**Integrated Sound Chapter 6 guitar lab**

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| **Abstract**  This is a great project for a musician who is interested in the physics of stringed instruments. If you've ever played an acoustic guitar, you may have noticed that picking a single string can make one or more of the other (unpicked) strings vibrate. When this happens, it's called *sympathetic* vibration. What intervals lead to the strongest sympathetic vibrations? Find out for yourself with this project.  **Objective**  The goal of this project is to determine which musical intervals are most effective at producing sympathetic vibrations on open guitar strings when another string is picked (plucked).  **Introduction**  In this project, you'll investigate the physics of standing waves on guitar strings. You'll learn about the different *modes* (i.e., patterns) of vibration that can be produced on a string, and you'll figure out how to produce the various modes by lightly touching the string at just the right place while you pick the string. This technique is called playing *harmonics* on the string.  You'll also 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 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. The wavelength of each mode is always twice the distance between two adjacent nodes.  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.  The second harmonic has a node halfway along the string, and antinodes at the 1/4 and 3/4 positions. This standing wave pattern shows one complete cycle of the wave. Thus, the wavelength of the second harmonic is equal to the length of the string.  In addition to the endpoints, the third harmonic has a nodes 1/3 and 2/3 of the way along the string, with antinodes in between. The wavelength of this mode with be equal to 2/3 of the length of the string.  Remember that the relationship between wavelength and frequency depends on the speed of the wave. We can rewrite the equation presented earlier as f = *v*/λ. If we take the ratio between the frequency, *f2*, of the second harmonic and the frequency, *f1*, of the first harmonic, the velocity term cancels out:   |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | *f2* *f1* | = | *v*/*L*  *v*/2*L* | = | 1  1/2 | = | 2 |   You can continue the calculations for the higher harmonics yourself. What is the frequency of the third harmonic, relative to the fundamental?  Now you have enough of an introduction to sound waves and guitars so that you can understand how one string can make another "sing." Picking is one way to start the string vibrating, but the strings can also be set in motion by the vibrations of the soundboard. If you pick a string (for example the high E string) and then quickly mute it (by touching it with your finger), you will hear that the guitar continues to produce sound. It sings!  How does this work? The various modes of vibration of the E string match some of the modes of vibration of other strings on the guitar. When the E string sets the soundboard in motion, the vibration of the soundboard can drive the other strings to vibrate at those matching modes. This phenomenon is called *sympathetic vibration*. What musical intervals can excite an open guitar string via sympathetic vibrations? The Experimental Procedure section, below, shows you how to find out.  **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 * Nodes * Antinodes * Wavelength * Frequency * Sympathetic vibrations * Musical intervals   ***Questions***   * Which notes, when played on the high E string, produce sympathetic vibrations in other open strings? * Which musical intervals (spaces between notes) are most effective at producing sympathetic vibrations?   **Materials and Equipment**  To do this experiment you will need the following materials and equipment:   * An acoustic guitar, properly tuned * Guitar pick * A quiet room * 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. The experiment must be done with a guitar that is in tune, so start out by tuning the guitar. 3. Remember that you need to do the experiment in a quiet room, where you can hear the guitar without a lot of background noise. 4. Pluck the open high E string, then immediately mute it (touch it with your finger to stop it from vibrating).    1. Listen carefully, and you should hear that the guitar is still making sound from sympathetic vibrations of one or more of the other five strings.    2. Your job is to determine which strings are sympathetically vibrating by muting the other strings, one by one. 5. Listen carefully to how the sound changes as you mute each string. Can you answer the following questions (you will have to repeat the procedure several times to confirm your observations):    1. Which string(s) contributes the *most* to the remaining sound after you mute the string that was plucked?    2. Which string(s) contributes the *least* to the remaining sound after you mute the string that was plucked?    3. **Advanced.** Which mode is sounding most prominently on each string? See the Science Buddies project [Don't You Fret! Standing Waves on a Guitar](http://www.sciencebuddies.org/mentoring/project_ideas/Phys_p055.shtml) for more information on standing wave modes on a vibrating string. 6. Now fret the high E string just behind the first fret. Pluck the string again and immediately mute it. 7. Repeat the observations you made in steps 4 and 5. Remember that you will have to repeat the procedure (fret the string, pluck it, mute it) several times in order to confirm your observations. 8. Repeat steps 6 and 7 for frets 2–12. 9. You will find it helpful to organize your data in a table like the one below:  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | **Plucked string (E, A, D, G, B, or e)** | **Fret (1–12)** | **Sympathetic vibrations? (y/n)** | | | | | | | **E** | **A** | **D** | **G** | **B** | **e** | |  |  |  |  |  |  |  |  | | etc. |  |  |  |  |  |  |  |  1. Can you identify any patterns in your data? For example, which note intervals produce sympathetic vibrations most often?   **Variations**   * Extend the experiment by using each of the other five strings on the guitar as the string that initially plucked. * 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). * 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 |

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