BASICS: Biophysics - A Step-by-step Introduction to Concepts for Students

Lesson Plan: Sound & Pitch

Background

Have you ever wondered how you are able to play and enjoy music every day? The Greek philosophers pondered the question of how sounds are created. Pythagoras worked with vibrating strings and devised a system of tuning that was named after him; Aristotle hypothesized that sound waves travel by the movement of air. If you're curious about the history of sound and its fascinating stories, more information can be found by clicking on the links in the Resources section.

Sound is formed by movements or vibrations of air. It appears in the form of waves, like the waves in the ocean. When these waves travel through the air and reach our ears, we hear sound (see Resources). **Frequency** is a measure of the number of waves in each time interval, usually in a second. Frequency is measured in **Hertz** (**Hz**), which is the number of waves per second. Frequency is a characteristic of sound. For example, a string that **vibrates** at a higher frequency will produce sound waves at a higher **pitch**. This means that pitch can be defined by its frequency. Vibration occurs when an object repeatedly moves back and forth from its original position. You can see vibrations if you play a stringed instrument such as a guitar: when you move or pluck a string, it rapidly moves back and forth. In addition, thinner strings on the guitar, which have a smaller mass or amount of matter, produce a higher pitch or frequency when plucked. In music, sound waves of specific frequencies or pitches are called **notes**. Notes are arranged in sequences to make music and songs.

Sound, notes, and songs can not only be produced by instruments such as pianos or violins, but also by the vibration of simple objects. One example is a ruler vibrating against a table (see **Experiment 1**). Another example is water glasses that are tuned to different notes by their water levels (**Experiment 2**). As the water level *increases*, the frequency of sound *decreases.* This is because the total mass of the water glass increases when the water level is higher, making it more difficult for the glass to vibrate, which leads to a lower frequency. Striking the glasses with a rigid rod causes the glass and the air in the glass to vibrate, producing different pitches, which can be played as notes. Thus, water glasses with different amounts of water can be used to produce different notes to play songs.

Objectives & Grade Level

Teach students basic characteristics of sound and pitch, enabling them to understand how different notes are produced to play simple songs. Appropriate for middle school to high school science classes. For interesting biological uses of sound by other organisms and applications of sound in medicine, see Advanced Notes.

Prior to the lesson, students should have a basic understanding of what notes are and how notes form songs.

After the lesson, students should have an understanding of how different sounds are produced by different frequencies of vibrations and how sound and notes can be produced by everyday objects.

Materials

- Ruler (plastic or metal rulers are better at producing sound, but a wooden ruler can also be used)
- Water

- Water glasses (or similar glasses, do not have to be the same size) – have several glasses on hand to produce different notes; thin-walled glasses may produce a wider range of notes
- A rod to strike the glasses (a spoon or fork can be used)
- Cell phone to download a free tuning application (e.g., Pano Tuner)

Procedure

Experiment 1: Vibration and Sound

Step 1: Place a ruler on a table or flat surface, with one end extending over the edge (see **Figure 1**).

Step 2: Quickly lift and release the extended end while firmly holding the ruler tightly against the table. Let the ruler vibrate against the table and listen to the pitch.

Step 3: Now change the length of the overhanging end of the ruler, and repeat Step 2. What do you observe? Is the ruler moving vertically, and is it moving slower or faster? Does the pitch get higher or lower when you increase the length of the overhanging end (**Figure 1B**)? What happens when you start with a long overhanging end, quickly lift and release the end, and then rapidly push the ruler onto the surface so that the overhanging end is short? (see **Note 1**)

Step 4: Download a tuning application (e.g., Pano Tuner). Can Pano Tuner identify the pitch of the sound that the ruler makes? (see **Note 2**)

