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The Physics of Sound and Music

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Eric Pulver

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# THE PHYSICS OF SOUND AND MUSIC

By

Eric J. Pulver

OF A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

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Professor Merle K. Heidemann

ABSTRACT

THE PHYSICS OF SOUND AND MUSIC

By

Eric J. Pulver

Students in physics classes did not appear to understand some of the basic concepts of wave mechanics, such as how and why waves move, wave types, and wave interference. Since sound is a wave phenomenon not utilized in the existing curriculum, a new unit on sound and music was developed to supplement the existing wave unit and reinforce these concepts. Through pre-test and post-test essays, subjects were quantitatively evaluated on their improvement in these conceptual areas after participating in the new unit. The sound and music unit itself was also qualitatively evaluated, as this was its first implementation. Overall, student understanding was increased due to the additional experiments and other activities provided in the sound and music unit.

## ACKNOWLEDGMENTS

I would like to show appreciation to the following people for all of their personal and professional support:

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# Introduction

## The Problem and The Pedagogy

Physics teachers at Holt High School have been utilizing primarily the same curriculum for decades. This experiment-based method of instruction has been powerful at helping students understand the basics of physics. In the years I have taught, however, I have found the unit on waves to be less effective than the other units in the course. Students in the past didn't seem to understand some of the basic concepts of wave mechanics, including how or why waves move, wave types, and wave interference. Although some of these topics were taught in earlier courses which specifically address Michigan Essential Goals & Objectives for Science Education outcomes for waves (Objectives 17, 18, & 20 - MEGOSE, 1991), students just did not fully understanding these concepts.

In the summer of 1997, through a course of study with the Division of Math and Science Education within the College of Natural Science at Michigan State University, I developed a unit which intended to address the shortcomings of the Holt physics curriculum. I called on the experience of others to help develop several of the activities which came from this research time. In addition to MSU personnel, several of the other physics teachers involved with the DMSE had experience with units involving sound waves. These discussions ultimately led to an experiment-based unit which would be consistent with my teaching technique and philosophy.

"We cannot merely give students a new concept or understanding. All teachers can do is create an environment where that particular concept or idea is available for exploration, analysis, and consideration." (Penick, 1996). It is through experimentation that students primarily gain their understanding. In the past, shallow glass-bottomed water containers known as ripple tanks had been used to project images of actual waves onto a screen below the tank. These are very effective and important tools in helping students see and test the waves in action. Observations of the visible and tangible ripples in the water were not complete enough, however, especially when dealing with the more advanced wave concepts such as diffraction patterns of light. Students had trouble because they didn't understand the fundamental elements of wave mechanics. In order to encourage better student understanding of the basics, another wave phenomenon needed to be studied - sound.

Studying sound in the high school physics class is not a novel idea; in fact, it is the topic of a chapter in most high school physics textbooks. At Holt High School, however, the PSSC (Physical Science Study Committee) Physics textbook which has been used since the early 1960's does not include sound as part of its curriculum, so this new unit described in this document, teaching the physics of sound and music, would be a first attempt.

The sound unit followed the wave units which had worked well in the past and was implemented as an additional unit. Students performed experiments on wave propagation, wave reflection, superposition, wave speed, refraction of waves, diffraction and interference with Slinky®s and the ripple tanks. In this way, the sound unit used background information and utilized scientific method, which "is a system of thought that deals with concepts which flow out of relevant facts. The process cannot be implemented without explanation of facts and the use of basic skills." (Grambs, 1991). The sound unit reinforced many of the skills learned in the previously performed ripple tank experiments by studying wave properties in a different medium before moving on to the more complicated topics requiring understanding of waves.

A further supplement to the sound unit, an investigation into musical notes and chords as they relate to wave mechanics, is a topic not traditional in the high school physics classroom. Music does, however, lend itself quite nicely as an extension of the sound unit and is of interest to many high school physics students. An untested, secondary purpose of this part of the unit was to offer an attraction which would entice more students into pursuing physics, perhaps those who wouldn't ordinarily consider participating in the elective physics and chemistry courses. Increasing the appeal for courses with a stigma that has plagued them for years should result in more students being introduced to the world of science.

The evaluation process of this unit was primarily through a pre- and post-tests, but other, more subjective assessment techniques were also implemented with the focus of the evaluative process being student understanding of concepts. The course was not restructured and students would still perform experiments, discuss findings and draw conclusions based on the collected data. Since there were to be no new instructional methods attempted, the purpose of the unit was to give students another set of phenomena from which to learn the concepts of wave mechanics.

