Orbital Palm Sander (8 hole/hook & loop)	1	93431-1VGA	Harbor Freight	$29.99	2	$59.98	3	$89.97	4	$119.96
Ball Pein Hammer set (8, 12, 16, 24 and 32 oz.)	2	36523-9VGA	Harbor Freight	$7.97	1	$7.97	1	$7.97	1	$7.97
28 pc. Standard & Metric Open End Wrench Set	2	42955	Sears/Craftsman	$159.99	1	$159.99	1	$159.99	1	$159.99
44 Pc HD Screwdriver Set ("high end")	2	50089	Sears/Craftsman	$79.99	1	$79.99	1	$79.99	1	$79.99
13 Piece Screwdriver Set ("low end")	2	1847-1VGA	Harbor Freight	$11.99	1	$11.99	1	$11.99	1	$11.99
7 Piece Pliers Set (general use)	2	93363-0VGA	Harbor Freight	$16.99	1	$16.99	1	$16.99	2	$33.98
5 Piece Precision Pliers Set (soldering stations)	1	4807-8VGA	Harbor Freight	$5.97	3	$17.91	4	$23.88	6	$35.82
7" Wire Stripper with Cutter	1	98410-1VGA	Harbor Freight	$5.99	2	$11.98	3	$17.97	4	$23.96
Japanese Flush Cut Saw (12" OAL/Cuts on pull stroke)	1	39273-7VGA	Harbor Freight	$9.99	2	$19.98	3	$29.97	4	$39.96
9" Benchtop Bandsaw (62" Blade)	2	96980-2VGA	Harbor Freight	$139.99	0	$0.00	0	$0.00	1	$139.99
Oscillating Edge/belt Spindle Sander (Rigid)	2	EB4424	Home Depot	$199.00	1	$199.00	2	$398.00	2	$398.00
Steel Secure Storage Cabinet with 2 Full-Width Drawers	1	1UBW6	Grainger	$1,921.00	1	$1,921.00	1	$1,921.00	1	$1,921.00
5 pc. Wood Chisel Set	1	36859	Sears/Craftsman	$34.99	1	$34.99	1	$34.99	1	$34.99
170 Pc Drill Bit Set (Brad Point)	2	148082	Woodcraft	$59.99	1	$59.99	1	$59.99	1	$59.99
Bar Clamp, 12" x 3" Bessey EZS One Handed	2	845104	Woodcraft	$19.79	10	$197.90	12	$237.48	16	$316.64
Bar Clamp, 18" x 3" Bessey EZS One Handed	2	845105	Woodcraft	$22.49	10	$224.90	12	$269.88	16	$359.84
Plug Cutter, Tapered; 1/4" (for fret dots)	1	146724	Woodcraft	$10.99	2	$21.98	2	$21.98	3	$32.97
Rubber Bands, 17" x 1/4 Width; Pkg of 50	1	1PE12	Grainger	$8.11	2	$16.22	2	$16.22	2	$16.22
Round Plastic Receptacle Base, Capacity 55 Gallons	1	3H240	Grainger	$99.45	1	$99.45	1	$99.45	1	$99.45
Round Dolly (for round wast containers)	1	5W007	Grainger	$74.40	1	$74.40	1	$74.40	1	$74.40
Flat Plastic Receptacle Lid, (for 55 Gal Rnd Container)	1	4W017	Grainger	$30.25	1	$30.25	1	$30.25	1	$30.25

Supplies and Consummables

Bona Novia Waterbased Floor Finish Gloss	1	WT230018002	online floor store	$39.99	1	$39.99	1	$39.99	1	$39.99
Bona Bonaseal Waterbased Floor Finish Sealer	1	WB200018005	online floor store	$37.60	1	$37.60	1	$37.60	1	$37.60
Bona Amberseal Waterborne Sanding Sealer	2	WB252018003	online floor store	$39.99	1	$39.99	1	$39.99	1	$39.99
Trash Can Liner, Capacity 55 Gallons, Gauge 0.670 Mils	1	2U383	Grainger	$72.10	1	$72.10	1	$72.10	1	$72.10
Digital Multimeter (8 Functions; 20 Ranges)	2	82141	Sears/Craftsman	$19.99	1	$19.99	2	$39.98	2	$39.98
Michigan Indust Tools-Helping Hand w/ Magnifier	1	7521	***[Google search]***	$9.30	2	$18.60	4	$37.20	6	$55.80
Fender Frontman 10G 10W Guitar Combo Amp (Black)	1	481602	Muscian's Friend	$59.99	1	$59.99	2	$119.98	2	$119.98
6-Ft. Shielded Cable, 1/4" Mono Plug to 1/8" Mono Plug	1	42-2433	Radio Shack	$5.99	1	$5.99	2	$11.98	2	$11.98
1/8" Right-Angle Adapter	2	274-372	Radio Shack	$3.59	1	$3.59	2	$7.18	2	$7.18
1/4" Mono Male x 1/4" Mono Male Cable 10 ft	1	099-0410-0xx	Muscian's Friend	$7.99	1	$7.99	2	$15.98	2	$15.98
Stikit Gold Paper Self-adhesive Abrasives (4 grit kit)		5770	Stewart Macdonald	$89.92	1	$89.92	1	$89.92	1	$89.92
Stikit Self-adhesive Abrasives (45ft x 2-3/4" x 120 grit)		5767	Stewart Macdonald	$23.59	2	$47.18	3	$70.77	4	$94.36
Stikit Self-adhesive Abrasives (45ft x 2-3/4" x 220 grit)		5768	Stewart Macdonald	$23.59	1	$23.59	2	$47.18	3	$70.77
Stikit Self-adhesive Abrasives (45ft x 2-3/4" x 320 grit)		5769	Stewart Macdonald	$23.59	1	$23.59	2	$47.18	3	$70.77
Sanding Sleeve A60 (7-1/2" x 2-1/4")		H3881	Grizzly	$3.95	4	$15.80	10	$39.50	15	$59.25
Sanding Sleeve A60 (1-1/8" x 4")		H3875	Grizzly	$3.95	4	$15.80	10	$39.50	15	$59.25
5" Sanding Disc, A120-A H&L 8 Hole, 100 pc.		H4077	Grizzly	$27.95	1	$27.95	1	$27.95	2	$55.90
5" Sanding Disc, A240-A H&L 8 Hole, 100 pc.		H4073	Grizzly	$26.95	1	$26.95	1	$26.95	2	$53.90
5" Sanding Disc, A320-A H&L 8 Hole, 100 pc.		H4071	Grizzly	$26.95	1	$26.95	1	$26.95	1	$26.95
5" Sanding Disc, A400-A H&L 8 Hole, 100 pc.		H4070	Grizzly	$26.95	1	$26.95	1	$26.95	1	$26.95
RIDGID Spindle Sanding Sleeve 10-pc		AC28400	Home Depot	$14.84	1	$14.84	2	$29.68	2	$29.68
SoftTouch Contour Sponge (Bx:20, Fine/320)		03075	Home Depot	$19.97	1	$19.97	1	$19.97	1	$19.97
SoftTouch Contour Sponge (Bx:20, SuperFine/500)		03076	Home Depot	$19.97	1	$19.97	1	$19.97	1	$19.97
Side Dot Rods (Blk, 10 pc; 5/64 (2 mm) DIA x 7.88")		LT-0496-023	AllParts	$6.50	3	$19.50	4	$26.00	6	$39.00
Side Dot Rods (Wht, 10 pc; 5/64 (2 mm) DIA x 7.88")		LT-0496-025	AllParts	$6.50	4	$26.00	5	$32.50	7	$45.50
Side Dot Rods (Red, 10 pc; 5/64 (2 mm) DIA x 7.88")		LT-0496-026	AllParts	$6.50	1	$6.50	1	$6.50	1	$6.50
Side Dot Rods (Cream, 10 pc; 5/64 (2 mm) DIA x 7.88")	3	LT-0496-028	AllParts	$6.50	1	$6.50	1	$6.50	1	$6.50
D'Addario EXL110 Regular Light Strings Bulk Pack (25)	1	103653978	Guitar Center	$89.99	0	$0.00	1	$89.99	2	$179.98
Nickel String Guides Bulk Pack, (50 pieces)	1	AP-0720-B01	All Parts	$85.00	0	$0.00	1	$85.00	2	$170.00
Chrome Strap Buttons Bulk Pack (30 Buttons w/ Screws)	1	AP-0670-B10	All Parts	$40.00	0	$0.00	2	$80.00	2	$80.00
String Ferrules for Guitar, Nickel (Bulk Pack, 50 pieces)	1	AP-0087-B01	All Parts	$50.00	0	$0.00	3	$150.00	3	$150.00
Hardwood: prototypes, 1st articles, & prelims/workshops	1		TBD	$300.00	1	$300.00	16	$1,100.00	25	$1,550.00
SBEG Electronics & Hardware Kit (Dual Humbuckers) http://ncmestorefront.mybisi.com/product/electronics-hardware-kit	1		NCME Storefront	$125.00	12	$1,500.00	16	$2,000.00	24	$3,000.00
Miscellaneous and incidental stuff			Various	$500.00	1	$500.00	1.5	$750.00	2	$1,000.00

Vendor List	URL	Notes
AllParts	http://www.allparts.com	
Bona Store (on-line)	http://store.mybonahome.com	
Grainger	http://www.grainger.com	
Grizzly	http://www.grizzly.com	
Guitar Center	http://www.guitarcenter.com	
Harbor Freight	http://www.harborfreight.com	
Home Depot	http://www.homedepot.com	
Luthiers Mercantile	http://www.lmii.com/	10% off for Educaiton
Online Floor Store	http://www.onlinefloorstore.com	
Stewart Macdonald	http://www.stewmac.com	10% off possible
The Fashion Designers Place	http://www.fdpstore.com	10% off for Educaiton
ToolsToday	http://www.toolstoday.com	Educational discount offered

	ITEM	VENDOR	MANUFACTURER	PART #	UNIT	QTY	COST
							$0.00
	BODY						$0.00
	NECK						$0.00
	PICK UPS						$0.00
	VOLUME POT 250K						$0.00
	TONE POT 250K						$0.00
	CAPACITOR						$0.00
	JACK PLUG						$0.00
	JACK PLATE						$0.00
	NECK PLATE						$0.00
	PICKGUARD						$0.00
	TUNING MACHINES						$0.00
	FRETS (if not included in neck assy)						$0.00
	FRETBOARD (if not included in neck assy)						$0.00
	NUT (if not included in neck assy)						$0.00
	BRIDGE						$0.00
	STRINGS						$0.00
	TRUSS ROD (if not included in neck assy)						$0.00
	FRET DOTS (if not included in neck assy)						$0.00
						TOTAL	$0.00

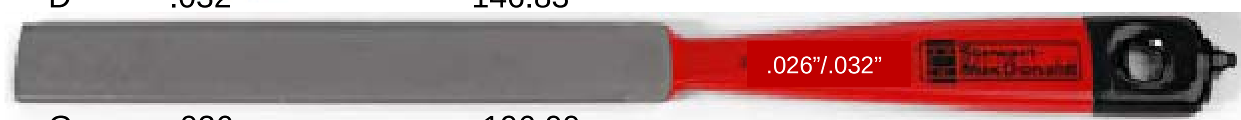
G

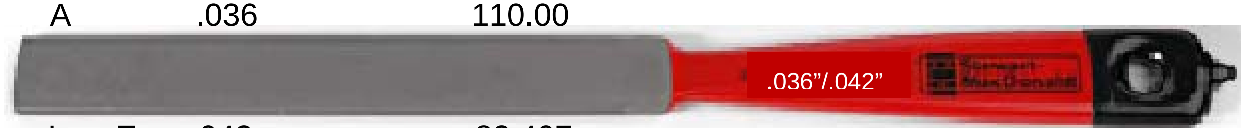
Part Name	Quantity Required	unit price	extended price	supplier	part number
Body					
Pickups					
Pick Guard					
Tuning Machines					
Neck					
Frets					
Bret Board					
Nut					
Truss Rod					
Fret Dots					
Bridge					
Strings					
Neck Plate					
String Ferrules					
1/4" mono audio jack					
1/4" jack plate					
500k ohm pot					
strap knob					
3 way pickup switch					
micro ferret capacitor					

H

NUT FILES

STRING	RADIUS	FREQUENCY - Hz
B	.016	246.94
High E	.012	329.63
D	.032	146.83
G	.026	196.00
A	.036	110.00
Low E	.042	82.407





J

Making a sketch by tracing a digital picture.

1. Find a digital picture online or otherwise. (Must be digital to be uploaded onto a JPEG.)

2. If from web browser or online source, right click and select 'save picture as'. Set a name and save it into a designated folder in your 'x drive'.

3. Start up the program "Adobe Illustrator" found in your programs list in the folder Adobe Design Premium CS3.

4. Open the picture file.

5. When making an outline of another picture file, the first step is to create a second layer. This is where your outline will be held.
   To do this, select the layers tool button on the right side of the screen. It will be at the bottom.

6. The layer window will pop up. You first want to lock the first layer by checking the empty box next to an icon of an eye. If you click the right one a picture of a lock will appear. This will be the reference layer for your outline.

7. The next step is to create the aforementioned sketch layer. While in the layer toolbox, select the icon at the bottom next to the trash can (delete icon). This is the create new layer icon. If you did this correctly, the same toolbox will display two different layers (1 and 2). You do not need to lock the second layer.

8. You may now exit the layer toolbar, pertaining that you successfully created two layers and locked the reference layer.

   Note: You can toggle between layers by hitting the ctrl and y keys
   You can use the scroll wheel for vertical movement and hold the ctrl button with the scroll wheel for horizontal movement. To zoom in and out, use the ctrl and + or – keys.

9. You may now begin sketching your picture. Select the pen tool from the tools on the right. Make sure you are in your reference layer. The pen tool works through clicking and dragging. First find an anchor point, this is the starting point for the line segment you will draw, next find an endpoint. Click and hold at the endpoint and manipulate the line to fit the area you are tracing. When the trace line fits, you may let go. Re click the endpoint to make that the new anchor point and find a new end point and repeat the process until you are satisfied with your drawing.

10. You may check your work by toggling between layers using the ctrl and y keystroke. When you are done, **export** the file as an AutoCAD (dwg) file.

11. Start up solid works and open the dwg file. Remember you wont find it unless you are specifically looking for a dwg file.

12. A window will popup giving you a list of selections to use. Select import as a new part and click next. Click next to see your drawing, if you do not see an outline of your drawing in any of the next few windows, you messed up. Give up and raise your hand and a teacher will assist you shortly.
13. If done correctly you can hit finish and a sketch will appear in a solid works environment. Good Job.

K

Janka hardness

A measure of the hardness of wood, produced by a variation on the Brinell hardness test. The test measures the force required to push a steel ball with a diameter of 11.28 millimeters (0.444 inches) into the wood to a depth of half the ball's diameter (the diameter was chosen to produce a circle with an area of 100 square millimeters). In Janka's original test. the results were expressed in units of pressure, but when the ASTM standardized the test (tentative issue in *1922*, standard first formally adopted in *1927*), it called for results in units of force.

The results are stated in various ways in different countries, which can lead to confusion, especially since the name of the actual unit employed is often not attached. In the United States, the measurement is in pounds-force. In Sweden it is apparently in kilogram-force (kgf), and in Australia, Janka hardness ratings are either in newtons (N) or kilonewtons (kN). Sometimes the results are treated as units, e.g., "360 janka."

The hardness of wood usually varies with the direction of the grain. If testing is done on the surface of a plank, with the force exerted perpendicular to the grain, the test is said to be of "side hardness." Side hardnesses of a block of wood measured in the direction of the tree's center (radially), and on a tangent to the tree's rings (tangentially), are typically very similar. End testing is also sometimes done (that is, testing the cut surface of a stump would be a test of end hardness). The side hardness of teak, for example, is in the range 3730 to 4800 newtons, while the end hardness is in the range 4150 to 4500 newtons.

The most common use of Janka hardness ratings is to determine whether a species is suitable for use as flooring.

Notes on the table

The pale blue background indicates species growing in North America. Common names, of course, are unreliable; two or more species often have the same common name. We show the name preferred by the Forest Products Laboratory. Except as noted, all samples were tested at 12% moisture content, typical of air-dried wood. Wood varies; a sample picked at random is expected to have a side hardness between about 80% and 120% of the value shown. Blank cells occur where a wood is sold commercially but so far we have found no hardness data.

Side Hardness of Some Woods

Common name	Scientific name	side hardness, Janka test, at 12% moisture content	

		kilonewtons	pounds-force
afromosia	*Pericopsis elata*	7.1	1560
albarco	*Cariniana* spp.	4.5	1020
alder, red	*Alnus rubra*	2.6	590
alder, white	*Alnus rhombifolia*		
andiroba	*Carapa guianensis*	5.0	1130
angelin	*Andira inermis*	7.8	1750
angelique	*Dicorynia guianensis*	5.7	1290
apple	*Malus sylvestris*	7.7	1730
ash, black	*Fraxinus nigra*	3.8	850
ash, blue	*Fraxinus quadrangulata*	9.0	2030
ash, green	*Fraxinus pennsylvanica*	5.3	1200
ash, oregon	*Fraxinus latifolia*	5.2	1160
ash, pumpkin	*Fraxinus profunda*	4.4	990
ash, white	*Fraxinus americana*	5.9	1320
aspen, bigtooth	*Populus grandidentata*	1.9	420
aspen, quaking	*Populus tremuloides*	1.6	350
avodire	*Turraeanthus africanus*	4.8	1080
azobe	*Lophira aiata*	14.9	3350
baldcypress	*Taxcodium distichum*	2.3	570
balsa	*Ochroma pyramidale*		
banak	*Virola* spp.	2.3	510
basswood, American	*Tilia americana*	1.8	410
basswood, Carolina	*Tilia caroliniana*		
basswood, white	*Tilia heterophylla*		
beech, American	*Fagus grandifolia*	5.8	1300
benge	*Guibourtia amoldiana*	7.8	1750
birch, gray	*Betula populifolia*	3.4	760
birch, paper	*Betula papyrifera*	4.0	910

birch, river	*Betula nigra*		
birch, sweet	*Betula lenta*	6.5	1470
birch, yellow	*Betula alleghaniensis*	5.6	1260
boxelder	*Acer negundo*	3.2	720
bubinga	*Guibourtia* spp.	12.0	2690
buckeye, Ohio	*Aesculus glabra*		
buckeye, yellow	*Aesculus octandra*	1.6	350
buckthorn, cascara	*Rhamnus purshiana*	4.6	1040
bulletwood	*Manilkara bidentata*	14.2	3190
butternut	*Juglans cinerea*	2.2	490
buttonwood	*Conocarpus erectus*		
catalpa, northern	*Catalpa speciosa*	2.4	550
catalpa, southern	*Catalpa bignonioides*	2.4	550
cativo	*Prioria copaifera*	2.8	630
cedar, Alaska	*Chamaecyparis nootkatensis*	2.6	580
cedar, atlantic white	*Chamaecyparis thyoides*	1.6	350
cedar, Port Orford	*Chamaecyparis lawsoniana*	3.2	720
cedar, yellow		2.6	580
ceiba	*Ceiba pentandra*	1.1	240
cherry, black	*Prunus serotina*	4.2	950
chestnut, American	*Castenea dentata*	2.4	540
chinkapin, giant	*Castanopsis chrysophylla*	3.2	730
coffeetree, Kentucky	*Gymnocladus dioicus*	6,2	1390
cottonwood) balsam poplar	*Populus balsamifera*	1.3	300
cottonwood, black	*Populus trichocarpa*	1.6	350
cottonwood, eastern	*Populus deltoides*	1.9	430
courbaril	*Hymenaea courbaril*	10.5	2350
cuangare	*Dialyanthera* spp.	1.7	380
cypress, Mexican	*Cupressus lustianica*	2.0	460

degame	*Calycophyllum candidissimum*	8.6	1940
determa	*Ocotea rubra*	2.9	660
dogwood, flowering	*Cornus florida*	9.6	2150
Douglas-fir, coast	*Pseudotsuga menziesii*	3.2	710
Douglas-fir. interior west	*Pseudotsuga menziesii*	2.9	660
Douglas-fir, interior north	*Pseudotsuga menziesii*	2.7	600
Douglas-fir, interior south	*Pseudotsuga menziesii*	2.3	510
ekop	*Tetraberlinia tubmaniana*		
elder, blue	*Sambucus cerulea*	3.7	840
elm, american	*Ulmus americana*	3.7	830
elm, cedar	*Ulmus crassifolia*	5.9	1320
elm, rock	*Ulmus thomasii*	5.9	1320
elm, slippery	*Ulmus rubra*	3.8	860
elm, winged	*Ulmus alata*	6.8	1540
fir, balsam	*Abies balsamea*	1.8	400
fir, California red	*Abies magnifica*	2.2	500
fir, grand	*Abies grandis*	2.2	490
fir, noble	*Abies procera*	1.8	410
fir, pacific silver	*Abies amabilis*	1.9	430
fir, subalpine	*Abies lasiocarpa*	1.6	350
fir, white	*Abies concolor*	2.1	480
goncalo alves	*Astronium graveolens*	9.6	2160
greenheart	*Chlorocardium rodiei*	10.5	2350
hackberry	*Celtis occidentalis*	3.9	880
hackberry, netleaf	*Celtis reticulata*		
(hackberry) sugarberry	*Celtis laevigata*		
hemlock, eastern	*Tsuga canadensis*	2.2	500
hemlock, mountain	*Tsuga mertensiana*	3.0	680

hemlock, western	*Tsuga heterophylla*	2.4	540
hickory, bitternut	*Carya cordiformis*		
hickory, black	*Carya texana*		
hickory, nutmeg	*Carya myristicaeformis*		
hickory, pecan	*Carya illinoensis*	8.1	1820
hickory, sand	*Carya pallida*		
hickory, water	*Carya aquatica*		
hickory. mockernut	*Carya tomentosa*		
hickory, pignut	*Carya glabra*		
hickory, shagbark	*Carya ovata*		
hickory, shellbark	*Carya lacinosa*		
holly, American	*Ilex opaca*	4.5	1020
honeylocust	*Gleditsia triacanthos*	7.0	1580
hophornbeam, eastern	*Ostrya virginiana*	8.3	1860
hornbeam, American	*Carpinus caroliniana*	7.9	1780
hura	*Hura crepitans*	2.4	550
ilomba	*Pycnanthus angolensis*	2.7	610
incense-cedar	*Libocedrus decurrens*	2.1	470
ipe	*Tabebula* spp., lapacho group	16.4	3680
iroko	*Chlorophora* spp.	5.6	1260
jarrah	*Eucalyptus marginata*	8.5	1910
jelutong	*Dyera costulata*	1.7 (@15%)	390
juniper, alligator	*Juniperus deppeana*	5.2	1160
juniper, western	*Juniperus occidentalis*		
kaneelhart	*Licaria* spp.	12.9	2900
kapur	*Dryobalanops* spp.	5.5	1230
karri	*Eucalyptus diversicolor*	9.1	2040
kempas	*Koompassia malaccensis*	7.6	1710
keruing	*Dipterocarpus* spp.	5.6	1270

larch, western	*Larix occidentalis*	3.7	830
laurel, California	*Umbellularia californica*	5.6	1270
laurel, mountain	*Kalmia latifolia*	8.0	1790
lignumvitae	*Guaiacum* spp.	20.0	4500
limba	*Terminalia superba*	2.2	490
locust, black	*Robinia pseudoacacia*	7.6	1700
macawood	*Platymiscium* spp.	14.0??	3150
madrone, Pacific	*Arbutus menziesii*	6.5	1460
(magnolia) cucumber tree	*Magnolia acuminata*	3.1	700
magnolia, southern	*Magnolia grandiflora*	4.5	1020
(magnolia) sweetbay	*Magnolia virginiana*		
mahogany, African	*Khaya* spp.	3.7	830
mahogany, true	*Swietenia macrophylla*	3.6	800
manbarklak	*Eschweilera* spp.	15.5	3480
manni	*Symphonia globulifera*	5.0	1120
maple, bigleaf	*Acer macrophyllum*	3.8	850
maple, black	*Acer nigrum*	5.2	1180
maple, red	*Acer rubrum*	4.2	950
maple, silver	*Acer saccharimum*	3.1	700
maple, sugar	*Acer saccharum*	6.4	1450
marishballi	*Lincania* spp.	15.9	3570
merbau	*Intsia* spp.	6.7 (@15%)	1500
mersawa	*Anisoptera* spp.	5.7	1290
mesquite	*Prosopis* spp.		
mora	*Mora* spp.	10.2	2300
oak, black	*Quercus velutina*	5.4	1210
oak, cherrybark	*Quercus falcata* var *pagodifolia*	6.6	1480
oak, southern red	*Quercus falcata*	4.7	1060

oak, laurel	*Quercus laurifolia*	5.4	1210
oak, northern red	*Quercus rubra*	5.7	1290
oak, pin	*Quercus palustris*	6.7	1510
oak, scarlet	*Quercus coccinea*	6.2	1400
oak, shumard	*Quercus shumardii*		
oak, water	*Quercus nigra*	5.3	1190
oak, willow	*Quercus phellos*	6.5	1460
oak, bur	*Quercus macrocarpa*	6.1	1370
oak, chestnut	*Quercus prinus*	5.0	1130
oak, live	*Quercus virginiana*		
oak, overcup	*Quercus lyrata*	5.3	1190
oak, post	*Quercus stellata*	6.0	1360
oak, swamp chestnut	*Quercus michauxii*	5.5	1240
oak, swamp white	*Quercus bicolor*	7.2	1620
oak, white	*Quercus alba*	6.0	1360
obeche	*Triplochiton scleroxylon*	1.9	430
okoume	*Aucoumea klaineana*	1.7	380
opepe	*Nauclea diderrichii*	7.3	1630
osage orange	*Maclura pomifera*	9.1 (green)	2040 (green)
ovangkoi	*Goubertia ehie*		
para-angelim	*Hymenolobium excelsum*	7.7	1720
parana-pine	*Araucaria augustifolia*	3.5	780
pau marfim	*Balfourodendron riedelianum*		
peroba de campos	*Paratecoma peroba*	7.1	1600
peroba rosa	*Aspidosperma* spp., peroba group	7.7	1730
persimmon, common	*Diospyros virginiana*	10.2	2300
pilon	*Hyeronima* spp.	7.6	1700
pine, Caribbean	*Pinus* caribaea	5.5	1240

pine, eastern white	*Pinus strobus*	1.7	380
pine, jack	*Pinus banksiana*	2.5	570
pine, Jeffrey	*Pinus jeffreyi*	2.2	500
pine, limber	*Pinus flexilis*	1.9	430
pine, loblolly	*Pinus taeda*	3.1	690
pine, lodgepole	*Pinus contorta*	2.1	480
pine, longleaf	*Pinus palustris*	3.9	870
pine, ocote	*Pinus oocarpa*	4.0	910
pine, pinyon	*Pinus edulis*	3.8	860
pine, pitch	*Pinus rigida*	2.8	620
pine, pond	*Pinus serotina*	3.3	740
pine, ponderosa	*Pinus ponderosa*	2.0	460
pine, Monterey	*Pinus radiata*	3.3	750*
pine. red	*Pinus resinosa*	2.5	560
pine, sand	*Pinus clausa*	3.3	730
pine, shortleaf	*Pinus echinata*	3.1	690
pine, slash	*Pinus elliotti*		
pine, spruce	*Pinus glabra*	2.9	660
pine, sugar	*Pinus lambertiana*	1.7	380
pine, Table Mountain	*Pinus pungens*	2.9	660
pine, virginia	*Pinus virginiana*	3.3	740
pine, western white	*Pinus monticola*	1.9	420
piquia	*Caryocar* spp.	7.7	1720
primavera	*Tabebula donnell-smithii*	2.9	660
purpleheart	*Peltogyne* spp.	8.3	1860
ramin	*Gonystylus bancanus*	5.8	1300
redcedar, eastern	*Juniperus virginiana*	4.0	900
redcedar, southern	*Juniperus silicicola*	2.7	610
redcedar, western	*Thuja plicata*	1.6	350

redwood, old growth	*Sequoia sempervirens*	2.1	480
redwood, second growth	*Sequoia sempervirens*	1.9	420
robe	*Tabebul* spp., roble group	4.3	960
rosewood, Brazilian	*Dalbergia nigra*	12.1	2720
rosewood, Indian	*Dalbergia latifolia*	14.1	3170
sande	*Brosimum* spp., utile group	4.0	900
santa maria	*Calophyllum brasiliense*	5.1	1150
sapele	*Entandrophragma cylindricum*	6.7	1510
sassafras	*Sassafras albidum*	2.8	630
sepetir	*Pseudosindora palustris*	6.3	1410
serviceberry	*Amelanchier* spp.	8.0	1800
shorea	*Shorea* spp., baulau group	7.9	1780
(shorea) dark red meranti	*Shorea* spp., lauan-meranti group	3.5	780
(shorea) light red meranti	*Shorea* spp., lauan-meranti group	2.0	460
(shorea) white meranti	*Shorea* spp., lauan-meranti group	5.1 (@15%)	1140
(shorea) yellow meranti	*Shorea* spp., lauan-meranti group	3.4	770
silverbell, Carolina	*Halesia carolina*	2.6	590
sourwood	*Oxydendrum arboreum*	4.2	940
Spanish-cedar	*Cedrela* spp.	2.7	600
spruce, black	*Picea mariana*	2.3	520
spruce, Engelmann	*Picea engelmanni*	1.7	390
spruce, red	*Picea rubra*	2.2	490
spruce, Sitka	*Picea sitchensis*	2.3	510
spruce, white	*Picea glauca*	2.1	480
sucupira	*Bowdichia* spp.		
sucupira	*Diplotropis purpurea*	9.5	2140
sumac, staghorn	*Rhus typhina*	3.0	680

sweetgum	*Liquidambar styraciflua*	3.8	850
sycamore, american	Platanus occidentalis	3.4	770
tamarack	*Larix laricina*	2.6	590
tanoak	*Lithocarpus densiflorus*		
teak	*Tectona grandis*	4.4	1000
tomillo	*Cedrelinga catenformis*		870 (green)
tree-of-heaven	*Ailanthus altissima*	7.7	1731
tupelo, black	*Nyssa sylvatica*	3.6	810
tupelo. water	*Nyssa aquatica*	3.9	880
wallaba	*Eperua* spp.	9.1	2040
walnut, black	*Juglans nigra*	4.5	1010
white-cedar, northern	*Thuja occidentalis*	1.4	320
willow, black	*Salix nigra*		
witch hazel	*Hamamelis virginica*	6.8	1530
yellow poplar	*Liriodendron tulipifera*	2.4	540
yew. Pacific	*Taxus brevifolia*	7.1	1600

*Authorities differ significantly on the hardness of *Pinus radiata*, with published values as high as 792 lbs-force (3.5 kilonewtons) and as low as 625 lbf (2.8 kN).

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RESOURCES

Standards:
ASTM D1037-99. Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials.
ASTM D143-94(2000)e1 Standard Methods of Testing Small Clear Specimens of Timber.
ISO 3350:1975. Wood–Determination of static hardness.
ISO 3351:1975. Wood–Determination of resistance to impact indentation.

Janka hardness ratings can also be found at sites selling flooring, such as:

www.wflooring.com/Technical_Info/Species_Tech_Info/species_hardness.htm

www.zoltanfloors.com/tech.html

Some information sources say or imply, incorrectly, that Janka hardness is measured in units of pressure, such as pounds per square inch, and that side hardness is a synonym for Janka hardness.

L

D'Addario

catalog supplement/string tension specifications

A complete technical reference for fretted instrument string tensions

This brochure was created to assist in selecting the ideal string for your instrument and playing style. Included in this brochure are tension tables and formulas to help you calculate what tension a particular string will have on your instrument.

table of contents

Introduction

String Tensions

A complete technical reference
for fretted instrument string tensions

Understanding what determines string tension.

In order to determine the tension at which a string will vibrate, you need three pieces of information: the Unit Weight, the Scale Length, and the Frequency of the string. You can use the charts in this brochure to get a pre-calculated tension for the D'Addario strings listed or you can use the formulas below to calculate the exact tension for any string using the scale length of your particular instrument. All of the charts illustrate string tensions for each string at a variety of pitches, in case you use alternative tunings.

UW- Unit Weight. In all the charts and formulas in the brochure, unit weight is expressed in pounds per linear inch (lb/in).

L- Scale Length. This is the vibrating length of the string. This is determined by measuring the distance from the nut to the bridge of the instrument in inches (in).

F- Frequency or pitch. This is the pitch at which you will be tuning the string expressed in cycles per second (Hertz).

On the following page are two fingerboard graphics detailing the various frequencies for the standard guitar and electric bass guitar.

