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Exploring Sound with Graphs

Experiments:

Sound Waves and Beats

- Go Direct Sound

Sound and Loudness

- Go Direct Sound

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Sound Waves and Beats

Sound waves consist of a series of air pressure variations. A microphone diaphragm records these variations by moving in response to the pressure changes. The diaphragm motion is then converted to an electrical signal. Using a microphone, you can explore the properties of common sounds.

The first property you will measure is the *period*, or the time for one complete cycle of repetition. Since period is a time measurement, it is usually written as T. The reciprocal of the period ($1/T$) is called the *frequency*, f, the number of complete cycles per second. Frequency is measured in hertz (Hz). 1 Hz = 1 s^{-1}

A second property of sound is the *amplitude*. As the pressure varies, it goes above and below the average pressure in the room. The maximum variation above or below the pressure mid-point is called the amplitude. The amplitude of a sound is closely related to its loudness.

In analyzing your data, you will see how well a sine function model fits the data. The displacement of the particles in the medium carrying a periodic wave can be modeled with a sinusoidal function. Your textbook may have an expression resembling this one:

$$y = A \sin(2\pi f t)$$

In the case of sound, a longitudinal wave, y refers to the change in air pressure that makes up the wave, A is the amplitude of the wave, and f is the frequency. Time is represented by t, and the sine function requires a factor of 2π when evaluated in radians.

When two sound waves overlap, air pressure variations will combine. For sound waves, this combination is additive. We say that sound follows the principle of *linear superposition*. Beats are an example of superposition. Two sounds of nearly the same frequency will create a distinctive variation of sound amplitude, which we call a beat.

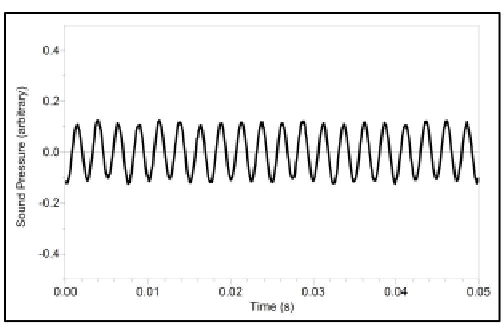

Figure 1

OBJECTIVES

- Measure the frequency and period of sound waves from a keyboard.
- Measure the amplitude of sound waves from a keyboard.
- Observe beats between the sounds of two notes from a keyboard.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis app
Go Direct Sound
electronic keyboard

PRELIMINARY QUESTIONS

1. Why are instruments tuned before being played as a group? In what different ways do musicians tune their instruments?

2. Given that sound waves consist of a series of air pressure increases and decreases, what would happen if an air pressure increase from one sound wave was located at the same place and time as a pressure decrease from another of the same amplitude?

3. How is it that we can hear all the instruments played by a group of musicians at once? Are there conditions under which you cannot hear all instruments? Can two sounds add up to create an experience that seems less intense than either sound on its own?

PROCEDURE

Part I Simple Waveforms

1. Launch Graphical Analysis. Connect the Go Direct Sound Sensor to your Chromebook, computer, or mobile device. Note that data are collected for only 0.03 s in order to be able to display the rapid pressure variations of sound waves.

2. Set your keyboard to produce a flute sound or pure tone.

3. Press and hold a key on the keyboard. Hold the Microphone close to the speaker and click or tap Collect to start data collection. When data collection is complete, a graph is displayed. The data should be sinusoidal in form, similar to Figure 1.

4. Export, print, or make a sketch of your graph.

5. Click or tap the graph to examine the data. Record the times for the first and last peaks of the waveform. Record the number of complete cycles that occur between your first measured time and the last. Divide the difference, Δt, by the number of cycles to determine the period of the note. Record the period in your data table.

6. Examine the graph again and record in the data table the maximum and minimum sound values for an adjacent peak and trough.

7. Calculate the amplitude of the wave by taking half of the difference between the maximum and minimum y values. Record the values in your data table.

8. Calculate the frequency of the note in Hz and record it in your data table.

9. Add a curve fit to your data.

   a. Click or tap Graph Tools, , and select Apply Curve Fit.

   b. From the Curve Fit menu, select Sine. Click or tap Apply.