**Scientific Background**

Sound waves are longitudinal waves which move through air. Longitudinal waves are the oscillations of molecules in the direction of transmission. As with any wave, sound moves in a straight path from its source at a constant speed, reflects from barriers, changes speed and direction (refracts) when changing media, spreads (diffracts) around objects and through openings, and follows the principle of superposition. In superposition, waves of the same type (sound, light, etc.) in the same medium will combine displacements where they meet. In other words, a crest which meets a crest will add to form a larger crest, and a trough and a crest will combine to form a position of no disturbance in the medium.

Sound waves are the result of a vibration in the medium of transmission. For example, in air, the molecules are disturbed with enough energy to continue the agitation to the adjacent particles. A significant disturbance will travel through many molecules. This disturbance results in changes in air pressure.

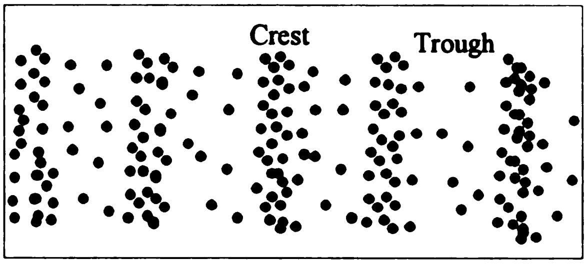



**Figure 1:** Representation of air molecules vibrating. Crests are areas of high pressure and molecular density. Troughs are areas of low pressure and molecular density.

Areas of higher pressure are where more molecules have been pushed together - these are the crests of the longitudinal wave. Figure 1 shows the distribution of air molecules when a sound wave propagates through them. When these disturbances reach a human ear, the tympanic membrane oscillates sympathetically with the changes in air pressure causing the person to sense the sound. The more frequent the oscillation, the higher the pitch that is perceived.

A standing wave is formed when a wave reflects back on itself and, through superposition, causes some locations to oscillate between crests and troughs (antinodes), while other positions show no disturbance in the medium (nodes). The nodes are areas of destructive interference and the antinodes are areas of constructive interference. The standing wave is a fundamental component in making music. A standing wave is produced in wind instruments by vibrating a column of air in the instrument. A stringed instrument creates a standing wave when vibrating with nodes at each connected end of the string. Rods, plates and bells - the other categories of musical instruments - also work in the same fashion.

"Of the many principles taught in elementary physics courses, almost every one is reducible to a mathematical statement." (Sutton, 1938). The musical scale is no exception. It is based on frequencies of sound waves. The A string on a violin, which has 440 vibrations per second is commonly used for "standard pitch," although some musicians use the middle C on the piano. Scientists generally use $A_{440}$ as standard pitch. The scale of musical notes is developed from the standard pitch based on simple whole number ratios as shown in Figure 2. Musical notes are pleasing to hear together when, through superposition, they create a simple wave pattern - these are called harmonies. The discordant sounds, which are not pleasing to the ear, are caused when waves combine to create a complex repeating wave pattern.

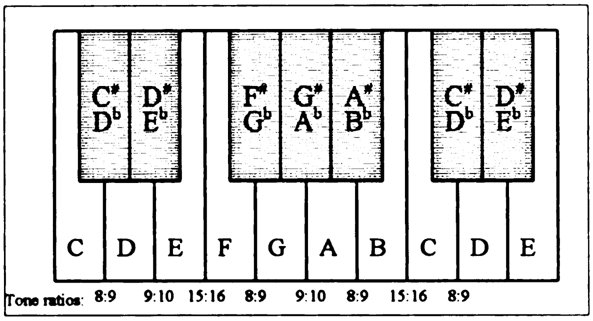


**Figure 2:** Relative frequencies of musical notes

**Demographics and Academic Profile of the Subjects**

The community in which this study occurred is a suburban community. Holt is largely a "bedroom community" with most residents commuting to work at nearby General Motors manufacturing plants, state government facilities, and the local university. This once rural area maintains very little ethnic diversity. The high school houses over eleven hundred students and slightly fewer than one hundred teachers, administrators, and support staff. The students who were the subjects of this course of study were one-hundred-five high school students consisting of four juniors, one-hundred-one seniors of which sixty-three were males and forty-two females. There were seven blacks, six Asians, and ninety-two whites, mostly from middle or upper-middle class homes, all of whom had signed up for the elective, senior-level physics course. The students studied were in five separate classes with each receiving the same instruction and being assessed on the same criteria. All of these students expect to graduate from high school and the majority plan to attend colleges or universities.