To calculate the tension of a string in pounds use the formula below, inserting the three variables described above:

T (Tension) = $(UW \times (2 \times L \times F)^2) / 386.4$

To convert the result into Newtons, simply multiply by 4.45.

If you know what tension you want the string to have, you can calculate the string unit weight. You can then use the charts in this guide to locate a string with approximately the same desired unit weight.

UW (unit weight) = $(T \times 386.4) / (2 \times L \times F)^2$

Scale Lengths

To calculate the exact tension for a string on your instrument, measure the scale length (nut to bridge) of your instrument and then use the formula on the previous page. The following scale lengths were used to determine the string tensions found on the tension charts in this brochure.

Acoustic/Electric/Classical Guitar = 25 1/2"
Electric Bass Guitar (Superlong Scale) = 36"
Electric Bass Guitar (Long Scale) = 34"
Electric Bass Guitar (Medium Scale) = 32"
Electric Bass Guitar (Short Scale) = 30"
Mandolin = 13 7/8"
Mandola = 15 7/8"
Mandocello = 25"
Mandobass = 42"
Banjo = 26 1/4" (19 5/8" for 5th string)

Fingerboard Legends for Pitch and Frequency at Standard Tuning

Guitar and Bass Guitar Fingerboard Legends

Use these graphics to determine the frequency (in Hertz) of the pitch you are looking for. Standard tunings were used for all guitar and electric bass guitar frequency measurements.

Pitch Notation

c' (Middle c) = 261.6 Hz
Note Above = d'
Note Below = b
Octave Above = c"
Octave Below = c
2 Octaves Below = C
3 Octaves Below = C'

	Nut / Open	1st Fret	2nd Fret	3rd Fret	4th Fret
1st String	e' - 329.6 Hz	f' - 349.2 Hz	f#' - 370.0 Hz	g' - 392.0 Hz	g#' - 415.3 Hz
2nd String	b - 246.9 Hz	c' - 261.6 Hz	c#' - 277.2 Hz	d' - 293.7 Hz	d#' - 311.1 Hz
3rd String	g - 196.0 Hz	g# - 207.7 Hz	a - 220.0 Hz	a# - 233.1 Hz	b - 246.9 Hz
4th String	d -146.8 Hz	d# - 155.6 Hz	e - 164.8 Hz	f - 174.6 Hz	f# - 185.0 Hz
5th String	A - 110.0 Hz	A# - 116.5 Hz	B - 123.5 Hz	c - 130.8 Hz	c# - 138.6 Hz
6th String	E - 82.4 Hz	F - 87.3 Hz	F# - 92.5 Hz	G - 98.0 Hz	G# - 103.8 Hz

Guitar Fingerboard Layout
(Standard Tuning)

4-String Layout (2nd–5th String)

	Nut / Open	1st Fret	2nd Fret	3rd Fret	4th Fret
1st String	c - 130.8 Hz	c# - 138.6 Hz	d - 146.8 Hz	d# - 155.6 Hz	e - 164.8 Hz
2nd String	G - 98.0 Hz	G# - 103.8 Hz	A - 110.0 Hz	A# - 116.5 Hz	B - 123.5 Hz
3rd String	D - 73.4 Hz	D# - 77.8 Hz	E - 82.4 Hz	F - 87.3 Hz	F# - 92.5 Hz
4th String	A' - 55.0 Hz	A#' - 58.3 Hz	B' - 61.7 Hz	C - 65.4 Hz	C# - 69.3 Hz
5th String	E' - 41.2 Hz	F' - 43.7 Hz	F#' - 46.3 Hz	G' - 49.0 Hz	G#' - 51.9 Hz
6th String	B" - 30.9 Hz	C' - 32.7 Hz	C#' - 34.7 Hz	D' - 36.7 Hz	D#' - 38.9 Hz

Bass Guitar Fingerboard Layout
(Standard 6-String Tuning)

Acoustic or Electric guitar

Plain Steel - Lock Twist

Item#	Unit Weight	g'	f'	e'	d'	c'	b	a	g
PL007	.00001085	11.2	8.9	7.9	6.3	5.0	4.5	3.5	2.8
PL008	.00001418	14.7	11.6	10.4	8.2	6.5	5.8	4.6	3.7
PL0085	.00001601	16.6	13.1	11.7	9.3	7.4	6.6	5.2	4.1
PL009	.00001794	18.6	14.7	13.1	10.4	8.3	7.4	5.8	4.6
PL0095	.00001999	20.7	16.4	14.6	11.6	9.2	8.2	6.5	5.2
PL010	.00002215	22.9	18.2	16.2	12.9	10.2	9.1	7.2	5.7
PL0105	.00002442	25.3	20.0	17.9	14.2	11.3	10.0	8.0	6.3
PL011	.00002680	27.7	22.0	19.6	15.6	12.3	11.0	8.7	6.9
PL0115	.00002930	30.3	24.0	21.4	17.0	13.5	12.0	9.5	7.6
PL012	.00003190	33.0	26.2	23.3	18.5	14.7	13.1	10.4	8.2
PL013	.00003744	38.7	30.7	27.4	21.7	17.2	15.4	12.2	9.7
Item#	Unit Weight	d'	c'	b	a	g	f	e	d
PL0135	.00004037	23.4	18.6	16.6	13.2	10.4	8.3	7.4	5.9
PL014	.00004342	25.2	20.0	17.8	14.1	11.2	8.9	7.9	6.3
PL015	.00004984	28.9	23.0	20.5	16.2	12.9	10.2	9.1	7.2
PL016	.00005671	32.9	26.1	23.3	18.5	14.7	11.6	10.4	8.2
PL017	.00006402	37.2	29.5	26.3	20.9	16.6	13.1	11.7	9.3
Item#	Unit Weight	b	a	g	f	e	d	c	B
PL018	.00007177	29.5	23.4	18.6	14.7	13.1	10.4	8.3	7.4
PL019	.00007997	32.8	26.1	20.7	16.4	14.6	11.6	9.2	8.2
PL020	.00008861	36.4	28.9	22.9	18.2	16.2	12.9	10.2	9.1
Item#	Unit Weight	a	g	f	e	d	c	B	A
PL022	.00010722	34.9	27.7	22.0	19.6	15.6	12.3	11.0	8.7
PL024	.00012760	41.6	33.0	26.2	23.3	18.5	14.7	13.1	10.4
PL026	.00014975	48.8	38.7	30.7	27.4	21.7	17.2	15.4	12.2

Plain Steel - Soldered Twist

Item#	Unit Weight	g'	f'	e'	d'	c'	b	a	g
KPL009	.00001794	18.6	14.7	13.1	10.4	8.3	7.4	5.8	4.6
KPL010	.00002215	22.9	18.2	16.2	12.9	10.2	9.1	7.2	5.7
KPL011	.00002680	27.7	22.0	19.6	15.6	12.3	11.0	8.7	6.9
KPL012	.00003190	33.0	26.2	23.3	18.5	14.7	13.1	10.4	8.2
KPL013	.00003744	38.7	30.7	27.4	21.7	17.2	15.4	12.2	9.7
Item#	Unit Weight	d'	c'	b	a	g	f	e	d
KPL014	.00004342	25.2	20.0	17.8	14.1	11.2	8.9	7.9	6.3
KPL016	.00005671	32.9	26.1	23.3	18.5	14.7	11.6	10.4	8.2
KPL017	.00006402	37.2	29.5	26.3	20.9	16.6	13.1	11.7	9.3
KPL020	.00008861	51.5	40.8	36.4	28.9	22.9	18.2	16.2	12.9

Plain Steel - Double Ball End

Item#	Unit Weight	g'	f'	e'	d'	c'	b	a	g
SPL009	.00001794	18.6	14.7	13.1	10.4	8.3	7.4	5.8	4.6
SPL010	.00002215	22.9	18.2	16.2	12.9	10.2	9.1	7.2	5.7
SPL011	.00002680	27.7	22.0	19.6	15.6	12.3	11.0	8.7	6.9
SPL013	.00003744	38.7	30.7	27.4	21.7	17.2	15.4	12.2	9.7
Item#	Unit Weight	d'	c'	b	a	g	f	e	d
SPL016	.00005671	32.9	26.1	23.3	18.5	14.7	11.6	10.4	8.2
SPL017	.00006402	37.2	29.5	26.3	20.9	16.6	13.1	11.7	9.3

XL - Nickelplated Steel Round Wound

Item#	Unit Weight	b	a	g	f	e	d	c	B
NW017	.00005524	-	18.0	14.3	11.3	10.1	8.0	6.4	5.7
NW018	.00006215	25.5	20.2	16.1	12.8	11.4	9.0	7.2	6.4
NW019	.00006947	28.5	22.6	18.0	14.3	12.7	10.1	8.0	7.1
NW020	.00007495	-	24.4	19.4	15.4	13.7	10.9	8.6	7.7
NW021	.00008293	34.0	27.0	21.4	17.0	15.2	12.0	9.6	8.5
NW022	.00009184	37.7	29.9	23.7	18.8	16.8	13.3	10.6	9.4
NW024	.00010857	44.6	35.4	28.1	22.3	19.8	15.8	12.5	11.1
NW026	.00012671	-	41.3	32.8	26.0	23.2	18.4	14.6	13.0
Item#	Unit Weight	f	e	d	c	B	A	G	F
NW028	.00014666	30.1	26.8	21.3	16.9	15.1	11.9	9.5	7.5
NW030	.00017236	35.4	31.5	25.0	19.9	17.7	14.0	11.1	8.8
NW032	.00019347	39.7	35.4	28.1	22.3	19.9	15.8	12.5	9.9
NW034	.00021590	44.3	39.5	31.3	24.9	22.2	17.6	14.0	11.1
NW036	.00023964	49.2	43.8	34.8	27.6	24.6	19.5	15.5	12.3
NW038	.00026471	54.3	48.4	38.4	30.5	27.2	21.6	17.1	13.6
Item#	Unit Weight	c	B	A	G	F	E	D	C
NW039	.00027932	32.2	28.7	22.8	18.1	14.3	12.8	10.1	8.0
NW042	.00032279	37.2	33.1	26.3	20.9	16.6	14.8	11.7	9.3
NW044	.00035182	40.5	36.1	28.7	22.7	18.0	16.1	12.8	10.1
NW046	.00038216	44.0	39.2	31.1	24.7	19.6	17.5	13.9	11.0
NW048	.00041382	47.7	42.5	33.7	26.8	21.2	18.9	15.0	11.9
NW049	.00043014	49.5	44.2	35.0	27.8	22.1	19.7	15.6	12.4
NW052	.00048109	55.4	49.4	39.2	31.1	24.7	22.0	17.4	13.9
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
NW054	.00053838	43.9	34.8	27.6	24.6	19.5	15.5	13.8	11.0
NW056	.00057598	46.9	37.2	29.5	26.3	20.9	16.6	14.8	11.7
NW059	.00064191	52.3	41.5	32.9	29.3	23.3	18.5	16.4	13.1
NW060	.00066542	54.2	43.0	34.1	30.4	24.1	19.2	17.1	13.5
NW062	.00070697	57.6	45.7	36.3	32.3	25.6	20.4	18.1	14.4
NW064	.00074984	61.1	48.5	38.5	34.3	27.2	21.6	19.2	15.3
NW066	.00079889	65.1	51.6	41.0	36.5	29.0	23.0	20.5	16.3
NW068	.00084614	68.9	54.7	43.4	38.7	30.7	24.4	21.7	17.2
NW070	.00089304	72.7	57.7	45.8	40.8	32.4	25.7	22.9	18.2
NW072	.00094124	76.7	60.8	48.3	43.0	34.1	27.1	24.1	19.2
NW074	.00098869	80.5	63.9	50.7	45.2	35.9	28.5	25.3	20.1
NW080	.00115011	93.7	74.4	59.0	52.6	41.7	33.1	29.5	23.4

XL - Nickelplated Steel Round Wound Steinberger

Item#	Unit Weight	b	a	g	f	e	d	c	B
SNW024	.00010857	44.6	35.4	28.1	22.3	19.8	15.8	12.5	11.1
SNW026	.00012671	-	41.3	32.8	26.0	23.2	18.4	14.6	13.0
Item#	Unit Weight	f	e	d	c	B	A	G	F
SNW032	.00019347	39.7	35.4	28.1	22.3	19.9	15.8	12.5	9.9
SNW036	.00023964	49.2	43.8	34.8	27.6	24.6	19.5	15.5	12.3
Item#	Unit Weight	c	B	A	G	F	E	D	C
SNW042	.00032279	37.2	33.1	26.3	20.9	16.6	14.8	11.7	9.3
SNW046	.00038216	44.0	39.2	31.1	24.7	19.6	17.5	13.9	11.0

XLS - Stainless Steel Round Wound

Item#	Unit Weight	b	a	g	f	e	d	c	B
XSG018	.00006588	27.0	21.5	17.0	13.5	12.0	9.6	7.6	6.8
XSG020	.00007919	-	25.8	20.5	16.2	14.5	11.5	9.1	8.1
XSG021	.00008774	-	28.6	22.7	18.0	16.0	12.7	10.1	9.0
XSG022	.00009731	39.9	31.7	25.2	20.0	17.8	14.1	11.2	10.0
XSG024	.00011501	-	37.5	29.7	23.6	21.0	16.7	13.2	11.8
XSG026	.00013419	-	43.7	34.7	27.5	24.5	19.5	15.5	13.8

XLS - Stainless Steel Round Wound

Item#	Unit Weight	f	e	d	c	B	A	G	F
XSG028	.00015493	31.8	28.3	22.5	17.8	15.9	12.6	10.0	7.9
XSG030	.00018203	37.4	33.3	26.4	21.0	18.7	14.8	11.8	9.3
XSG032	.00020398	41.9	37.3	29.6	23.5	20.9	16.6	13.2	10.5
XSG034	.00022729	46.6	41.6	33.0	26.2	23.3	18.5	14.7	11.7
XSG036	.00025198	51.7	46.1	36.6	29.0	25.9	20.5	16.3	12.9
XSG038	.00027804	-	50.8	40.3	32.0	28.5	22.6	18.0	14.3
Item#	Unit Weight	c	B	A	G	F	E	D	C
XSG040	.00031044	35.8	31.9	25.3	20.1	15.9	14.2	11.3	8.9
XSG042	.00033924	39.1	34.8	27.6	21.9	17.4	15.5	12.3	9.8
XSG046	.00040096	46.2	41.2	32.7	25.9	20.6	18.3	14.5	11.5
XSG048	.00043387	50.0	44.5	35.3	28.0	22.3	19.8	15.7	12.5
XSG050	.00046816	53.9	48.1	38.1	30.3	24.0	21.4	17.0	13.5
XSG052	.00050382	58.0	51.7	41.0	32.6	25.8	23.0	18.3	14.5
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
XSG054	.00056388	45.9	36.5	28.9	25.8	20.4	16.2	14.4	11.5
XSG056	.00060297	49.1	39.0	30.9	27.6	21.9	17.4	15.5	12.3
XSG070	.00092592	75.4	59.9	47.5	42.3	33.6	26.7	23.7	18.9

Half Round - Stainless Steel Half Round

Item#	Unit Weight	a	g	f	e	d	c	B	A
HRG022	.00011271	36.7	29.1	23.1	20.6	16.3	13.0	11.6	9.2
HRG024	.00012857	41.9	33.2	26.4	23.5	18.7	14.8	13.2	10.5
HRG026	.00014750	-	38.1	30.3	27.0	21.4	17.0	15.1	12.0
Item#	Unit Weight	f	e	d	c	B	A	G	F
HRG030	.00018970	38.9	34.7	27.5	21.8	19.5	15.5	12.3	9.7
HRG032	.00021100	43.3	38.6	30.6	24.3	21.7	17.2	13.6	10.8
HRG036	.00025650	52.6	46.9	37.2	29.5	26.3	20.9	16.6	13.2
Item#	Unit Weight	c	B	A	G	F	E	D	C
HRG039	.00029700	34.2	30.5	24.2	19.2	15.2	13.6	10.8	8.6
HRG042	.00033400	38.5	34.3	27.2	21.6	17.1	15.3	12.1	9.6
HRG046	.00039810	45.8	40.9	32.4	25.7	20.4	18.2	14.4	11.5
HRG052	.00049500	57.0	50.8	40.3	32.0	25.4	22.6	18.0	14.3
HRG056	.00056700	65.3	58.2	46.2	36.7	29.1	25.9	20.6	16.3

Chromes - Stainless Steel Flat Wound

Item#	Unit Weight	b	a	g	f	e	d	c	B
CG020	.00007812	32.1	25.4	20.2	16.0	14.3	11.3	9.0	8.0
CG022	.00009784	-	31.9	25.3	20.1	17.9	14.2	11.3	10.0
CG024	.00011601	-	37.8	30.0	23.8	21.2	16.8	13.4	11.9
CG026	.00013574	-	44.2	35.1	27.9	24.8	19.7	15.6	13.9
Item#	Unit Weight	g	f	e	d	c	B	A	G
CG028	.00014683	38.0	30.1	26.8	21.3	16.9	15.1	12.0	9.5
CG030	.00016958	43.9	34.8	31.0	24.6	19.5	17.4	13.8	11.0
CG032	.00019233	49.7	39.5	35.2	27.9	22.1	19.7	15.7	12.4
CG035	.00024197	62.6	49.7	44.2	35.1	27.9	24.8	19.7	15.6
Item#	Unit Weight	d	c	B	A	G	F	E	D
CG038	.00026520	38.5	30.5	27.2	21.6	17.1	13.6	12.1	9.6
CG040	.00031676	46.0	36.5	32.5	25.8	20.5	16.3	14.5	11.5
CG042	.00034377	49.9	39.6	35.3	28.0	22.2	17.6	15.7	12.5
CG045	.00040393	58.6	46.5	41.5	32.9	26.1	20.7	18.5	14.6
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
CG048	.00043541	35.5	28.1	22.3	19.9	15.8	12.5	11.2	8.9
CG050	.00047042	38.3	30.4	24.1	21.5	17.1	13.5	12.1	9.6
CG052	.00049667	40.5	32.1	25.5	22.7	18.0	14.3	12.7	10.1
CG056	.00059075	48.1	38.2	30.3	27.0	21.4	17.0	15.1	12.0
CG065	.00089364	72.8	57.8	45.8	40.8	32.4	25.7	22.9	18.2

pedal steel guitar

XLS - Stainless Steel Round Wound Pedal Steel

Item#	Unit Weight	g#	g	f#	f	e	d#	d	c#
SPS024	.00011501	30.2	26.9	24.0	21.3	19.0	17.0	15.1	13.4
SPS026	.00013419	35.2	31.4	28.0	24.9	22.2	19.8	17.6	15.7
SPS030	.00018203	47.8	42.6	37.9	33.8	30.1	26.8	23.9	21.3
Item#	Unit Weight	e	d#	d	c#	c	B	A#	A
SPS034	.00022729	37.6	33.5	29.8	26.6	23.7	21.1	18.8	16.7
SPS036	.00025198	41.7	37.1	33.1	29.5	26.2	23.4	20.8	18.6
SPS038	.00027804	46.0	41.0	36.5	32.5	29.0	25.8	23.0	20.5
Item#	Unit Weight	B	A#	A	G#	G	F#	F	E
SPS042	.00033924	31.5	28.0	25.0	22.3	19.8	17.7	15.7	14.0
SPS054	.00056388	52.4	46.6	41.5	37.0	33.0	29.4	26.2	23.3
Item#	Unit Weight	G	F#	F	E	D#	D	C#	C
SPS070	.00092592	54.1	48.2	43.0	38.3	34.1	30.4	27.1	24.1

acoustic guitar

Phosphor Bronze - Round Wound (EXP Coated and Uncoated)

Item#	Unit Weight	b	a	g	f	e	d	c	B
PB020	.00008106	-	26.4	21.0	16.6	14.8	11.8	9.3	8.3
PB021	.00008944	-	29.1	23.1	18.4	16.4	13.0	10.3	9.2
PB022	.00009876	40.5	32.2	25.5	20.3	18.1	14.3	11.4	10.1
PB023	.00010801	44.3	35.2	27.9	22.2	19.7	15.7	12.4	11.1
PB024	.00011682	-	38.1	30.2	24.0	21.4	16.9	13.5	12.0
PB025	.00012686	-	41.3	32.8	26.0	23.2	18.4	14.6	13.0
PB026	.00013640	-	44.4	35.3	28.0	24.9	19.8	15.7	14.0
PB027	.00014834	-	-	38.4	30.4	27.1	21.5	17.1	15.2
Item#	Unit Weight	f	e	d	c	B	A	G	F
PB029	.00017381	35.7	31.8	25.2	20.0	17.8	14.2	11.2	8.9
PB030	.00018660	38.3	34.1	27.1	21.5	19.2	15.2	12.1	9.6
PB032	.00021018	43.1	38.4	30.5	24.2	21.6	17.1	13.6	10.8
PB034	.00023887	-	43.7	34.7	27.5	24.5	19.5	15.4	12.3
PB035	.00025365	52.1	46.4	36.8	29.2	26.0	20.7	16.4	13.0
PB036	.00026830	55.1	49.0	38.9	30.9	27.5	21.9	17.3	13.8
Item#	Unit Weight	c	B	A	G	F	E	D	C
PB039	.00031125	35.8	32.0	25.4	20.1	16.0	14.2	11.3	9.0
PB042	.00036722	42.3	37.7	29.9	23.7	18.8	16.8	13.3	10.6
PB045	.00041751	48.1	42.9	34.0	27.0	21.4	19.1	15.1	12.0
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
PB047	.00045289	36.9	29.3	23.2	20.7	16.4	13.0	11.6	9.2
PB049	.00049151	40.0	31.8	25.2	22.5	17.8	14.2	12.6	10.0
PB052	.00055223	45.0	35.7	28.3	25.2	20.0	15.9	14.2	11.2
PB053	.00056962	46.4	36.8	29.2	26.0	20.7	16.4	14.6	11.6
PB056D	.00063477	51.7	41.0	32.6	29.0	23.0	18.3	16.3	12.9
PB059	.00070535	57.5	45.6	36.2	32.2	25.6	20.3	18.1	14.4
PB060	.00073039	59.5	47.2	37.5	33.4	26.5	21.0	18.7	14.9
PB062	.00077682	63.3	50.2	39.9	35.5	28.2	22.4	19.9	15.8
PB064	.00082780	67.4	53.5	42.5	37.8	30.0	23.8	21.2	16.9
PB066	.00087718	71.4	56.7	45.0	40.1	31.8	25.3	22.5	17.9
PB070	.00096833	78.9	62.6	49.7	44.3	35.1	27.9	24.8	19.7

Flat Tops - Phosphor Bronze Polished

Item#	Unit Weight	a	g	f	e	d	c	B	A
FT023	.00012568	40.9	32.5	25.8	23.0	18.2	14.5	12.9	10.2
FT024	.00013651	44.5	35.3	28.0	25.0	19.8	15.7	14.0	11.1
FT026	.00015894	-	41.1	32.6	29.1	23.1	18.3	16.3	12.9
FT028	.00017209	56.1	44.5	35.3	31.5	25.0	19.8	17.7	14.0
Item#	Unit Weight	f	e	d	c	B	A	G	F
FT030	.00019785	40.6	36.2	28.7	22.8	20.3	16.1	12.8	10.1
FT032	.00023852	48.9	43.6	34.6	27.5	24.5	19.4	15.4	12.2
FT035	.00027781	-	50.8	40.3	32.0	28.5	22.6	18.0	14.3
FT036	.00029273	60.1	53.5	42.5	33.7	30.1	23.8	18.9	15.0
Item#	Unit Weight	c	B	A	G	F	E	D	C
FT039	.00032904	37.9	33.8	26.8	21.3	16.9	15.0	11.9	9.5
FT042	.00036219	41.7	37.2	29.5	23.4	18.6	16.6	13.1	10.4
FT044	.00041047	47.3	42.1	33.4	26.5	21.1	18.8	14.9	11.8
FT045	.00042603	49.1	43.7	34.7	27.5	21.9	19.5	15.5	12.3
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
FT047	.00046166	37.6	29.8	23.7	21.1	16.7	13.3	11.8	9.4
FT053	.00055793	45.4	36.1	28.6	25.5	20.2	16.1	14.3	11.4
FT056	.00064108	52.2	41.4	32.9	29.3	23.2	18.5	16.4	13.1

80-20'S- 80/20 Brass Round Wound

Item#	Unit Weight	b	a	g	f	e	d	c	B
BW020	.00007862	-	25.6	20.3	16.1	14.4	11.4	9.1	8.1
BW021	.00008684	-	28.3	22.5	17.8	15.9	12.6	10.0	8.9
BW022	.00009600	39.4	31.3	24.8	19.7	17.6	13.9	11.1	9.9
BW023	.00010509	43.1	34.2	27.2	21.6	19.2	15.2	12.1	10.8
BW024	.00011353	-	37.0	29.4	23.3	20.8	16.5	13.1	11.7
BW025	.00012339	-	40.2	31.9	25.3	22.6	17.9	14.2	12.7
BW026	.00013253	-	43.2	34.3	27.2	24.2	19.2	15.3	13.6
BW027	.00014397	-	46.9	37.2	29.5	26.3	20.9	16.6	14.8
Item#	Unit Weight	f	e	d	c	B	A	G	F
BW029	.00016838	34.6	30.8	24.4	19.4	17.3	13.7	10.9	8.6
BW030	.00018092	37.1	33.1	26.2	20.8	18.6	14.7	11.7	9.3
BW032	.00020352	41.8	37.2	29.5	23.4	20.9	16.6	13.2	10.4
BW034	.00022752	46.7	41.6	33.0	26.2	23.4	18.5	14.7	11.7
BW035	.00024006	49.3	43.9	34.8	27.6	24.6	19.6	15.5	12.3
BW036	.00025417	52.2	46.5	36.9	29.3	26.1	20.7	16.4	13.0
Item#	Unit Weight	c	B	A	G	F	E	D	C
BW039	.00030063	34.6	30.9	24.5	19.4	15.4	13.7	10.9	8.7
BW042	.00034808	40.1	35.7	28.4	22.5	17.9	15.9	12.6	10.0
BW045	.00040245	46.3	41.3	32.8	26.0	20.6	18.4	14.6	11.6
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
BW047	.00043634	35.5	28.2	22.4	19.9	15.8	12.6	11.2	8.9
BW049	.00047368	38.6	30.6	24.3	21.6	17.2	13.6	12.1	9.6
BW052	.00053224	43.4	34.4	27.3	24.3	19.3	15.3	13.6	10.8
BW053	.00054852	44.7	35.5	28.1	25.1	19.9	15.8	14.1	11.2
BW056	.00061132	49.8	39.5	31.4	27.9	22.2	17.6	15.7	12.4
BW059	.00068005	55.4	44.0	34.9	31.1	24.7	19.6	17.4	13.8

Great American Bronze - 85/15 Brass Round Wound

Item#	Unit Weight	b	a	g	f	e	d	c	B
ZW022	.00009802	40.2	31.9	25.3	20.1	17.9	14.2	11.3	10.1
ZW024	.00011594	-	37.8	30.0	23.8	21.2	16.8	13.4	11.9
ZW025	.00012592	-	41.0	32.6	25.8	23.0	18.3	14.5	12.9
ZW026	.00013536	-	44.1	35.0	27.8	24.7	19.6	15.6	13.9
Item#	Unit Weight	f	e	d	c	B	A	G	F
ZW030	.00018507	38.0	33.8	26.8	21.3	19.0	15.1	12.0	9.5
ZW032	.00020839	42.8	38.1	30.2	24.0	21.4	17.0	13.5	10.7
ZW034	.00023316	47.8	42.6	33.8	26.9	23.9	19.0	15.1	12.0
ZW035	.00024610	50.5	45.0	35.7	28.3	25.3	20.0	15.9	12.6
ZW036	.00026045	53.4	47.6	37.8	30.0	26.7	21.2	16.8	13.4
Item#	Unit Weight	c	B	A	G	F	E	D	C
ZW040	.00032631	37.6	33.5	26.6	21.1	16.7	14.9	11.8	9.4
ZW042	.00035735	41.2	36.7	29.1	23.1	18.3	16.3	13.0	10.3
ZW044	.00038985	44.9	40.0	31.8	25.2	20.0	17.8	14.1	11.2
ZW045	.00040665	46.8	41.7	33.1	26.3	20.9	18.6	14.7	11.7
ZW046	.00042565	49.0	43.7	34.7	27.5	21.8	19.5	15.4	12.3
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
ZW050	.00050824	41.4	32.9	26.1	23.2	18.4	14.6	13.0	10.3
ZW052	.00054686	44.5	35.4	28.1	25.0	19.8	15.7	14.0	11.1
ZW054	.00058694	47.8	37.9	30.1	26.8	21.3	16.9	15.0	12.0
ZW056	.00062847	51.2	40.6	32.2	28.7	22.8	18.1	16.1	12.8

classical guitar

Pro•Arté - Laser Select Clear Nylon (EXP Coated and Uncoated)

Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
J4301	.00002024	16.6	14.8	11.8	9.3	8.3	6.6	5.2	4.2
J4302	.00002729	22.4	20.0	15.8	12.6	11.2	8.9	7.1	5.6
J4303	.00004525	37.1	33.1	26.3	20.8	18.6	14.7	11.7	9.3
J4401/EXP	.00002243	18.4	16.4	13.0	10.3	9.2	7.3	5.8	4.6
J4402/EXP	.00003046	25.0	22.3	17.7	14.0	12.5	9.9	7.9	6.3
J4403/EXP	.00004989	40.9	36.5	29.0	23.0	20.5	16.3	12.9	10.2
J4501/EXP	.00002092	17.2	15.3	12.1	9.6	8.6	6.8	5.4	4.3
J4502/EXP	.00002827	23.2	20.7	16.4	13.0	11.6	9.2	7.3	5.8
J4503/EXP	.00004679	38.4	34.2	27.2	21.6	19.2	15.2	12.1	9.6
J4601/EXP	.00002161	17.7	15.8	12.5	10.0	8.9	7.0	5.6	4.4
J4602/EXP	.00002924	24.0	21.4	17.0	13.5	12.0	9.5	7.6	6.0
J4603/EXP	.00004795	39.4	35.1	27.8	22.1	19.7	15.6	12.4	9.8
J4701	.00002092	17.2	15.3	12.1	9.6	8.6	6.8	5.4	4.3
J4702	.00002827	23.2	20.7	16.4	13.0	11.6	9.2	7.3	5.8
J4703	.00004679	38.4	34.2	27.2	21.6	19.2	15.2	12.1	9.6
J4801	.00002161	17.7	15.8	12.5	10.0	8.9	7.0	5.6	4.4
J4802	.00002924	24.0	21.4	17.0	13.5	12.0	9.5	7.6	6.0
J4803	.00004795	39.4	35.1	27.8	22.1	19.7	15.6	12.4	9.8
J5101	.00002161	17.7	15.8	12.5	10.0	8.9	7.0	5.6	4.4
J5102	.00002924	24.0	21.4	17.0	13.5	12.0	9.5	7.6	6.0
J5103	.00004795	39.4	35.1	27.8	22.1	19.7	15.6	12.4	9.8

Pro•Arté - Laser Select Black Nylon

J4901	.00002092	17.2	15.3	12.1	9.6	8.6	6.8	5.4	4.3
J4902	.00002827	23.2	20.7	16.4	13.0	11.6	9.2	7.3	5.8
J4903	.00004679	38.4	34.2	27.2	21.6	19.2	15.2	12.1	9.6
J5001	.00002161	17.7	15.8	12.5	10.0	8.9	7.0	5.6	4.4
J5002	.00002924	24.0	21.4	17.0	13.5	12.0	9.5	7.6	6.0
J5003	.00004795	39.4	35.1	27.8	22.1	19.7	15.6	12.4	9.8

Pro•Arté - Silverplated Wound

Item#	Unit Weight	d	c	B	A	G	F	E	D
J4304	.00010203	14.8	11.7	10.5	8.3	6.6	5.2	4.7	3.7
J4305	.00015347	-	17.7	15.8	12.5	9.9	7.9	7.0	5.6
J4306	.00028881	-	-	-	23.5	18.7	14.8	13.2	10.5
J4404	.00011237	16.3	12.9	11.5	9.2	7.3	5.8	5.1	4.1
J4405	.00019521	-	-	20.0	15.9	12.6	10.0	8.9	7.1
J4406	.00034351	-	-	-	-	-	17.6	15.7	12.5
J4504	.00010754	15.6	12.4	11.0	8.8	7.0	5.5	4.9	3.9
J4505	.00018416	-	-	18.9	15.0	11.9	9.4	8.4	6.7
J4506	.00030632	-	-	-	-	19.8	15.7	14.0	11.1
J4604	.00011237	16.3	12.9	11.5	9.2	7.3	5.8	5.1	4.1
J4605	.00019521	-	-	20.0	15.9	12.6	10.0	8.9	7.1
J4606	.00031726	-	-	-	-	20.5	16.3	14.5	11.5
J4904	.00010754	15.6	12.4	11.0	8.8	7.0	5.5	4.9	3.9
J4905	.00018416	-	-	18.9	15.0	11.9	9.4	8.4	6.7
J4906	.00030632	-	-	-	-	19.8	15.7	14.0	11.1
J5004	.00011237	16.3	12.9	11.5	9.2	7.3	5.8	5.1	4.1
J5005	.00019521	-	-	20.0	15.9	12.6	10.0	8.9	7.1
J5006	.00031726	-	-	-	-	20.5	16.3	14.5	11.5

