Lesson Title	18. Physics of Sound and Hearing
Lesson Designer	Nicole Granucci
Standards	☐ CCSS ☑ NGSS ☐ ASCA ☐ Other **PS4.A: Wave Properties** The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing.
Learning Objectives	Students will: 1. Calculate the frequency of a sound wave given a graph 2. Determine your hearing range 3. Calculate the intensity of common sounds

Timeline	Duration
Day 1 - Students do the activity on determining the frequency of the tuning forks. Day 2 - Students can take a hearing test Day 3 - Students can learn about intensity and loudness and then do an activity to organize the loudness of objects.	Activity 1 – 45 minutes Activity 2 – 20 minutes Activity 3 – 20 minutes

Teaching Strategies/Student Actions	Monitoring
• Lab Activity - See attached below for delivery	• Teacher will model and explain expectations - task oriented and behavioral. • Teacher will move around the room to observe student progress. • Teacher will provide feedback and suggestions for students. • Teacher will remind students of time remaining for each portion of the activity (i.e., You have five minutes remaining to collect data).

Product Description	Lab Data sheet at the end of this activity.
Evaluation	Lab Data sheet at the end of this activity.

Resources and Materials	Additional Notes
Physics of Sound and Music Reading/Resources https://www.physicsclassroom.com/class/sound	

Understanding Physics of Hearing

Speech and hearing are one of the most important ways we communicate with others. In this lesson, we will investigate how we hear sounds, how our brain interprets them and investigate some basic properties of speech. What are sounds and where do they come from? Sound waves are generated when matter is set into vibration. Any form of matter can generate sound waves. The most common way sound travels is in air, however, sound can travel through water and solids as well. One device that generates a pure tone is called a tuning fork. When a tuning fork is set into vibration, it pushes the air adjacent to it. This creates a domino effect where the air is pushed together called a compression and where the air is vacant from an area called rarefaction. The combination of compression and rarefaction results in a wave pattern that can be interpreted by the ear. Figure 1 gives a visual of the compression and rarefactions generated by a sound wave.
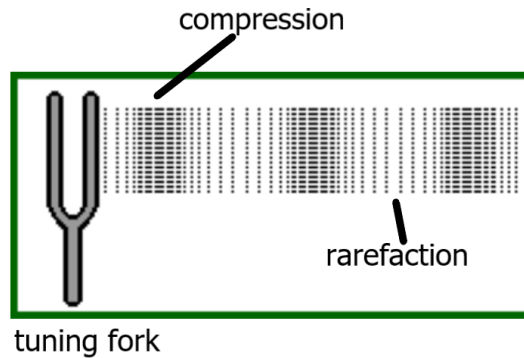

Figure 1 – Compression and rarefactions of a sound wave generated by a tuning fork.
Photo credit: Physicsclassroom animation.

Although this depicts how a sound wave is generated, it better to use the wave model to interpret the qualities of sound waves. Figure 2 gives the wave model and common wave characteristics. The amplitude of the wave is the measure of the waves energy from the midpoint of the wave, also known as the equilibrium position, to either a crest or trough of the wave. The wavelength measures the size of the wave. On the diagram, it measures one full wave cycle. The crest is the peak of the wave which matches up with the compression of the wave. The trough is the lowest part of the wave which matches up with the rarefactions of the wave.
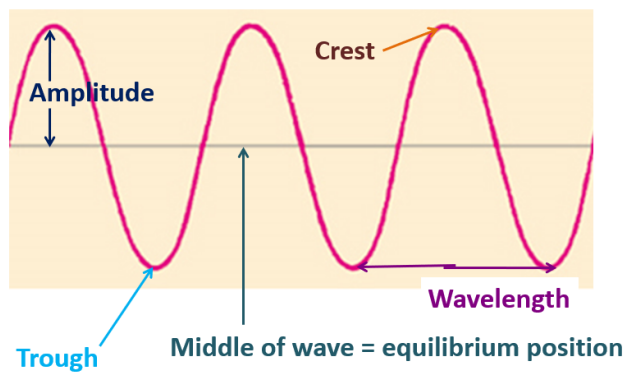

Figure 2 – Diagram of a wave model

These wave patterns can be picked up by the human ear and interpreted into sound. The ear detects mechanical waves and translates them into electric pulses in the auditory nerve. The ear is divided into three parts, the inner ear, the middle ear and the outer ear. The outer ear mostly consists of the ear canal. The middle ear includes the ear drum, the small bones of the ear and the Eustachian tube. And the inner ear contains the cochlea (the spiral shaped object) with fluid and tiny hair cells to convert the motion to electrical signals.[1] Figure 3 gives a cross-sectional glimpse of the human ear.

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[1] Physics of the Body. John R. Cameron. James G. Skofronick. Roderick M. Grant. Medical Physics Publishing © 1999
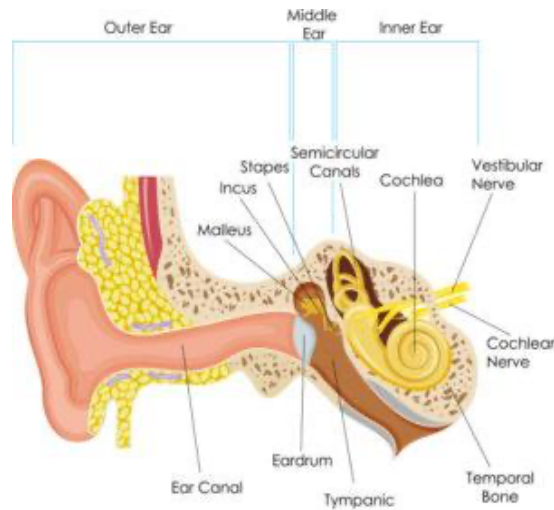
Figure 3 – Anatomy of the human ear

In order for the brain to perceive a sound wave, it has to be within the human hearing range for both frequency and intensity. Frequency is the number of oscillations that occurs over a period of time. This is typically the number of sound vibrations per second, measured in a unit of Hertz (Hz). This is modeled by the mathematical equation below

$$f = \frac{\#\ of\ oscillations}{time\ (s)} \quad (1)$$

Pitch is how people interpret the frequency. The higher the frequency, the higher the pitch. For example, a piccolo would have a high pitch due to the high frequencies it generates. Whereas a tube has a low pitch, or low frequency. Frequency is the physical measurement of the sound wave, whereas the pitch is how the brain interprets that sound wave.