Most of the students in these classes had passed advanced algebra and many were taking either a functions and trigonometry based course called "Pre-Calculus,"or the advanced placement calculus course. "Students must be taught mathematical skills for solving problems in physics. It cannot be assumed that a student who has studied trigonometry and algebra can automatically master all of the skills and knowledge required to solve physics problems." (Washton, 1960). Therefore, many classroom hours had been dedicated early in the school year enhancing the students' problem-solving skills using the process shown in Figure 3 to make the problem solving-process second nature for the students. This ensured mathematics competency by students for the study of more conceptually complicated topics.

***<u>Problem Solving Steps</u>***

1. *Read the problem*
2. *Write down what you know*
3. *Write down what you don't know - what is the problem asking for?*
4. *Find the correct equation to use and write it down.*
5. *Rewrite the equation with the correct numbers in it and solve it.*
6. *Write the answer down with the correct units.*

**Figure 3:** Steps to solve mathematically based problems. Taken from Adamovic & Hedden, 1997.

The sound unit was introduced in the course after about twenty five weeks into the forty week school year. By this time, the students had worked together for no less than one quarter of the school year and in most cases three quarters of the school year. Students had already worked through units involving extensive experimentation with kinematics, light and optics, as well as waves. Thus, the students had formed their own work groups and established roles within the group structure. Some students prefer to be hands-on with the experiments, while others would rather "crunch the numbers." Each student came to this unit with an investigative role and technique which has been developed within the group. This teamwork promoted student-to-student interactions through cooperation in which the teacher leads the discovery process with guiding questions from which an individual student's answer prompts another thought within the team, and so on, until conclusions can be drawn. The students, when presented with a problem and the tools of investigation, assumed their roles and worked to collect data as part of a team through experiments, then analyzed and individually formulated conclusions based on their data. This was a technique with which the students were very familiar, as they had learned through this method for their entire course of physics.

## Implementation of Unit

The goal of the sound unit was intended to facilitate an understanding of sound motion, and ultimately, to cause students to appreciate the more complicated concepts of superposition which create pleasing harmonies in music. "The foremost purpose of any demonstration experiment is to clarify a physical principle or to show some interesting application of that principle." (Sutton, 1938) A series of demonstrations and experiments were developed to illustrate waves and sound during research done in the summer of 1997 and are listed sequentially as presented in Appendix A. The students experienced a continuation of the fundamental wave properties first learned with the ripple tank experiments and gained a greater clarity of these concepts. Extension exercises were also designed to enhance student understanding of the concepts discovered or investigated in the experiments.

Students reported individually on their experiments by collecting the necessary data, answering the questions provided with the experiments, and making conclusions based on the data. Students were very familiar with this method of reporting. All prior physics units required the same type of student summary. These reports were graded for the students but were not considered part of the assessment for this thesis.

To paraphrase an old Broadway musical - we started at the very beginning. In the instance of the sound unit, which required almost three full weeks of instruction, we began with an experiment which investigated the speed of sound. The title of the experiment was, appropriately, "***Experiment #1: Speed of Sound in Air.***" After a brief discussion of molecular involvement in the propagation of sound as compression waves, students were led outdoors to the school's athletic fields. Equipped with stopwatches, the students used their reactions to determine the time between seeing the smoke from a starter's pistol and hearing the sound when fired at varying distances from the students. Students used their knowledge of speed, acquired during an earlier unit on motion, to calculate speed of anything which moves given the distances and the measured values for time. This experiment was found to work fairly well at greater distances and combined classroom data provided an average value near the expected 330 meters per second. Students had difficulty reacting accurately when the stimuli of seeing the smoke and hearing the sound were close together in time. Student reports were evaluated based on the ability to identify the speed of sound as constant. Explanation of discrepancies from ideal data came from classroom discussions and were to be included in student reports.