Pro•Arté - Flat Silverplated Copper Wound

J5104	.00013029	18.9	15.0	13.4	10.6	8.4	6.7	6.0	4.7
J5105	.00020135	-	-	20.7	16.4	13.0	10.3	9.2	7.3
J5106	.00035008	-	-	-	-	-	18.0	16.0	12.7

Pro•Arté - 80/20 Brass Wound

J4704	.00010616	15.4	12.2	10.9	8.6	6.9	5.4	4.9	3.8
J4705	.00017311	-	19.9	17.8	14.1	11.2	8.9	7.9	6.3
J4706	.00029100	-	-	-	-	18.8	14.9	13.3	10.6
J4804	.00011237	16.3	12.9	11.5	9.2	7.3	5.8	5.1	4.1
J4805	.00018171	-	-	18.7	14.8	11.7	9.3	8.3	6.6
J4806	.00030632	-	-	-	-	19.8	15.7	14.0	11.1

Pro•Arté Composite - Trebles

Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
J4403C	.00005298	43.5	38.7	30.8	24.4	21.7	17.3	13.7	10.9
J4503C	.00004795	39.4	35.1	27.8	22.1	19.7	15.6	12.4	9.8
J4603C	.00005066	41.6	37.0	29.4	23.3	20.8	16.5	13.1	10.4

Pro•Arté Composite - Silverplated Copper Wound

Item#	Unit Weight	d	c	B	A	G	F	E	D
J4404C	.00011581	16.8	13.3	11.9	9.4	7.5	5.9	5.3	4.2
J4405C	.00020381	-	23.5	20.9	16.6	13.2	10.5	9.3	7.4
J4406C	.00036758	-	-	-	-	23.8	18.9	16.8	13.3
J4504C	.00009858	14.3	11.4	10.1	8.0	6.4	5.1	4.5	3.6
J4505C	.00017925	-	20.6	18.4	14.6	11.6	9.2	8.2	6.5
J4506C	.00033257	-	-	-	-	21.5	17.1	15.2	12.1
J4604C	.00011030	16.0	12.7	11.3	9.0	7.1	5.7	5.0	4.0
J4605C	.00020381	-	23.5	20.9	16.6	13.2	10.5	9.3	7.4
J4606C	.00035226	-	-	-	-	22.8	18.1	16.1	12.8

Pro•Arté Composite - Silverplated Copper Wound & Lightly Polished

J4504LP	.00009582	13.9	11.0	9.8	7.8	6.2	4.9	4.4	3.5
J4505LP	.00017066	-	19.7	17.5	13.9	11.0	8.8	7.8	6.2
J4506LP	.00031288	-	-	-	-	20.2	16.1	14.3	11.3
J4604LP	.00011168	16.2	12.9	11.5	9.1	7.2	5.7	5.1	4.1
J4605LP	.00019890	-	22.9	20.4	16.2	12.9	10.2	9.1	7.2
J4606LP	.00033914	-	-	-	-	21.9	17.4	15.5	12.3

D'Addario Classic - Rectified Clear Nylon

Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
J2801	.00002065	16.9	15.1	12.0	9.5	8.5	6.7	5.3	4.2
J2802	.00002900	23.8	21.2	16.8	13.4	11.9	9.4	7.5	6.0
J2803	.00004602	37.8	33.7	26.7	21.2	18.9	15.0	11.9	9.4
J2901	.00001928	15.8	14.1	11.2	8.9	7.9	6.3	5.0	4.0
J2902	.00002803	23.0	20.5	16.3	12.9	11.5	9.1	7.2	5.8
J2903	.00004486	36.8	32.8	26.0	20.7	18.4	14.6	11.6	9.2
J3001	.00002065	16.9	15.1	12.0	9.5	8.5	6.7	5.3	4.2
J3002	.00002900	23.8	21.2	16.8	13.4	11.9	9.4	7.5	6.0
J3003	.00004602	37.8	33.7	26.7	21.2	18.9	15.0	11.9	9.4
J3101	.00002284	18.7	16.7	13.3	10.5	9.4	7.4	5.9	4.7
J3102	.00003022	24.8	22.1	17.5	13.9	12.4	9.8	7.8	6.2
J3103	.00004989	40.9	36.5	29.0	23.0	20.5	16.3	12.9	10.2

D'Addario Classic - Flat Sterling Silver Wound

Item#	Unit Weight	d	c	B	A	G	F	E	D
J2804	.00011030	16.0	12.7	11.3	9.0	7.1	5.7	5.0	4.0
J2805	.00021363	-	-	-	17.4	13.8	11.0	9.8	7.7
J2806	.00031726	-	-	-	-	20.5	16.3	14.5	11.5

D'Addario Classic - Silverplated Copper Wound

J2904	.00010203	14.8	11.7	10.5	8.3	6.6	5.2	4.7	3.7
J2905	.00015347	-	17.7	15.8	12.5	9.9	7.9	7.0	5.6
J2906	.00028881	-	-	-	-	18.7	14.8	13.2	10.5
J3004	.00010616	15.4	12.2	10.9	8.6	6.9	5.4	4.9	3.8
J3005	.00018416	-	-	18.9	15.0	11.9	9.4	8.4	6.7
J3006	.00030194	-	-	-	-	19.5	15.5	13.8	11.0
J3104	.00011512	16.7	13.3	11.8	9.4	7.4	5.9	5.3	4.2
J3105	.00019153	-	-	19.7	15.6	12.4	9.8	8.8	6.9
J3106	.00031726	-	-	-	-	20.5	16.3	14.5	11.5

Rectified Clear Nylon

Item#	Unit Weight	g'	f'	e'	d'	c'	b	a	g
NYL018	.00000916	9.5	7.5	6.7	5.3	4.2	3.8	3.0	2.4
NYL019	.00001020	10.6	8.4	7.5	5.9	4.7	4.2	3.3	2.6
NYL020	.00001130	11.7	9.3	8.3	6.6	5.2	4.6	3.7	2.9
NYL021	.00001246	12.9	10.2	9.1	7.2	5.7	5.1	4.1	3.2
NYL022	.00001368	14.1	11.2	10.0	7.9	6.3	5.6	4.5	3.5
NYL024	.00001628	16.8	13.4	11.9	9.5	7.5	6.7	5.3	4.2
NYL027	.00002060	21.3	16.9	15.1	12.0	9.5	8.5	6.7	5.3
NYL028	.00002216	22.9	18.2	16.2	12.9	10.2	9.1	7.2	5.7
NYL029	.00002377	24.6	19.5	17.4	13.8	10.9	9.8	7.7	6.1
NYL030	.00002543	26.3	20.9	18.6	14.8	11.7	10.4	8.3	6.6
NYL031	.00002716	28.1	22.3	19.9	15.8	12.5	11.1	8.8	7.0
NYL032	.00002894	29.9	23.8	21.2	16.8	13.3	11.9	9.4	7.5

Item#	Unit Weight	e'	d'	c'	b	a	g	f	e
NYL033	.00003078	22.5	17.9	14.2	12.6	10.0	8.0	6.3	5.6
NYL034	.00003267	23.9	19.0	15.0	13.4	10.6	8.4	6.7	6.0
NYL038	.00004081	29.8	23.7	18.8	16.7	13.3	10.6	8.4	7.5
NYL039	.00004298	31.4	25.0	19.8	17.6	14.0	11.1	8.8	7.9
NYL040	.00004522	33.1	26.3	20.8	18.6	14.7	11.7	9.3	8.3
NYL041	.00004751	34.7	27.6	21.9	19.5	15.5	12.3	9.7	8.7

Silverplated Copper Wound on Nylon

Item#	Unit Weight	g	f	e	d	c	B	A	G
NYL019W	.00005341	-	11.0	9.8	7.7	6.2	5.5	4.4	3.5
NYL020W	.00005341	-	11.0	9.8	7.7	6.2	5.5	4.4	3.5
NYL022W	.00006498	-	-	11.9	9.4	7.5	6.7	5.3	4.2
NYL024W	.00007408	-	15.2	13.5	10.7	8.5	7.6	6.0	4.8
NYL025W	.00007023	18.2	14.4	12.8	10.2	8.1	7.2	5.7	4.5
NYL026W	.00009438	-	-	17.3	13.7	10.9	9.7	7.7	6.1
NYL028W	.00010511	-	21.6	19.2	15.2	12.1	10.8	8.6	6.8
NYL029W	.00011667	-	-	21.3	16.9	13.4	12.0	9.5	7.5
NYL030W	.00012419	-	-	22.7	18.0	14.3	12.8	10.1	8.0
NYL031W	.00012821	-	26.3	23.4	18.6	14.8	13.2	10.4	8.3
Item#	Unit Weight	d	c	B	A	G	F	E	D
NYL033W	.00017913	-	20.6	18.4	14.6	11.6	9.2	8.2	6.5
NYL034W	.00019270	-	-	19.8	15.7	12.5	9.9	8.8	7.0
NYL035W	.00020667	-	-	-	16.8	13.4	10.6	9.4	7.5
NYL036W	.00022105	-	-	-	18.0	14.3	11.3	10.1	8.0
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
NYL040W	.00028260	-	18.3	14.5	12.9	10.2	8.1	7.2	5.8
NYL041W	.00028319	23.1	18.3	14.5	12.9	10.3	8.2	7.3	5.8
NYL042W	.00030466	24.8	19.7	15.6	13.9	11.0	8.8	7.8	6.2
NYL043W	.00033302	-	-	17.1	15.2	12.1	9.6	8.5	6.8
NYL045W	.00036470	-	-	18.7	16.7	13.2	10.5	9.3	7.4
NYL048W	.00041400	-	-	21.2	18.9	15.0	11.9	10.6	8.4
NYL050W	.00045369	-	-	23.3	20.7	16.5	13.1	11.6	9.2
NYL052W	.00049500	-	-	25.4	22.6	18.0	14.3	12.7	10.1
NYL054W	.00053793	-	-	-	24.6	19.5	15.5	13.8	11.0
NYL056W	.00059624	-	-	-	-	21.6	17.2	15.3	12.1

FOLK GUITAR

Black Nylon - Ball End

Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
BEB028	.00002161	17.7	15.8	12.5	10.0	8.9	7.0	5.6	4.4
BEB032	.00002778	22.8	20.3	16.1	12.8	11.4	9.1	7.2	5.7
BEB040	.00004873	40.0	35.6	28.3	22.4	20.0	15.9	12.6	10.0

Clear Nylon - Ball End

BEC028	.00002133	17.5	15.6	12.4	9.8	8.8	7.0	5.5	4.4
BEC032	.00002754	22.6	20.1	16.0	12.7	11.3	9.0	7.1	5.7
BEC040	.00004447	36.5	32.5	25.8	20.5	18.2	14.5	11.5	9.1

80/20 Brass Wound on Nylon - Ball End

Item#	Unit Weight	e	d	c	B	A	G	F	E
BEB031W	.00011650	21.3	16.9	13.4	12.0	9.5	7.5	6.0	5.3
BEB037W	.00018785	-	-	21.6	19.3	15.3	12.1	9.6	8.6
BEB045W	.00030850	-	-	-	-	25.1	19.9	15.8	14.1

Silverplated Copper Wound on Nylon - Ball End

BES031W	.00012271	22.4	17.8	14.1	12.6	10.0	7.9	6.3	5.6
BES037W	.00020258	-	-	23.3	20.8	16.5	13.1	10.4	9.3
BES045W	.00033257	-	-	-	-	-	21.5	17.1	15.2

ELECTRIC BASS GUITAR

XL - Nickelplated Round Wound Guitar/Bass

Item#	Unit Weight	f	e	d	c	B	A	G	F
NWB024	.00009959	28.3	25.2	20.0	15.9	14.2	11.2	8.9	7.1
NWB034	.00019915	-	50.4	40.0	31.7	28.3	22.5	17.8	14.1
NWB044	.00033751	-	-	67.8	53.8	48.0	38.0	30.2	24.0
Item#	Unit Weight	E	D	C	B'	A'	G'	F'	E'
NWB056	.00053791	34.0	27.0	21.4	19.1	15.2	12.0	9.6	8.5
NWB072 & -F6	.00092253	58.4	46.3	36.8	32.7	26.0	20.6	16.4	14.6
NWB084 & -F6	.00126465	80.0	63.5	50.4	44.9	35.6	28.3	22.5	20.0

XL - Nickelplated Round Wound

Long Scale

Item#	Unit Weight	b	a	g	f	e	d	c	B
XLB018P	.00007265	53.0	42.1	33.4	26.5	23.6	18.7	14.9	13.3
XLB020P	.00009093	66.3	52.7	41.8	33.2	29.6	23.4	18.6	16.6
XLB028W	.00015433	-	-	-	-	-	39.8	31.6	28.2
Item#	Unit Weight	c	B	A	G	F	E	D	C
XLB042	.00032252	66.0	58.9	46.7	37.1	29.4	26.2	20.8	16.5
XLB052	.00051322	-	-	-	59.0	46.8	41.7	33.1	26.3
Item#	Unit Weight	d	c	B	A	G	F	E	D
XLB032	.00019000	49.0	38.9	34.7	27.5	21.8	17.3	15.4	12.2
XLB035	.00022362	57.7	45.8	40.8	32.4	25.7	20.4	18.2	14.4
XLB040	.00029322	-	-	53.5	42.5	33.7	26.7	23.8	18.9
XLB045	.00037240	-	-	68.0	53.9	42.8	34.0	30.3	24.0
XLB050	.00046463	-	-	84.8	67.3	53.4	42.4	37.8	30.0
Item#	Unit Weight	F	E	D	C	B'	A'	G'	F'
XLB055	.00054816	50.0	44.5	35.3	28.1	25.0	19.8	15.7	12.5
XLB060	.00066540	60.7	54.1	42.9	34.1	30.3	24.1	19.1	15.2
XLB065	.00079569	72.6	64.7	51.3	40.7	36.2	28.8	22.9	18.2
XLB070	.00093218	85.0	75.7	60.1	47.7	42.5	33.7	26.8	21.3
XLB075	.00104973	95.7	85.3	67.7	53.7	47.8	38.0	30.2	24.0
XLB080	.00116023	105.8	94.3	74.8	59.4	52.9	42.0	33.3	26.5
XLB085	.00133702	121.9	108.6	86.2	68.4	60.9	48.4	38.4	30.6
Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
XLB090	.00150277	54.4	43.2	34.3	30.5	24.2	19.2	17.2	13.6
XLB095	.00169349	61.3	48.7	38.7	34.4	27.3	21.7	19.4	15.3
XLB100	.00179687	65.0	51.6	41.1	36.5	29.0	23.0	20.5	16.3
XLB105	.00198395	71.8	57.0	45.3	40.3	32.0	25.4	22.7	18.0
XLB110	.00227440	82.3	65.3	52.0	46.2	36.7	29.1	26.0	20.6
XLB120	.00250280	90.6	71.9	57.2	50.8	40.3	32.0	28.6	22.7
XLB125	.00274810	99.5	79.0	62.8	55.8	44.3	35.2	31.4	24.9
XLB130	.00301941	109.3	86.8	69.0	61.3	48.7	38.6	34.5	27.3
XLB135	.00315944	114.4	90.8	72.2	64.2	50.9	40.4	36.1	28.6
XLB145	.00363204	131.5	104.4	83.0	73.8	58.5	46.5	41.5	32.9
XLB120T	.00250280	90.6	71.9	57.2	50.8	40.3	32.0	28.6	22.7
XLB125T	.00274810	99.5	79.0	62.8	55.8	44.3	35.2	31.4	24.9
XLB130T	.00301941	109.3	86.8	69.0	61.3	48.7	38.6	34.5	27.3
XLB135T	.00315944	114.4	90.8	72.2	64.2	50.9	40.4	36.1	28.6
XLB145T	.00363204	131.5	104.4	83.0	73.8	58.5	46.5	41.5	32.9

Short Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
XB045S	.00037240	52.9	42.0	33.3	26.4	23.6	18.7	14.8	13.2
XB050S	.00049956	71.0	56.3	44.7	35.5	31.6	25.1	19.9	17.7
XB065S	.00079569	-	89.7	71.2	56.5	50.3	39.9	31.7	28.2
XB070S	.00106585	-	-	95.4	75.7	67.4	53.5	42.5	37.8

XL - Nickelplated Round Wound (cont.)

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
XB080S	.00116023	46.2	41.2	32.7	26.0	20.6	18.3	14.6	11.6
XB085S	.00145122	57.8	51.5	40.9	32.5	25.8	23.0	18.2	14.5
XB100S	.00179687	71.6	63.7	50.6	40.2	32.0	28.4	22.5	17.9
XB105S	.00214990	85.7	76.3	60.6	48.1	38.3	34.0	27.0	21.4

Medium Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
XB040M	.00029322	47.4	37.6	29.9	23.7	21.1	16.7	13.3	11.8
XB045M	.00037240	60.2	47.8	37.9	30.1	26.8	21.3	16.9	15.0
XB050M	.00046463	75.1	59.6	47.3	37.5	33.4	26.5	21.1	18.8
XB060M	.00066713	-	85.6	67.9	53.9	48.0	38.1	30.2	26.9
XB065M	.00079569	-	-	81.0	64.3	57.3	45.4	36.1	32.1
XB070M	.00093218	-	-	94.9	75.3	67.1	53.2	42.3	37.6

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
XB075M	.00105407	47.8	42.5	33.8	26.8	21.3	19.0	15.0	11.9
XB080M	.00116023	52.6	46.8	37.2	29.5	23.5	20.9	16.6	13.2
XB085M	.00127548	57.8	51.5	40.9	32.5	25.8	23.0	18.2	14.5
XB095M	.00167838	76.1	67.7	53.8	42.7	34.0	30.2	24.0	19.0
XB100M	.00179687	81.5	72.5	57.6	45.7	36.4	32.3	25.7	20.4
XB105M	.00198395	90.0	80.1	63.6	50.5	40.2	35.7	28.3	22.5

Superlong Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
XB040SL	.00029322	-	47.6	37.8	30.0	26.7	21.2	16.8	15.0
XB045SL	.00037240	-	60.5	48.0	38.1	33.9	26.9	21.4	19.0
XB050SL	.00046463	-	75.4	59.9	47.5	42.3	33.6	26.7	23.7
XB060SL	.00066540	-	-	85.7	68.0	60.6	48.1	38.2	34.0
XB065SL	.00079569	-	-	-	81.4	72.5	57.5	45.7	40.6
XB070SL	.00093218	-	-	-	95.3	84.9	67.4	53.5	47.6

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
XB075SL	.00104973	60.2	53.6	42.6	33.8	26.9	23.9	19.0	15.1
XB080SL	.00116023	66.6	59.3	47.1	37.4	29.7	26.4	21.0	16.6
XB085SL	.00133702	76.7	68.3	54.3	43.1	34.3	30.4	24.2	19.2
XB090SL	.00150177	86.2	76.7	60.9	48.4	38.5	34.2	27.1	21.5
XB095SL	.00169349	97.2	86.5	68.7	54.6	43.4	38.6	30.6	24.3
XB100SL	.00179687	103.1	91.8	72.9	57.9	46.0	40.9	32.5	25.8
XB105SL	.00198395	113.8	101.3	80.5	63.9	50.8	45.2	35.9	28.5
XB110SL	.00227461	130.5	116.2	92.3	73.3	58.3	51.8	41.1	32.6

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
XB125SL	.00274810	111.5	88.5	70.4	62.6	49.7	39.4	35.2	27.9
XB130SL	.00301941	122.5	97.3	77.4	68.8	54.6	43.3	38.7	30.6
XB145SL	.00363204	147.4	117.0	93.1	82.7	65.6	52.1	46.5	36.9
XB125TSL	.00274810	111.5	88.5	70.4	62.6	49.7	39.4	35.2	27.9
XB130TSL	.00301941	122.5	97.3	77.4	68.8	54.6	43.3	38.7	30.6
XB145TSL	.00363204	147.4	117.0	93.1	82.7	65.6	52.1	46.5	36.9

XL - Nickelplated Round Wound Steinberger

Long Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
SXL045	.00037240	68.0	53.9	42.8	34.0	30.3	24.0	19.1	17.0
SXL050	.00046463	84.8	67.3	53.4	42.4	37.8	30.0	23.8	21.2
SXL065	.00079569	-	-	-	72.6	64.7	51.3	40.7	36.2
SXL070	.00093218	-	-	-	85.0	75.7	60.1	47.7	42.5

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
SXL080	.00116023	59.4	52.9	42.0	33.3	26.5	23.6	18.7	14.8
SXL085	.00133702	68.4	60.9	48.4	38.4	30.6	27.2	21.6	17.1
SXL100	.00179687	92.0	81.9	65.0	51.6	41.1	36.5	29.0	23.0
SXL105	.00198395	101.5	90.4	71.8	57.0	45.3	40.3	32.0	25.4

XL - Nickelplated Round Wound Steinberger (cont.)

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
SXL130	.00301941	109.3	86.8	69.0	61.3	48.7	38.6	34.5	27.3

Half Round - Pure Nickel Half Round

Long Scale

Item#	Unit Weight	d	c	B	A	G	F	E	D
NHR030	.00019977	51.5	40.9	36.5	28.9	23.0	18.2	16.2	12.9
NHR040	.00031672	-	64.8	57.8	45.9	36.4	28.9	25.7	20.4
NHR045	.00039328	-	80.5	71.8	56.9	45.2	35.9	32.0	25.4
NHR050	.00046898	-	96.0	85.6	67.9	53.9	42.8	38.1	30.2

Item#	Unit Weight	F	E	D	C	B'	A'	G'	F'
NHR055	.00058122	53.0	47.2	37.5	29.7	26.5	21.0	16.7	13.3
NHR060	.00070573	64.4	57.3	45.5	36.1	32.2	25.5	20.3	16.1
NHR065	.00080500	73.4	65.4	51.9	41.2	36.7	29.1	23.1	18.4
NHR070	.00096476	88.0	78.4	62.2	49.4	44.0	34.9	27.7	22.0
NHR075	.00103455	94.4	84.1	66.7	53.0	47.1	37.5	29.7	23.6
NHR080	.00118785	108.3	96.5	76.6	60.8	54.1	43.0	34.1	27.1
NHR085	.00138122	126.0	112.2	89.1	70.7	62.9	50.0	39.7	31.6

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
NHR090	.00140885	51.0	40.5	32.2	28.6	22.7	18.0	16.1	12.8
NHR095	.00166888	60.4	48.0	38.1	33.9	26.9	21.4	19.1	15.1
NHR100	.00185103	67.0	53.2	42.3	37.6	29.8	23.7	21.2	16.8
NHR105	.00205287	74.3	59.0	46.9	41.7	33.1	26.3	23.5	18.6
NHR110	.00220548	79.8	63.4	50.4	44.8	35.5	28.2	25.2	20.0
NHR130	.00301941	109.3	86.8	69.0	61.3	48.7	38.6	34.5	27.3

Short Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
NHR045S	.00039328	55.9	44.3	35.2	27.9	24.9	19.7	15.7	13.9
NHR065S	.00080500	-	90.7	72.0	57.2	50.9	40.4	32.1	28.6

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
NHR080S	.00118785	47.3	42.1	33.5	26.6	21.1	18.8	14.9	11.8
NHR100S	.00185103	73.8	65.7	52.2	41.4	32.9	29.3	23.2	18.4

Medium Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
NHR045M	.00039328	63.6	50.4	40.0	31.8	28.3	22.5	17.8	15.9
NHR065M	.00080500	-	-	82.0	65.0	57.9	46.0	36.5	32.5

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
NHR080M	.00118785	53.9	47.9	38.1	30.2	24.0	21.4	17.0	13.5
NHR100M	.00185103	83.9	74.7	59.4	47.1	37.5	33.3	26.4	21.0

Superlong Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
NHR045SL	.00039328	80.5	63.8	50.7	40.2	35.8	28.4	22.6	20.1
NHR065SL	.00080500	-	-	-	82.3	73.3	58.2	46.2	41.1

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
NHR080SL	.00118785	68.2	60.7	48.2	38.3	30.4	27.1	21.5	17.0
NHR100SL	.00185103	106.2	94.5	75.1	59.6	47.4	42.2	33.4	26.6

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
NHR130SL	.00301941	122.5	97.3	77.4	68.8	54.6	43.3	38.7	30.6

Chromes - Stainless Steel Flat Wound

Long Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
CB040	.00032716	59.7	47.4	37.6	29.8	26.6	21.1	16.7	14.9
CB045	.00039763	72.6	57.6	45.7	36.3	32.3	25.6	20.4	18.1
CB050	.00047855	87.3	69.3	55.0	43.6	38.9	30.9	24.5	21.8
CB055	.00056769	103.6	82.2	65.2	51.8	46.1	36.6	29.1	25.9
CB060	.00070108	-	101.5	80.6	63.9	57.0	45.2	35.9	31.9
CB065	.00080655	-	-	92.7	73.6	65.5	52.0	41.3	36.7
CB070	.00093374	-	-	107.3	85.2	75.9	60.2	47.8	42.5

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
CB075	.00100553	51.5	45.8	36.4	28.9	23.0	20.4	16.2	12.9
CB080	.00120719	61.8	55.0	43.7	34.7	27.6	24.5	19.5	15.4
CB085	.00138675	71.0	63.2	50.2	39.8	31.7	28.2	22.4	17.7
CB090	.00148896	76.2	67.8	53.9	42.8	34.0	30.2	24.0	19.1
CB095	.00173288	88.7	78.9	62.7	49.8	39.6	35.2	27.9	22.2
CB100	.00189041	96.8	86.1	68.4	54.3	43.2	38.4	30.5	24.2
CB105	.00204302	104.6	93.1	74.0	58.7	46.7	41.5	32.9	26.1
CB110	.00226455	115.9	103.2	82.0	65.1	51.8	46.0	36.5	29.0

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
CB132	.00314193	113.7	90.3	71.8	63.8	50.6	40.2	35.9	28.4

Superlong Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
CB040SL	.00032716	66.9	53.1	42.2	33.5	29.8	23.6	18.8	16.7
CB045SL	.00039763	81.4	64.6	51.2	40.7	36.2	28.7	22.8	20.3
CB060SL	.00070108	-	113.8	90.3	71.7	63.9	50.7	40.2	35.8
CB065SL	.00080655	-	-	103.9	82.5	73.5	58.3	46.3	41.2

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
CB075SL	.00100553	57.7	51.4	40.8	32.4	25.8	22.9	18.2	14.4
CB080SL	.00120719	69.3	61.7	49.0	38.9	30.9	27.5	21.8	17.3
CB095SL	.00173288	99.4	88.5	70.3	55.8	44.4	39.5	31.3	24.9
CB100SL	.00189041	108.5	96.6	76.7	60.9	48.4	43.1	34.2	27.1

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
CB132SL	.00314193	127.5	101.2	80.5	71.6	56.8	45.1	40.2	31.9

ProSteels - ProSteel Round Wound

Long Scale

Item#	Unit Weight	d	c	B	A	G	F	E	D
PSB032	.00020465	52.8	41.9	37.4	29.6	23.5	18.7	16.6	13.2
PSB040	.00029409	-	-	53.7	42.6	33.8	26.8	23.9	19.0
PSB045	.00036457	-	-	66.5	52.8	41.9	33.2	29.6	23.5
PSB050	.00042635	-	87.3	77.8	61.7	49.0	38.9	34.6	27.5
PSB055	.00058296	-	-	-	84.4	67.0	53.2	47.4	37.6

Item#	Unit Weight	F	E	D	C	B'	A'	G'	F'
PSB060	.00067781	61.8	55.1	43.7	34.7	30.9	24.5	19.5	15.5
PSB065	.00073365	66.9	59.6	47.3	37.6	33.4	26.6	21.1	16.8
PSB070	.00087014	79.4	70.7	56.1	44.5	39.6	31.5	25.0	19.9
PSB075	.00095857	87.4	77.9	61.8	49.1	43.7	34.7	27.5	21.9
PSB080	.00111879	102.0	90.9	72.1	57.3	51.0	40.5	32.1	25.6
PSB085	.00124034	113.1	100.8	80.0	63.5	56.5	44.9	35.6	28.3

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
PSB090	.00151382	54.8	43.5	34.6	30.8	24.4	19.4	17.3	13.7
PSB095	.00156550	56.7	45.0	35.8	31.8	25.2	20.0	17.9	14.2

ProSteels - ProSteel Round Wound (Cont.)

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
PSB100	.00169349	61.3	48.7	38.7	34.4	27.3	21.7	19.4	15.3
PSB105	.00183626	66.5	52.8	42.0	37.3	29.6	23.5	21.0	16.6
PSB110	.00218579	79.1	62.8	50.0	44.4	35.2	28.0	25.0	19.8
PSB125	.00263432	95.4	75.7	60.2	53.5	42.5	33.7	30.1	23.8
PSB130	.00277435	100.4	79.7	63.4	56.4	44.7	35.5	31.7	25.1
PSB145	.00327321	118.5	94.0	74.8	66.5	52.8	41.9	37.4	29.6

Short Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
PSB045S	.00036457	51.8	41.1	32.6	25.9	23.1	18.3	14.5	12.9
PSB065S	.00073365	-	82.7	65.6	52.1	46.4	36.8	29.2	26.0

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
PSB080S	.00111879	44.6	39.7	31.5	25.0	19.9	17.7	14.0	11.1
PSB100S	.00169349	67.5	60.1	47.7	37.9	30.1	26.8	21.3	16.9

Medium Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
PSB045M	.00036457	58.9	46.8	37.1	29.5	26.2	20.8	16.5	14.7
PSB065M	.00073365	-	-	74.7	59.3	52.8	41.9	33.3	29.6

Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
PSB080M	.00111879	50.7	45.1	35.9	28.5	22.6	20.1	16.0	12.7
PSB100M	.00169349	76.8	68.3	54.3	43.1	34.3	30.5	24.2	19.2

Superlong Scale

Item#	Unit Weight	d	c	B	A	G	F	E	D
PSB032SL	.00020465	-	47.0	41.9	33.2	26.4	20.9	18.6	14.8
PSB040SL	.00029409	-	-	-	47.7	37.9	30.1	26.8	21.3
PSB045SL	.00036457	-	-	-	59.2	47.0	37.3	33.2	26.4
PSB050SL	.00042635	-	-	87.2	69.2	54.9	43.6	38.8	30.8

Item#	Unit Weight	F	E	D	C	B'	A'	G'	F'
PSB060SL	.00067781	69.3	61.7	49.0	38.9	34.6	27.5	21.8	17.4
PSB065SL	.00073365	75.0	66.8	53.0	42.1	37.5	29.8	23.6	18.8
PSB070SL	.00087014	89.0	79.3	62.9	49.9	44.4	35.3	28.0	22.3
PSB075SL	.00095857	98.0	87.3	69.3	55.0	49.0	38.9	30.9	24.6
PSB080SL	.00111879	-	101.9	80.9	64.2	57.1	45.4	36.0	28.7
PSB085SL	.00124034	126.8	113.0	89.7	71.2	63.3	50.3	40.0	31.8

Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
PSB090SL	.00151382	61.4	48.8	38.8	34.5	27.4	21.7	19.4	15.4
PSB095SL	.00156550	63.5	50.4	40.1	35.7	28.3	22.5	20.1	15.9
PSB100SL	.00169349	68.7	54.6	43.4	38.6	30.6	24.3	21.7	17.2
PSB105SL	.00183626	74.5	59.1	47.0	41.8	33.2	26.3	23.5	18.6
PSB110SL	.00218579	88.7	70.4	56.0	49.8	39.5	31.4	28.0	22.2
PSB130SL	.00277435	112.6	89.4	71.1	63.2	50.1	39.8	35.5	28.1

Acoustic Bass Guitar

Phosphor Bronze - Round Wound

Long Scale

Item#	Unit Weight	B	A	G	F	E	D	C	B'
PBB045	.00041330	-	59.8	47.5	37.7	33.6	26.6	21.2	18.8
PBB065	.00086394	-	-	-	78.8	70.2	55.7	44.2	39.4
Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
PBB080	.00130940	67.0	59.7	47.4	37.6	29.9	26.6	21.1	16.8
PBB100	.00197902	101.3	90.2	71.6	56.9	45.2	40.2	31.9	25.3
Item#	Unit Weight	A'	G'	F'	E'	D'	C'	B''	A''
PBB130	.00324696	117.5	93.3	74.2	66.0	52.3	41.5	37.1	29.4

Mandolin Family Strings

Mandolin

Item#	Unit Weight	f''	e''	d''	c''	b'	a'	g'	f'
J6201	.00002215	21.5	19.2	15.2	12.1	10.8	8.5	6.8	5.4
J6202	.00004342	42.2	37.6	29.8	23.7	21.1	16.8	13.3	10.6
Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
J6203	.00011024	26.8	23.9	19.0	15.0	13.4	10.6	8.4	6.7
J6204	.00022308	54.2	48.3	38.3	30.4	27.1	21.5	17.1	13.6
Item#	Unit Weight	f''	e''	d''	c''	b'	a'	g'	f'
J6701	.00002680	26.1	23.2	18.4	14.6	13.0	10.3	8.2	6.5
J6702	.00004342	42.2	37.6	29.8	23.7	21.1	16.8	13.3	10.6
Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
J6703	.00011462	27.9	24.8	19.7	15.6	13.9	11.1	8.8	7.0
J6704	.00027459	-	59.4	47.2	37.4	33.4	26.5	21.0	16.7

Mandolin Family Strings (cont.)