Wavelength and frequency are related through the wave equation

$$v = f\lambda \quad (2)$$

Where v is the speed of the wave in (m/s), f is the frequency of the wave in (Hz) and the wavelength of the wave is measured in (m). Frequency and wavelength are inversely related. The larger the wavelength, the smaller the frequency. This is way tubas have a low frequency. The sound wave generated by a large instrument makes larger wavelengths, but small frequencies that give its iconic low pitch. Figure 4 gives a visual of the inverse relationship between frequency and wavelength.
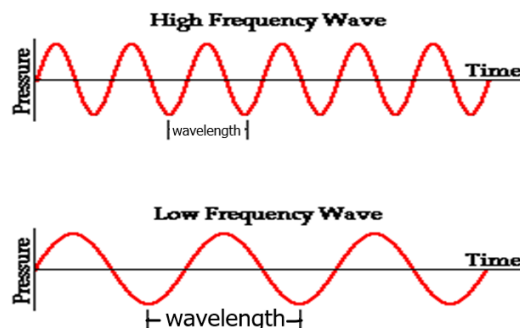

Figure 4 – Large wavelengths generate low frequencies. Small wavelengths generate high frequencies. Photo credit: Physicsclassroom.

The average human hearing range of frequencies is from 20Hz to 20,000Hz. This means that most people can hear sounds generated in that range. Sounds that are outside of the range are impossible for people to perceive. However, sounds can still be measured with equipment that is outside our range of hearing using a microphone. If the sound waves are lower than we perceive, they are call infrasonic, and if they are higher, they are called ultrasonic. Ultrasound in the medical field works by using frequencies higher than people can perceive. These frequencies can be absorbed and reflected by body tissue, through generating an image for things like fluid movement and organs.

Not only does a sound wave must be within the hearing range, but it has to be loud enough to be perceived too. In physics, the loudness of a sound is measured by the intensity. This gives the amount of power a sound wave has over a spherical area, given by the equation below:

$$I \ = \ \frac{P}{4\pi r^2} \ \ (3)$$

Where P is the power of the sound wave measured in (W), $4\pi r^2$ is the surface area of a sphere and I gives the intensity in (W/m^2) of a sound wave as it spread out over a surface of a sphere from the sound source. The intensity of the sound waves are very small ranging from 1.0×10^{-12} W/m^2, the smallest perceivable sound wave to 1×10^2 W/m^2 where it is ear damagingly loud. The brain interpret loudness in orders of ten. For example, if one person is clapping, it will be perceived with a certainly loudness. However, when two people clap their hands, the brain does not necessarily interpret that as louder. Its only when at least 10 people are clapping does the brain que that as measurably louder. Because of this, loudness that our brains interprets is measured in decibels. Where "deci" means ten and "bels" means loudness. Going from an intensity of 1×10^{-6} Wm^2 to 1×10^{-3} W/m^2 is a change of 30 decibels. That is because for every order of magnitude of 10, that is a change in decibels. For people to perceive a sound, it has to be both at the right frequency and the right loudness. Figure 5 depicts the human hearing range in regards to both frequency an intensity. The area for speech is the perfect spot for human hearing. Its at a comfortable intensity as well as frequency. Naturally, this is the most sensitive spot for people to hear.
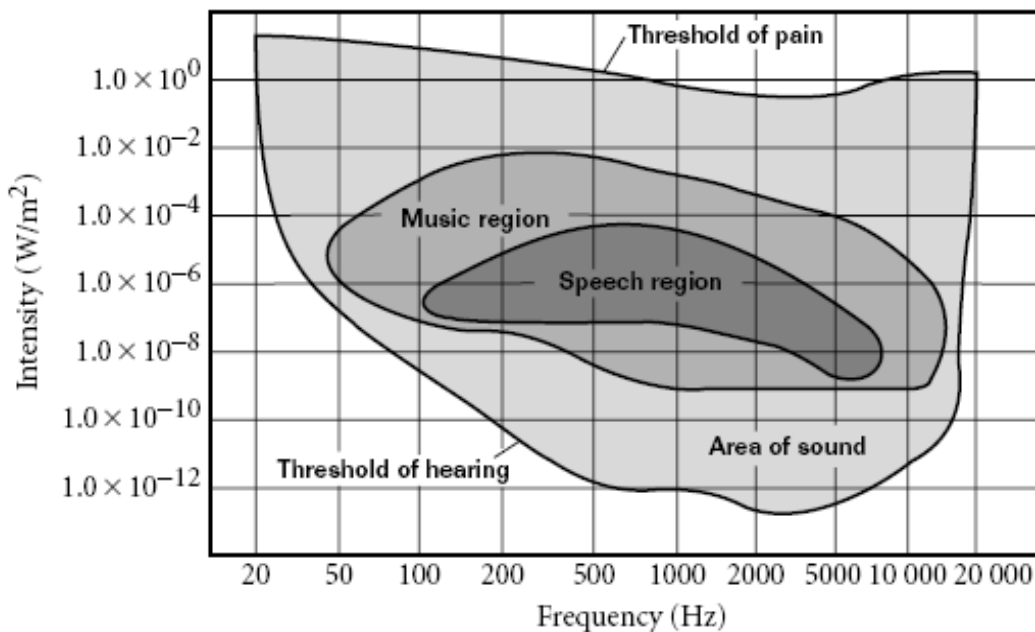

Figure 5 – Human hearing range in regard to intensity and frequency of a sound wave.