A short demonstration activity was used to begin the next experiment. Students had already been exposed to a standing wave on a Slinky® and in the ripple tank in the previous unit. In addition, the concept of superposition had been introduced and discussed in the preceding weeks. Another demonstration of the standing wave requires a piece of equipment specifically designed to create a standing wave on a string by vibrating it at varying frequencies. Since this device was not available, an economically prudent alternative was devised during the summer research of 1997. This involved using a variable speed electric drill spinning a metal coat hanger which had been cut and bent to hold one end of the string. The other end of the string was fixed to the wall. When viewed from the side, students can see a standing wave pattern. As they had observed standing waves in the ripple tanks before, students could again see yet another example of a standing wave and identify its parts. Some guided discussion during and following the demonstration showed an improvement in student understanding of this presentation.

For the next experiment, students used the standing wave concept to understand resonance. Some discussion led to the drawing of a diagram similar to Figure 4, showing students the standing sound wave. Unfortunately, the diagram may have contributed to the misconception that sound waves were transverse - despite discussion specifically describing the longitudinal nature of sound waves.

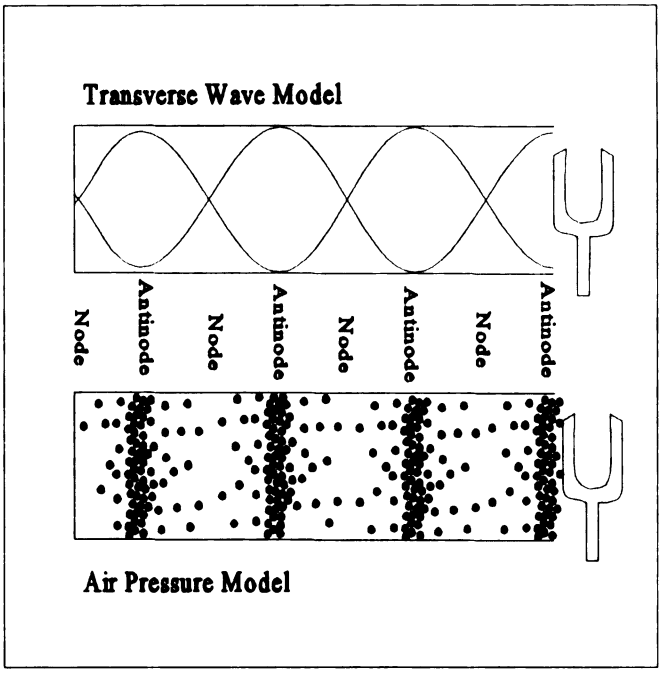



**Figure 4:** Resonance occurs in a column of air by creating an antinode at an open end. Represented here by the transverse wave model (which students understand more easily) and the more accurate longitudinal wave, due to air pressure differences.

Sound waves were then made to resonate in the tube with the equipment provided. The length of the resonating air column, which was made variable by submerging it in water, was then used to determine wavelength. This value was then used to find the speed of sound at different temperatures. Students were instructed that resonance occurs when an antinode vibrates at the mouth of an open-ended tube. A tuning fork - a simple way of creating a constant, known frequency - was held at the open end of the tube creating the vibrations necessary to make the wave "stand."

Students performed the experiment "***Experiment #2: Temperature and the Speed of Sound***" by producing resonance within a glass tube which was partially submerged in notes. Unfortunately, students couldn't see the waves in the glass tube, and - for some of them - the experiment was "magic." A worksheet titled ***"Resonance Worksheet #1: The Air Column"*** dealt with the mathematical relationships within a vibrating column of air and supplemented the experiment. Student reports were graded based on their explanation of the relationships between air column length, frequency, and wave speed, as well as descriptions of the standing wave phenomenon.

Vibrating strings were used in the next experiment as the source of resonance. In ***"Experiment #3: Vibrating Strings,"*** the students used a homemade sonometer that I developed and tested for this thesis. The students placed a specified length of string under a predetermined amount of tension. The vibration of this string was reproduced on another string under varying tensions and lengths. The mathematical relationships between length and tension of the string were graphed and determined. A few problems were faced with the design of this experiment. Although students could see the string vibrate and see the nodes and antinodes, it was difficult for many of them to think of this as a wave. Some students had difficulty matching frequencies because the homemade sonometer was not hollow bodied and therefore difficult to hear. The force supplied to the strings by hanging masses was quantified. However, due to a shortage of supplies, many students were required to wait for other student groups, resulting in unnecessary time off the task. The direct relationship between string length and the square root of the tension, which was derived graphically, became one area of focus for these experimental results and student conclusions. Another concept which was immediately obvious to the students dealt with the inverse relationship between length of the vibrating string and its pitch. This is a relation very similar to one developed in the previous unit where wavelength and frequency were inversely proportional. Classroom discussion was utilized to help make these concepts understandable for all students. Another worksheet creatively titled "***Resonance Worksheet #2: The Vibrating String***" followed the experiment. The worksheet dealt with the mathematical relations of a vibrating string and its tension, length, density, and pitch.