Item#	Unit Weight	f''	e''	d''	c''	b'	a'	g'	f'
J7401/EXP	.00002680	26.1	23.2	18.4	14.6	13.0	10.3	8.2	6.5
J7402/EXP	.00004984	48.5	43.2	34.3	27.2	24.2	19.2	15.3	12.1
Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
J7403/EXP	.00013550	32.9	29.3	23.3	18.5	16.5	13.1	10.4	8.2
J7404/EXP	.00032850	-	-	56.5	44.8	39.9	31.7	25.1	20.0
Item#	Unit Weight	f''	e''	d''	c''	b'	a'	g'	f'
J7501/EXP	.00002930	28.5	25.4	20.1	16.0	14.2	11.3	9.0	7.1
J7502/EXP	.00005671	55.1	49.1	39.0	30.9	27.6	21.9	17.4	13.8
Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
J7503/EXP	.00013550	32.9	29.3	23.3	18.5	16.5	13.1	10.4	8.2
J7504/EXP	.00034500	-	-	59.3	47.1	41.9	33.3	26.4	21.0

Mandolin - Flat Tops

Item#	Unit Weight	f''	e''	d''	c''	b'	a'	g'	f'
FT7401	.00002680	26.1	23.2	18.4	14.6	13.0	10.3	8.2	6.5
FT7402	.00005313	-	-	-	-	25.8	20.5	16.3	12.9
Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
FT7403	.00015881	38.6	34.4	27.3	21.7	19.3	15.3	12.2	9.6
FT7404	.00032915	-	-	-	44.9	40.0	31.7	25.2	20.0

Mandola

Item#	Unit Weight	b'	a'	g'	f'	e'	d'	c'	b
J7601	.00004984	31.7	25.2	20.0	15.9	14.1	11.2	8.9	7.9
J7602	.00012640	-	-	-	40.2	35.8	28.4	22.6	20.1
Item#	Unit Weight	a	g	f	e	d	c	B	A
J7603	.00025365	32.0	25.4	20.2	18.0	14.3	11.3	10.1	8.0
J7604	.00055000	69.4	55.1	43.7	39.0	30.9	24.5	21.9	17.4

Mandola - Flat Tops

Item#	Unit Weight	b'	a'	g'	f'	e'	d'	c'	b
FT7601	.00005999	38.2	30.3	24.0	19.1	17.0	13.5	10.7	9.5
FT7602	.00013642	-	-	-	43.4	38.7	30.7	24.4	21.7
Item#	Unit Weight	a	g	f	e	d	c	B	A
FT7603	.00027838	35.2	27.9	22.1	19.7	15.7	12.4	11.1	8.8
FT7604	.00055787	70.4	55.9	44.4	39.5	31.4	24.9	22.2	17.6

Mandocello

Item#	Unit Weight	b	a	g	f	e	d	c	B
J7801	.00011528	-	36.1	28.7	22.7	20.3	16.1	12.8	11.4
J7802	.00028330	-	-	-	-	-	39.5	31.4	28.0
Item#	Unit Weight	A	G	F	E	D	C	B'	A'
J7803	.00056166	44.0	34.9	27.7	24.7	19.6	15.5	13.8	11.0
J7804	.00121779	95.3	75.7	60.0	53.5	42.4	33.7	30.0	23.8

Mandobass

Item#	Unit Weight	B	A	G	F	E	D	C	B'
J7901	.00046015	128.2	101.7	80.7	64.0	57.1	45.3	35.9	32.0
J7902	.00071558	-	158.1	125.5	99.6	88.7	70.4	55.9	49.7
Item#	Unit Weight	C	B'	A'	G'	F'	E'	D'	C'
J7903	.00159126	124.3	110.6	87.9	69.8	55.5	49.3	39.1	31.1
J7904	.00302935	236.6	210.6	167.3	132.8	105.6	93.9	74.5	59.2

Banjo & Loop End String Tensions

Ball End - Plain Steel

Item#	Unit Weight	g'	f'	e'	d'	c'	b	a	g
J6901B	.00001794	20.0	15.9	14.2	11.3	8.9	8.0	6.3	5.0
J6902B	.00002680	29.9	23.8	21.2	16.8	13.3	11.9	9.4	7.5
Item#	Unit Weight	b	a	g	f	e	d	c	B
J6903B	.00003744	16.6	13.2	10.5	8.3	7.4	5.9	4.7	4.2
J6904B	.00007830	-	27.6	21.9	17.4	15.5	12.3	9.7	8.7
Item#	Unit Weight	c''	b'	a'	g'	f'	e'	d'	c'
J6905B	.00001794	19.6	17.5	13.9	11.0	8.7	7.8	6.2	4.9

Loop End - Plain Steel

Item#	Unit Weight	a'	g'	f'	e'	d'	c'	b	a
LE008	.00001418	20.0	15.8	12.6	11.2	8.9	7.1	6.3	5.0
LE009	.00001794	-	20.0	15.9	14.2	11.3	8.9	8.0	6.3
LE010	.00002215	-	24.7	19.6	17.5	13.9	11.0	9.8	7.8
LE011	.00002680	-	29.9	23.8	21.2	16.8	13.3	11.9	9.4
LE012	.00003190	-	35.6	28.3	25.2	20.0	15.9	14.1	11.2
Item#	Unit Weight	f'	e'	d'	c'	b	a	g	f
LE013	.00003744	33.2	29.6	23.5	18.6	16.6	13.2	10.5	8.3
LE014	.00004342	38.5	34.3	27.2	21.6	19.2	15.3	12.1	9.6
LE015	.00004984	44.2	39.4	31.3	24.8	22.1	17.5	13.9	11.0
LE016	.00005671	50.3	44.8	35.6	28.2	25.1	20.0	15.8	12.6
LE017	.00006402	56.8	50.6	40.1	31.9	28.4	22.5	17.9	14.2
LE018	.00007177	63.6	56.7	45.0	35.7	31.8	25.3	20.0	15.9

Loop End - Nickelplated Steel Round Wound

Item#	Unit Weight	c'	b	a	g	f	e	d	c
LE018W	.00006003	-	26.6	21.1	16.8	13.3	11.9	9.4	7.5
LE020W	.00007282	-	-	25.6	20.3	16.1	14.4	11.4	9.1
LE022W	.00008879	-	39.3	31.2	24.8	19.7	17.5	13.9	11.0
LE023W	.00009739	-	43.2	34.3	27.2	21.6	19.2	15.3	12.1
LE024W	.00010857	-	-	38.2	30.3	24.1	21.4	17.0	13.5
Item#	Unit Weight	g	f	e	d	c	B	A	G
LE026W	.00012316	34.4	27.3	24.3	19.3	15.3	13.7	10.8	8.6
LE028W	.00014311	40.0	31.7	28.3	22.4	17.8	15.9	12.6	10.0
LE030W	.00016792	46.9	37.2	33.2	26.3	20.9	18.6	14.8	11.7
LE032W	.00018902	52.8	41.9	37.3	29.6	23.5	21.0	16.6	13.2
LE034W	.00021145	-	46.9	41.7	33.1	26.3	23.4	18.6	14.8
LE036W	.00023520	-	52.1	46.4	36.8	29.3	26.1	20.7	16.4
LE038W	.00026026	-	-	51.4	40.8	32.4	28.9	22.9	18.2
LE040W	.00028933	-	64.1	57.1	45.3	36.0	32.1	25.5	20.2
LE042W	.00031703	-	70.3	62.6	49.7	39.4	35.2	27.9	22.1
Item#	Unit Weight	d	c	B	A	G	F	E	D
LE044W	.00034606	54.2	43.0	38.4	30.4	24.2	19.2	17.1	13.6
LE046W	.00037640	59.0	46.8	41.7	33.1	26.3	20.9	18.6	14.7
LE048W	.00040806	63.9	50.8	45.2	35.9	28.5	22.6	20.1	16.0
LE049W	.00042438	66.5	52.8	47.1	37.3	29.6	23.5	20.9	16.6
LE052W	.00047533	-	59.1	52.7	41.8	33.2	26.3	23.5	18.6
LE054W	.00053073	83.1	66.0	58.8	46.7	37.1	29.4	26.2	20.8
LE056W	.00056832	-	70.7	63.0	50.0	39.7	31.5	28.1	22.3
LE059W	.00063211	99.0	78.6	70.1	55.6	44.1	35.0	31.2	24.8

Loop End - Phosphor Bronze Round Wound

Item#	Unit Weight	b	a	g	f	e	d	c	B
LE018PB	.00006835	-	-	19.1	15.1	13.5	10.7	8.5	7.6
LE020PB	.00007894	-	27.8	22.0	17.5	15.6	12.4	9.8	8.8
LE022PB	.00009571	-	33.7	26.7	21.2	18.9	15.0	11.9	10.6
LE023PB	.00010471	-	36.8	29.2	23.2	20.7	16.4	13.0	11.6
LE024PB	.00011352	-	39.9	31.7	25.2	22.4	17.8	14.1	12.6
Item#	Unit Weight	f	e	d	c	B	A	G	F
LE026PB	.00013285	29.4	26.2	20.8	16.5	14.7	11.7	9.3	7.4
LE028PB	.00015514	34.4	30.6	24.3	19.3	17.2	13.6	10.8	8.6
LE030PB	.00018215	40.4	36.0	28.5	22.7	20.2	16.0	12.7	10.1
LE032PB	.00020573	45.6	40.6	32.2	25.6	22.8	18.1	14.4	11.4
LE034PB	.00023532	-	46.5	36.9	29.3	26.1	20.7	16.4	13.0
LE036PB	.00026350	58.4	52.0	41.3	32.8	29.2	23.2	18.4	14.6
LE038PB	.00029110	-	-	45.6	36.2	32.3	25.6	20.3	16.1
LE040PB	.00032463	-	64.1	50.9	40.4	36.0	28.6	22.7	18.0
LE042PB	.00036248	-	-	56.8	45.1	40.2	31.9	25.3	20.1
Item#	Unit Weight	d	c	B	A	G	F	E	D
LE045PB	.00041278	64.7	51.3	45.8	36.3	28.8	22.9	20.4	16.2
LE047PB	.00044815	-	55.7	49.7	39.4	31.3	24.8	22.1	17.6
LE049PB	.00048575	-	60.4	53.9	42.7	33.9	26.9	24.0	19.0
LE052PB	.00054457	85.3	67.7	60.4	47.9	38.0	30.2	26.9	21.3
LE053PB	.00056386	-	70.1	62.5	49.6	39.4	31.2	27.8	22.1
LE056PB	.00062711	-	78.0	69.5	55.2	43.8	34.7	31.0	24.6
LE059PB	.00069554	109.0	86.5	77.1	61.2	48.6	38.5	34.3	27.2

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Musical Note Frequencies - Guitar and Piano

The table below lists all acoustic guitar note frequencies, and most piano note frequencies, in Hertz (cycles-per-second).

The Piano octave groupings have a pale blue background (key of C).
The Guitar octave groupings have a pale yellow background (key of E).
Other major key octave groupings are shown in other colors.

Guitar Notes - Musical Frequencies Table

Chromatic Scale 12 half-notes per octave			-			**Diatonic Scales (Major) (8 notes per octave)**					**Note Frequency Hz.**	1.999999901 (12 times root 2 below)
Piano Octaves	**Guitar Octaves**	**Note # Key of E**	-	**Guitar String**	-	**Key of E**	**Key of G**	**Key of A**	**Key of C**	**Key of D**	Piano Octaves	12th Root of 2
-	-	-		-		-	-	-	-	-	-	-
E2	E	1		**# 6**		do (1)	-	so (5)	-	re (2)	**82.407**	1.05946309
F2	F	2					ti (7)	la (6)	fa (4)	mi (3)	87.31	1.05946309
F#	F#	3				re (2)	-	-	-	-	92.50	1.05946309
G2	G	4				mi (3)	do (1)	ti (7)	so (5)	fa (4)	98.00	1.05946309
G#	G#	5				-	-	-	la (6)	-	103.83	1.05946309
A2	A	6		**# 5**		fa (4)	re (2)	do (1)	-	so (5)	**110.00**	1.05946309
A#	A#	7				-	mi (3)	-	ti (7)	la (6)	116.54	1.05946309
B2	B	8				so (5)	-	re (2)	-	-	123.47	1.05946309
C3	C	9				la (6)	fa (4)	mi (3)	do (1)	ti (7)	130.81	1.05946309
C#	C#	10				-	-	-	-	-	138.59	1.05946309
D3	D	11		**# 4**		ti (7)	so (5)	fa (4)	re (2)	do (1)	**146.83**	1.05946309
D#	D#	12				-	la (6)	-	mi (3)	-	155.56	1.05946309

E3	E	1				do (1)	-	so (5)		re (2)	164.81	1.05946309
F3	F	2				-	ti (7)	la (6)	fa (4)	mi (3)	174.61	1.05946309
F#	F#	3				re (2)	-	-	-	-	185.00	1.05946309
G3	G	4		**# 3**		mi (3)	do (1)	ti (7)	so (5)	fa (4)	**196.00**	1.05946309
G#	G#	5				-	-	-	la (6)	-	207.65	1.05946309
A3	A	6				fa (4)	re (2)	do (1)	-	so (5)	220.00	1.05946309
A#	A#	7				-	mi (3)	-	ti (7)	la (6)	233.08	1.05946309
B3	B	8		**# 2**		so (5)	-	re (2)	-	-	**246.94**	1.05946309
C4	C	9				la (6)	fa (4)	mi (3)	do (1)	ti (7)	**261.63**	1.05946309
C#	C#	10				-	-	-	-	-	277.18	1.05946309
D4	D	11				ti (7)	so (5)	fa (4)	re (2)	do (1)	293.67	1.05946309
D#	D#	12				-	la (6)	-	mi (3)	-	311.13	1.05946309
E4	E	1		**# 1**		do (1)	-	so (5)	-	re (2)	**329.63**	1.05946309
F4	F	2	-	1st fret	-	-	ti (7)	la (6)	fa (4)	mi (3)	349.23	1.05946309
F#	F#	3		2nd fret		re (2)	-	-	-	-	369.99	1.05946309
G4	G	4		3rd fret		mi (3)	do (1)	ti (7)	so (5)	fa (4)	392.00	1.05946309
G#	G#	5		4th fret		-	-	-	la (6)	-	415.30	1.05946309
A4	A	6		5th fret		fa (4)	re (2)	do (1)	-	so (5)	**440**	1.05946309
A#	A#	7		6th fret		-	mi (3)	-	ti (7)	la (6)	466.16	1.05946309
B4	B	8		7th fret		so (5)	-	re (2)	-	-	493.88	1.05946309
C5	C5	9		8th fret		la (6)	fa (4)	mi (3)	do (1)	ti (7)	523.25	1.05946309
C#	C#	10		9th fret		-	-	-	-	-	554.37	1.05946309
D5	D	11		10th fret		ti (7)	so (5)	fa (4)	re (2)	do (1)	587.33	1.05946309
D#	D#	12		11th fret		-	la (6)	-	mi (3)	-	622.25	1.05946309
E5	E	1		12th fret		do (1)	-	so (5)	-	re (2)	659.26	1.05946309
F5	F	2		13th fret		-	ti (7)	la (6)	fa (4)	mi (3)	698.46	1.05946309
F#	F#	3		14th fret		re (2)	-	-	-	-	739.99	1.05946309
G5	G	4		15th fret		mi (3)	do (1)	ti (7)	so (5)	fa (4)	783.99	1.05946309
G#	G#	5		16th fret		-	-	-	la (6)	-	830.61	1.05946309
A5	A	6		17th fret		fa (4)	re (2)	do (1)	-	so (5)	**880.00**	1.05946309
A#	A#	7		18th fret		-	mi (3)	-	ti (7)	la (6)	932.33	1.05946309
B5	B	8		19th fret		so (5)	-	re (2)	-	-	987.77	1.05946309
C6	C	9		20th fret		la (6)	fa (4)	mi (3)	do (1)	ti (7)	1,046.50	1.05946309
C#	C#	10		21st fret		-	-	-	-	-	1,108.73	1.05946309
D6	D	11		22nd fret		ti (7)	so (5)	fa (4)	re (2)	do (1)	1,174.66	1.05946309
D#	D#	12		23rd fret		-	la (6)	-	mi (3)	-	1,244.51	1.05946309
E6	E	1		24th fret		do (1)	-	so (5)	-	re (2)	1,318.51	1.05946309
F6	F	2		25th fret		-	ti (7)	la (6)	fa (4)	mi (3)	1,396.91	1.05946309
F#	F#	3				re (2)	-	-	-	-	1,479.98	1.05946309
						(1)= Tonic (4)= Sub-dominant			(5)= Dominant (7)= Seventh		**261.63 = Middle C**	

	Each horizontal line = 1 half-note = 1 fret Chromatic Scale = Each half-note is 5.95% higher in frequency than the previous note. 1 octave = 12 half-notes = doubling of frequency

50	50	50	10	80	10	60	60	60	60	60	65	75

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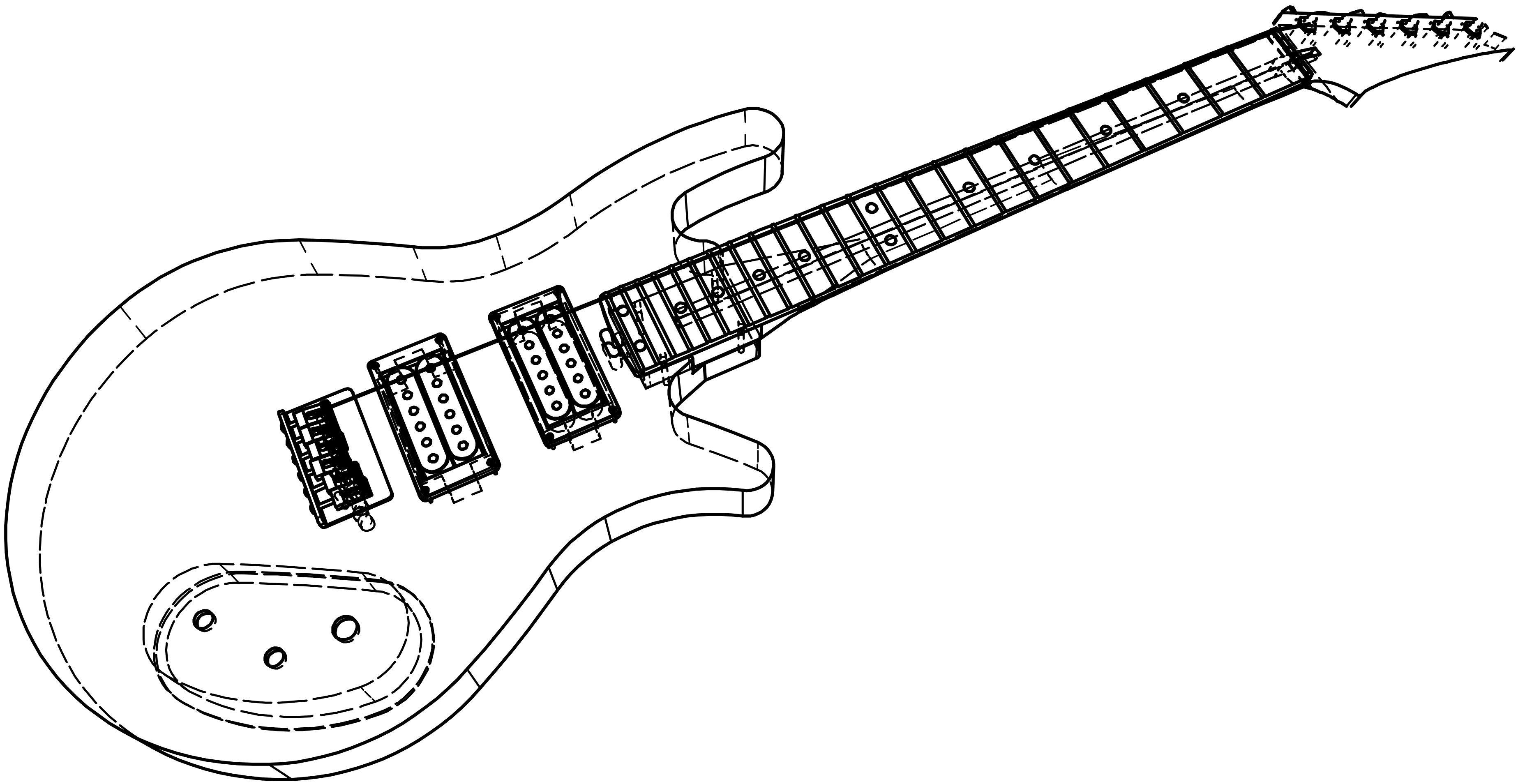
Vaughn's Summaries

http://www.vaughns-1-pagers.com

This Vaughns 1-Pagers Music Note Frequency Chart web page was updated on 2010-04-14.



DRAWN Philip Smith	12/21/2009	NOTE: Features common to ALL 25-1/2" scale length guitars.
CHECKED		TITLE PLM/STEM GUITAR STANDARDS
QA		
MFG		
APPROVED		
		SIZE A — DWG NO PRODUCTION_STANDARDS VER 1 — REV
		SCALE — SHEET 1 OF 6

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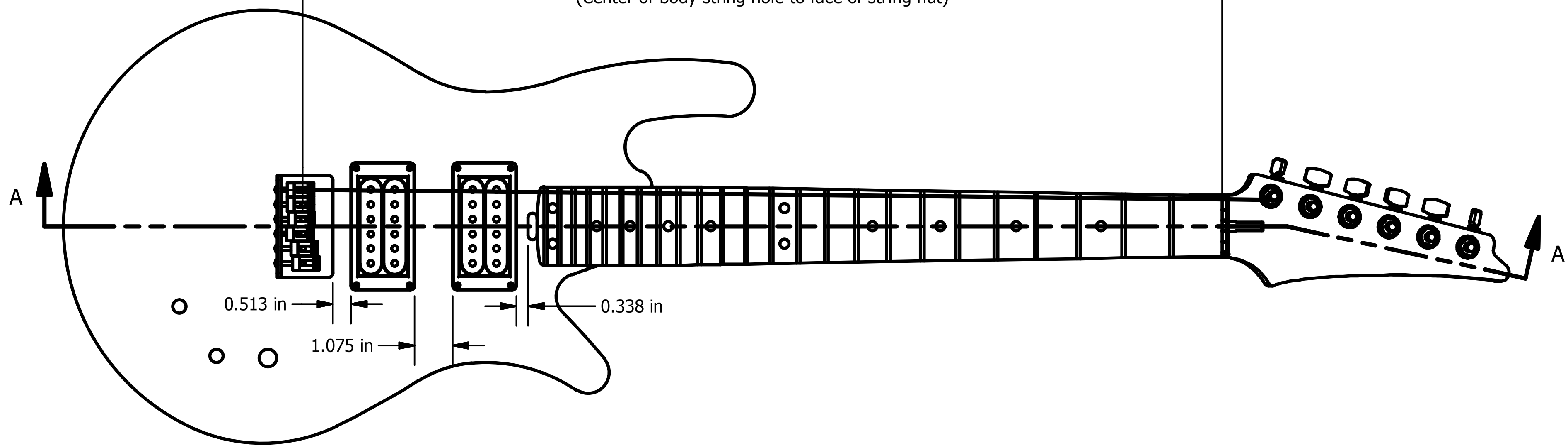
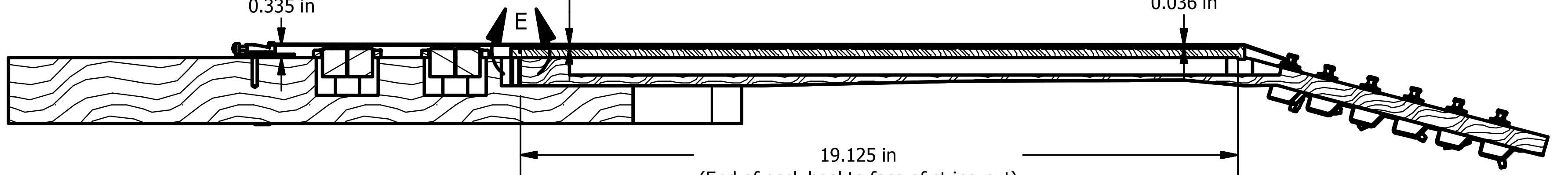
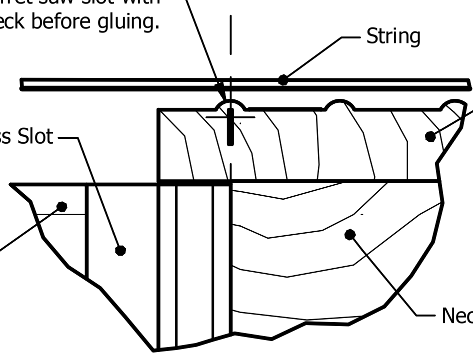




SECTION A-A



DETAIL E
FRETBOARD ASSEMBLY ALIGNMENT

DRAWN Philip Smith	12/21/2009	NOTE: Features common to ALL 25-1/2" scale length guitars.			
CHECKED					
QA		TITLE			
MFG					
APPROVED		PLM/STEM GUITAR STANDARDS			
		SIZE A		DWG NO PRODUCTION_STANDARDS VER 1	REV
		SCALE		SHEET 2 OF 6	

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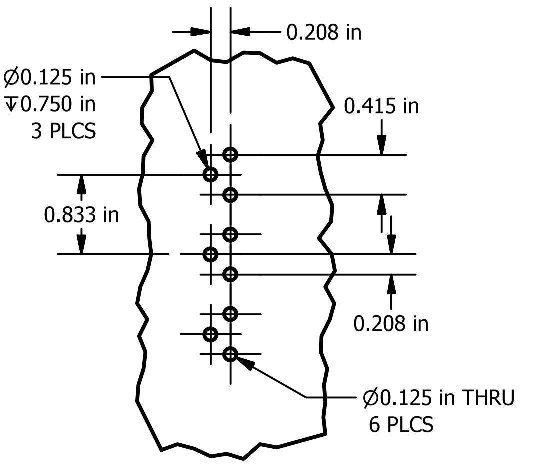
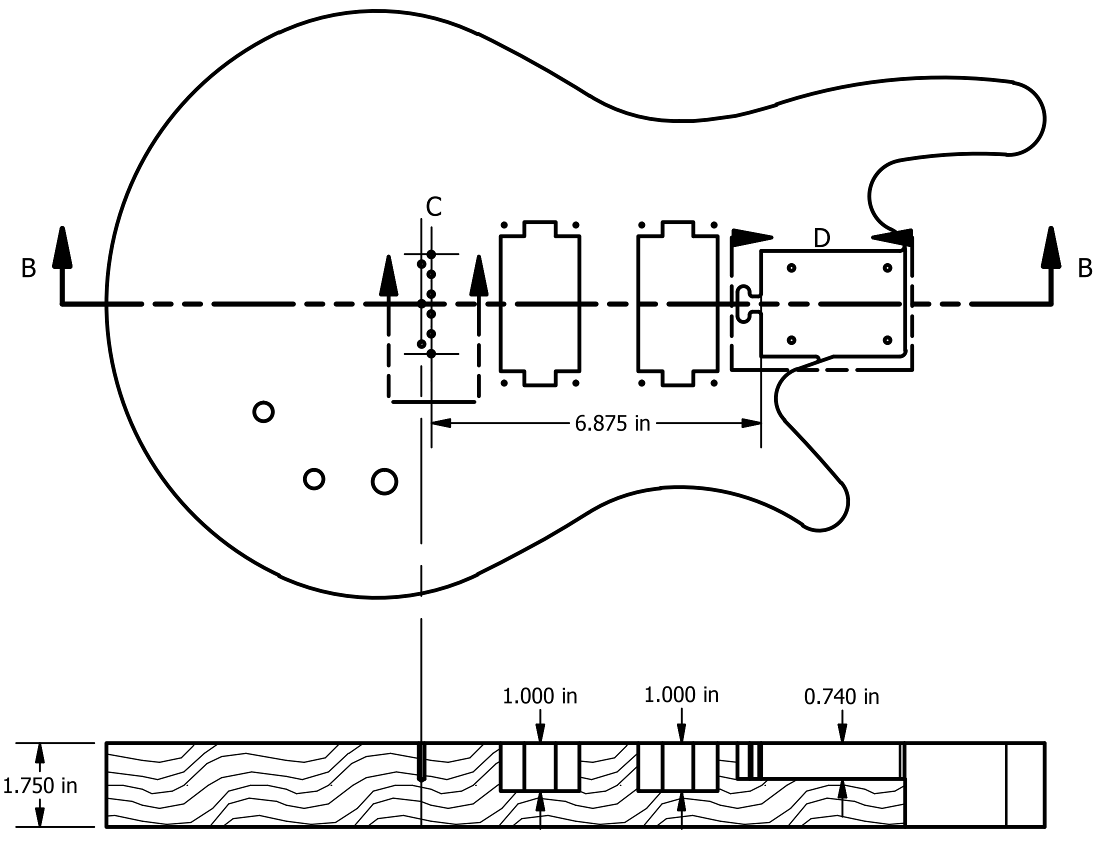
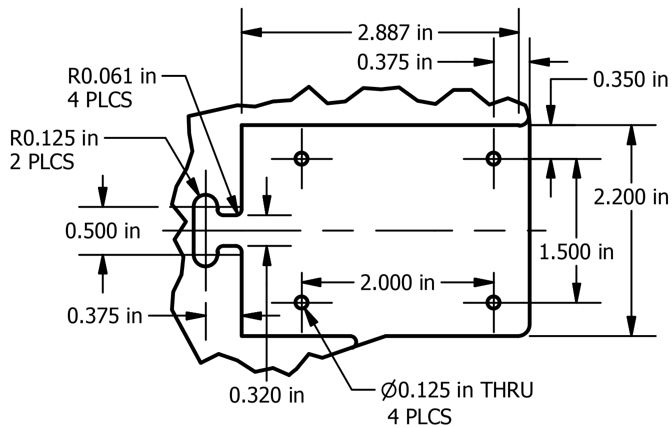


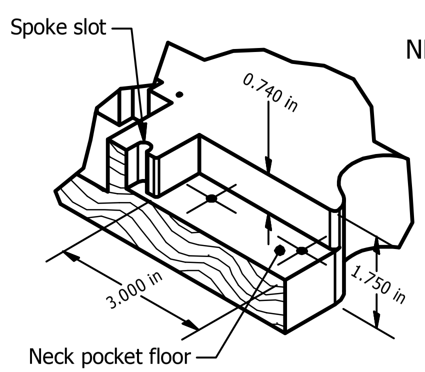
DETAIL C
BRIDGE MOUNT (TYPICAL)
SCALE 1 / 2



SECTION B-B
SCALE 1 / 4



DETAIL D
NECK MOUNT (TYPICAL)
SCALE 1 / 2



DRAWN Philip Smith	12/21/2009	NOTE: Features common to ALL 25-1/2" scale length guitars.			
CHECKED					
QA		TITLE			
MFG		PLM/STEM GUITAR STANDARDS			
APPROVED					
		SIZE A		DWG NO PRODUCTION_STANDARDS VER 1	REV
		SCALE		SHEET 3 OF 6	