Part 1 – Measure the frequency of a sound wave

Introduction

Sound waves are mechanical waves, waves generated by matter, through a forced vibration. The vibration cases the air particles to compress (compressions) and move apart (called rarefactions). These series of compressions and rarefactions generate a series of pressure waves. 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 and a computer interface, you can explore the properties of common sounds.

The first property you will measure is the frequency, f, the number of complete cycles per second. Frequency is measured in hertz (Hz). 1 Hz = 1 s^{-1}. If there are multiple cycles, then you can find the frequency by taking the total number of cycles and the time it takes to makes those cycles

$$f \; = \; \frac{\# \; of \; cycles}{\Delta t} \qquad \textbf{(1)}$$

Frequency measures how high/low a sound wave sounds, also known as a pitch. A high frequency sound wave like 1000Hz will have a high pitch sound whereas a 200Hz sound wave will have a low pitch sound.

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. The greater the amplitude, the louder the sound wave.
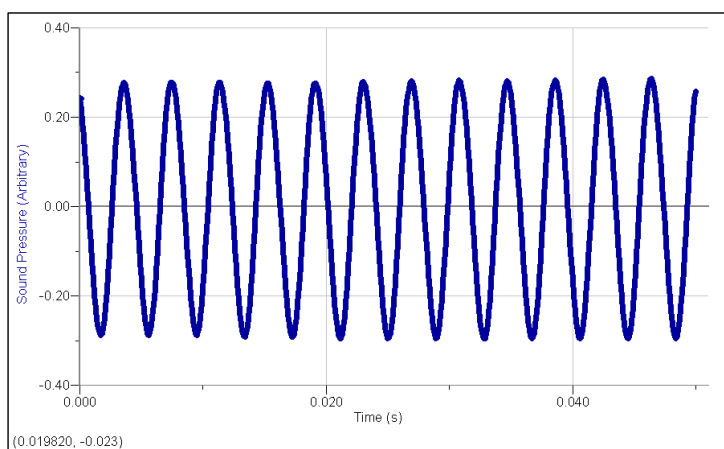

Figure: Example of a pure tone sound wave generated by a tuning fork; Tuning Fork C 512Hz

In this lab, you will measure the frequency of tuning forks. These generate pure tones which resemble a sine wave. To find the frequency, the video will highlight a portion of the sound wave. The number of cycles will be counted in addition to measuring the time it takes to make the highlighted cycles. This will be compared to the actual value of the frequency on the tuning fork. The tuning fork also has the note that it plays. Musical notes include A,B,C,D,E,F,G. The number next to the note refers to the order on the piano. For example A3 means that this is the third A on the piano.

Measuring the Frequency of a Tuning Fork

1. Select one of the six tuning fork graphs to measure.
2. Label the actual tuning fork value given from the graph of the tuning fork. Label this under "Actual tuning fork frequency" on table 1.
3. Count the number of full present in the graph. Record this value under "number of cycles". Note the start time of where you started your count and the end time. Record the two times in data table 1. See example of cycle, start time and end time measurement below.
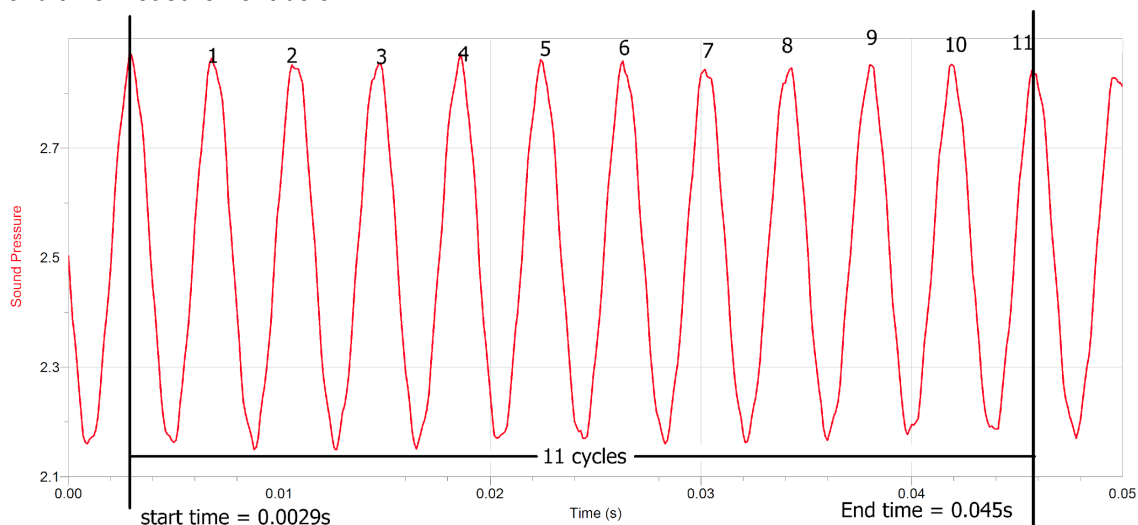
4. Calculate the Δt by taking the final time and subtracting the initial time.