Musical notes, their related frequencies, were presented to the students. The musical scale was laid out as a number of frequencies which existed at whole number ratios with each other (see Figure 5). A worksheet titled "***Music Worksheet #1: The Notes,***" emphasized these ratios. Students then used knowledge of the scales and relative frequencies and discussion to match frequencies at the simplest whole number ratios to create harmonies. Some classes had "brave" students who were willing to vocalize with each other in an attempt to create harmonies. The simplest example students used was the octave, which has a two-to-one frequency ratio, creating superposition with every other wavelength of one tone and every wavelength of the other tone. Students were given a complete four octave scale with frequency values to assist their investigations. Other ratios between 1:1 and 2:1 were explored and another worksheet, titled "***Music Worksheet #2: The Harmonies and Chords,***" was

| Diatonic | C | D | E | F | G | A | B | C |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Just Tempered | 9:8 | 10:9 | 16:15 | 9:8 | 10:9 | 9:8 | 16:15 | |
| Equally Tempered | $\sqrt[6]{2}$ | $\sqrt[6]{2}$ | $\sqrt[12]{2}$ | $\sqrt[6]{2}$ | $\sqrt[6]{2}$ | $\sqrt[6]{2}$ | $\sqrt[12]{2}$ | |

**Figure 5:** Tone Intervals in the Just Scale and Equally Tempered Scale

completed.

A day of "playing" was the final investigative activity for the unit. Students who owned musical instruments were encouraged to bring them to class. Using a homemade voice amplifier (designed by me specifically for this thesis) and an oscilloscope, students were encouraged to play around with the visual representation of each instrument - including their voices. This was a very free-form day, as some classes had many participants, while others did not. Class discussion was invaluable in the clarification of concepts which were brought to the surface. Students brought only wind or stringed instruments representing the two types of resonance studied in class.

Among the instruments were the cornet and trumpet, which sounded the same to all listeners in the class. These were shown on the oscilloscope at the same time using separate, individual inputs. The difference in the trace was minimal, but students were able to see overtones with the trumpet which were not present for the cornet and vice versa. Several students played in harmony in the same amplifier to produce complex traces on the oscilloscope. "Beats" were produced using two guitar strings slightly out of tune with each other. These visual representations of the "new" waves acted as a catalyst to revisit the concept of superposition.

Upon completion of the unit, a review of major concepts and a test was given to evaluate the students' proficiency with the concepts presented in the unit. This ***"Sound and Music Quiz"*** utilized multiple choice and computation to determine student understanding. Another assessment was titled **"Wave Assessment"** and given specifically for this study to determine students' proficiency with the concepts of wave mechanics as a pre-test and post-test device. Although students had previously answered the same questions, for consistency in this study, the responses were never identical.

This unit took approximately three weeks or fifteen class periods. Each of the three experiments took at least one day for set up and a day for evaluation and discussion; Experiment #3 required an additional half class. The four worksheets each took one class period plus homework time. A demonstration activity required about a half class with discussion. Preparation for the unit quiz and the quiz itself used two class periods. The pre-test and post-tests for this thesis was also a single day event and the beginning and end of the unit.

## Evaluation of Unit

### Overview

The evaluation process of this unit for the purpose of this thesis was primarily through a pre-test and post-test, but other, more subjective, assessment techniques were also implemented. The focus of the evaluative process was student understanding of concepts relating to waves. There were no new instructional methods attempted, as the purpose of the unit was to give students another set of phenomena from which to learn the concepts of wave mechanics.

A pre-test and post-test were given based on concepts related to waves which had been taught prior to this sound waves unit. The assessment was in essay form, with no limits given to length of response or time to respond. The concepts assessed were those that had been identified as ones which, based on past performance on prior years' examinations, students lacked proficiency. The topics of the questions addressed included describing mechanical energy transfer in the propagation of waves, comparing and contrasting transverse and longitudinal waves, showing understanding of the relationship of wave speed, wavelength and frequency, comparing and contrasting constructive and destructive interference, showing understanding of standing waves, and explaining how one "feels" sound. These topics, while not exclusively the goals of the waves unit, represented the bulk of the desired conceptual base. Based on their responses to six questions, students were scored on a basic rubric of four points per question (see Appendix B), in an attempt to keep the evaluation as objective as possible. The rare score of four on an individual question showed complete proficiency while a score of zero reflected a totally incorrect perception. The average student score for all questions on the pre-test was 25.61% (4.61 points earned out of a possible 18 points). Later, after the unit was taught the same test was administered as a post-test; the average score was 46.39% (8.35 out of 18). Because these are averages, these numbers didn't necessarily reflect the growth individual students experienced. The actual student data are outlined in Table 1, in Appendix C.