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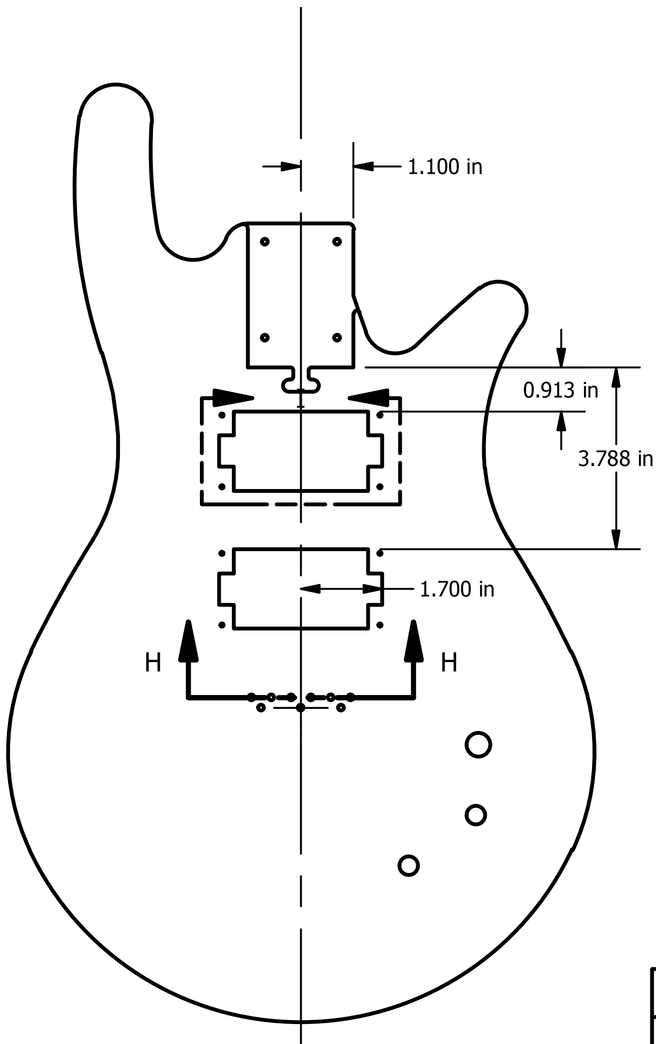
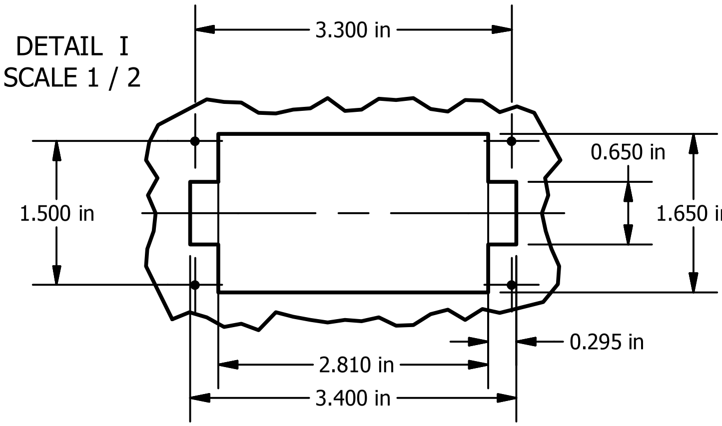
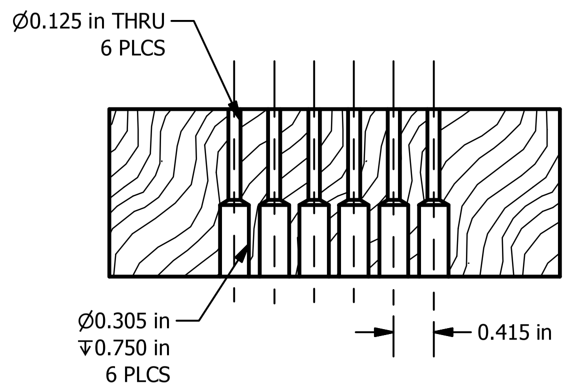


DETAIL I
SCALE 1 / 2



SECTION H-H
SCALE 1 / 2



DRAWN Philip Smith	12/21/2009	NOTE: Features common to ALL 25-1/2" scale length guitars.
CHECKED		
QA		TITLE
MFG		PLM/STEM GUITAR STANDARDS
APPROVED		
		SIZE A / DWG NO PRODUCTION_STANDARDS VER 1 / REV
		SCALE / SHEET 4 OF 6

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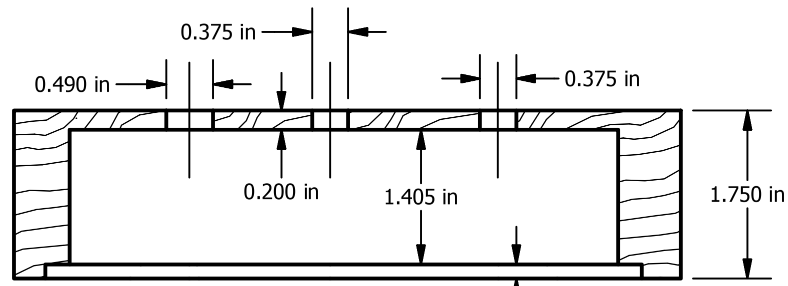
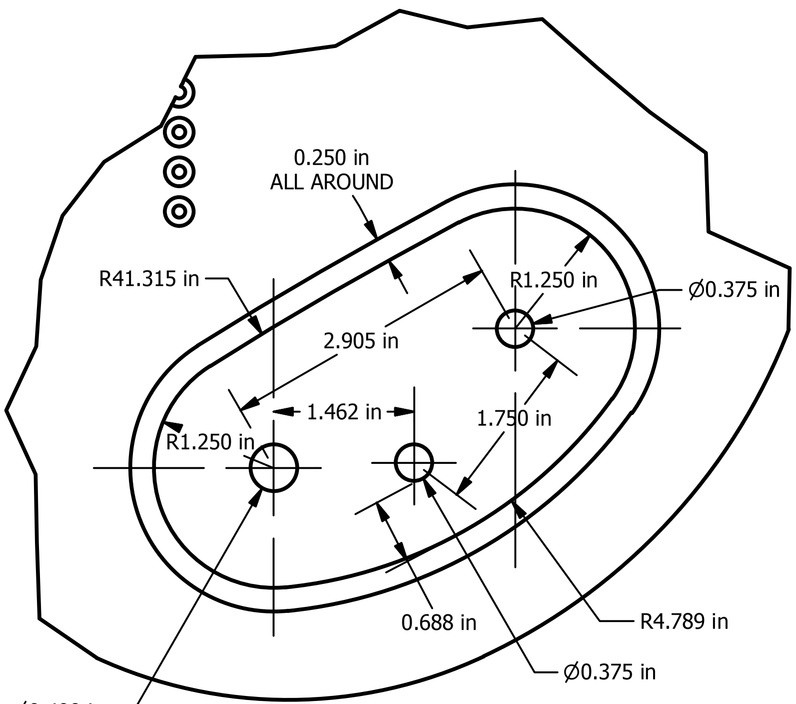
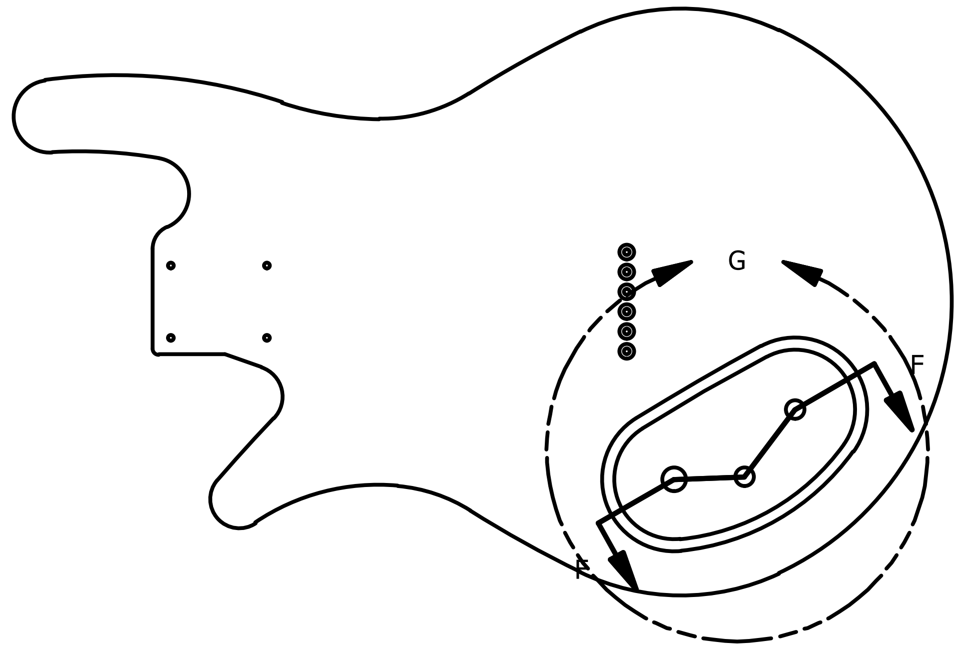


SECTION F-F
SCALE 1 / 2



DETAIL G
SCALE 1 / 2



DRAWN Philip Smith	12/21/2009	NOTE: Features common to ALL 25-1/2" scale length guitars.
CHECKED		
QA		TITLE
MFG		PLM/STEM GUITAR STANDARDS
APPROVED		
		SIZE A / DWG NO PRODUCTION_STANDARDS VER 1 / REV
		SCALE / SHEET 5 OF 6

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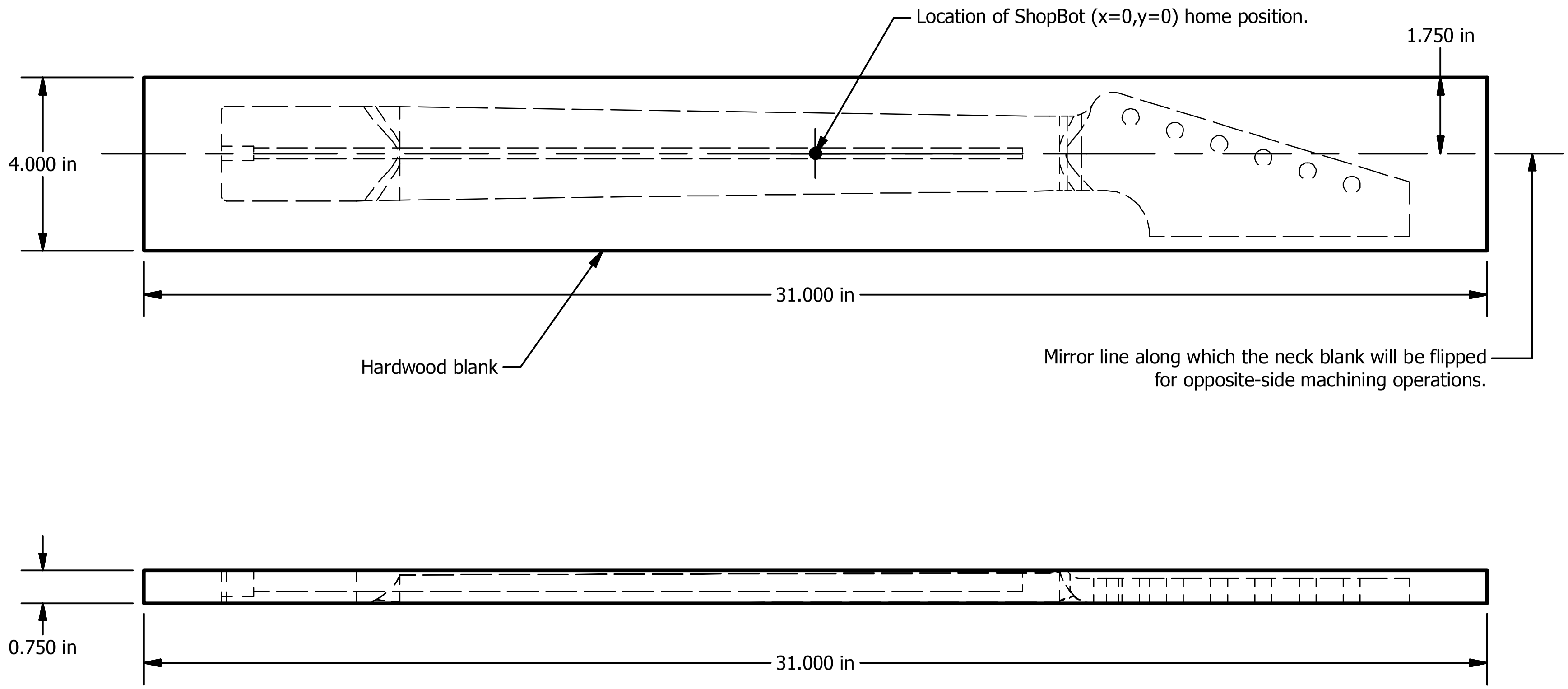

DRAWN Philip Smith	12/21/2009	NOTE: Features common to ALL 25-1/2" scale length guitars.			
CHECKED					
QA		TITLE			
MFG		PLM/STEM GUITAR STANDARDS			
APPROVED					
		SIZE A		DWG NO PRODUCTION_STANDARDS VER 1	REV
		SCALE		SHEET 6 OF 6	

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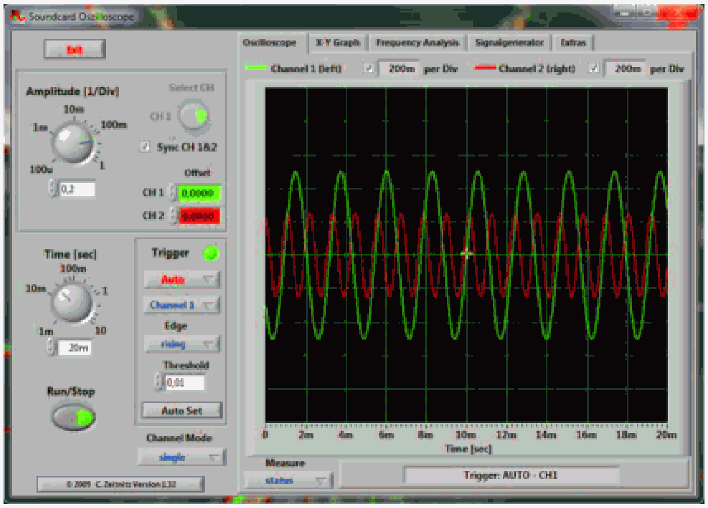
Inhalt

- Projekte
- Soundcard Scope
  - Deutsch
  - English
  - FAQs
- WaveIO
- Know How
- Intern
- Kontakt

Soundcard Oscilloscope

deutsche Version

Author: Christian Zeitnitz



Main features:

The Soundcard Oscilloscope receives its data from the Soundcard with 44.1kHz and 16 Bit resolution. The data source can be selected in the Windows mixer (Microphone, Line-In or Wave). The frequency range depends on the sound card, but 20-20000Hz should be possible with all modern cards. The low frequency end is limited by the AC coupling of the line-in signal. Be aware, that most microphone inputs are only mono.

The oscilloscope contains in addition a signal generator for 2 channels for Sine, Square, Triangular and Sawtooth wave forms in the frequency range from 0 to 20kHz. These signals are available at the speaker output of the sound card. These can be fed back to the oscillocope in order to generate Lissajous figures in the x-y mode.

Download the latest version: scope V1.32

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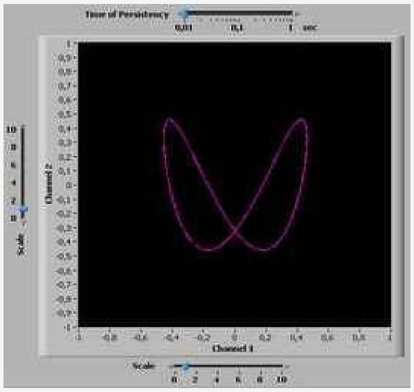
Additional features



- Trigger modes: off, automatic, normal and single shot
- Triggerlevel can be set with the mouse
- The signals of the two channels can be added, subtracted and multiplied
- x-y mode
- Frequency analysis (Fourier spectrum)
- Frequency filter: low-, high- and band-pass
- Cursors to measure amplitude, time and frequency in the main window
- Audio Recorder to save data to a wave file
- For multi soundcard system, the used card can be selected in the settings tab

The program has completely been written in LabView (™ by National Instruments). For the actual Sound I/O part the WaveIO package by the same author has been used.

Signal Sources

The signals for the oscilloscope can be internal to the computer (MP3 player, function generator etc.) or from external sources (line-in, microphone). For external sources care has to be taken, not to exceed the voltage range of the inputs. The range is usually only ±0.7V !! If higher voltage need to be analyzed, a voltage divider has to be used. Additional protection diodes are recommended in order to avoid any damage to the sound card and to the computer.

Requirements

This program will run on Windows 2000/XP/Vista computers with a sound card and 30MByte space on disk. It will not install on older versions of Windows. The speed requirements are not very hard. A 1GHz machine is suffient. On slower CPUs the load on the system might lead to reduced responsiveness of the system.

Terms of usage and licenses

This Software and all previous versions are NO Freeware!

- The use of the software and of the documentation is granted free of charge for private and non-commercial use in educational institutions
- Any commercial application requires a corresponding license (see below)
- Distribution and sale of the program is prohibited. Contact the author in order to obtain a resale license.

If you like to support the further development of this program please obtain a private license by following this link

Commercial usage: In order to obtain a commercial license follow this link

Downloads

Instructions: Unpack the file into a directory of your choice and run the setup.exe program. Enjoy !

Version 1.32

- Changes
  - New cursor to measure the signal properties (when the acquisition is stopped) including an onscreen display of the corresponding time and amplitudes
  - First version which can be licensed
    - Private license to support the further development of the program
    - Commercial license for the usage in companies and non-public educational institutions
- Version 1.32 of the program (all languages): scope_132
- Only the english manual of version 1.32

Version 1.31

Please uninstall any previous version of the scope software before installing this version

- Changes
  - The different graphs (Oszilloscope, XY-Graph und frequency spectrum) can be stored as graphic files as well as a data files (CSV-file)
  - Time- und amplitude cursor can be activated simultaniously
- Version 1.31 of the program (all languages): scope_131 (ca. 25MB)
- Only the english manual for version 1.31

Version 1.30

- Changes
  - Improved stability on slower computers
  - The offset of the signal can now be set with the mouse directly on the signal screen
  - Optional automatic on-screen frequency and amplitude measurement
  - Possibility to measure the transfer function between two signals
  - French and czech Versions available
- Acknowledgement
  - Thanks to Francis Brouchier for providing the french translation
  - Thanks to Jakub Jermár and Leoš Dvorák for providing the czech version

Version 1.24

- Changes
  - Bug in re-sampling routine removed
    - Re-sampling effects only the display and not recorded wave forms
    - For long time settings the time scale was wrong!
    - This bug is present in ALL prior versions!
  - Multiple language version (english, german)
  - Persistence of the XY-Graph adjustable
  - Amplitude of frequency analysis graph scales automatically (can be disabled)
  - Program remembers the selected sound card for input and output
  - Display of sound properties/mixer from the Extras tab works now on Vista
- Acknowledgement
  - Thanks to Helio and the american teachers for spotting the mentioned bug

Due to a bug in the re-samlping of data (thanks Helio), all versions prior to 1.24 should be updated!

Version 1.23

- ***Update to Version 1.24***

Version 1.22

- Changes
  - Peak hold function in frequency analysis
  - Signal generator allows now to generate white noise and a frequency sweep
  - Cue points are no longer written to the .wav file by the sound recorder. The Media Player was confused by these extra data

Version 1.21

Version 1.20

- The Audio Recorder had some unwanted features:
  - Minimal time window on file was 50ms long
  - Trigger was sometimes not stored on the file

- Update to Version 1.21

Version 1.10

Version 1.04

Final Remarks

The program requires a correctly installed and configured soundcard on your Windows computer. In case of problems consult the manual and the frequently asked question.

If you still have a software related problem send mail to C.Zeitnitz

Build Procedure Listing

Body – No fly zone is neck attachment pocket flat surface

- Shape surfaces (personal choice)
- Scrape flat surfaces
- Route edges if desired
- Prefit parts - Pick-up (may need to use chisel to widen slot)
- Drill jack hole (7/8")
- Drill access to pickup pockets (long bit)
- Sand surfaces
  - Start with 150
  - Once end grain areas are smooth move to 220/240 on body

Create custom neck plate on laser cutter

Neck – No fly zone is neck attachment surface, truss rod slot, nut slot and fret board surface

- Sand machining marks from back of neck (150 grit)
- Design headstock
- Have headstock cut out
- Neck to headstock transition sanding (careful do not sand much off) (150 grit moving to 220)
- Flatten fret board surface by sanding on a granite block
- Insert truss rod (file surfaces if needed for truss rod to lay flat)
- See Fret Board preparation

STOP!!!!

- 8. Once fret board and the neck have the alignment holes positioned then add glue to the surfaces (wipe off extra with damp cloth)
- 9. Clamp fret Board to Neck - use 5-6 clamps

Fret Board Preparation

- Flatten Fret board on granite block
- Drill 2 holes using wire drill bit at Fret 2 and Fret 17
- Tap t pins into neck for alignment purposes
- Pull t-pins to make sure you can get them out once glue is applied
- Align T-pins on fretboard and neck (always check twice)
- Resume Neck assembly!

Applying surface finish to body and neck

- Sand surfaces to 220 grit sandpaper
- Apply sanding sealer to body or neck/fretboard (personal choice on application to fretboard, I recommend it to keep the fretboard clan during finishing)
- Lightly sand the first sealer coat with 220 grit paper
- Apply sealer again and let dry
- Lightly sand with 220 grit sand paper again
- Apply surface finish and let dry
- Lightly sand using 320 grit sand paper
- Apply finish sand and let dry sand with 320 grit again
- Apply finish sand and let dry sand with 400 grit again
- Apply finish sand and let dry sand with 600 grit again
- Apply final finish coat

Electronics (complete after applying surface finish to Body)

- Pre fabricate wiring Harness - Potentiometers, capacitor and wires for jack
- Make sure soldering iron is hot (tin tip)
- When fabricating harness pre-wire harness and heat connection location, touch solder to connection and coat connection pull solder away then pull heat away (Do NOT blow on connection)
- Optional: Use metallic tape and line electronics pocket for grounding (make sure pickup and jack hole is not covered)
- Insert wiring harness into guitar and tighten nuts down, hand tight
- Attach pickups to body – use pilot holes for ring screws
- Solder in pickups to wiring harness (Cover guitar body to prevent solder dripping)
- Solder jack connection in place
- The Big test!!! Plug into the amp, take a screw driver and tap the pickups and see if they make noise. If not there is a wiring problem….. if there is , congratulations move on to the next step

Final assembly

1. Neck - fretboard
    - Sand fretboard (150 grit then finish sand with 220 and 320 paper just a few finish strokes) to 12" radius using PSA sand paper and a sanding block (Use Chalk)
    - Cut fret wire to size (2.75-3" long)
    - Press fretwire into place (Easy Hulkster not too much pressure)
    - Make sure all frets are seated
    - Nip off the ends of the fret wire with the cutters
    - Apply a drop of super glue to each fret (both sides of fret board

- ☐ Apply blue painters tape to fretboad between the frets
- ☐ Use a fret file to bevel the fret edges and make them flush to the fret board
- ☐ Apply sharpie marker to the frets
- ☐ Use 220 grit sand paper and run it over the frets sanding away the sharpie marker
- ☐ Check the frets again by using a straight edge and then applying sharpie to suspect frets
- ☐ Make sure all of the sharpie is sanded off
- ☐ Use small diamond files to dress the frets (TAKE YOUR TIME) round the edges of the frets
- ☐ Use stick sander to finish the rounding process
- ☐ Remove tape from fret board and clean with Naptha
- ☐ Apply a light coat of surface finish if desired.
- ☐ Attach Tuning machines to headstock (tap and tighten)

2. Body
    - ☐ Press in ferrules using drill press or tap in with hammer
    - ☐ Attach Bridge to body
    - ☐ Fasten neck to body using neck plate and screws
3. Nut
    - ☐ Test fit of Nut in Nut slot (file if necessary)
    - ☐ Mark edges of neck on nut
    - ☐ Use flat pencil to mark Nut slots No fly zone by laying on frets and creating arched line)!
    - ☐ Sand the nut material so it fits flush with the neck do not sand the top)
    - ☐ Measure in 1/8” from both ends of the nut and mark the nut with pencil
    - ☐ Use string layout gauge and lay out the rest of the string positions
    - ☐ Use a nut file (.016) to cut small groves in the nut
    - ☐ Use nut files to cut groves of correct sizes based on string sizes (low E .046 High E .012) Not too deep yet!
    - ☐ String guitar and place nut

Q

Guitar Manufacturing Production Notes

This document contains the manufacturing processes instituted at
Sinclair Community College
Dayton, Ohio

Prepared by: Philip D. Smith Jr.
March 26, 2010

Table of Contents

Body & Neck Blanks

Body Blanks

Materials

The body blanks used for this project are constructed from combinations of hardwoods, and designed to offer the strength required for almost 100lbs of applied string tension. To help eliminate the possibility of accidentally placing a weak piece of lumber in a position requiring full strength, there are no softwoods used in this project.

Typical hardwoods employed are poplar, Brazilian mahogany, white maple, ambrosia maple, hickory, bubinga, oak, and sassafras. (This list is non-exclusive)

Construction

Body blanks are glued together in "packs," with the grains running primarily along the centerline of the guitar body. The overall dimensions of the pack are **22" long** by **14" wide** by **1.750" thick**. Note that the critical dimension is the thickness of the blank: the tooling is designed around this thickness.

Optimally, the center block (or "main beam") must be at least 4" inches wide in order to support the neck, pickup pockets, and bridge. All other pieces can vary in width. It is not advised to create the main beam by laminating wood strips; the reason is that the laminates will shrink over time at different rates, thus causing stresses in the center block that could result in separation.

Tolerances

The maximum allowable variation of the body blank thickness is +/- 0.025"

The ramifications of falling outside of this tolerance will mean that the electronics cavity will be machined incorrectly. This will produce a deck thickness that is either too thin (<0.175") or too thick (>0.225") for the proper mounting of the potentiometers and pickup switch.

The body blank widths and lengths can vary as much as 1" without problem since they will be trimmed in the machining processes. (It is critical to be aware that some material **must be** available in order to properly secure the blanks during the machining process)

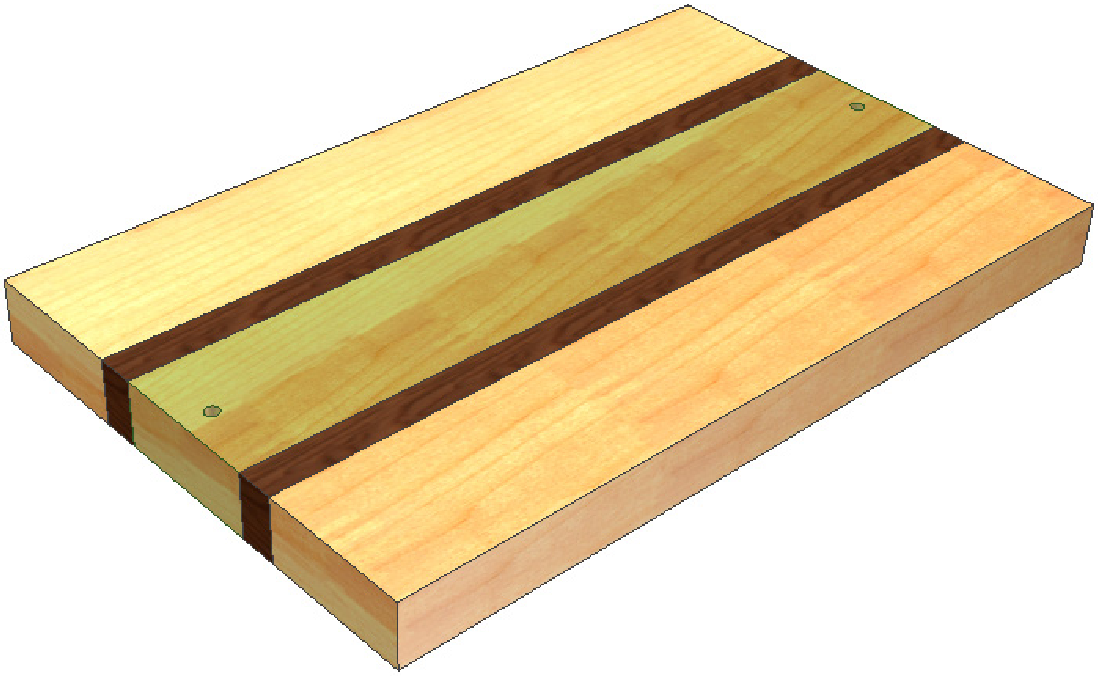
Securing for Machining

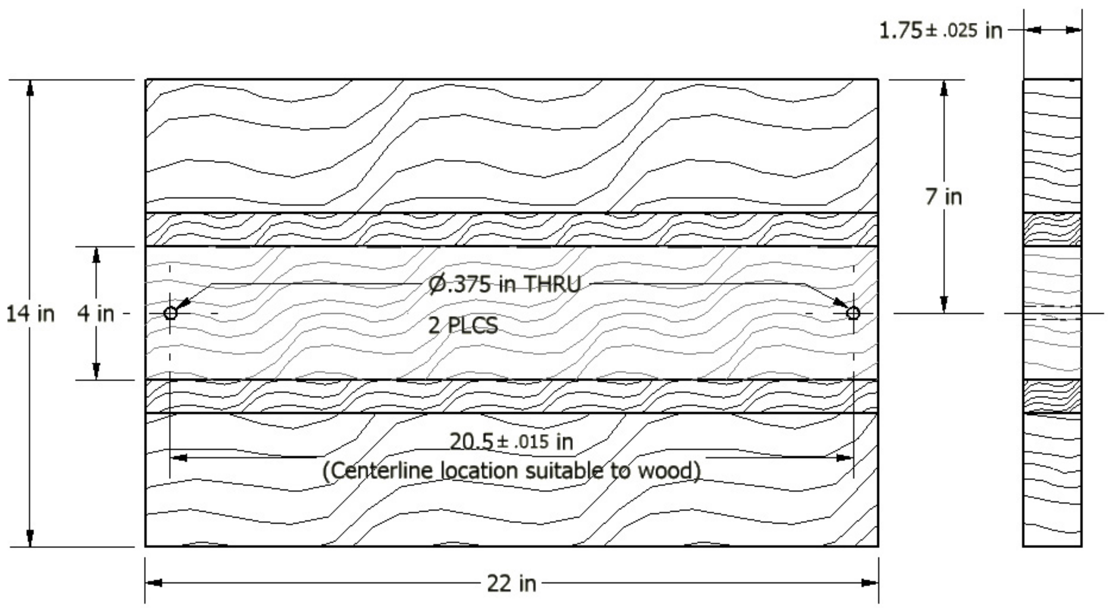
The blank can be secured in ANY fashion, but there must be at least 20"x13" (based around the center of the blank) of available material for machining. The milling cutter WILL strike holding devices within this envelope.

The optimal mounting practice is to place threaded studs along the centerline of the body blank. It has been determined that only two are required, and finish results are extremely satisfactory.

Also note that since there is full-depth drilling, do not use steel as a base plate (aluminum or other soft material is satisfactory)

Body Blank Diagrams





Body Blank Tooling Requirements

The following machine tooling is used in the processing of the bodies:

- ***1/4" diameter, straight-end mill with a length of 2-1/2" and a cutting length of 1"***
- ***Craftsmen 1/8" diameter hex-drive (Sears Item# 00964056000, Model# 64056.) with the mounting shank machined down to 0.250" diameter to allow it to be used in the Shopbot's router or spindle head.***

The milling cutter should extend at least 1.75" beyond the bottom of the lowest point of the milling head's chuck. This is to ensure that there is ample clearance for machining the electronics cavity.