10. The curve fit is expressed as y = a * sin(bx + c) + d, and contains four parameters; it is more complicated than the textbook model, but the basic sinusoidal form is the same. Comparing terms, listing the textbook model's terms first, the amplitude, *A*, corresponds to parameter a in the curve fit, and $2\pi f$ corresponds to parameter b. Time, *t*, is represented by the variable x. The new parameters c and d shift the fitted function left-right and up-down, respectively, and may be necessary to obtain a good fit. Only the values of parameters a and b are important to this experiment. In particular, the numeric value of b allows you to find the frequency, *f*, using $b = 2\pi f$.

    a. Enter the value of a, the amplitude, in the data table.

    b. Enter the value of b in the data table.

    c. Enter the values for c and d in the data table.

11. Repeat Steps 3–10 for an adjacent key on the keyboard.

12. Answer the Analysis questions for Part I before proceeding to Part II.

Part II Beats

13. Two pure tones with different frequencies sounded at once will create the phenomenon known as beats. Sometimes the waves will reinforce one another and other times they will combine to a reduced intensity. This happens on a regular basis because of the fixed frequency of each tone. To observe beats, simultaneously hold down the two adjacent keys on the keyboard that you used earlier and listen for the combined sound. If the beats are slow enough, you should be able to hear a variation in intensity. When the beats are too rapid to be audible as intensity variations, a single rough-sounding tone is heard. At even greater frequency differences, two separate tones may be heard, as well as various difference tones.

    a. To capture the beats, it is necessary to collect data for a longer period of time. To do this, click or tap File, , and select New Experiment. A new experiment should open with the sensor still connected. If the sensor is not connected, re-connect Go Direct Sound to your Chromebook, computer, or mobile device.

    b. Click or tap Mode to open Data Collection Settings.

    c. Change Rate to 2500 samples/s and End Collection to 0.05 s.

    d. Click or tap Done.

14. Start the two tones sounding and click or tap Collect to start data collection.

15. Note the shape of your waveform graph. You should see a time variation of the sound amplitude. The pattern will be complex, with a slower variation of amplitude on top of a more rapid variation. Ignoring the more rapid variation and concentrating in the overall pattern, count the number of amplitude maxima after the first maximum and record it in the data table.

16. Record the times for the first and last amplitude maxima. As you did before, find the time interval for several complete beats. Divide the time interval, Δt, by the number of cycles to

determine the period of beats (in seconds). Calculate the *beat frequency* in Hz from the beat period. Record these values in your data table.

17. Proceed to the Analysis question for Part II.

ANALYSIS

Part I Simple Waveforms

1. Did the curve fit line fit the waveform well? In what ways was the curve fit line similar to the data and in what ways was it different? Zooming in on part of your graph may help you answer this question.

2. Since the parameter b corresponds to $2\pi f$ (i.e., $f = b/(2\pi)$), use your this parameter to determine the frequency. Enter the value in your data table. Compare this frequency to the frequency calculated earlier. Which would you expect to be more accurate? Why?

3. Compare the parameter a to the amplitude you determined using the Examine function.

Part II Beats

4. How is the beat frequency that you measured related to the two individual frequencies? Compare your conclusion with information given in your textbook.

DATA TABLE

Part I Simple Waveforms

Note	Number of cycles	Time of first max (s)	Time of last max (s)	Δt (s)	Period (s)	Calculated frequency (Hz)

Note	Peak	Trough	Amplitude

Note	Parameter a	Parameter b	Parameter c	Parameter d	$f = b/2\pi$ (Hz)

Part II Beats

Number of cycles	Time of first max (s)	Time of last max (s)	Δt (s)	Beat (s)	Calculated beat frequency (Hz)

EXTENSIONS

1. There are commercial products available called *active noise cancellers,* which consist of a set of headphones, microphones, and some electronics. Intended for wearing in noisy environments where the user must still be able to hear (for example, radio communications), the headphones reduce noise far beyond the simple acoustic isolation of the headphones. How might such a product work?

2. The trigonometric identity

$$\sin x + \sin y = 2\sin\left(\frac{x+y}{2}\right)\cos\left(\frac{x-y}{2}\right)$$

   is useful in modeling beats. Show how the beat frequency you measured above can be predicted using two sinusoidal waves of frequency f_1 and f_2, whose pressure variations are described by $\sin(2\pi f_1 t)$ and $\sin(2\pi f_2 t)$.