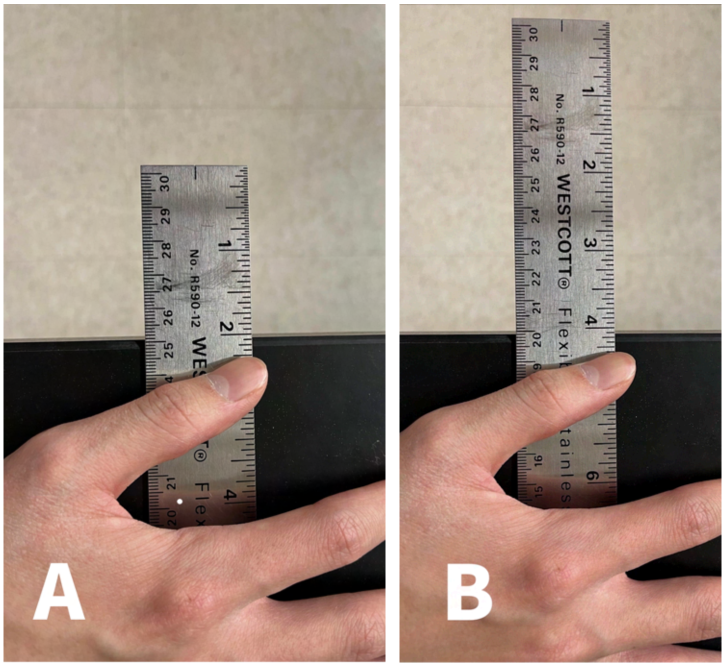

Figure 1 Vibrating Ruler. A) The ruler is pressed tightly against the table along its length so that only a small portion of the ruler can move freely. **B**) A larger region of the ruler extends beyond the edge of the table so that more of the ruler can move freely.

Experiment 2: Water Xylophone

Step 1: Identify the number of unique notes in the song you want to play. You will need one water glass for each note you play. Let's start with a simple song with just three notes: the first line of the well-known children's song *Twinkle Twinkle Little Star*. The notes are as follows:

C C G G A A G Twinkle Twinkle Little Star

Figure 2 Three-Note Water Xylophone. This water xylophone can be used to play the first line of *Twinkle Twinkle Little Star*. The note produced by each glass is shown.

Step 2: To make a glass that produces each note, first strike each empty water glass to produce a sound and identify its pitch with the tuner that you downloaded for Experiment 1. The empty water glass produces the highest pitch the water glass can make. Select the water glass with the highest pitch. The notes you need for the first line of *Twinkle Twinkle Little Star* are A, G, and C. Pano Tuner will show you the note and frequency of the sound made by the water glass. Use the glass water with the highest pitch to produce the note A. If the water glass can reach a frequency of approximately 3520 Hz or higher, tune the water glass to 3520 Hz by pouring water into it and striking it to see if the sound produced matches the frequency of 3520 Hz. If the frequency is higher than 3520 Hz, pour more water into the water glass; if the frequency is lower than 3520 Hz, pour water out of the water glass. If the empty water glass cannot reach a frequency of 3520 Hz, tune the water glass to 1760 Hz following the procedure above to obtain a water glass that produces the note A.

After tuning a water glass to A, move on to the next note: G. Use the water glass with the second highest pitch to produce the note G. If you used 3520 Hz for A, tune the water glass for G to 3136 Hz by pouring water into it and striking it to see if the sound produced matches the frequency of 3136 Hz. If the frequency is higher than 3136 Hz, pour more water into the water glass; if the frequency is lower than 3136 Hz, pour water out of the water glass. If you used 1760 Hz for A, tune the water glass for G to 1568 Hz following the procedure above to obtain a water glass that produces the note G.

After tuning a water glass to G, move on to the last note: C. If you used 3520 Hz for A, tune the water glass for C to 2093 Hz by pouring water into it and striking it to see if the sound produced matches the frequency of 2093 Hz. If the frequency is higher than 2093 Hz, pour more water into the water glass; if the frequency is lower than 2093 Hz, pour water out of the water glass. If you used 1760 Hz for A, tune the water glass to 1047 Hz following the procedure above to obtain a water glass that produces the note C.

Step 3: Play your song! Strike the water glasses in the order that the notes are to be played and sing along with the notes - you've just made a water xylophone! Here's a version of the first line of *Twinkle Twinkle Little Star* on a water xylophone: drive.google.com/file/d/1a5X7u60Pk1dey8d7d2PIIW-g5YHvEpPb/view?usp=drive_links

Step 4: Now let's try a song with more notes. A simple melody of *Ode to Joy* by Ludwig van Beethoven can be played with five notes! The A glass made for *Twinkle Twinkle Little* Star will not be used for this song, but you will need three more water glasses to produce three additional notes: F, E, and D. If you used 3520 Hz as the frequency for A when playing the first line of *Twinkle Twinkle Little* Star, you should use 2794 Hz for F, 2637 Hz for E and 2349 Hz for D. If you used 1760 Hz as the frequency for A when playing the first line of *Twinkle Twinkle Little* Star, you should use 1397 Hz for F, 1319 Hz for E, and 1175 Hz for D. Repeat the procedure that you used above in **Step 2** to obtain water glasses that produce F, E, and D. Strike the water glasses in sequence to produce the following notes to play the song:

E E F G G F E D C C D E E D D

E E F G G F E D C C D E D C C

D D E C D E F E C D E F E D C D

E E F G G F E D C C D E D C C

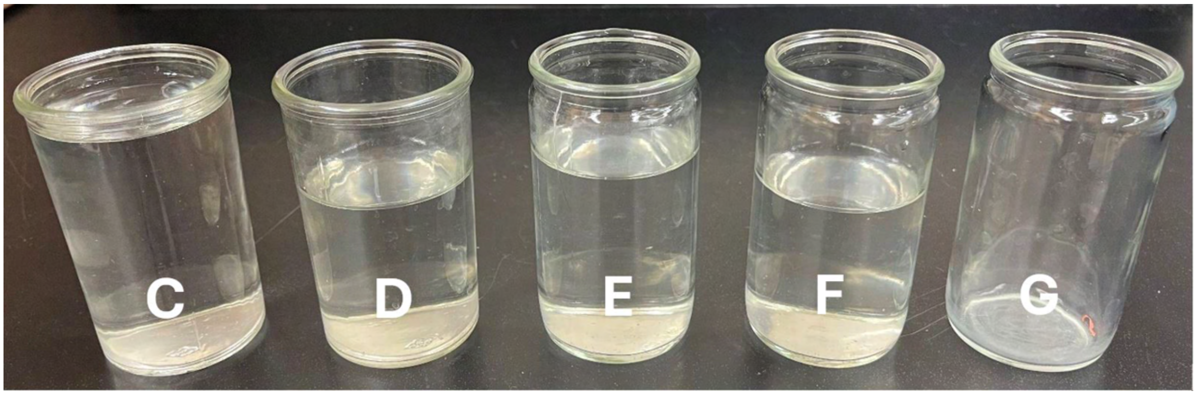

Figure 3 Five-Note Water Xylophone. This water xylophone uses C and G from Figure 2 and 3 new water glasses. It can be used to play *Ode to Joy*. The note produced by each glass is shown.

Here's an example of *Ode to Joy* on a water xylophone: drive.google.com/file/d/1EB_MD3hEPwHbSMdFDp9a9D1gDcDHizZz/view?usp=drive_link

Step 5: Now let's play the entire *Twinkle Twinkle Little Star* song! Add the A glass that you removed from the previous step to those above for *Ode to Joy*, and now you have six notes! Strike the water glasses in sequence to produce the following notes to play the song:

C C G G A A G	Twinkle Twinkle, Little Star
F F E E D D C	How I wonder what you are

G G F F E E D	Up above the world so high
G G F F E E D	Like a diamond in the sky
C C G G A A G	Twinkle Twinkle, Little Star
F F E E D D C	How I wonder what you are

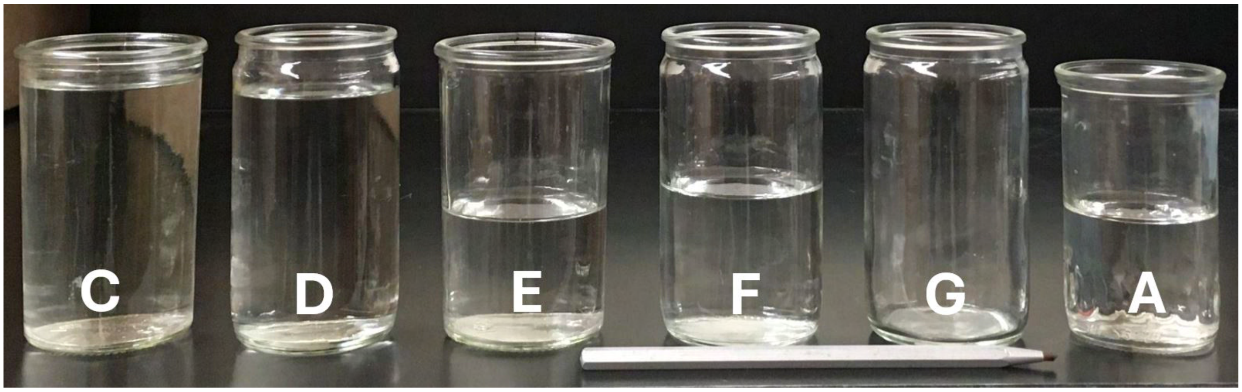

Figure 4 Six-Note Water Xylophone. This water xylophone uses all of the water glasses to play *Twinkle Twinkle Little Star*. The note produced by each glass is shown.