**Quantitative Data**

Each question was, as objectively as possible, evaluated using the assessment rubric in Appendix B. These data are presented in histograms to demonstrate frequency of pre-test and post-test scores for comparison. For all test items the same one hundred five (n=105) subjects were assessed. This large sample size was intended to increase the reliability of the data. Some samples of student responses are also included for the more subjective assessment. The names of these students have been changed to protect anonymity.

**Question 1:**

*"How is mechanical energy transfer responsible for wave propagation?"* grading rubric:

0. No or totally incorrect response.
1. Vibrating air molecules bounce off one another.
2. Vibrating molecules of the medium of propagation collide causing a periodic wave to form.
3. Energy is transferred by particles in the medium colliding in a periodic fashion. The vibrating source moves the molecules of the medium immediately adjacent to it. These molecules move the adjacent molecules and the energy is transferred until the energy is "used up" or lost to external forces.

"Chad", a senior male, answered Question One on the pre-test by saying, "Mechanical energy will transfer from one object to another and that makes waves go forth (propagation). In air, there are tiny magnetic fields around the molecules, so when the force comes and pushes them together, they pass the energy on to keep their own space. That's what continues the wave along in any medium, the mechanical energy transfer." In accordance with the grading rubric, this response earned "Chad" two points on the pre-test. On the post-test, "Chad" responded by saying, "Mechanical energy is basically the energy that allows work to be done so it is mainly responsible for wave propagation because the energy that is available in air molecules (mechanical) allows the wave to continue since the kinetic energy (energy of motion) can be transferred from the molecules prior to the next molecules. The next molecules accept the energy of the molecules that hit them, and the wave continues to go onward as long as some kinetic energy is left (since the molecules have mechanical energy)" This response earned "Chad" four points. Figure 6 shows a histogram of scores earned on question number one. The total test group improved their performance on this question by 0.632 points.

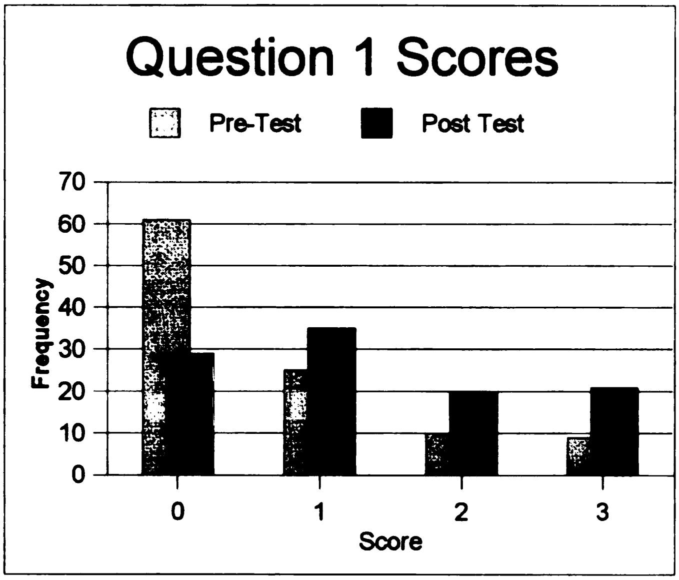



**Figure 6:** Histogram of pre-test and post-test scores for Question 1.

**Question 2:**

*"Explain the difference between transverse waves and longitudinal waves"* grading rubric:

0. No or totally incorrect response.
1. Transverse waves have amplitudes which are vertical and longitudinal waves have amplitudes which are horizontal.
2. Transverse waves are like sine waves and have disturbances which are perpendicular

to the direction of motion ***OR*** longitudinal waves are compression waves which vibrate in the direction of motion.

3. A transverse wave causes the particles of the medium to vibrate in a direction that is perpendicular to the direction the wave is moving. A longitudinal wave causes the particles of the medium to vibrate in a direction parallel with the direction of the wave.