3. Most of the attention in beats is paid to the overall intensity pattern that we hear. Use the analysis tools to determine the frequency of the variation that lies inside the pattern (the one inside the envelope). How is this frequency related to the individual frequencies that generated the beats?

4. Examine the pattern you get when you play two adjacent notes on a keyboard. How does this change as the two notes played get further and further apart? How does it stay the same?

Sound and Loudness

OVERVIEW

The goal of this activity is for students to determine a relationship between sound wave amplitude and decibel level. In the Preliminary Observations, students observe sound waves breaking a glass tumbler, either by watching a video or live demonstration. Students then discuss how the sound wave could break the glass, which particular wave characteristics are important in the process, and how one could measure them.

Safety Precaution: Because this investigation involves making loud noises, care must be taken to protect everyone's hearing.

WHAT SHOULD STUDENTS KNOW BEFORE DOING THIS ACTIVITY?

Students should be able to identify and understand basic wave characteristics (frequency, wavelength, amplitude) and how to observe and measure those characteristics. Students should have a passing familiarity with the decibel scale, which is used to measure sound level.

LEARNING OUTCOMES

- Design and perform an investigation.
- Draw a conclusion from evidence.
- Understand the relationship between wave amplitude and decibel level.

NEXT GENERATION SCIENCE STANDARDS

Disciplinary Core Ideas	Crosscutting Concepts	Science and Engineering Practices
PS4.A Wave Properties	Cause and Effect Systems and System Models Energy and Matter Influence of Science, Engineering and Technology on Society and the Natural World Stability and Change	Asking Questions and Defining Problems Planning and Carrying Out Investigations Analyzing and Interpreting Data Engaging in Argument from Evidence Using Mathematics and Computational Thinking Obtaining, Evaluating, and Communicating Information

ESTIMATED TIME

Students should be able to complete the Preliminary Observations, planning, and data collection in the space of one 40-minute class period. Because of the nature of this investigation, students may require additional space (e.g., another classroom or outside) in order to collect data without interfering with a neighboring lab group. Reaching a conclusion and class discussion can take an additional 20 minutes or more of the next class period.

MATERIALS

Make the following materials available for student use. **Note**: If you choose to do a demonstration for the Preliminary Observations rather than showing the video, you will need a sound source and a glass tumbler or wine glass.

computer, Chromebook, or mobile device
data-collection program
data-collection interface (if necessary)
sound source (e.g., the LabQuest 2 Audio Function Generator and speakers)
decibel meter (e.g., Vernier Sound Level Meter or Sound Level Sensor)
Vernier Microphone
other materials as requested by students

PRELIMINARY OBSERVATIONS

For the Preliminary Observations, show a video such as "How to Break Glass With Your Voice" from Hard Science, demonstrating how sound waves can break a wine glass. Alternatively, if you have the necessary materials, you can demonstrate this effect yourself. See the Tips section for more details.

After the demonstration, ask students to diagram the energy flow during the event. What does work on what? Where does the energy flow begin and end?

During your discussion, be certain that students understand that sound waves carry energy and can do work—even enough work to break glass. Consider: The amount of energy carried by a wave depends on its amplitude: a larger amplitude equals more energy. For a sound wave, its amplitude is observed/felt by its loudness (i.e., a large amplitude sound wave is louder than a small amplitude sound wave). The decibel scale is a familiar measure of sound wave loudness, but how does it relate to wave amplitude?

After the Preliminary Observations and discussion, frame the investigation. Explain that lab groups are tasked with determining the relationship between wave amplitude and sound level. You may want to remind students that sound waves can vary in frequency as well as amplitude, so they will need to control for the sound wave frequency.

IMPLEMENTATION

In order to determine the relationship between wave amplitude and sound level, students will need to measure both using some combination of sensors that will measure sound level in decibels and sound wave amplitude. The Vernier microphone can be used to measure sound wave amplitude (in arbitrary units) and there are multiple options for measuring sound level.

Student groups will need to decide how to create sound waves and measure their amplitudes and sound levels reliably. Encourage students to fix their sound sources and measurement tools, using ring stands and other laboratory equipment, so that positions between them do not change from trial to trial. Likewise, encourage students to measure across a large range of wave amplitudes and sound levels. Doing so will make the relationship between amplitude and sound level more obvious.