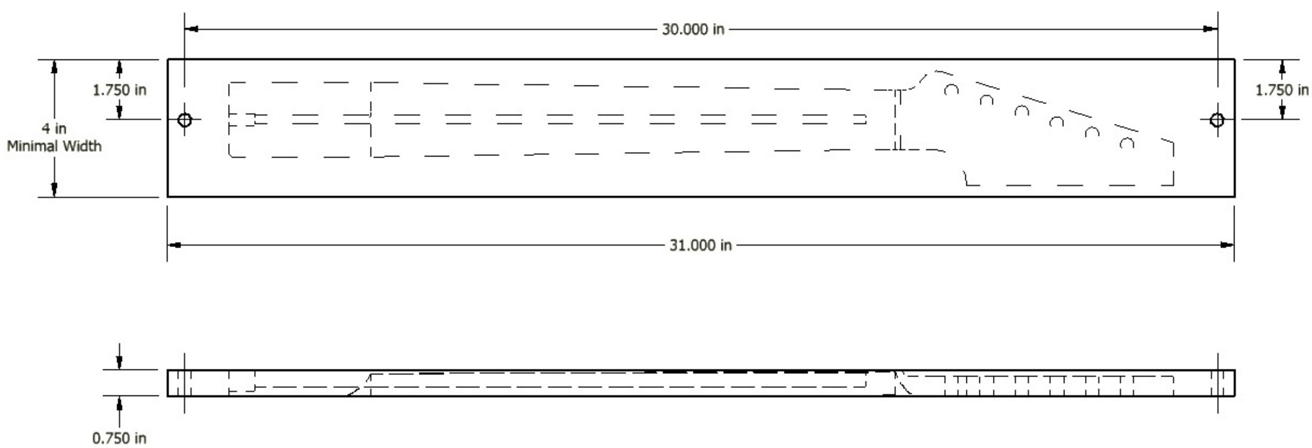
The drill bit must be able to reach 2" below the bottom of the lowest point of the milling head's chuck. This is to allow for full-depth drilling of the string and neck mount holes.

Neck Blanks

Materials

The neck blanks are made from a single piece of white maple, **31" long** by **4" minimal width** by **0.750" thick**. Since the centerline of the neck is offset due to allowances made for the headstock, and to reduce material waste, the mirroring line falls approximately 1-3/4" from one edge of the blank.

Neck Blank Diagrams



Tolerances

The maximum allowable variation of the neck blank thickness is +/- 0.010"

The ramifications of falling outside of this tolerance will mean that the truss rod slot will machine through the back of the neck, or the headstock will be too thick for the tuners to be properly mounted.

The neck blank widths can vary over 4”; however, the blank lengths must be over 30” to allow for proper profile machining of the outer edges. As with body machining, some excess material must be available for securing during machining.

Securing for Machining

The blank can be secured in ANY fashion, but there must be at least 28”x4” (based around the center of the blank) of available material for machining. The milling cutter WILL strike holding devices within this envelope.

The optimal mounting practice is to place threaded studs along the centerline of the neck blank. It has been determined that only two are required, and finish results are extremely satisfactory.

Since there is full-depth milling, **do not use steel as a base plate!** It HIGHLY RECOMMENDED that you use a hardwood consumable beneath the blank since the milling tool path plunges beyond the thickness of the neck blank to a depth of 0.900”. Therefore, it is advisable for your consumable to be at least 1/2” thick. (We use a maple consumable that is 3/4” thick.)

Neck Blank Tooling Requirements

The following milling cutters are used in the processing of the necks:

- ***1/4” diameter, straight-end mill with a length of 2-1/2” and a cutting length of 1”***
- ***1/2” diameter, ball-nosed mill with a length of 2-1/2” and a cutting length of 1”***

The 1/4” straight-end milling cutter should extend at least 1.5” beyond the bottom of the lowest point of the milling head’s chuck. This is to ensure that there is ample clearance for machining the full-depth profile.

The 1/2” ball-nosed milling cutter must be able to reach 1” below the bottom of the lowest point of the milling head’s chuck. This is to allow for full-depth contouring of the neck back.

Important Computer Requirements

The ShopBot controller requires the full attention of the commanding computer system. Errant miscommunication between the desktop computer and the control box (black computer-like tower connected directly to the ShopBot) can lead to the ShopBot performing unexpected cuts.

In order to ensure that the ShopBot controller has the dedicated attention of your desktop computer:

- ***Disable all virus scanners***
- ***Remove the computer from the network***
- ***Disable Window's Automatic Update Service***
- ***Disable all screen savers***
- ***Disable/Remove webcams and their associated software***
- ***Uninstall all software that provides automatic updates (I.E. Adobe Acrobat, QuickTime, etc.)***
- ***Remove any unnecessary tasks from the registry tree: HKLM\Software\Microsoft\Windows\Current Version\Run AND from HKCU\Software\Microsoft\Windows\Current Version\Run***
- ***Remove all scheduled tasks (C:\Windows\Tasks)***
- ***Remove unnecessary programs from Start/Programs/Startup folder***
- ***Set power management scheme for full power (no hibernation or sleep)***
- ***Do not run any other software other than ShopBot applications during cutting operations.***

R

Build Procedure Listing

Body – No fly zone is neck attachment pocket flat surface

- ☐ Shape surfaces (personal choice)
- ☐ Scrape flat surfaces
- ☐ Route edges if desired
- ☐ Prefit parts - Pick-up (may need to use chisel to widen slot)
- ☐ Drill jack hole (7/8")
- ☐ Drill access to pickup pockets (long bit)
- ☐ Sand surfaces
    - Start with 150
    - Once end grain areas are smooth move to 220/240 on body

Create custom neck plate on laser cutter

Neck – No fly zone is neck attachment surface, truss rod slot, nut slot and fret board surface

- ☐ Sand machining marks from back of neck (150 grit)
- ☐ Design headstock
- ☐ Have headstock cut out
- ☐ Neck to headstock transition sanding (careful do not sand much off) (150 grit moving to 220)
- ☐ Flatten fret board surface by sanding on a granite block
- ☐ Insert truss rod (file surfaces if needed for truss rod to lay flat)
- ☐ See Fret Board preparation

STOP!!!!

- ☐ 8. Once fret board and the neck have the alignment holes positioned then add glue to the surfaces (wipe off extra with damp cloth)
- ☐ 9. Clamp fret Board to Neck - use 5-6 clamps

Fret Board Preparation

- ☐ Flatten Fret board on granite block
- ☐ Drill 2 holes using wire drill bit at Fret 2 and Fret 17
- ☐ Tap t pins into neck for alignment purposes
- ☐ Pull t-pins to make sure you can get them out once glue is applied
- ☐ Align T-pins on fretboard and neck (always check twice)
- ☐ Resume Neck assembly!

Applying surface finish to body and neck

- Sand surfaces to 220 grit sandpaper
- Apply sanding sealer to body or neck/fretboard (personal choice on application to fretboard, I recommend it to keep the fretboard clan during finishing)
- Lightly sand the first sealer coat with 220 grit paper
- Apply sealer again and let dry
- Lightly sand with 220 grit sand paper again
- Apply surface finish and let dry
- Lightly sand using 320 grit sand paper
- Apply finish sand and let dry sand with 320 grit again
- Apply finish sand and let dry sand with 400 grit again
- Apply finish sand and let dry sand with 600 grit again
- Apply final finish coat

Electronics (complete after applying surface finish to Body)

- Pre fabricate wiring Harness - Potentiometers, capacitor and wires for jack
- Make sure soldering iron is hot (tin tip)
- When fabricating harness pre-wire harness and heat connection location, touch solder to connection and coat connection pull solder away then pull heat away (Do NOT blow on connection)
- Optional: Use metallic tape and line electronics pocket for grounding (make sure pickup and jack hole is not covered)
- Insert wiring harness into guitar and tighten nuts down, hand tight
- Attach pickups to body – use pilot holes for ring screws
- Solder in pickups to wiring harness (Cover guitar body to prevent solder dripping)
- Solder jack connection in place
- The Big test!!! Plug into the amp, take a screw driver and tap the pickups and see if they make noise. If not there is a wiring problem….. if there is , congratulations move on to the next step

Final assembly

1. Neck - fretboard
    - Sand fretboard (150 grit then finish sand with 220 and 320 paper just a few finish strokes) to 12” radius using PSA sand paper and a sanding block (Use Chalk)
    - Cut fret wire to size (2.75-3” long)
    - Press fretwire into place (Easy Hulkster not too much pressure)
    - Make sure all frets are seated
    - Nip off the ends of the fret wire with the cutters
    - Apply a drop of super glue to each fret (both sides of fret board

- Apply blue painters tape to fretboad between the frets
- Use a fret file to bevel the fret edges and make them flush to the fret board
- Apply sharpie marker to the frets
- Use 220 grit sand paper and run it over the frets sanding away the sharpie marker
- Check the frets again by using a straight edge and then applying sharpie to suspect frets
- Make sure all of the sharpie is sanded off
- Use small diamond files to dress the frets (TAKE YOUR TIME) round the edges of the frets
- Use stick sander to finish the rounding process
- Remove tape from fret board and clean with Naptha
- Apply a light coat of surface finish if desired.
- Attach Tuning machines to headstock (tap and tighten)

2. Body
    - Press in ferrules using drill press or tap in with hammer
    - Attach Bridge to body
    - Fasten neck to body using neck plate and screws
3. Nut
    - Test fit of Nut in Nut slot (file if necessary)
    - Mark edges of neck on nut
    - Use flat pencil to mark Nut slots No fly zone by laying on frets and creating arched line)!
    - Sand the nut material so it fits flush with the neck do not sand the top)
    - Measure in 1/8" from both ends of the nut and mark the nut with pencil
    - Use string layout gauge and lay out the rest of the string positions
    - Use a nut file (.016) to cut small groves in the nut
    - Use nut files to cut groves of correct sizes based on string sizes (low E .046 High E .012) Not too deep yet!
    - String guitar and place nut

S

Assembling an Electric Guitar

Mark French and Brad Harriger

Introduction

This set of instructions was written to accompany guitar making workshops held at Purdue University. We assume you have never made a guitar before and that you may not even have worked with wood before. If you follow these directions, take your time and enjoy the process, you'll make great sounding guitar.

It's easy to get enthused about making a guitar and want to add custom touches. A little bit of customization is OK, but too much means you won't get finished. It's way better to finish the week with a nice, completed guitar in your hand than to be still looking at an unassembled pile of customized parts. We want you to make the guitar your own, but we'll steer you away from trying to make changes that will take too much time.

Don't be discouraged if you make mistakes. If you can't bear to fix mistakes, you probably shouldn't be making guitars. Seriously, most mistakes can be fixed, usually without leaving much of a trace. The most important thing is to let somebody know as soon as you find an error so it can be fixed before it gets bigger.

Parts

At the beginning of the process, you should have a kit of parts. This kit will include everything you need to make a guitar. Be careful not to lose anything. The list of parts depends on what guitar you are making. These instructions cover both a single pickup guitar and one with two pickups and a switch.

Figure 1 – Rough Milled Necks and Bodies

Parts List

Number	Description	Qty	Notes
1	Neck Blank	1	Paddle headstock, slotted for truss rod
2	Body Blank	1	
3	Fretboard	1	Slotted and radiused, but no dots or inlays
4	Truss Rod	1	
5	Tuners	6	May include bushings, washers and nuts
6	Tuner screws	6	3/8” #2 stainless steel pan head Phillips sheet metal screws. Not needed for all types of tuner
7	Nut Blank	1	
8	Neck plate	1	
9	Neck Screws	4	1-3/4” #8 stainless oval head Phillips sheet metal screws
10	Fret Wire	3	Medium-Medium fret wire bent to an 8-10 inch radius. Best to start with this and experiment with other styles on your next instrument.
11	Neck Dots	12	Wood or mother of pearl. You don’t need to install these if you don’t want to
12	Side Dot Rod	1	Black or white 1/16” Delrin plastic. Don’t need this either if you don’t want side dots.
13	Potentiometers	2	Either 250kΩ or 500kΩ depending on your wiring. Includes hex nuts and flat washers
14	Knobs	2	One for each potentiometer
15	Capacitor	1	Either 22pF or 47pF depending on your wiring
16	Hookup Wire	2ft	Different colors of stranded 22 gauge wire
17	Pickup	1	Either single or double size humbucker
18	Mounting Screws	2	1” #4 stainless Phillips sheet metal screws for single size 1” #3-48 machine screws for double size humbuckers
19	Pickup Ring	1	Only needed for double sized humbuckers
20	Ring Screws	4	¾” #4 oval head Phillips stainless steel sheet metal screws. Only needed for double sized humbucker
21	Pickup Springs	2	Coil springs or sections of ¼ inch silicone tubing
22	Bridge	1	There are three different bridges currently being used. Two use screws to attach to the body and one uses threaded studs.
23	Bridge Screws	3 or 4	Four 1” #4 flat head stainless steel Phillips sheet metal screws Three 1” #8 flat head stainless steel Phillips sheet metal screws
24	Body Ferrules	6	Only needed for one type of bridge
25	Strap Buttons	2	
26	Strap Button Screws	2	1” #8 oval head stainless steel Phillips sheet metal screws
27	Electronics Pocket Cover	1	Either white or black
28	Pocket cover screws	4	¾” #4 stainless steel Phillips sheet metal screws
29	Output Jack	1	¼ inch phono jack with hex nut and lock washer
30	Jack Plate	1	
31	Jack Plate Screws	2 or 4	3/4” #4 oval head stainless steel Phillips sheet metal screws
			Two Pickup Guitars Only
29	2nd Pickup	1	Double size
30	2nd Pickup Ring	1	Double size, might be higher than first one
31	Pickup Ring Screws	4	¾” #4 oval head Phillips stainless steel sheet metal screws. Only needed for double sized humbucker
32	Mounting Screws	2	1” #4 stainless Phillips sheet metal screws for single size 1” #3-48 machine screws for double size humbuckers
33	Ring Screws	4	¾” #4 oval head Phillips stainless steel sheet metal screws. Only needed for double sized humbucker
34	Pickup Springs	2	Coil springs or sections of ¼ inch silicone tubing
35	3-way Switch	1	Includes knurled ring and flat washer if Gibson type switch. Includes oval head machine screws if blade switch
36	Switch Knob	1	Threaded for Gibson type switch or slotted for blade switch

Preparing the Body for Finishing
The body has been milled from a block of wood 1.75 inches thick. All the necessary pockets have been milled out and all the holes have been drilled. This was done on a computer controlled milling machine and all the dimensions should be correct to a few thousandths of an inch.

Figure 2 shows a body with the back radiused and holes drilled. The large hole (7/8 inch diameter) in the edge is for the output jack. The larger of the two holes inside the electronics pocket is to run the pickup wire(s) into the electronics pocket. The smaller of the two holes is for the bridge ground.

Figure 2 – Guitar Body with Body Radius and Holes Drilled

Before the body can be finished, you will need to do the final shaping and sand it smooth. The final shaping is up to you. Some people like a simple slab body like that on a Fender Telecaster. Figure 3 shows a Telecaster with wear on the paint. This wear may be real (due to extended use) or simulated (done at the factory) so that the guitar appears to be a vintage instrument.

Figure 3 – A Telecaster Showing either Real or Simulated Wear

The Telecaster is a very early design and the slab body was probably adopted to make the guitar easy to make. Some players found it uncomfortable and Fender's response to this problem was the Stratocaster, a more refined design with a deeply contoured body.

Figure 4 – Body Contouring on a Fender Stratocaster

Contouring is strictly for comfort and appearance; it doesn't affect the sound, so contour or not as you wish. Rough contouring should be done with a rasp and a pneumatic sanding drum. Figure 5 shows a pneumatic drum being used to contour a body. Note that the body is securely clamped down.

Figure 5 – Contouring a Body Using a Pneumatic Sanding Drum

Figure 6 shows a body being contoured by hand with a rasp. A sharp rasp can remove a lot of material quickly and accurately. It is a more precise tool than the pneumatic sander, but leaves a rougher surface. Unless you have previous experience with a pneumatic sander, it's generally a good idea to do the rough shaping with a rasp and refine the surface with the sander. Figure 6 shows a machine cut rasp with very heavy teeth. In general, you will have better results using a hand-cut rasp with slightly finer teeth.

Figure 6 – Shaping a Body with a Rasp

Once you have done the rough shaping with a rasp and pneumatic sander, you can do the final shaping and smooth the body using sandpaper. Sandpaper should be used only when the contouring is close to the desired final shape. Start with 120 grit sandpaper. You should try to smooth any rough areas and relieve hard edges that might make the guitar uncomfortable to hold or to play.

A quick note about sandpaper: Sandpaper is designated by its grit. Grit is the number of abrasive elements per square inch. Coarse sandpaper is 80-100 grit. You'll do much of your shaping with 120 grit sandpaper. Fine sandpaper is about 220 grit. You'll use this for the final sanding before applying the first coat of sealer. Very fine sandpaper is 320 grit. This is for smoothing the sealer coat before applying the top coats.

Always sand wood parallel to the grain. If you sand across the grain, you will make scratches that you'll then have to sand out. Also, don't use fine sandpaper too soon. Coarse sandpaper is for shaping and leveling. Only when the shape is correct should you go to finer sandpaper. If you try to level a rough surface with smooth sandpaper, all you will do is make the tops of the bumps smooth.

After the body is contoured, it should be sanded smooth. You can smooth the body with 180-240 grit sandpaper. Take your time to remove any machining marks and make sure the entire body is smooth. **You can't do a good finish over a badly prepared surface!**

Finishing the Body

The finish on your guitar will be applied in either two or three layers.

- If you want a natural finish, you'll apply a sealing layer and then a clear top coat.
- If you want a tinted finish, you'll apply a sealing layer, a tinted layer and a clear top coat.

The first layer seals the wood grain and forms a smooth surface for the next layers. Typically, you'll want to apply two coats of sealer and sand in between them. Apply the first coat of sealer and let it dry completely. Then sand with 220 grit sandpaper. If the sealer is dry, the sandpaper should make dust. If it isn't dry, the sandpaper will get gummy with partially cured sealer. After the first coat of sealer has been sanded smooth, apply a second coat. Just like before, let it dry and sand it.

Sealer is formulated to dry quickly, sometimes as little as 60 minutes. If you plan your work, you can avoid delays. For example, apply a coat of sealer right before lunch or at the end of the work day so it can dry while you are away. At the very least, you can let the sealer dry while you work on something else.

A word about finishes:
One way to organize finishes is by whether there is any chemistry when they dry. Shellac and lacquer dry by evaporation. They are made of solids dissolved in a volatile solvent. When the solvent completely evaporates, the solid is left. Shellac is made from refined secretions from the Lac bug dissolved in alcohol. Lacquer is made from nitrocellulose dissolved in a solvent made from a mixture of volatile organic compounds (VOCs). It's nasty stuff so always wear a cartridge breather.

Other finishes undergo a chemical reaction. This means that the chemical makeup of the cured finish is different than that of the wet finish. This class includes oils, polyurethane, epoxies, catalyzed finishes and light cured finishes.

There are many different combinations of materials that can be used to do a nice finish on a guitar. It's probably more important to be familiar with the properties of the type you are using that to select any particular finish. It is also very important to select a sealer and top coat that are compatible with one another; otherwise the finish may peel off. It's happened to us and, trust us, it's a bad feeling.

It can be really temping to plan a complicated finish. Especially if this is your first guitar, though, you should keep it simple. The simplest choice is a clear finish that is even and shows off the grain of the wood underneath. The nice part of a clear finish is that it is easy to touch up or repair.

Slightly more involved is a single color – either solid paint or translucent stain. Well done, this can be very attractive. A nice variation of the single color finish is to concentrate the color around the edge of the instrument in something like a sunburst pattern. Figure 7 shows several guitars with single color finishes and two with clear finish.

Figure 7 – Guitar Bodies Drying After Finishing

If you are willing to do two colors and tape off some interesting pattern, another dimension of creativity is possible. Figure 8 shows a guitar painted simply with white and black. The first color was black. The builder then taped off an angular spiral pattern so that a white layer could be applied. After the white dried, he removed the tape, leaving the taped off pattern in black. Finally, a protective clear coat was applied over the color coats.

Figure 8 – A Two Color Instrument before the Clear Coat

A nice, but slightly more involved finish is a sunburst. Sunbursts usually have either two or three colors and can have several different themes. Figure 9 shows a three color antique cherry sunburst. It's perhaps not a good idea to try a sunburst yourself on your first guitar, but a workshop instructor can spray one for you if you like.

Figure 9 – A Three Tone Sunburst on a Double Cutaway Guitar

Designing the Headstock

You'll be able to design your own headstock using computer aided design (CAD) software. The shape of the headstock is up to you – it's a chance to make the guitar uniquely yours. However, the tuners must fit on it and it must be strong enough to withstand the tension of the strings.

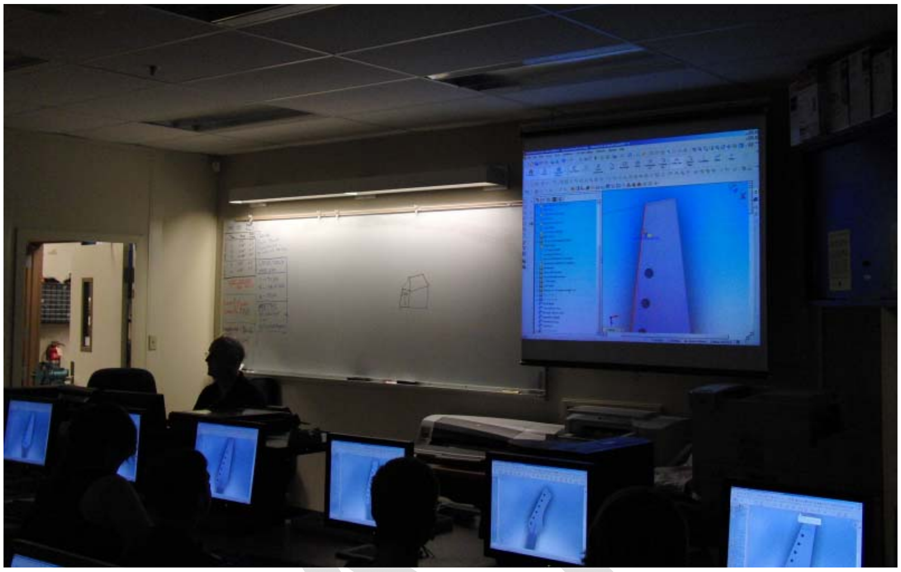


Figure 10 – Designing Headstocks in the Computer Aided Design Lab

After you design your headstock, your design will be loaded into a computer controlled milling machine that will cut out the headstock for you. After the headstock is milled, you will sand and finish it.

Figure 11 – Headstock Being Milled

Preparing Fretboard

The fretboard is where the player interacts most with the instrument, so it is important to get it right. The fretboard you get has the fret slots already cut in it and has been sanded to the correct radius (usually 12 inches or 305mm). It has also been cut to the right shape; the nut end is about 1.69 inches (42.9 mm) wide and the heel end is 2 3/16 inches (2.12 inches or 53.8 mm).

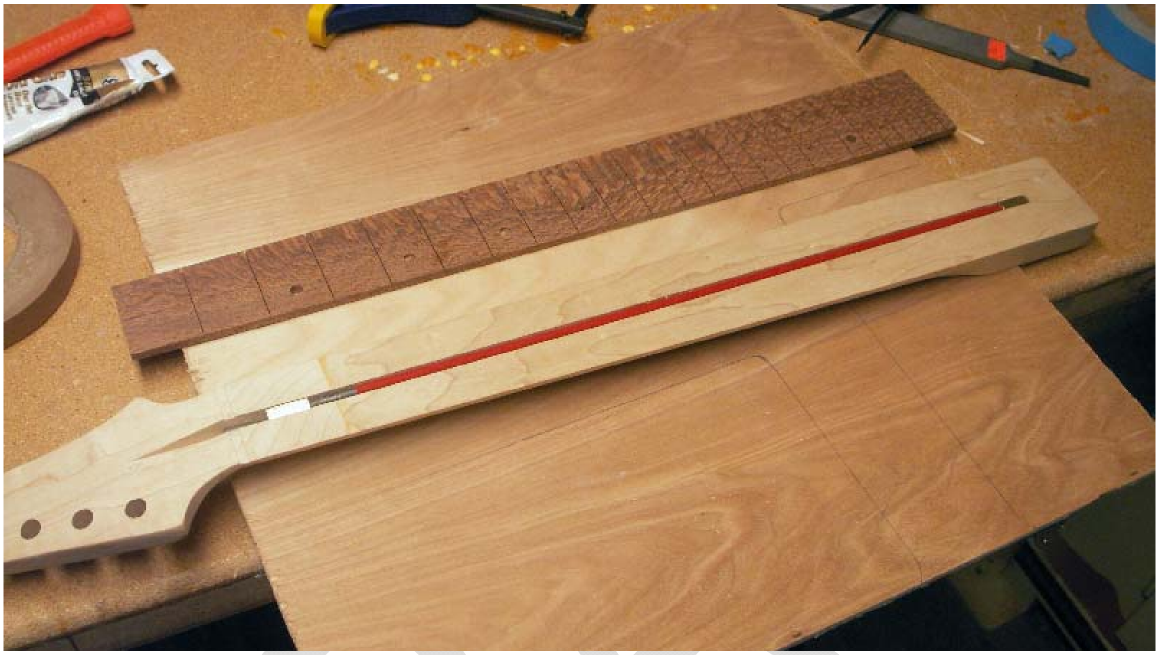


Figure 12 – Neck with Truss Rod and Fretboard

You will need to sand both the flat and curved sides of the fretboard before you do anything else. First, you can level the flat side by putting a piece of fine sticky-back sandpaper on a very flat surface and moving the fret board back and forth. A granite surface plate is ideal, but a table saw is also flat enough. It helps to make chalk marks on the back surface of the fretboard before sanding. When all the chalk is sanded off, the surface is flat.

The rounded surface needs to be sanded as well. It has been sanded to a 12 inch radius using coarse sandpaper and needs to be smoothed before finishing. It is best to use a radius block and 220 grit sandpaper. It helps to use a strip of double sided tape to fix the fretboard to a flat surface before sanding it with the radius block. When the radiused side is smooth, seal it with at least one coat of Tru-Oil sealer. This keeps dirt and sawdust from being rubbed into the fretboard as the dots are installed and the fretboard is fixed to the neck. Make sure not to get oil on the back (flat side) of the fretboard. This is the surface that will be glued to the neck and the glue only sticks to bare wood.

After the fretboard has been finish sanded and sealed, you can install fret dots. Typically, the dots are either mother of pearl (MOP) or wood. Mother of pearl is made from the inside of oyster shells and the dots are thin – about 0.040 in. You can cut wood dots from any wood you like using a tapered plug cutter.

Mark the locations of the dots on the fretboard and drill ¼ inch holes using either a brad point or Forstner bit. Holes for MOP dots are shallow so that the dots stick up above the surface of the fretboard. After the holes are drilled, the dots can be glued in place with superglue. When the glue is dry, the dots are sanded flush with a radius block and fine sandpaper. 320 grit sandpaper is ideal.

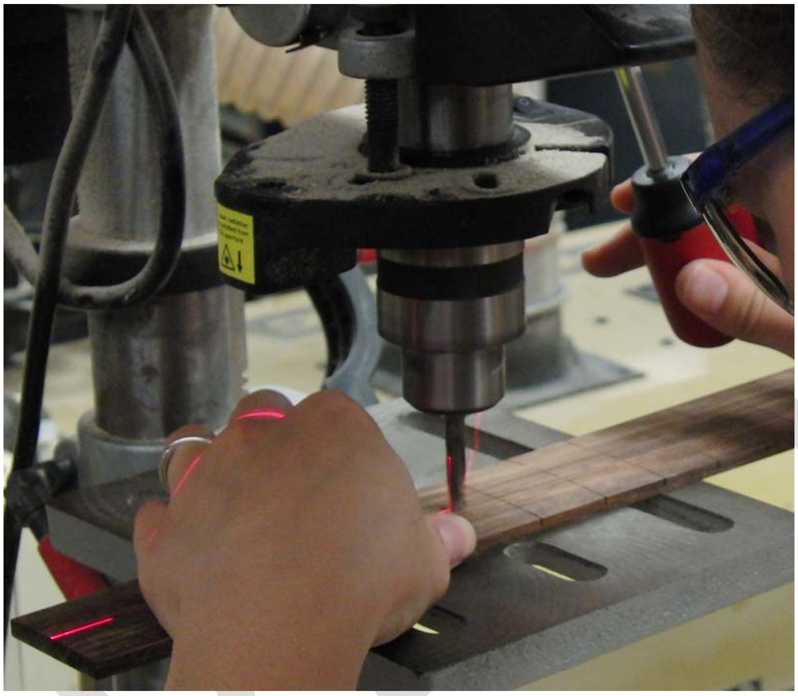


Figure 13 – Drilling Holes for Fretboard Dots

For wood dots, drill ¼ inch holes at least 1/8 inch deep. While it is not preferred, don't worry if you drill completely through the fretboard. Cut the wood plugs from a hard, contrasting wood using a plug cutter. Pop the plugs free from the larger board using a small screwdriver. The plugs will have a smooth side - what had been the smooth surface of the board - and a rough side where it was broken free.

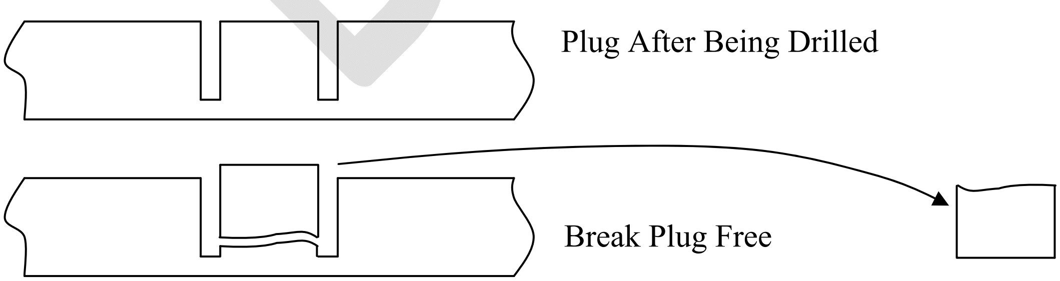


Figure 14 – Cutting Wood Plugs from a Board

Figure 15 – Fretboard with Dot Holes Drilled

To install a plug, put a drop of wood glue in the hole, making sure it coats the sides of the hole. Then tap a plug in, smooth side down. It is OK to use a small hammer to lightly seat the plug. Also, make sure the grain of the plug is lined up with the grain of the fretboard.

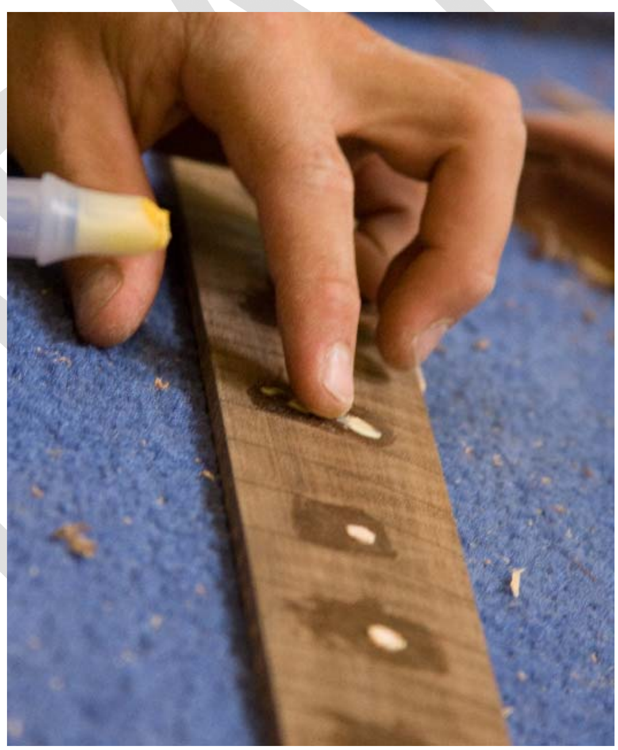


Figure 16 – Gluing Wood Dots into the Fretboard

After the glue dries, carefully level the plug with the fretboard. If there isn't much material to remove, use sandpaper and a radius block. If the plug sticks up more than 1/8 inch, you can carefully saw some of the excess off with a small hand saw. Use masking tape to protect the fretboard from being scratched by the saw teeth. Then, finish up with sandpaper. When the dots are flush with the rest of the fretboard, apply another coat of Tru-Oil sealer to the fretboard.

Preparing Neck for Assembly

Before the fretboard is glued to the neck, you need to flatten the flat surface of the neck (the one with the slot in it). This is basically the same thing you did with the flat side of the fretboard. Mark the flat parts of the neck with some chalk and sand it on the same flat surface you used for the fretboard. When all the chalk is removed, the neck is flat.