$$\Delta t = \text{Final time} - \text{Initial time}$$
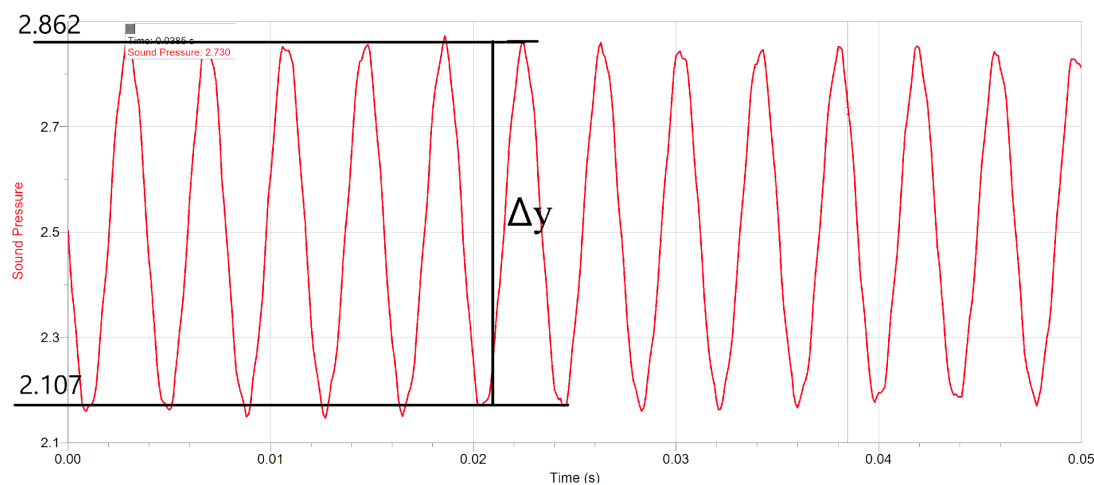
5. Calculate the frequency of the sound wave using equation 1.

$$f = \frac{\# \ of \ cycles}{\Delta t}$$

6. Calculate the percent error.

$$percent \ error = \frac{experimental \ frequency - actual \ frequency}{actual \ frequency} * 100\%$$

7. Select one peak and measure the Δy. Measure the peak y values and the low peak value. Record the peak/low value. See peak measurements below.

Example of taking Δy measurement by marking the high peak values and low peak value.

8. Calculate Δy by subtracting the high and low y values.

$$\varDelta y = high\ peak\ value - low\ peak\ value$$

9. Find the amplitude by taking the Δy measurement and dividing it by 2.

$$amplitude = \frac{\varDelta y}{2}$$

10. Repeat this experiment for a second tuning fork.

Analysis Questions

1. Which tuning fork had the higher frequency? Does this result in a high or low pitch?

2. Which tuning fork had a higher amplitude? Does this result in a loud or soft sound?

3. Which tuning fork had a higher percent error? What could account for the discrepancy?

Part 2 – Take a Hearing Test!

Objective: Determine your hearing range using a high frequency and low frequency function generator

According to theory, the average human hearing range is from 20 Hz to 20,000Hz. What is your personal hearing range? In this activity, you will determine you personal hearing range to see if it matches the average human hearing range. First, you will test your ability to detect high frequencies. Use the best pair of headphones you have to take this test. If you do not have headphones, use your computer speakers as best as you can. There are two websites for the different range of tests. The first one will determine you high range of hearing. Since your ear are sensitive to high pitches, you can hear the frequencies at almost any volume. However, as the pitches start to approach out of your range, you will notice a decrease in volume of the pitch. The higher pitches, even when you do not actually hear them, can be uncomfortable to our ears. Our ears are much less sensitive to low frequencies thus it is important that the volume is very loud to be able to hear them. This test will only test your sensitivity to frequencies and not the sensitivity of loudness. Also note that this test is for fun and does not render any medical information. If you have hearing concerns please consult your physician.

High range hearing test:
1. Go to Website: http://www.noiseaddicts.com/2009/03/can-you-hear-this-hearing-test/
2. Use earbuds if possible and play each frequency one at a time. In the box below the frequency depict whether you were able to detect the sound (detect), hard to tell if you could hear it (unsure) or cannot hear it (undetected). Feel free to add any addition comments to the frequency as well.

Low range hearing test:
1. Go to this website: https://onlinetonegenerator.com/
2. Turn the volume up all the way – use earbuds if possible.
3. Use earbuds if possible and play each frequency one at a time. In the box below the frequency depict whether you were able to detect the sound (detect), hard to tell if you could hear it (unsure) or cannot hear it (undetected). Feel free to add any addition comments to the frequency as well. It is very likely that at 60Hz or lower you will not be able to hear it because of the speaker quality.

Part 3 – Understanding Intensity and Loudness

Part I – Calculating Intensities

The intensity, or how loud a soundwave is, is based on two main characteristics: the distance of the source of the sound and how powerful the source of the sound is. Naturally, a siren is a very powerful source of sound, therefore it will have a higher intensity. However, the intensity is also based on how far away you are from the sound wave. The closer you are, the greater the intensity. If you start walking away from the source of sound, the sound level dramatically decreases in a model scientists call an inverse square. This means that as the distance increases, the intensity decreases non-linearly.

$$I \; = \; \frac{P}{4\pi r^2} \;\; (3)$$

Where P is the power of the sound wave measured in (W), r is the distance from the source of the sound to the observer and I gives the intensity in (W/m^2) of a sound wave as it spread out over a surface of a sphere from the sound source.

Use the Intensity Equation to calculate the intensities of the following:

1. Calculate the intensity of a vacuum cleaner at 1 m away with a power of 1.25x10^{-4} W.

2. Calculate the intensity of two people having a conversation 4m away with a power of 2.5x10^{-8} W.

3. Calculate the minimum power that a person can hear at 100Hz at a distance of 1 m and an intensity of 1.00 x10^{-11} W/m^2.

4. How far away would you have to stand at a rock concert to not cause ear damage due to the intensity of the speakers? Assume the intensity is 1.25x10^{-4} W and that the power tolerated by people is 100 W.