"Angela", a senior female, earned two points on her pre-test by responding "A transverse wave moves in an up and down motion. A longitudinal wave moves in a side to side motion." "Angela" responded to the same question on the post-test by saying "Transverse waves move perpendicular to the direction of motion, where as longitudinal waves move parallel to the direction of motion." This response earned "Angela" all of the possible points. Figure 7 shows a histogram of scores earned on question number two. The total test group improved their performance on this question by 0.688 points.

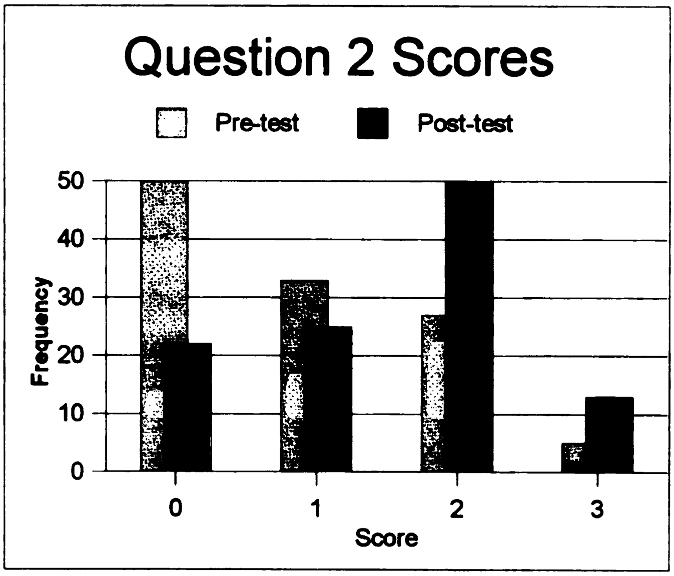


**Figure 7:** Histogram of Pre-test and Post-test Scores for Question 2.

**Question 3:**

*How does a wave's speed relate to its frequency? Its wavelength?* grading rubric:

0. No or totally incorrect response.
1. $v = f\lambda$.
2. Speed varies directly with frequency and wavelength.
3. With a constant wavelength, the wave's speed is directly related to its frequency. With a constant frequency, a wave's speed is directly related to its wavelength. v =

$f\lambda$.

"Misty", a senior female, responded to this question this way "A wave's speed is proportional to its frequency and frequency times wavelength equals speed. So, if wavelength or frequency increase, so will speed. However, if frequency or wavelength increases, the opposite (frequency or wavelength) will decrease." This earned "Misty" two points on the pre-test. On the post-test, however she responded, "The faster a wave is going, the more frequent it will be if wavelength is constant. The bigger the wavelength, the greater the speed if frequency is constant. Frequency times wavelength is speed." This response as outlined in the grading rubric, of course, earned four points for "Misty". Figure 8 shows a histogram of scores earned on question number three. The total test group improved their performance on this question by 0.488 points - this was the least change from the pre-test score in this study.

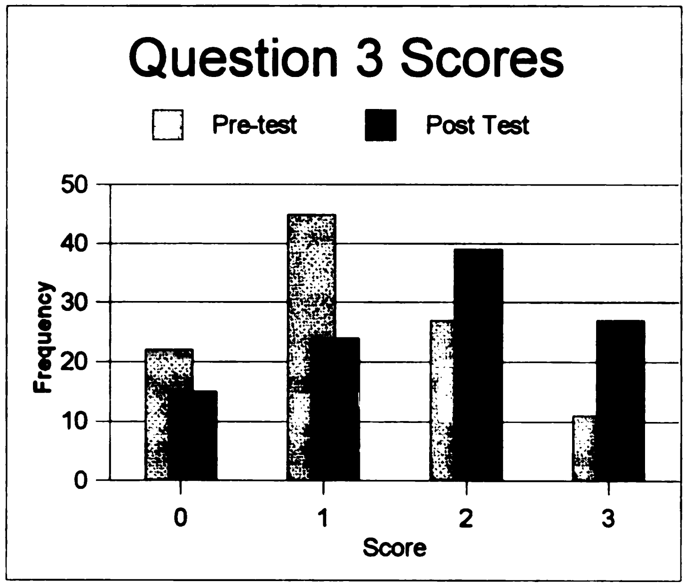


**Figure 8:** Histogram of Pre-test and Post-test Scores for Question 3.

**Question 4:**

*"Explain constructive and destructive interference."* grading rubric

0. No or totally incorrect response.
1. Constructive interference is making big waves, destructive is making small or no waves.
2. Constructive interference makes bigger waves, destructive interference makes no

waves because of superposition.