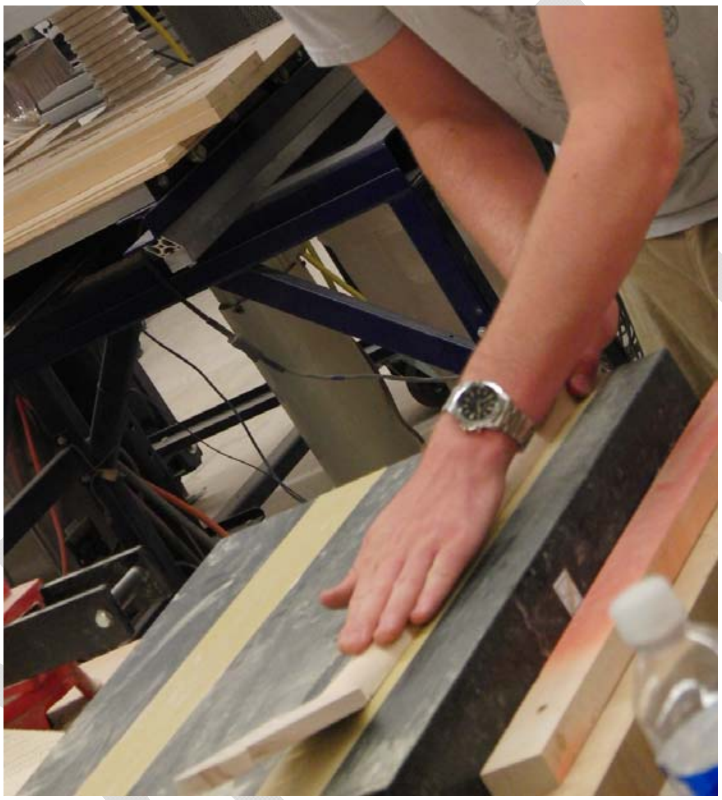


Figure 17 – Flattening Neck Before Gluing on Fretboard

The next step is to make sure the truss rod fits into the slot correctly. It goes in the slot with the nut at the headstock end of the neck. Also, the nut should be toward the bottom of the slot. The brass blocks should be flush with the flat side of the neck. If they are not, make sure the slot is free of any wood chips. If either of the blocks still protrudes from the slot, talk to one of the instructors. When you are done with this step, the neck is ready to be assembled.

Figure 18 – Correct Truss Rod Orientation with Nut at Bottom of the Slot

Assembling Neck

The first step is to make sure the fretboard will be at the right location on the neck. The 24th fret slot should be even with the heel of the neck. Also, the nut end of the neck should line up exactly with the nut slot in the neck as shown in Figure 19. The next step is to make sure that the fretboard is pinned to the neck so that it won't slip when being glued on. Wet wood glue is extremely slippery and you can't count on the fretboard staying in place while the glue dries.

Align the fretboard on the neck **without** any glue and clamp it in place. Then drill a small hole through the bottom of the first fret slot about ½" off center. Then put a push pin through the hole, pinning the fretboard to the neck. Do the same thing at the 20th fret slot. Now you can remove the clamps and prepare to glue the fretboard to the neck.

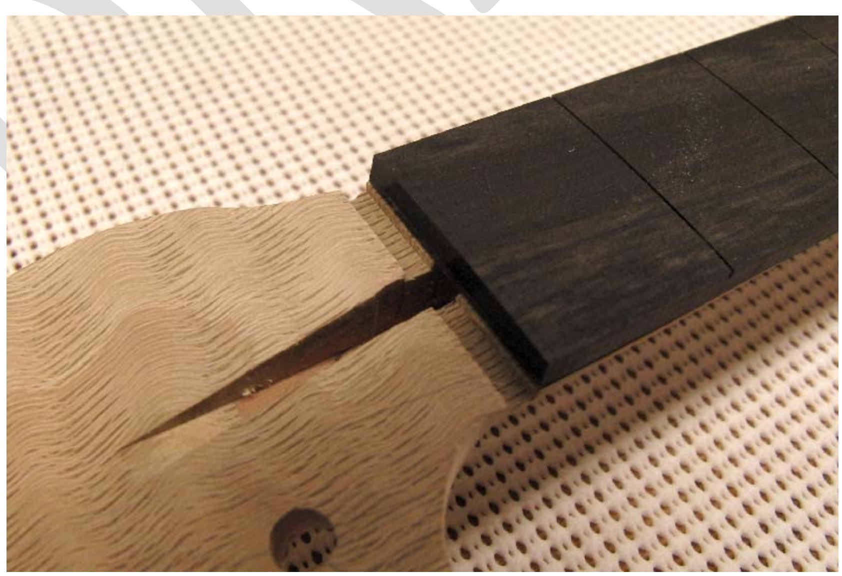


Figure 19 – Fretboard Correctly Aligned on Neck

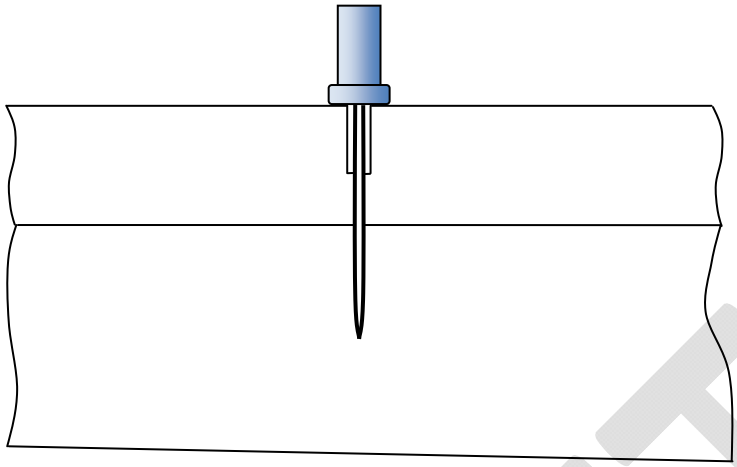


Figure 20 – Using a Push Pin to Fix Fretboard before Gluing

Before applying glue to the neck, do one last check to make sure there is no debris in the truss rod slot and make sure the truss rod is seated correctly. Then cover the truss rod slot with a piece of ¾" wide masking tape; this will keep glue off the truss rod. Then, apply a thin, even layer of wood glue to the neck where the fretboard will join it. Before placing the fretboard on the neck, remove the tape to leave a clean wood surface.

Now, place the fretboard on the neck and insert your two push pins to make sure it is aligned. The most effective way to apply a uniform pressure while the glue dries is to use heavy rubber bands. Two or even three of them wrapped tightly around the neck creates a heavy, even pressure between the fretboard and the neck. Be sure to distribute the windings evenly so that there is pressure distributed all along the neck.

Figure 21 – Heavy Rubber Bands Being used to Clamp a Fretboard to a Neck (picture courtesy of Stewart MacDonald, www.stewmac.com)

Sanding and Finishing Neck

Once the neck and fretboard have dried, finish sanding the neck and make sure the curved surface of the fretboard is straight (as measured down the centerline of the neck). Use a straight edge at the center line of the fretboard to look for high or low spots. If the neck is not perfectly straight – and it probably won't be – start by adjusting the truss rod. If you are unsure of how to do this, ask one of the instructors to help you.

Once the neck is as straight as you can get it by adjusting the truss rod, use a radius bar to carefully level the fretboard. The radius bar (see Figure 21) has a concave surface with a 12" radius that matches the convex surface of your fretboard. Put a piece of 180 grit or 220 grit sticky back sandpaper the full length of the radius bar and then clamp the radius bar, sandpaper side up, into a guitar vise.

Carefully sand any high spots off the fretboard. It can be helpful to mark a couple lines down the fretboard using chalk. The chalk will be sanded away wherever the fretboard contacts the sanding bar. The chalk will stay in low spots that don't contact the sanding bar. When all the chalk marks have been sanded off, the neck should be level.

If the fretboard is close to level and only needs work over a small area, you can use a smaller, wood radius sanding block as shown in Figure 23. Be careful with the shorter blocks, since it's possible to sand a low spot into the fretboard with them.

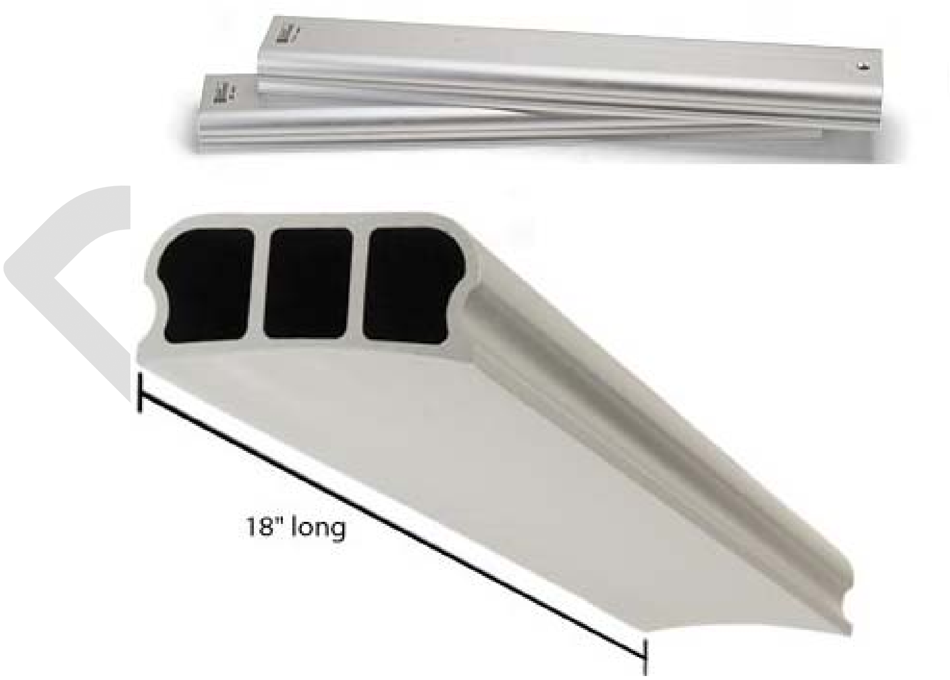


Figure 22 – A Radius Sanding Bar used for Leveling the Fretboard (image courtesy of Stewart MacDonald, www.stewmac.com)

Figure 23 – A Short Radius Being Used to Level a Fretboard

Now that your neck has been finish sanded and the fret board is level, you can apply finish to the neck. Wipe a coat of Tru-Oil sealer on both the fretboard and the neck and let it dry thoroughly. Depending on the humidity, this may take less than an hour. If you notice any bumps or other flaws that need to be sanded out, do this now with fine (about 220 grit) sandpaper and apply another coat of sealer.

When you are satisfied with the seal coat, sand it lightly with very fine sandpaper – 320 grit or 400 grit. If you like, you can apply another coat of sealer and smooth it again, but this is not required.

Figure 24 – Tru-Oil Sealer and Finish

When you are done with the sealer coat, you should apply two coats of Tru-Oil finish. This is a similar formulation to the sealer, but dries to more of a shine and takes a little longer to dry. It is often a good idea to apply a coat of finish right before lunch or at the end of the day so you can do other things while it dries. Most players prefer a matte or satin finish on the fretboard. If you don't want a shiny finish on the fretboard, don't apply finish on it after the sealer coats.

It is very important for the neck to feel smooth under the player's hand. Smooth the finish between coats using either very fine sandpaper or #0000 steel wool. Tru-Oil is durable and easy to touch up; if you ever scratch the finish, you can just sand lightly, if necessary, and just apply some more finish.

When you are done with the finish on the neck, it is time to install the frets.

Fretting

Fret wire has a rounded section called a crown and a straight section called a tang. When fret wire is installed, the tang is tapped into the fret slots and the crown stands out from the fret board. The tang has small teeth protruding from it so the fret won't pull out.

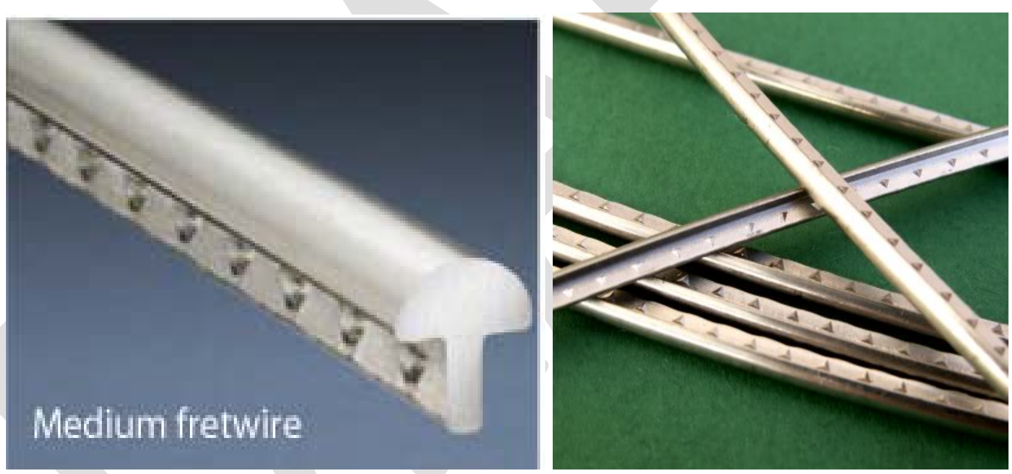


Figure 25 – Fret Wire

Fret wire is usually supplied either in rolls or in straight pieces. Either way, it needs to be bent to the correct radius before being installed. The radius of the fret wire needs to be a little smaller than the radius of the fret board. Since the fret board radius is 12", the wire should be bent to around a 9" radius. The easiest way to bend the wire is with a tool designed specifically for the job (Figure 26). However the wire can also be bent with a simple wooden form or even by hand with a little practice.

Figure 26 – Fret Wire Bender (image courtesy Stewart MacDonald, www.stewmac.com)

There are two common ways to install fret wire. The first one is to tap it in with a small hammer and the second is to use a small arbor press. If you are using a hammer, tap the ends of the fret in first and then tap the center into place. Remember that you are only trying to seat the fret, not drive nails. You only need to tap the wire in.

Figure 27 – Arbor Press for Installing Frets (image courtesy Stewart MacDonald, www.stewmac.com)

Figure 28 – Seating the Center of a Fret with a Fretting Hammer (image courtesy of Stewart MacDonald, www.stewmac.com)

Figure 29 – Neck Caul (image courtesy Stewart MacDonald, www.stewmac.com)

The arbor press applies an even force across the fret and works quickly with only a bit of practice. Again, only use enough force to seat the fret. The gearing gives you quite a bit of leverage, so make sure you don't apply too much force. It is possible to crush the crown right into the fretboard if you pull hard enough. Also, make sure to support the neck on a convex block (called a caul) when using the arbor press.

Cut the fret wire into approximately 3in lengths so that when the frets are installed, each one sticks out about ¼ in. Figure 30 shows a neck with most of the frets installed

Figure 30 – Neck with Most Frets in Place

Once the frets are put in place, put a drop of thin super glue on each end of each fret so that it will be drawn into the fret slots. This reinforces the wood around the frets and helps hold them in place. It also makes the wood a little more durable in case frets need to be replaced later.

The next step is to trim the frets to the correct length and to dress the ends. Cut the frets flush with the end of the fretboard using fret end nippers (see Figure 31)

Figure 31 – Trimming the Fret Ends Flush (image courtesy of Stewart MacDonald, www.stewmac.com)

When the frets have been trimmed, the next step is to dress the ends. Clamp the neck in a guitar vise with one edge of the fretboard up so that you have clear access to the entire edge of the neck. Then, file the ends of the frets so that they are flush with the edge of the fretboard. Use a 6" fine tooth file – the middle one in Figure 32.

Once the frets have been filed flush with the edge of the fretboard, the next step is to bevel the edges at a 35˚ angle to the edge of the fretboard (or 55˚ from the plane of the fretboard). This can be done freehand with the same file used to file the fret ends, but there is a dedicated tool with the file set at the correct angle (Figure 33).

Figure 32 – Files Used for Leveling Frets and Fretboards (image courtesy Stewart MacDonald, www.stewmac.com)

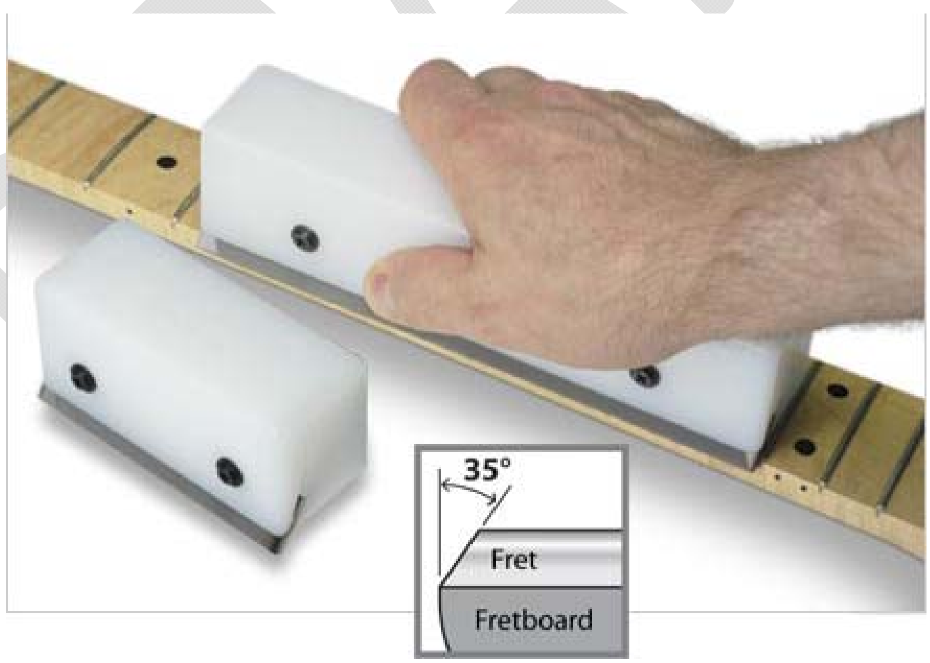


Figure 33 – Fret Beveling File (image courtesy Stewart MacDonald, www.stewmac.com)

The last step in dressing the fret ends is to debur the ends. The most convenient tool is a diamond fret file. Lightly file the ends of the frets to remove any burs. You aren't trying to round off the ends of the frets, just to remove any sharp edges that would be uncomfortable for the player's hands.

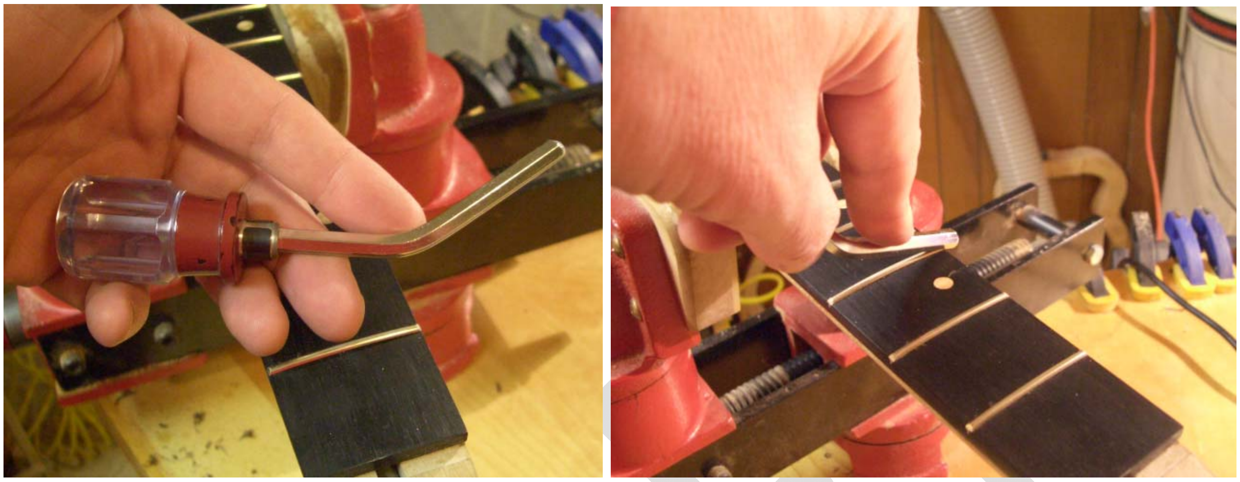


Figure 34 – Diamond Fret File

Figure 35 – A Correctly Dressed Fret End

Making Wiring Harness

Before you can assemble the guitar, you will need to make a wiring harness. It is easier to make most of the connections before the wiring goes into the guitar. The only connections you will make after installing the wiring harness are the bridge ground and the pickup connection(s). Your parts kit will include all the components needed to make the wiring harness.

It is easier to make the solder connections if you temporarily mount the potentiometers and the output jack in a piece of cardboard. This holds them steady while you work.

Figure 36 – Making a Wiring Harness

If your guitar has one pickup, there is no switch in the wiring harness. If your guitar has two pickups, there will be a three way switch. There are several styles of switches commonly used, but they all do the same thing. Figure 37 shows a common type of three way switch. This one mounts using a round hole in the front of the guitar.

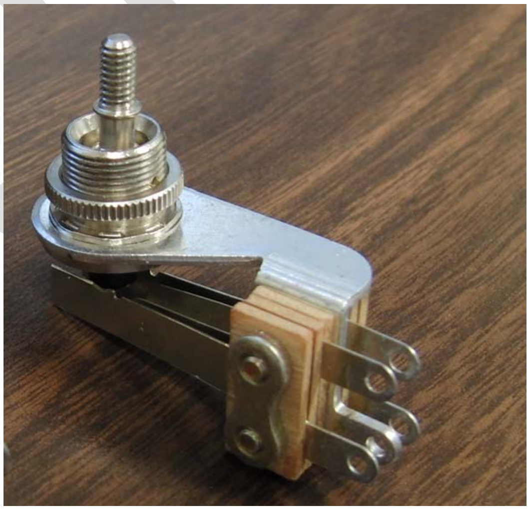


Figure 37 – A Typical Three Way Switch

There are many different wiring arrangements used in electric guitars. For this workshop, you will use one of the most simple and common of these. If your guitar has one pickup, use the wiring diagram below in Figure 38. If your guitar has two pickups, use the wiring diagram in Figure 39. You can find a very complete selection of wiring diagrams at the Seymour Duncan web site (www.seymourduncan.com).

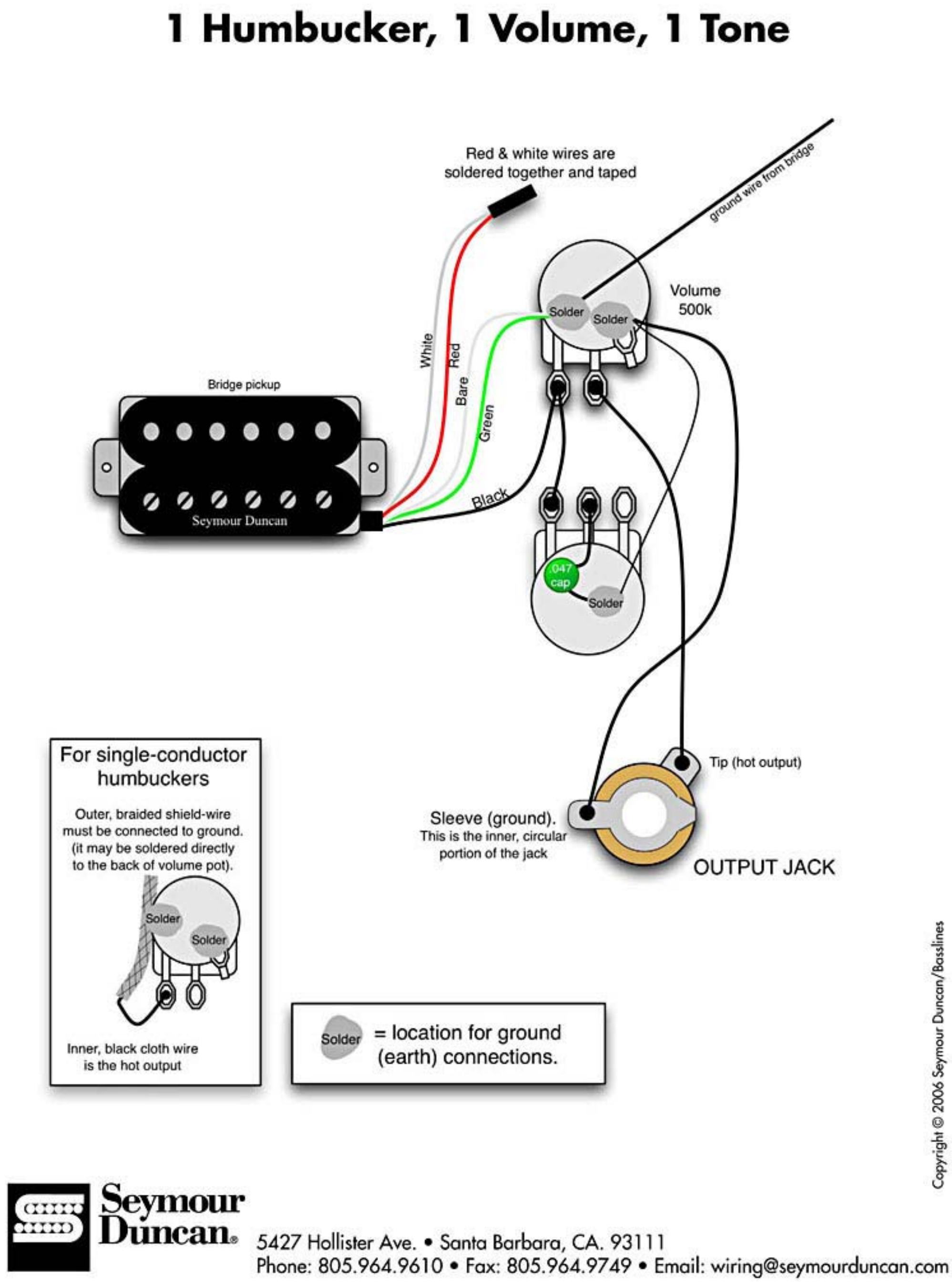


Figure 38 – Wiring Diagram for Single Pickup Guitar (image courtesy of Seymour Duncan, www.seymourduncan.com)

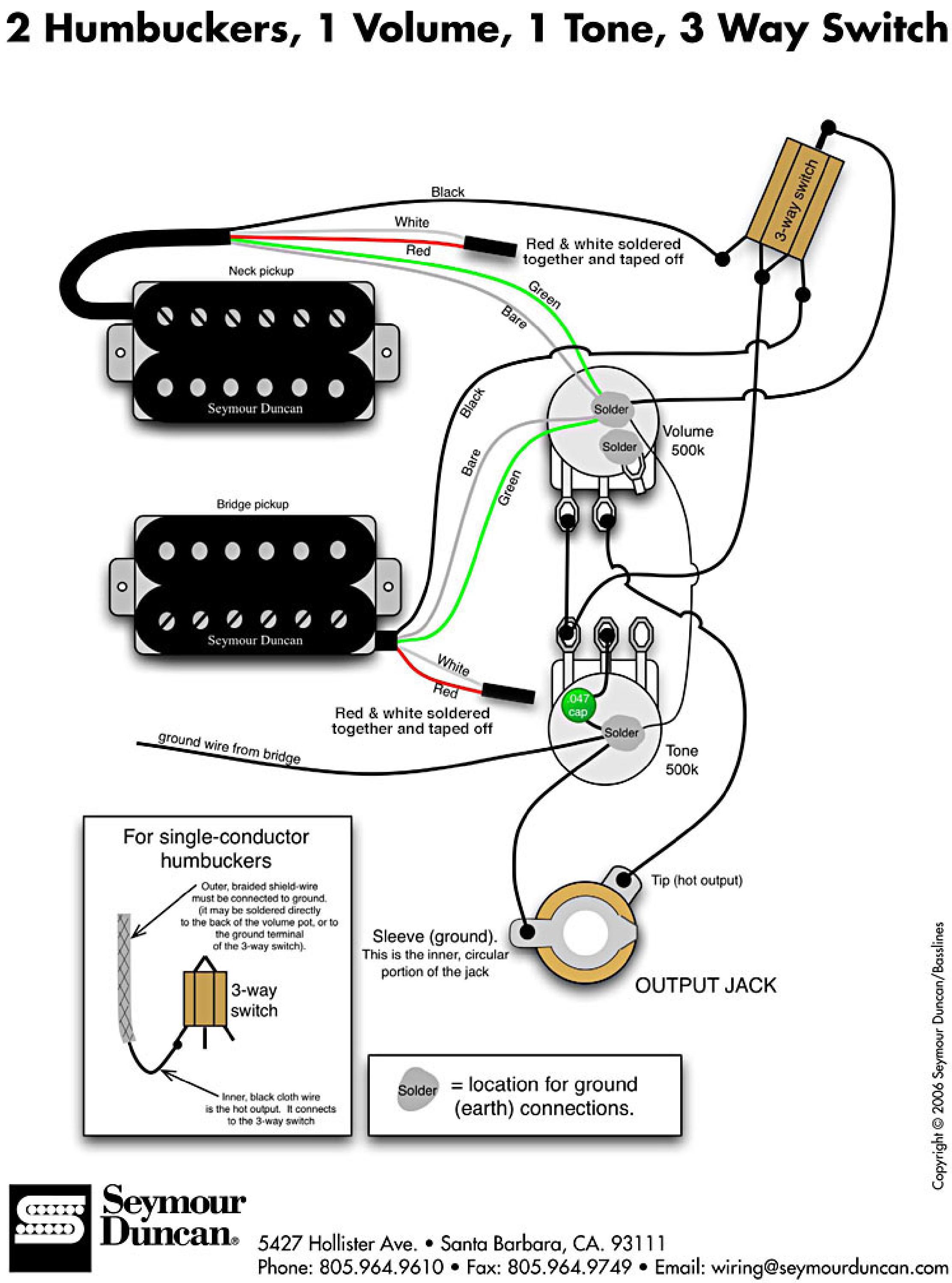


Figure 39 – Wiring Diagram for Two Pickup Guitar (image courtesy of Seymour Duncan, www.seymourduncan.com)

Assembling Guitar
Now, you are ready to assemble your guitar. Install the bridge, making sure that the bridge ground wire is in place. To make sure that the bridge ground works, check the electrical resistance between the top of the bridge and the free end of the ground wire; there should be no resistance.

Now, install the wiring harness in the electronics pocket and make the final connections with the pickup and the bridge ground. Secure the potentiometers with nuts and lock washers. Also, secure the output jack to the jack plate, then screw the jack plate to the body using #4 sheet metal screws.

Figure 40 – Jack Plate Secured to the Body

It is usually convenient to install the tuners before the neck is attached to the body. There are several different type of tuner, but most of them have a nut surrounding the string post that must be tightened in order to hold the tuner in place. Also, most tuners have a small screw on the back the keeps the tuner from rotating. Figure 41 shows typical tuners from the front. There is a heavy washer between the retaining nut and the wood headstock. Figure 42 shows the same tuners from the back - note the small (#2) screws. Be sure to install the tuning machines to that the gearbox is toward the body.

Figure 41 – Tuning Machines Mounted on a Headstock

Figure 42 – The Back of a Headstock Showing the Small Set Screws

The next step is to screw the neck to the body. Be sure that the neck is completely seated in the neck pocket before tightening the neck screws. If the neck is seated well, there will be no gap between the bottom of the neck and the top surface of the neck pocket. Figure 43 shows the neck plate with the screws installed. The screws are 1 ¾" #8 sheet metal screws. Figure 44 shows the same instrument from the side. Note there is no gap at the joint between the bottom of the neck and the top surface of the neck pocket.

Figure 43 – Neck Fixed to Body with a Neck Plate and Screws

Figure 44 – Neck Properly Seated In Pocket

This is a good time to install the strap buttons. One should go at the back of the body and the other one should go at the top of the upper bout. If there is a horn at the top of the body, the strap button should be placed at the end. It is important that the balance point (center of gravity) of the instrument be behind the front strap button. If it isn't you will likely have balance problems with the instrument when playing while standing up. The strap button is just held in place with a #8 sheet metal screw.

Figure 45 – Rear Strap Button

Making the String Nut

The last part to be installed on the guitar is the string nut. The nut can be made of many different materials including plastics, wood, brass and bone. You will likely be made of Corian, a durable plastic sold for counter tops. It is inexpensive, effective, easy to shape and comes in many different colors.

Start by sanding the nut blank so that it fits snugly in the nut slot. You should be able to seat it with finger pressure, but it shouldn't be loose enough to wiggle. Also trim the sides so that it is exactly as wide as the fretboard. The next step is to radius the top so that it matches the radius of the neck. Use a wood pencil that has been cut in half the long way to mark the nut as shown in Figure 46. Figure 47 shows the result.

Now sand the nut to the top of the radius line you just marked. If you are worried about sanding too far down, it's fine to leave a little material (1/32" or so) above the pencil mark. Also, make sure the top of the radiused nut is sloped toward the headstock by about 15º as shown in Figure 48.