Part II – Organizing/Quantifying Loudness of Common Activities

1. With a partner, organize the sounds by intensity level.
2. Check with your teacher to see how well you organized the intensity level of common sounds.
3. Answer analysis questions

Part 1 – Measuring the Frequency of a Sound Wave Data Table

Tuning Fork 1 Data

Actual Tuning Fork Frequency (Hz)	Number of cycles	*Start Time* (s)	*End Time* (s)	Δ*t* (s)

Show full Calculation of Frequency:	Show full calculation of Δ*t* (s)	Show full Calculation of Percent Error

High Peak Measurement	Low Peak Measurement	Δ*y*	*Amplitude*

Tuning Fork 2 Data

Actual Tuning Fork Frequency (Hz)	Number of cycles	Start Time (s)	End Time (s)	Δt (s)

Show full Calculation of Frequency:	Show full calculation of Δt (s)	Show full Calculation of Percent Error

High Peak Measurement	Low Peak Measurement	Δy	Amplitude

Analysis Questions

1. Which tuning fork had the higher frequency? Does this result in a high or low pitch?

2. Which tuning fork had a higher amplitude? Does this result in a loud or soft sound?

3. Which tuning fork had a higher percent error? What could account for the discrepancy?

Part 2 – Hearing Test Data Sheet

Data Table 1 - Frequencies of High range Hearing test

8000 Hz	10,000Hz	12,000Hz	14,000 Hz	15,000Hz	16,000Hz

17,000Hz	18,000 Hz	19,000Hz	20,000Hz	21,000 Hz	22,000Hz

Data Table 2 - Frequencies of High range Hearing test

250 Hz	200 Hz	150 Hz	100 Hz	90 Hz	80 Hz	70 Hz

60 Hz	50 Hz	40 Hz	30 Hz	20 Hz	10 Hz

Analysis Questions

1. Did you notice as the frequencies got higher that they got softer as they approached out of range? Or did the frequencies remain the same intensity throughout?

2. Did you notice any wavering in intensity as you approached higher frequencies?

3. What was your hearing range? List the low and high frequency range you have personally. How does this compare to the human hearing range?

4. Are there any factors that might attribute to your hearing range you would like to share?

5. What surprised you most when taking the hearing test?

Part 3 – Understanding Intensity and Loudness Data Sheet

Part I – Calculating Intensities

	Show full calculation
1	
2	
3	
4	

Part II – Organizing Intensities

Decibel level	Intensity (W/m^2)	Noise	List of Noises
0	1.0×10^{-12}		Vacuum Cleaner
10	1.0×10^{-11}		Thunder Clap Subway
20	1.0×10^{-10}		Whisper Busy Traffic
30	1.0×10^{-9}		Quiet Whisper Rustling Leaves
40	1.0×10^{-8}		Threshold of Pain Threshold of Hearing
50	1.0×10^{-7}		Rock Concert Air conditioner at 6m
60	1.0×10^{-6}		Mosquito buzzing Normal conversation
70	1.0×10^{-5}		Nearby jet airplane
80	1.0×10^{-4}		
90	1.0×10^{-3}		
100	1.0×10^{-2}		
110	1.0×10^{-1}		
120	1.0×10^{0}		
130	1.0×10^{1}		
150	1.0×10^{3}		

Compare with the actual list of Intensities

Intensity (W/m^2)	Decibel level (dB)	Examples
1.0×10^{-12}	0	threshold of hearing
1.0×10^{-11}	10	rustling leaves
1.0×10^{-10}	20	quiet whisper
1.0×10^{-9}	30	whisper
1.0×10^{-8}	40	mosquito buzzing
1.0×10^{-7}	50	normal conversation
1.0×10^{-6}	60	air conditioning at 6 m
1.0×10^{-5}	70	vacuum cleaner
1.0×10^{-4}	80	busy traffic, alarm clock
1.0×10^{-3}	90	lawn mower
1.0×10^{-2}	100	subway, power motor
1.0×10^{-1}	110	auto horn at 1 m
1.0×10^{0}	120	threshold of pain
1.0×10^{1}	130	thunderclap, machine gun
1.0×10^{3}	150	nearby jet airplane