Here's an example of the full song of *Twinkle Twinkle Little Star*:
drive.google.com/file/d/1CIDxv4ZA3P3QcvK9RrrnrO0ZpA7ZfSK1/view?usp=drive_link

Notes

1. As you change the length of the ruler overhanging end, you should find that the pitch goes up when you shorten the length of the overhanging end and the pitch goes down when you lengthen it. The shorter end vibrates faster and the higher frequency gives a higher pitch. If you change the length quickly while the ruler is still vibrating, you can produce a sound similar to a **glissando** (**sliding between notes**) in piano or violin! Amazingly, you just produced a glissando by sliding your ruler!

2. No, the tuner cannot identify the sound that the ruler makes. The tuner can only detect consistent pitches. The frequency of the ruler's vibration varies considerably: once displaced, the ruler moves less and less, and eventually becomes still. This leads to a rapid change of pitch, and the tuner is unable to identify a specific pitch.

3. Sound waves: Sound requires a medium or substance in which to travel because it is a mechanical wave. Its speed of propagation depends on the medium's density and elasticity – sound travels fastest in solids, slower in water and other liquids, and slowest in air. A sound emitter generates vibrations in the medium, creating regions of localized movement of **molecules**, the small units that make up substances.

Advanced Notes

1. Ultrasound and sonar: A sound wave with a frequency above 20,000 Hz is defined as **ultrasound**. Ultrasound, although undetectable by the human ear, is frequently encountered in nature. Animals such as bats and dolphins produce ultrasounds that bounce off surrounding objects and return to them as they survey their environment – this is called **echolocation**. Objects that are farther away will receive and reflect the sound waves later because the sound travels for a longer distance. **Ultrasonography**, or ultrasound imaging of patients, uses this principle while estimating the amplitude or strength of the signal received. This gives information on the properties of the tissue or organ, which can be used to construct an ultrasound image that doctors use in diagnosis.

Sonar uses a similar principle to detect distant objects and is used in diverse applications: sonar is used by the military to detect submarines, by fishermen to detect schools of fish, and by doctors to detect abnormal growths. Whales emit sounds and use a type of echolocation, or sonar to locate prey and navigate.

2. Doppler Effect and use in healthcare: The **Doppler Effect** describes the frequency shift when a sound being emitted is moving toward or away from an observer. For example, when an ambulance zooms past you, the siren's pitch is higher when the ambulance is approaching you and lower when the ambulance has passed you and is moving away. Doppler ultrasound methods used in clinics for diagnosis of patients apply this effect by detecting a frequency shift in the signal that is received. One frequent use of Doppler ultrasound is in determining how fast blood is flowing through an individual's blood vessels. An ultrasound device is pressed against the area of interest and used to send and receive ultrasound waves. The sound waves reflect off of red blood cells moving in the blood vessels. The blood flowing toward or away from the device will produce a frequency shift of the signal. The frequency shift is then converted to information such as blood velocity and blood pressure. This information helps doctors detect stiffening or clotting of vessels.

3. Bioacoustics and infrasound in nature: Bioacoustics is a field that studies how animals produce and receive sound to communicate with each other and detect their surroundings. As noted above, animals can use ultrasound to interact with each other and the environment. In addition, animals use **infrasound**, sound waves below 20 Hz frequency, to communicate. Infrasound is too low to be heard by humans. It occurs naturally in **geological** (relating to the earth) or **meteorological** (relating to the atmosphere, or air and other gases surrounding the earth) events, such as earthquakes, volcanic eruptions, or storms. One advantage of infrasound communications is that infrasound waves can travel a large distance due to their low frequency.

Resources

1. Sound: en.wikipedia.org/wiki/Sound
2. History: britannica.com/science/acoustics/Early-experimentation
3. How we hear (physiology): hopkinsmedicine.org/health/conditions-and-diseases/how-the-ear-works
4. Bioacoustics: en.wikipedia.org/wiki/Bioacoustics
5. Infrasound: ctbto.org/our-work/monitoring-technologies/infrasound-monitoring
6. Audio files for our water xylophone recordings of *Twinkle Twinkle Little Star* (first line, full version) and *Ode to Joy* are posted with this lesson plan at the Biophysical Society website.

Acknowledgments

We thank Professor Rohit Singh and Professor Emeritus Harold Erickson for reviewing this lesson plan and providing valuable comments that were taken into account in revising the lesson plan. The music and lyrics used in this lesson plan, *Twinkle Twinkle Little Star* and *Ode to Joy*, are in the public domain and no longer under copyright protection.

Authors

Zimiao Meng
Pratt School of Engineering, Class of 2027
Duke University

Sharyn A. Endow, PhD
Professor of Cell Biology
Department of Cell Biology
Duke University Medical Center