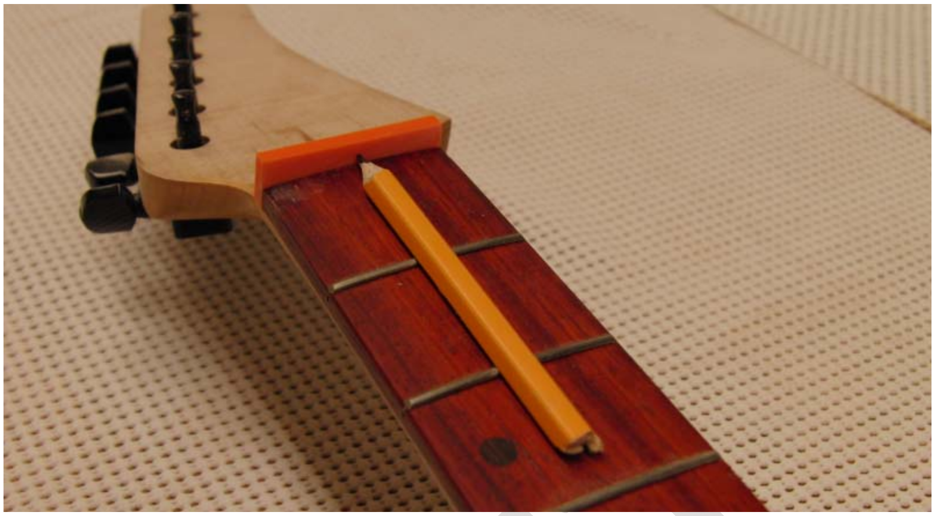


Figure 46 – Marking the Neck Radius on the Nut

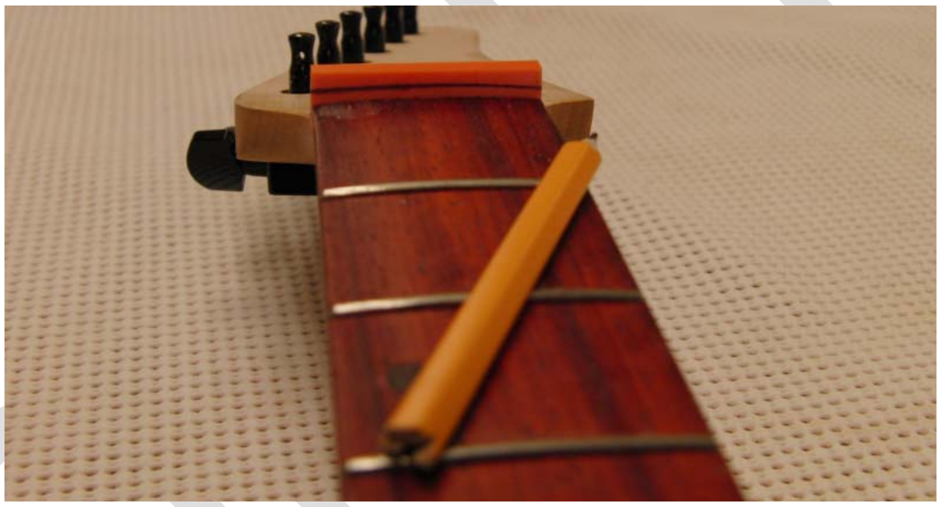


Figure 47 – String Nut with the Radius Marked Correctly

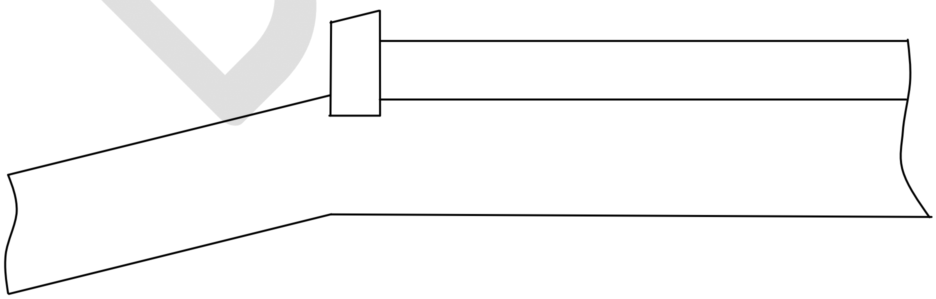


Figure 48 – Taper the String Nut towards the Headstock

Once you have sanded the nut to the correct radius, you can mark the locations of the strings. Using a sharp pencil, first mark the locations of the 1^{st} and 6^{th} strings. String 1 is the lightest treble string and string 6 is the heaviest bass string.

The 1^{st} and 6^{th} strings should be 1/8" from the edge of the nut. Some players like the 6^{th} string to be a little closer to the edge of the nut. When you are locating strings, even tiny distances are important – moving a string even 1/64" is enough to be noticeable to a skilled player. Figure 49 shows the first two strings locations marked on a string nut.

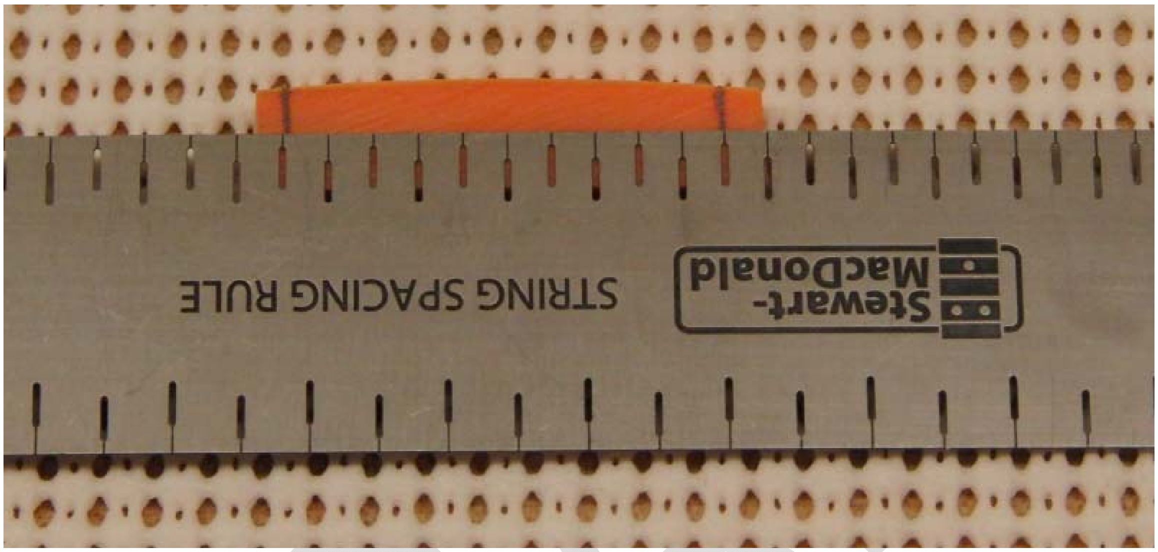


Figure 49 – Locations of 1^{st} and 6^{th} Strings

Strings are not evenly spaced on center. Rather, the distance between the strings is the same across the neck. To get this spacing correct, use a string spacing rule as shown in Figure 50.

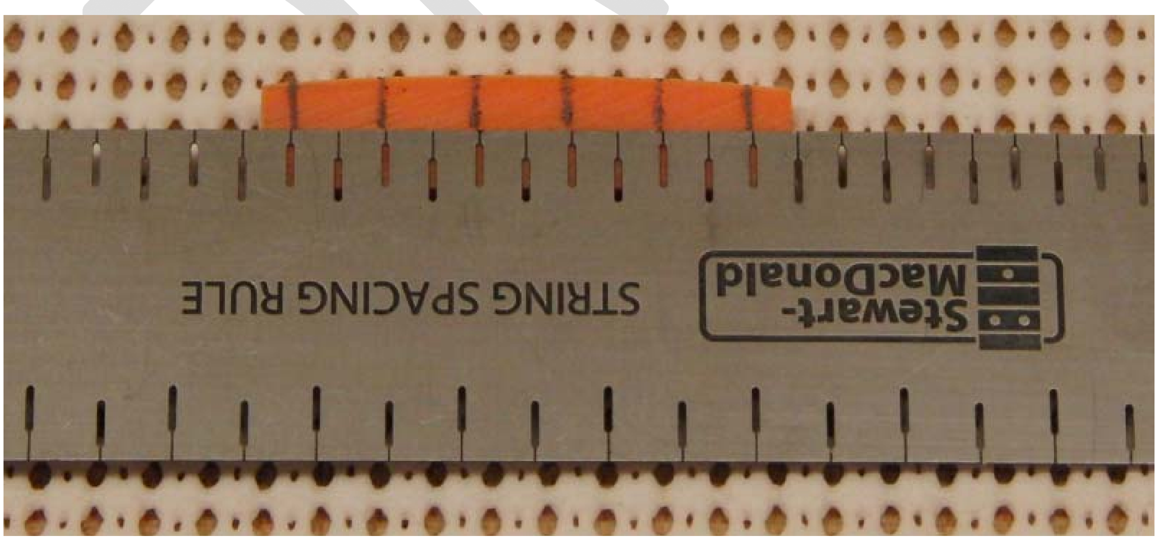


Figure 50 – Laying Out String Locations with a String Spacing Rule

There are slots along both sides of the string space rule and you just select the side you need; you'll need the side with the slots closest together. Make sure you have it placed so the larger spacing is on the bass side of the nut and then move the rule until you find a group of six slots where the outer two line up with your first two pencil marks. Also, the slots are staggered so they are alternately closer and farther from the edge. You can't mix and match – you have to use one or the other. In Figure 50, the slots closer to the edge of the rule are being used.

The last step in making the string nut is to file the string slots. You'll need three nut slotting files as shown in Figure 51. They have a total of six different edge radii. Start with the sharpest one (the one marked .012"/.016") and find the sharpest edge. You'll have to do this by feel and appearance since the blades aren't marked directly.

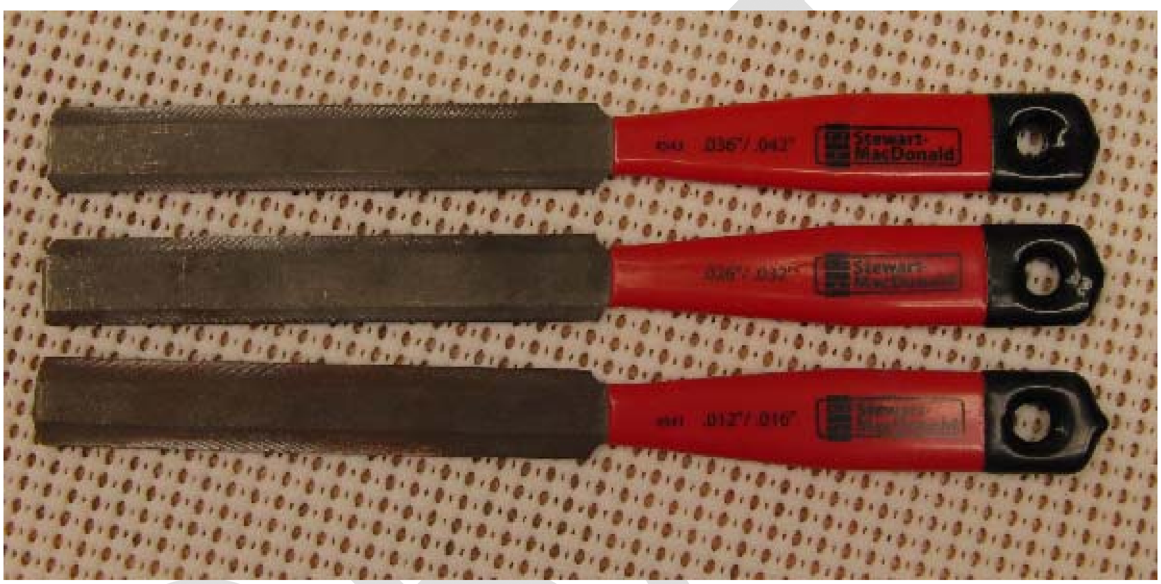


Figure 51 – Nut Slotting Files

File a shallow slot across top of the nut, splitting each of your pencil marks. Accuracy is very important, so take your time and get it right. Make sure the file is perpendicular to the face of the nut (parallel to the centerline of the guitar). Once the thin notches are made, widen the bass ones using a larger radius file. At this point, you are just making a notch big enough to hold the strings in place; you'll deepen the slots later to set the correct string height. Now, it's time to install the strings.

Stringing Your Guitar

Insert the strings through the bridge or the back of the body, depending on the type of bridge on your guitar. The ball ends of the strings prevent the strings from pulling through. Also make sure you put the strings in the proper order – treble on the right and bass on the left as you look at the front of the guitar. Figure 52 shows color coded D'Addario strings installed on a top-loading bridge. When winding the strings around the tuner post, make sure that the strings leave the post on the side of the post towards the center of the headstock. Figure 41 shows strings on a 3/3 headstock and Figure 53 shows strings on a 6 inline headstock.

Now that your guitar has a nice finish on it, make sure to put a soft pad between it and the bench top. Note that some finishes react with some soft plastics. The type of pad shown Figure 54 is often sold for drawer liners. It is inexpensive and effective, but reacts with lacquer finishes. The guitar in this picture has a Tru-Oil finish over tinted shellac, so there was no problem.

Figure 52 – Color-coded Strings Made by D'Addario (www.daddario.com)

Figure 53 – Strings on an Inline Head

Figure 54 – A Guitar on a Protective Pad

The wound strings don't generally need to be twisted after going through the hole in the tuner post since the windings create friction. However the plain strings need some additional locking. There are several different ways to secure the strings around the tuner posts. Here is one that works pretty well. Start by putting the plain string through the hole in the tuner as shown in Figure 55. Be sure to leave enough slack in the string to allow it to wind around the tuner post several times.

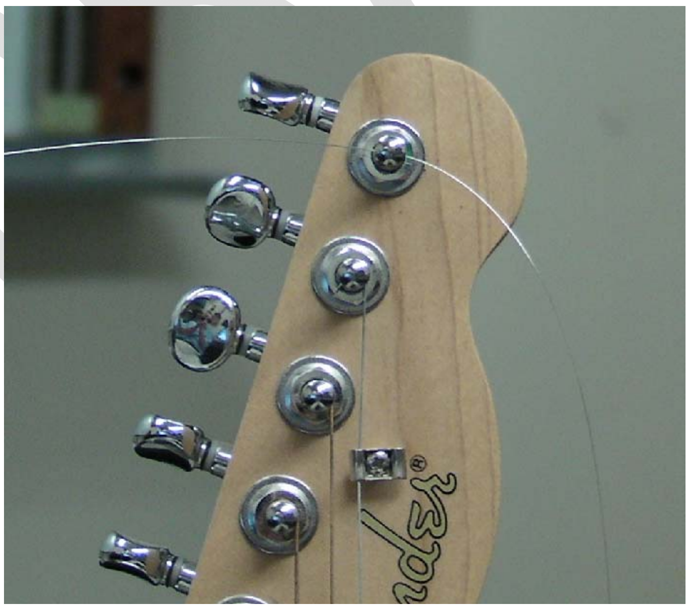


Figure 55 – Inserting Plain String through Hole in Tuner Post

Next, bend the free end of the string forward as shown in Figure 56 and then wrap the free end around as shown in Figure 57.

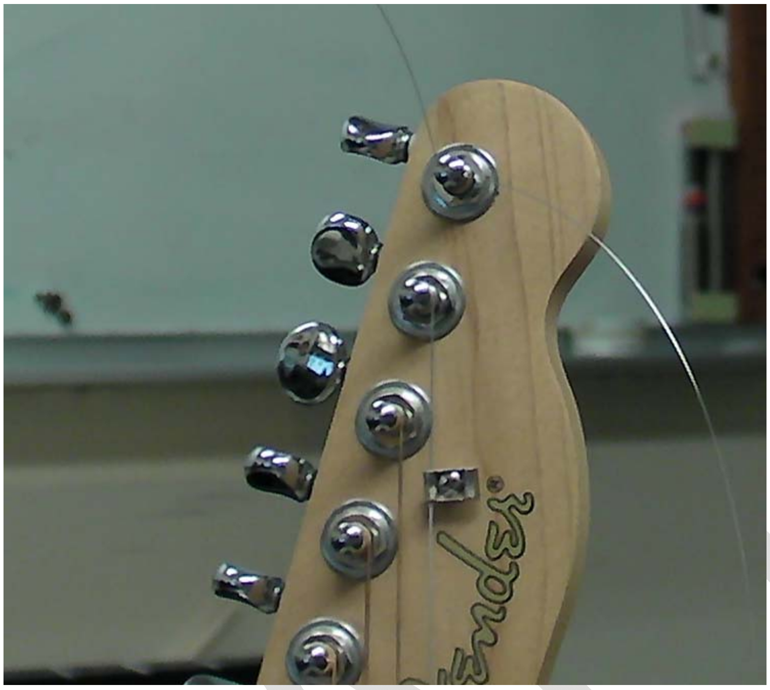


Figure 56 – Bending String Forward

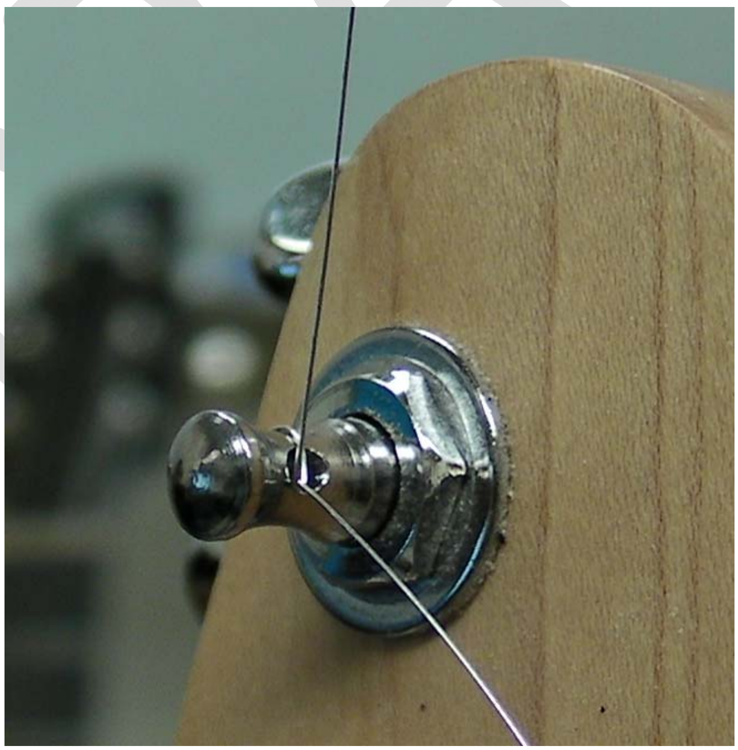


Figure 57 – Free End Wrapped Around

Finally, turn the tuner knob with a tuner wrench so that the string winds up neatly around the tuner post as shown in Figure 58. Use a pair of wire cutters to trim the excess string. Be careful, though, the short trimmed end is really sharp – think hypodermic needle.

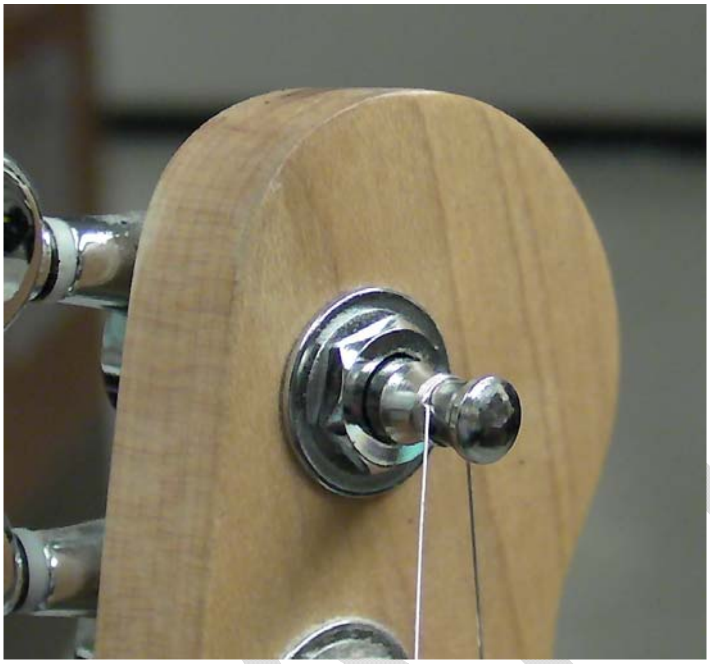


Figure 58 – String Wound onto Tuner Post

Figure 59 – Trimmed End of String (Sharp!)

Setting String Action

Your guitar is now completely assembled. However, before you can play it, you will need to set the string height, the saddle position and tune it. Start by setting the string height. Players often call the string height the action. Different players prefer different string heights and you may well want to change the string height later. Since it's easier to lower than to raise the strings, it makes sense to set them a little high at first. The height is defined as the distance from the bottom of the string to the top of the fret. Use these heights for now:

- 0.030" at the 1st fret (0.76 mm)
- 0.090" at the 12th fret (2.3 mm)

Figure 60 shows how to use a string action gauge to check the height of the string above the fret.

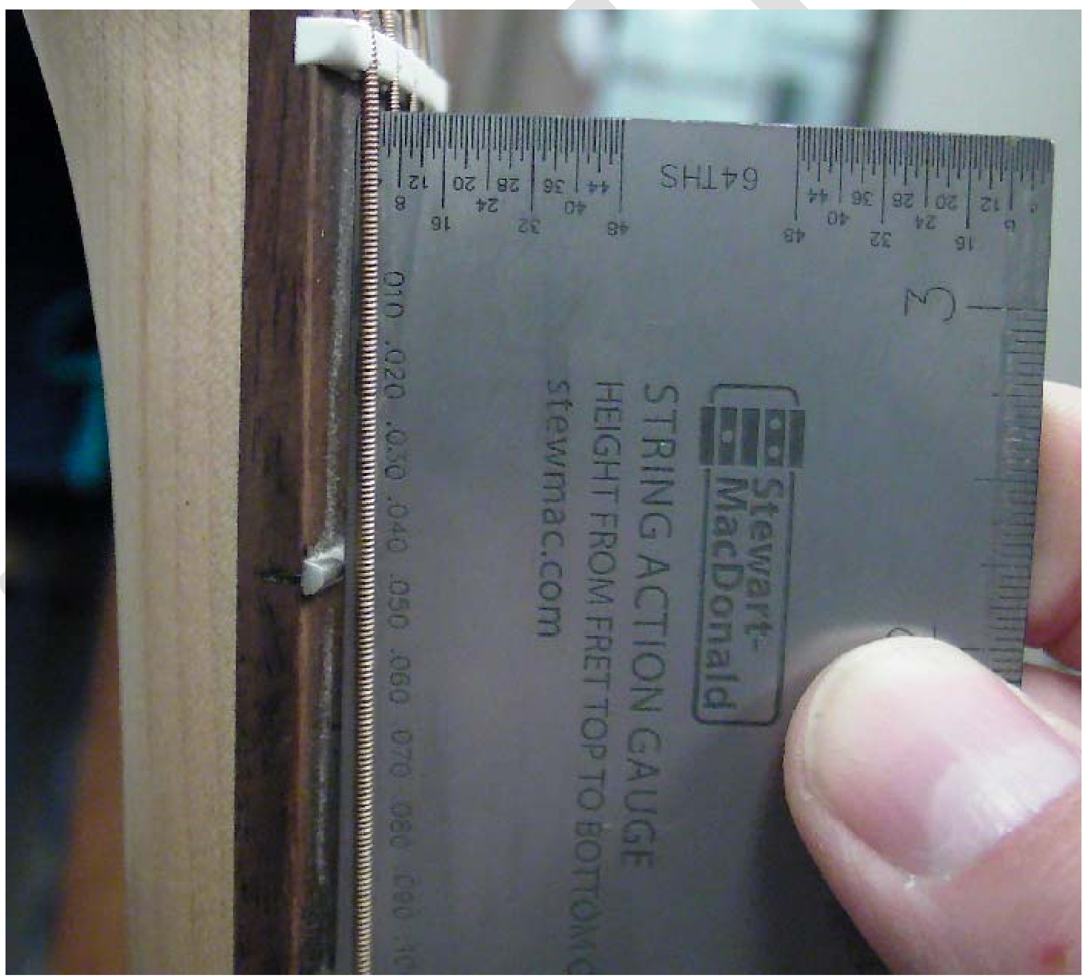


Figure 60 – Using String Action Gauge

The strings are likely to be way too high since you haven't finished slotting the string nut. Lower the strings at the first fret by filing the nut slots deeper. Simply pop the string out of the slot, file as needed and replace the string to check the height. The strings don't have to be at concert pitch, but they should be tight enough that they are straight. Heavy strings will bend slightly between the nut and 1st fret if the tension is very low and this could give you an incorrect height measurement.

Height at the 12th fret is changed by raising or lowering the bridge saddles using an Allen wrench. Each saddle has two small set screws that adjusted in unison the keep the saddle level. In addition setting the action, the saddles should be adjusted so that they maintain the 12" radius of the fretboard. Figure 61 shows a typical bridge with adjustable saddles.

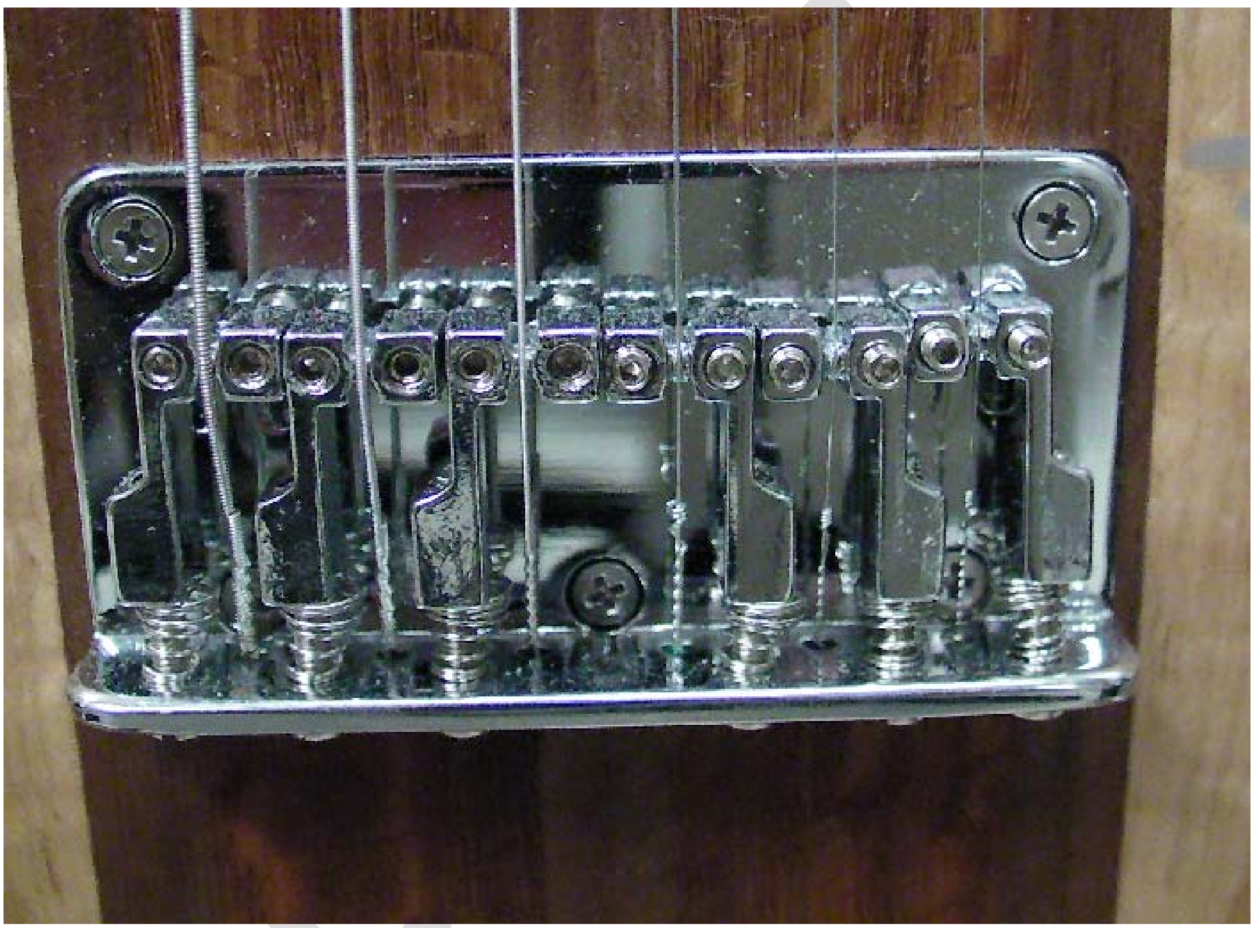


Figure 61 – Adjustable Saddles on an Electric Guitar Bridge

Setting Intonation

The last adjustment to be made is intonation. Adjusting the saddle requires moving the saddle forwards or back using screws at the back of the bridge (Figure 62). Intonation adjustments are required because real strings do not behave exactly like the mathematical ideal used to calculate the fret locations. Rather, the pitch of the strings is increasingly too high as you fret notes high up the neck. To correct for this effect (called inharmonicity), the saddles are moved back slightly from their theoretically correct position.

Figure 62 – Intonation Adjustment Screws

To set intonation, bring the instrument to concert pitch using an electronic tuner. Then, one by one, compare the open string pitch to the pitch at the 12 fret. These notes should be exactly an octave apart, but the 12th fret is likely to be sharp. If this is the case, move the saddle back slightly (about 1/16" is enough to start with). Re-tune the open string and repeat the process until the open string and the 12th fret are exactly an octave apart – a chromatic tuner will show the same note for both of them.

After you've set the intonation, you are done. You've made your own electric guitar! Now go play it.

T

Additional Reading

- Technical Books
  - Engineering the Guitar: Theory and Practice by Mark French, Springer, 2008.

  - The Physics of Musical Instruments by Neville Fletcher and Thomas Rossing, Springer 2008

- Electric Guitar Construction - General
  - Build Your Own Electric Guitar: Complete Instructions and Full-Size Plans by Martin Oakam, Trafalgar Square Books, 2006
  - Building Electric Guitars: How to Make Solid-Body, Hollow-Body and Semi-Acoustic Electric Guitars and Bass Guitars by Martin Koch, Koch Verlag, 2001
  - Electric Guitar Construction: A Guide for the First Time Builder by Tom Hirst, Centerstream Publications, 2002
  - Make Your Own Electric Guitar, 2^{nd} ed. by Melvyn Hiscock, NBS Publications 2003

- Electric Guitar Construction - Specialized
  - How to Make Your Electric Guitar Play Great by Dan Erlewine, Backbeat Books, 2001
  - Fret Work Step by Step by Dan Erlewine, Stewart MacDonald, 1994
  - Complete Illustrated Guide to Finishing by Jeff Jewitt and Susan Jewitt, Taunton Press, 2004

- Electronics
  - The Guitar Pickup Handbook by Dave Hunter, Backbeat Books, 2009
  - Guitar Electronics for Musicians by Donald Brosnac, Omnibus Press, 2009

Suppliers

- Irwin Industrial Tools, www.irwin.com
  - Their Quick Grip clamps are where it's at. You'll never use a C-clamp again. Also, their little dovetail pull saw is perfect for cleaning out fret slots.
- Stewart MacDonald, www.stewmac.com
  - If they don't have it, you don't need it. They have a staff of experts who also develop new tools and write instructional books. Prices are competitive, but you can occasionally find better deals elsewhere. They offer at 10% educational discount and quantity discounts that usually make up the difference.
- Seymour Duncan, www.seymourduncan.com
  - Lots and lots of high quality pickups. Hard to imagine a need they can't fill. Their web site has zillions of wiring diagrams and other useful information
- Woodcraft, www.woodcraft.com
  - Tools and other supplies for hardcore woodworkers. Tools are generally of high quality. One of the few places to buy center finding rules.

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107 College Drive
Butler, PA 16002
724.287.8711

Sinclair Community College
444 West Third Street
Dayton, OH 45402
800.315.3000

Purdue University
West Lafayette, IN 47907
765.494.4600

Ventura College
4667 Telegraph Road
Ventura, CA 93003
805.654.6400

New Philadelphia High School
343 Ray Avenue NW
New Philadelphia, OH 44663
330.364.0644

College of the Redwoods
7351 Tompkins Hill Road
Eureka, CA 95501
800.641.0400

Southern Wells High School
9120 South 300 West
Poneto, IN 46781
765.728.2496

Butler Senior High School
120 Campus lane
Butler, PA 16001
724.214.3200

Eureka High School
3200 Walford Avenue
Eureka, CA 95503
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