Analysis Questions

1. What patterns do you notice in the value of intensity and the decibel level?

2. Which noises were hardest to rank?

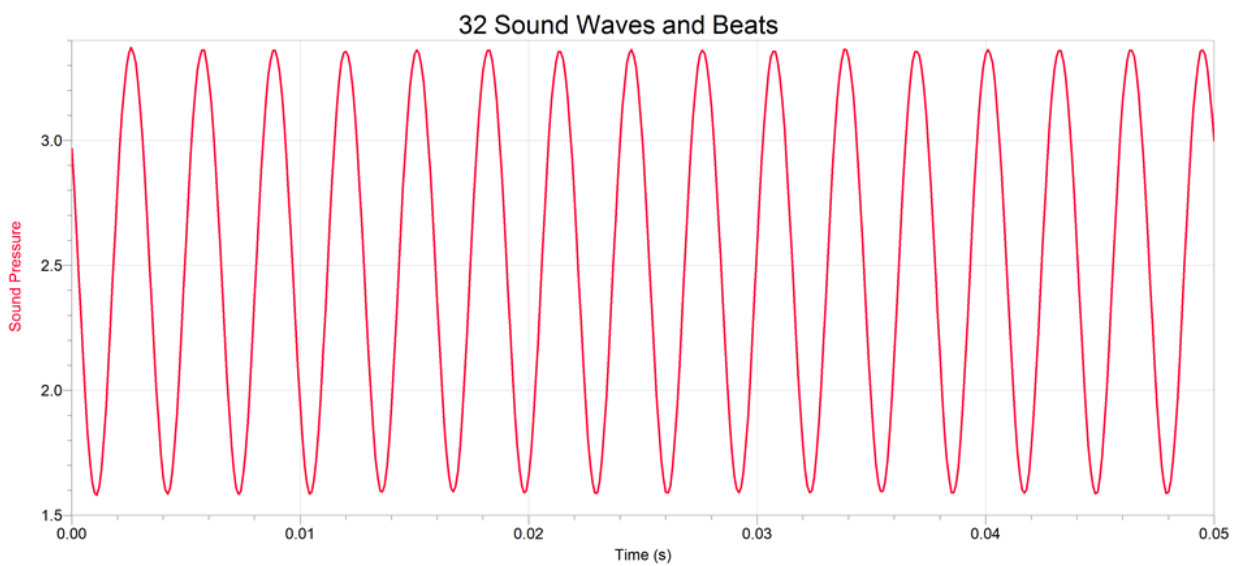3. What surprises did you have while ranking the intensities of sounds?
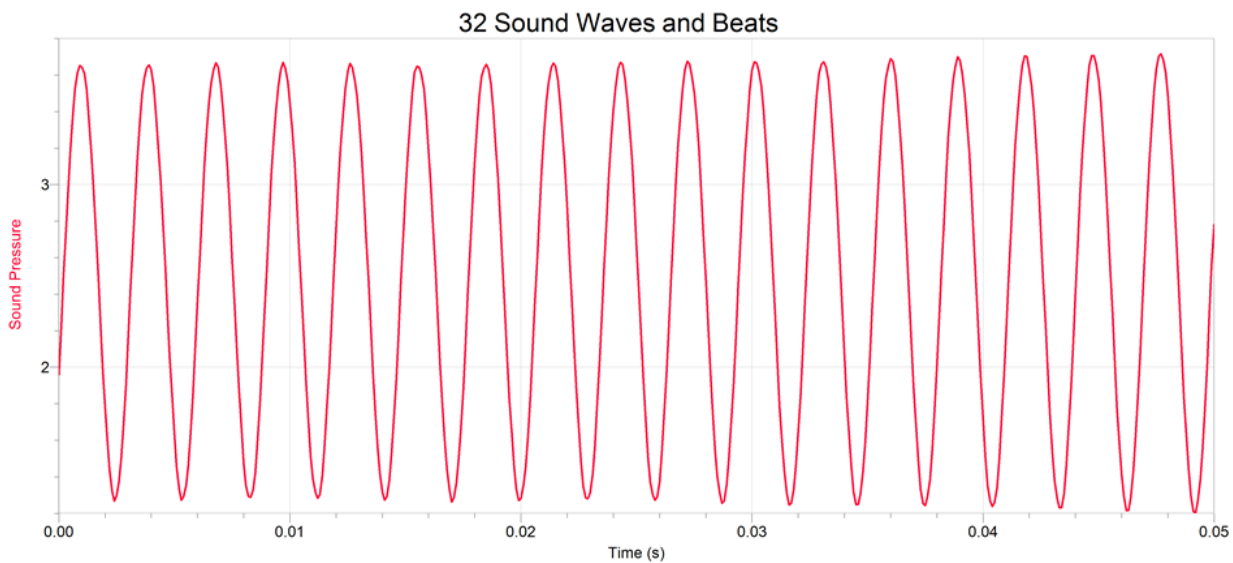
Lab data for tuning forks

