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| **Abstract**  This is a rockin' project for guitarists with an interest in the physics behind the music. Have you ever wondered why the pitch of the note changes when you fret the string? You can find out for yourself with this project on the fundamental physics of stringed instruments.  **Objective**  The goal of this project is to measure the frequency of the vibrations of a guitar string as the effective length of the string is changed by fretting it.  **Introduction**  In this project, you'll investigate the basic physics of standing waves on guitar strings. You'll learn how the *frequency* (perceived as pitch) of the string vibration changes as the effective length of the string is changed by fretting it.  You'll need to understand some basic properties of waves to get the most out of this project. We'll provide a quick introduction here, but for a more complete understanding we recommend some background research on your own. The Bibliography section, below, has some good starting points for researching this project. We especially recommend exploring the "Sound Waves and Music" articles (Henderson, 2004).  What is sound? Sound is a wave, a pattern—simple or complex, depending on the sound—of changing air pressure. Sound is produced by vibrations of objects. The vibrations push and pull on air molecules. The pushes cause a local compression of the air (increase in pressure), and the pulls cause a local rarefaction of the air (decrease in pressure). Since the air molecules are already in constant motion, the compressions and rarefactions starting at the original source are rapidly transmitted through the air as an expanding wave. When you throw a stone into a still pond, you see a pattern of waves rippling out in circles on the surface of the water, centered about the place where the stone went in. Sound waves travel through the air in a similar manner, but in all three dimensions. If you could see them, the pattern of sound waves from the stone hitting the water would resemble an expanding hemisphere. The sound waves from the stone also travel much faster than the rippling water waves from the stone (you hear the sound long before the ripples reach you). The exact speed depends on the number of air molecules and their intrinsic (existing) motion, which are reflected in the air pressure and temperature. At sea level (one atmosphere of pressure) and room temperature (20°C), the speed of sound in air is about 344 m/s.  One way to describe a wave is by its speed. In addition to speed, we will also find it useful to describe waves by their *frequency*, *period*, and *wavelength*. Let's start with frequency (*f*). The top part of Figure 1, below, represents the compressions (darker areas) and rarefactions (lighter areas) of a pure-tone (i.e., single frequency) sound wave traveling in air (Henderson, 2004). If we were to measure the changes in pressure with a detector, and graph the results, we could see how the pressure changes over time, as shown in the bottom part of Figure 1. The peaks in the graph correspond to the compressions (increase in pressure) and the troughs in the graph correspond to the rarefactions (decrease in pressure).   |  | | --- | | Illustration of a sound wave as compression and rarefaction of air, and as a graph of pressure vs. time. | | Figure 1. Illustration of a sound wave as compression and rarefaction of air, and as a graph of pressure vs. time (Henderson, 2004). |   Notice how the pressure rises and falls in a regular cycle. The frequency of a wave describes how many cycles of the wave occur per unit time. Frequency is measured in Hertz (Hz), which is the number of cycles per second. Figure 2, below, shows examples of sound waves of two different frequencies (Henderson, 2004).   |  | | --- | | Graphs of high and low frequency waves. | | Figure 2. Graphs of high (top) and low (bottom) frequency waves (Henderson, 2004). |   Figure 2 also shows the period (*T*) of the wave, which is the time that elapses during a single cycle of the wave. The period is simply the reciprocal of the frequency (*T* = 1/*f*). For a sound wave, the frequency corresponds to the perception of the pitch of the sound. The higher the frequency, the higher the perceived pitch. On average, the frequency range for human hearing is from 20 Hz at the low end to 20,000 Hz at the high end.  The wavelength is the distance (in space) between corresponding points on a single cycle of a wave (e.g., the distance from one compression maximum (crest) to the next). The wavelength (λ), frequency (*f*), and speed (*v*) of a wave are related by a simple equation: *v* = *f*λ. So if we know any two of these variables (wavelength, frequency, speed), we can calculate the third.  Now it is time to take a look at how sound waves are produced by a musical instrument: in this case, the guitar. For a scientist, it is always a good idea to know as much as you can about your experimental apparatus! Figure 3, below, is a photograph of a guitar.   |  | | --- | | Top view of an acoustic guitar. | | Figure 3. Top view of an acoustic guitar. |   The guitar has six tightly-stretched steel strings which are picked (plucked) with fingers or a plastic pick to make them vibrate. The strings are anchored beneath the *bridge* of the guitar by the bridge pins (see Figure 4). Each string passes over the *saddle* on the bridge. The saddle transmits the vibrations through the bridge to the soundboard of the guitar (the entire front face of the instrument). The soundboard, with its large surface area, amplifies the sound of the strings. (One way to see this for yourself is with the mechanism from a music box. First try playing it while holding it in the air. Then, place it in contact with the soundboard of the guitar and play it again. You'll see that the sound is greatly amplified by the wood.)   |  | | --- | | Detail view of an acoustic guitar bridge, showing the bridge pins and saddle. | | Figure 4. Detail view of an acoustic guitar bridge, showing the bridge pins and saddle. |   The string vibrates between two fixed points:   1. where it is stretched over the saddle of the bridge (Figure 4) and 2. near the opposite end of the string, where it passes over the *nut*(Figure 5).   After passing over the nut, the strings wrap around tuning posts. A worm gear mechanism allows the posts to be turned in order to raise or lower the tension on the string.   |  | | --- | | Detail view of an acoustic guitar headstock, showing the nut and tuning pins. | | Figure 5. Detail view of an acoustic guitar headstock, showing the nut and tuning pins. The top portion of the neck (first fret) is also shown. The strings are labeled, from low "E" to the high "e." |   When a guitar string is picked, the vibration produces a *standing wave* on the string. The fixed points of the string don't move (nodes), while other points on the string oscillate back and forth maximally (antinodes). Figure 6, below, shows some of the standing wave patterns that can occur on a vibrating string (Nave, 2006a).   |  | | --- | | Standing waves on a vibrating string. | | Figure 6. Standing waves on a vibrating string, showing the fundamental (top), first harmonic (middle), and second harmonic (bottom) vibrational modes. (Nave, 2006a) |   The fundamental mode (Figure 5, top) has a single antinode halfway along the string. There are only two nodes: the endpoints of the string. Thus, the wavelength of the fundamental vibration is twice the length (*L*) of the string.  Figure 6 shows that the string can vibrate at several different natural modes (harmonics). Each of these vibrational modes has nodes at the fixed ends of the string. The higher harmonics have one or more additional nodes along the length of the string. In this project, we will be focusing on the fundamental mode of vibration, where the two endpoints are the only nodes of the standing wave. See the Variations sections for a project that goes a little further to explore the higher harmonics.  In this project you'll use the equation relating the speed, frequency, and wavelength of a wave (*v* = *f*λ) to predict how the fundamental frequency of vibration of the string will change as you change the effective length of the string by fretting it.  **Terms, Concepts, and Questions to Start Background Research**  To do this project, you should do research that enables you to understand the following terms and concepts:   * Guitar parts:   + Strings   + Bridge   + Saddle   + Nut   + Frets   + Soundboard * String vibrations * Standing waves * Wavelength * Frequency * Wave velocity   ***Questions***   * What is the relationship between the length of a string and the wavelength of the fundamental tone it produces when plucked? * What is the relationship between the velocity, frequency, and wavelength of a wave?   **Materials and Equipment**  To do this experiment you will need the following materials and equipment:   * Guitar   + As you can see from the pictures in the Introduction, we used an acoustic guitar for this project.   + An electric guitar—or other stringed instrument—can be used instead. * Guitar pick * Electronic tuner (to tell you what note you've played)   + One alternative is to use a computer with tuning software, such as [enable Tuner®](http://www.enableencore.com/encore/tuner.htm) by Enable Software®. To use this software, you'll need:     - A Windows-based computer with a 16-bit soundcard     - A microphone     - A big advantage of this tuner is that it displays the frequency of the note that you played   + Another alternative is to use a stand-alone electronic tuner. There are many models, available at most music stores. You want a chromatic tuner with a built-in microphone. It will sense the note that you play and indicate whether you are sharp (above) or flat (below), relative to the closest reference note. If you can find one that displays the frequency of the note you played, that is best.   + Yet another alternative is to work with a partner who has an electric keyboard or piano and who knows how to match notes to the guitar. * Sewing tape measure (best if marked in metric units) * Lab notebook * Pen or pencil   .  **Experimental Procedure**   1. Do your background research so that you are knowledgeable about the terms, concepts, and questions, above. 2. For each string, measure:    * The full length of the string. This is the distance between the saddle (see Figure 4) and the nut (see Figure 5).    * The distance between the saddle and each fret.    * The simplest way to do this is to tape the zero end of the sewing tape measure to the string right at the saddle. Line up the zero mark with the point where the string touches the saddle. Align the tape measure along the length of the string, and tape it in place at the nut end of the string. Now you can easily read off the total length of the string, and the string length at each fret. 3. Get set up to play and record the notes with your tuner software (or chromatic tuner).    * The experiment is best done with a guitar that is in tune, so the first step is to tune the guitar.    * Place the microphone (or chromatic tuner) close enough to the guitar so that the tuner software (or tuner) registers the note even when you play softly. 4. Pluck the open high E string. From the readout of the tuner software, write down the frequency of the note played. The screenshot in Figure 7 shows where to read the measured frequency from the enable Tuner software display.  |  | | --- | | Screenshot of the enable Tuner® software display. | | Figure 7. Screenshot of the enable Tuner® software display, showing where to read the measured frequency of the note that was played. The target frequency of the open strings is displayed in the lower portion of the window, as shown. |  * + If you are using a chromatic tuner without a frequency readout, write down the note played from the chromatic tuner readout.   + You can look up the standard frequency of the note using Figure 8.  1. Now fret the string just behind the first fret. 2. Pluck the string again. 3. Make sure the note is clear and ringing, then write down the frequency of the note played. If the note does not play properly, adjust your fretting finger if necessary, and play the note again.    * If you are using a chromatic tuner without a frequency readout, write down the note played from the chromatic tuner readout.    * You can look up the standard frequency of the note using Figure 8, below.  |  | | --- | | Frequencies of piano notes with frequencies of six open guitar strings marked with asterisks. | | Figure 8. Fundamental frequencies of the 88 notes on the piano (Irvine, 2000). The six open strings on the guitar (E2, A2, D3, G3, B3, E4) are marked with blue asterisks. |  * + When using a tuner without a frequency readout, you will have to use your knowledge of music and careful listening to determine the correct octave of the note played. For example, the open high E-string on the guitar is E4 (329.63 Hz). When fretted on the twelfth fret, the note is E5 (659.25 Hz).  1. Repeat steps 5–7 for frets 2–12. 2. Repeat steps 4–7 for each of the other five strings. 3. You can organize the data you collect for each string in a table like the one below.  |  |  |  | | --- | --- | --- | | **String \_\_\_** | | | | **fret** | **string length (cm)** | **frequency (Hz)** | | 0 (open string) |  |  | | 1 |  |  | | 2 |  |  | | 3 |  |  | | 4 |  |  | | 5 |  |  | | 6  7 |  |  |  1. Using your length and frequency data and the equation *v* = *fλ*, calculate the speed of the wave on each string. Remember that the wavelength of the fundamental (lowest) frequency of a vibrating string is *twice* the length of the string.   **Variations**   * Use a spreadsheet program (like Microsoft Excel® or WordPerfect QuattroPro®) to make your wave velocity calculations. The Bibliography has an Excel® tutorial to get you started working with spreadsheets (James, date unknown). * To see how you can make a guitar string vibrate at higher frequencies (*harmonics*) by lightly touching the string at certain points instead of fretting it, see the Science Buddies project [Don't You Fret! Standing Waves on a Guitar](http://www.sciencebuddies.org/mentoring/project_ideas/Phys_p055.shtml). * If you play acoustic guitar, maybe you've noticed that sometimes one (or more) of the guitar strings will vibrate after you've picked a different string. This is called *sympathetic vibration*. You can investigate the physics behind sympathetic vibrations with the Science Buddies project [How to Make a Guitar Sing](http://www.sciencebuddies.org/mentoring/project_ideas/Phys_p054.shtml). * For an experiment on sympathetic vibrations using a piano, see the Science Buddies project [How to Make a Piano Sing](http://www.sciencebuddies.org/mentoring/project_ideas/Phys_p022.shtml). * For more science project ideas in this area of science, see [Music Project Ideas](http://www.sciencebuddies.org/science-fair-projects/recommender_interest_area.php?ia=Music).   **Credits**  Andrew Olson, Ph.D., Science Buddies  Last edit date: 2011-10-26 12:00:00 | http://www.sciencebuddies.org/science-fair-projects/project_ideas/space.gif |

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