ANALYSIS

Students should create a graph of decibel level *vs*. wave amplitude and apply an appropriate curve fit to determine the relationship between the two. It will be obvious that sound level is not directly proportional to wave amplitude. Graphs will show that as the wave amplitude increases, the loudness increases as well, albeit at an ever decreasing rate.

At this point you may decide to lead a discussion about how the decibel scale is based on sound *intensity*, not simply the wave's amplitude. Sound intensity is a measure of how the energy is spread out across a given area; it is measured in units of watts per square meter (W/m^2). The intensity is proportional to the square of the wave amplitude. Instruct students to create a new column of data by squaring the wave amplitude and plot the loudness versus this new "intensity."

Linearizing or applying a curve fit to this refinement of their data should, ideally, lead to a logarithmic relationship between loudness and sound intensity. But, depending on their data, some lab groups may find that other mathematical models fit their graphs better. Discuss as a class how different groups decided on a particular mathematical model.

SAMPLE RESULTS

The data presented in this section were collected using a Vernier Sound Level Sensor and Microphone. Both sensors were positioned about 15 cm (6 in.) from a pair of computer speakers playing a 1000 Hz tone using the Audio Function Generator app on LabQuest 2. The curve fits were created using Logger *Pro* 3.

Investigation 1

We adjusted the volume on the computer speakers until the Sound Level Meter read a nice round number (e.g., 70 dB). We then measured the wave amplitude from the waveform collected by the Microphone using the default data-collection parameters (10,000 samples/s for 0.03 seconds).

See the Tips section for information regarding the determination of wave amplitude.

Table 1	
Wave amplitude (arbitrary units)	Loudness (dB)
0.03	70
0.04	75
0.05	80
0.08	85
0.15	90

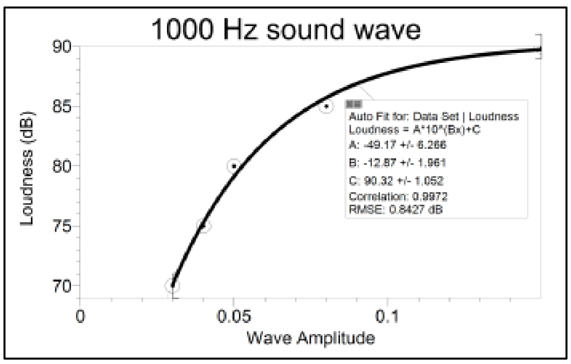

Figure 1

Table 2	
"Intensity" [a.k.a. amplitude squared] (arbitrary units)	Loudness (dB)
0.0009	70
0.0016	75
0.0025	80
0.0064	85
0.0225	90

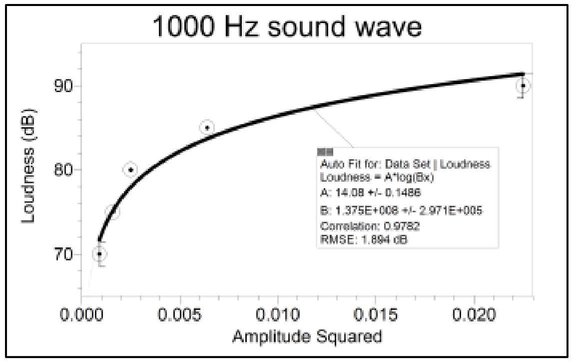

Figure 2

TIPS

1. In the Electronic Resources you will find many useful files, including sample program and a PDF of the student pages so you can print the activity for your students or distribute the file to them electronically. Sign in to your account at **vernier.com/account** to access the Electronic Resources. See Appendix A for more information.

2. **Safety Precaution**: Because this investigation involves making loud noises, care must be taken to protect the hearing of students. Appropriate limits should be set on the loudness of sounds and human ears should be kept several feet from the speakers. You may wish to provide disposable earplugs for students and yourself.