32 Sound Waves and Beats
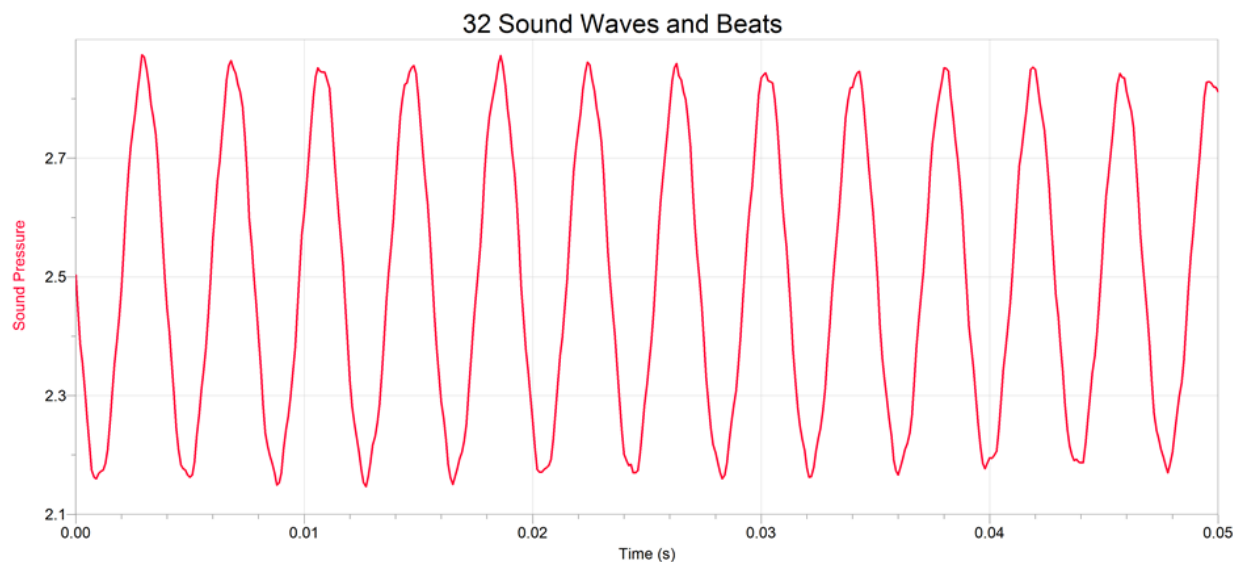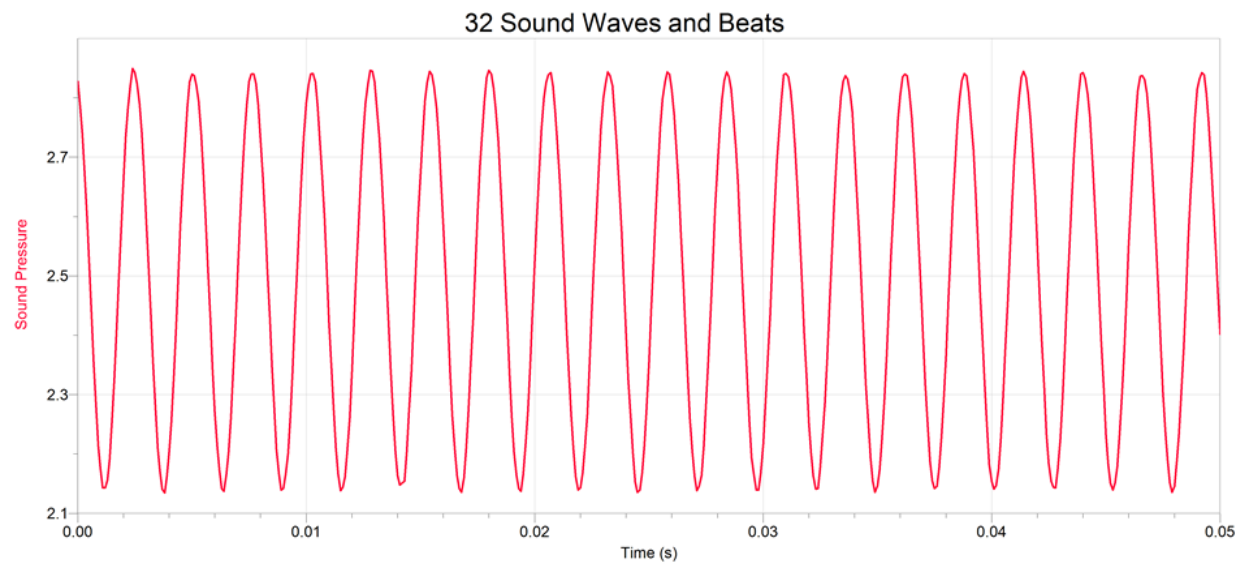

Tuning Fork 256 HZ C3

32 Sound Waves and Beats
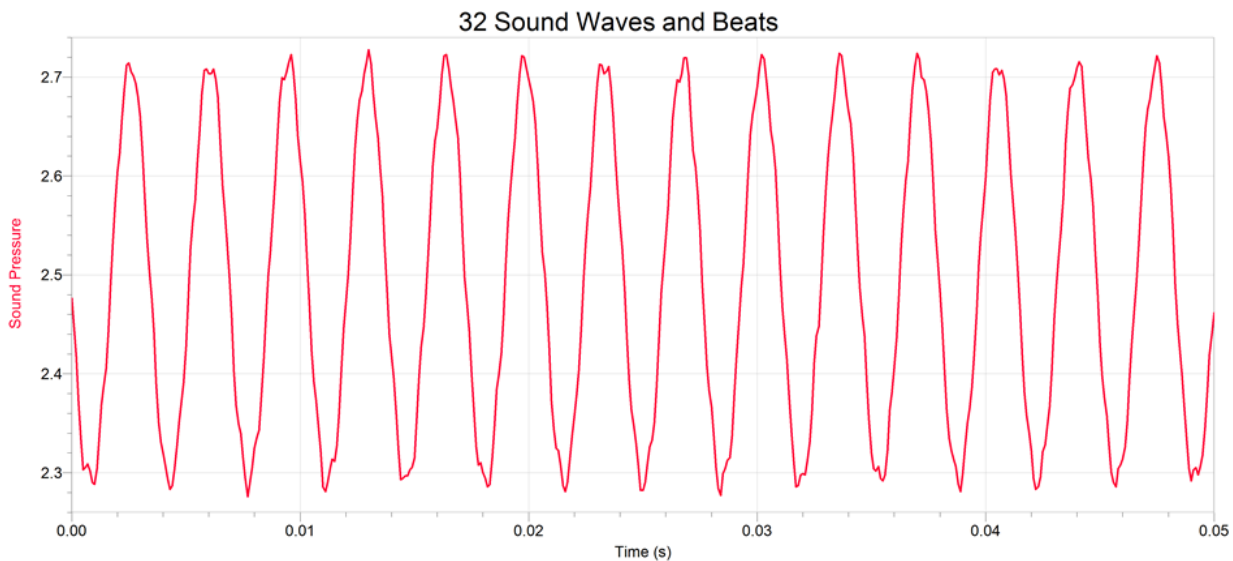
Tuning Fork 288 HZ D3

Tuning Fork 320 HZ E3

Tuning Fork 341.3 HZ F3