3. An excellent article on breaking a wine glass with sound is "Resonant wineglasses and Ping-Pong™ balls" by Bill Berner (2000). Find additional glass-breaking tips at **www.breakglass.org/How-does-sound-break-glass.html**

4. Sound level can be measured using a decibel meter, such as the Vernier Sound Level Sensor. There are also a number of readily available sound-level apps for smartphones. Take care in choosing an app as their accuracy can be limited; for details, see **vernier.com/til/3487**

5. Wave amplitude is measured most easily using a sensor such as the Vernier Microphone. Such sensors take a "snapshot" of a sound wave. While the amplitude units for the Microphone are arbitrary, they do offer a relative comparison from one sound wave to another—provided the experimental setup remains the same (i.e., the distance from the sound source to the microphone stays the same). As with sound level, smartphone apps that can be used to capture sound waves are plentiful. Because the exact amplitude is less important than the relative amplitude, sound wave smartphone apps may perform adequately.

6. The Vernier Sound Level Sensor is A-weighted, meaning that its response to sound loudness mirrors that of the human ear. This sensor specifically discriminates against low frequency sound with an optimized response in the range of 500 to 10,000 Hz. If using the Sound Level Sensor, students should choose a frequency in that range to use during their investigation.

7. The Vernier Sound Level Meter has a switch to choose A- or C-weighting; C-weighting is nearly unfiltered with respect to frequency. Either setting is acceptable but see the preceding Tip if using A-weighting.

8. The Sound Level Sensor and Microphone should each have their sensing elements as close to each other as possible since sound level varies with position.

9. Ambient background noise is an unavoidable source of error in this experiment. Students should attempt to perform their data collection with as little background noise as possible. Having students stagger their data collection times during the period or block and using other available spaces in the school may be necessary.

10. If using the LabQuest Audio Function Generator App, the tone quality will be improved if you use an external speaker rather than relying on the speaker built into the LabQuest.

EXTENSIONS

Assign one or more of the following extensions once students have concluded their investigations. While we provide guidance for what to expect from students in response to extensions, we do not include sample data or conclusions.

1. Investigate sound dampening. What materials work well for dampening sound waves?

Acoustical engineers work with architectural engineers to select materials that attenuate sound. For example, a wall constructed with gypsum board on a wooden frame will attenuate sound differently than a cinder block wall with the same surface area.

2. In the United States, there are local and federal standards that regulate exposure to noise in the workplace. Investigate local standards for noise levels. What is the sound level threshold at which ear protection is required? Given what you have learned about the decibel scale, why do you think that threshold was chosen?

Most localities set the threshold noise at around 80 dB. Beyond that level, ear protection is required. Because the decibel scale is a logarithmic scale, an increase of only 3 dB is a doubling in intensity. So, sound waves above 80 dB grow more damaging very quickly.

Sound and Loudness

Imagine standing at the end of a runway as a commercial jet thunders towards you. As it approaches, you can feel the ground beneath you start to shake. The rumble of the jet engines grows so loud, you can feel it in your chest. When the jet is practically on top of you, you might begin to wonder, "How loud is this? Am I going to be able to hear anything after it passes?"

PRELIMINARY OBSERVATIONS

Sounds waves, like a moving airplane, carry energy. This energy is spread among the air molecules that are involved in the wave. How much energy does a wave carry? Your instructor will show how sound waves can break a glass. As you watch the demonstration, ask yourself "Which wave characteristics are related to the energy carried by the wave?"

PROCEDURE

1. Discuss and decide how you will measure sound wave amplitude and sound level.
   - Consider the environment in which you are working. How can you minimize interference from other lab groups, who are also creating and measuring sound waves?
   - Make sure other wave variables are held constant during your investigation.
2. Develop a procedure for your investigation.
   - A result of your investigation should be a mathematical relationship between sound level and wave amplitude.
   - Include the measurement equipment you will use.
   - Decide how much data or observation to take in order to have enough information to satisfy your purpose and stand up to questioning by your peers.

Safety Precaution: Because this investigation involves making loud noises, care must be taken to protect the your hearing. Consider what steps you can take in your procedure to avoid exposure to very loud sounds.

3. Carry out the investigation and record your data and observations. Make sure all group members have access to the data.

ANALYSIS

Examine your graphs. What mathematical model best represents the relationship between the variables you have measured? Use your data-analysis software to linearize or perform a curve fit on your data. You may need to do some research.

EXTENSIONS

1. Investigate sound dampening. What materials are good for dampening sound waves?

2. In the United States, there are local and federal standards that regulate exposure to noise in the workplace. Investigate local standards for noise levels. What is the sound level threshold at which ear protection is required? Given what you have learned about the decibel scale, why do you think that threshold was chosen?