32 Sound Waves and Beats

Tuning Fork 384 HZ G3

32 Sound Waves and Beats

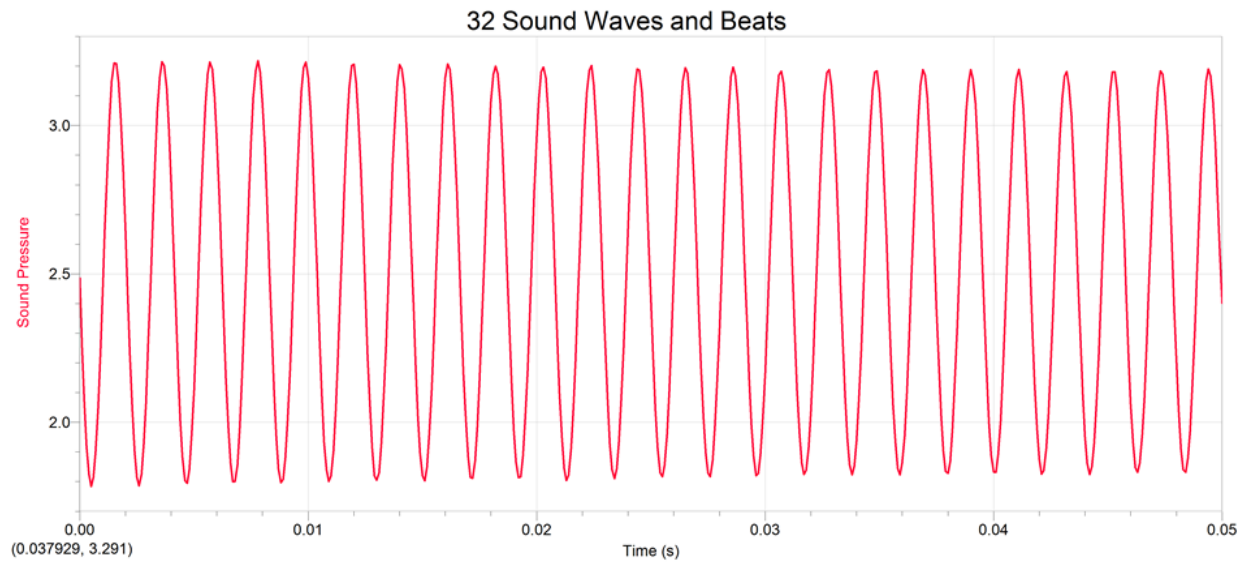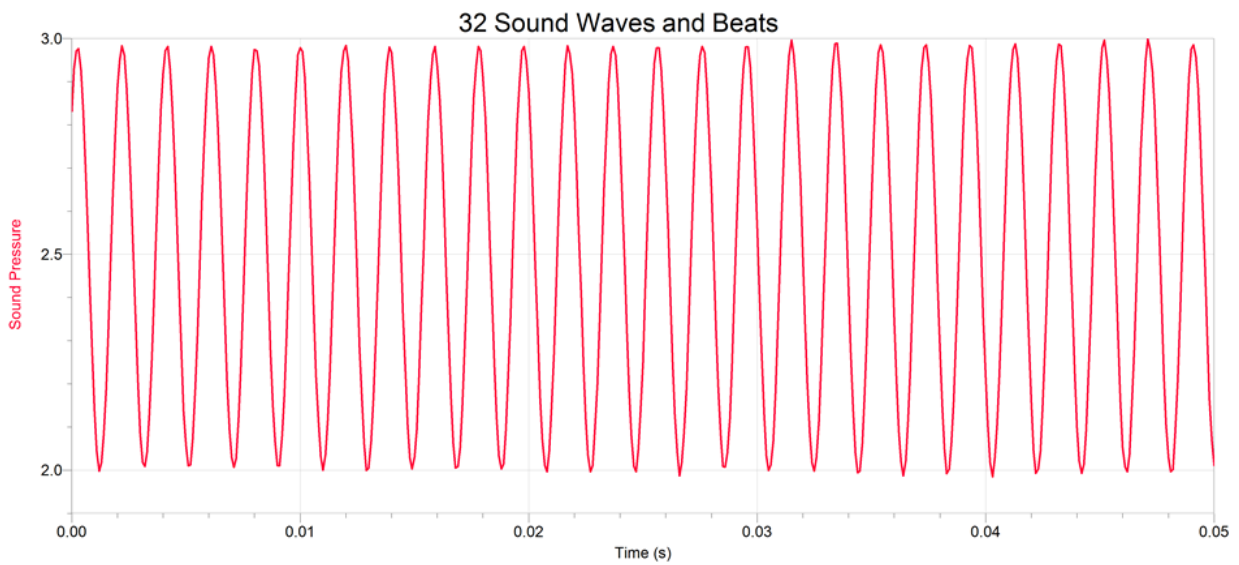(0.031216, 2.7782)
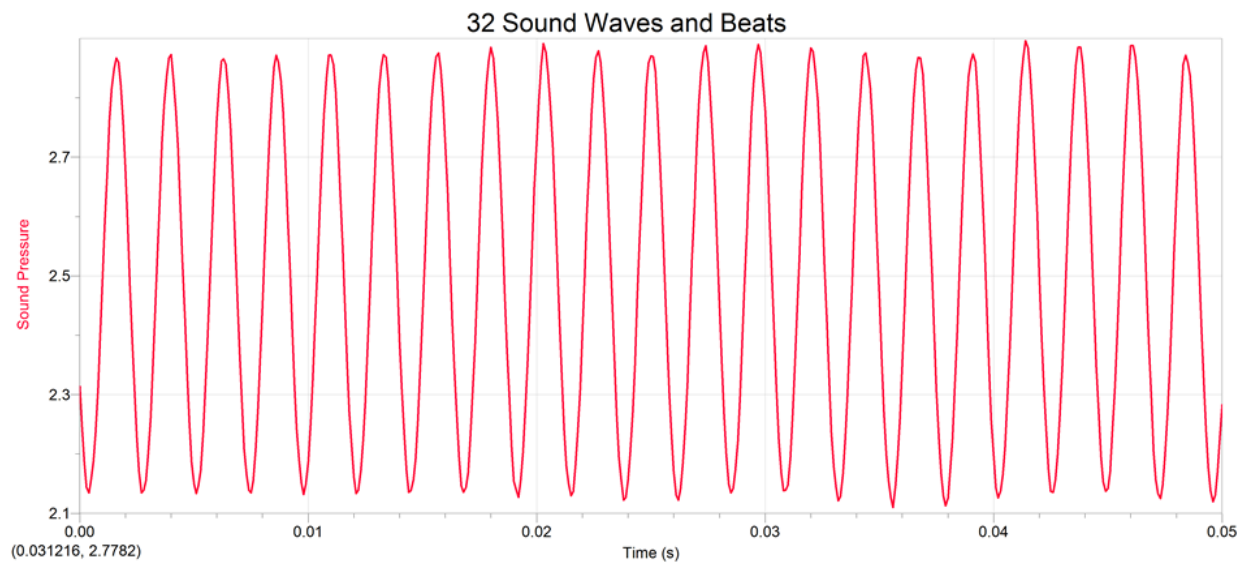
Tuning Fork 426 HZ A3

Tuning Fork 480 HZ B3

Tuning Fork 512 HZ C4