3. The principle of superposition allows for the adding of the displacement of individual waves at a particular position in the medium to form one displacement. Constructive interference occurs when the wave displacements are in the same direction, destructive interference occurs when two waves -of equal displacement - overlap to result in zero disturbance of the medium.

"Jeff", a junior male, responded to the fourth question on the pre-test by saying, "Constructive interference increases the velocity and frequency of a wave while decreasing its wavelength. An example would be a wind blowing behind a wave. Destructive interference decreases the velocity and frequency while increasing its wavelength. An example would be a wind blowing in front of a wave against its direction of motion." Obviously, "Jeff" had no idea what interference was and created his own definition using his knowledge of the words constructive and destructive. He, of course, only earned one point for this response. In all fairness to "Jeff", and his many peers who responded similarly, very little class time had been dedicated to studying wave interference prior to the sound unit. After the sound unit, "Jeff" responded to the same question this way, "Destructive interference is the point on a wave where a node is formed. Constructive interference is the point on a wave where an antinode is formed. An antinode is a point on the wave where a crest or trough is formed. There is ½ of a wavelength between antinodes." While "Jeff" did not earn all of the points as outlined by the grading rubric, he did show a much firmer grasp of the concept of interference, earning three points. Figure 9 shows a histogram of scores earned on question number four. The total test group improved their performance on this question by 0.664 points.

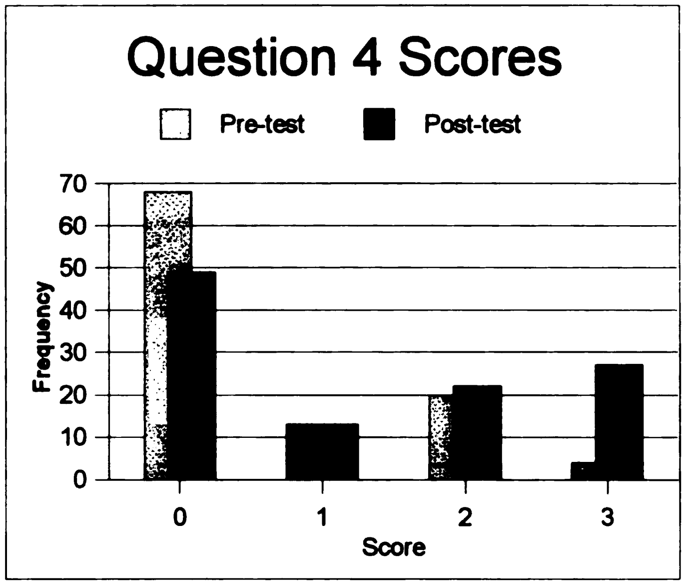



**Figure 9:** Histogram of Pre-test and Post-test Scores for Question 4.

**Question 5:**

*"How does a standing wave 'stand?'"* grading rubric:

0. No or totally incorrect response.
1. By creating nodes and antinodes through destructive and constructive interference.
2. Reflecting a wave so that it interferes with itself causes nodes and antinodes.
3. A standing wave is the result of identical waves moving in opposite directions. The reflection of one periodic wave source is a possible method of producing standing waves. The areas of maximum displacement - due to constructive interference - are called antinodes. The areas of total non-disturbance - due to destructive interference - are called nodes.

"Charlie", a senior male, remembered some of the definition of a standing wave in his pre-test response to this question. "A standing wave stands when the incident and refracted waves meet up due to high frequency and velocity making the waves hit each other over and over quickly making the human eye see it as one wave when really it is many waves reflecting back and forth." This response was only worth one point. "Charlie" understood things a little more clearly by the time he took his post-test and earned three points. "A standing wave stands still when the crest and trough are lined up, making the wave look still at the same time and a wave sequence such as:  " Figure 10 shows a histogram of scores earned on question number five. The total test group improved their performance on this question by 0.648 points.

**Question 6:**

*"Explain how you can 'feel' the music at a rock concert."* grading rubric:

0. No or totally incorrect response
1. They turn up the volume causing the air to vibrate around the audience.
2. High energy output of the speakers vibrates the air causing longitudinal waves. The air around the audience is constantly vibrated - the skin detects this vibration allowing the sound to be "felt."
3. The speakers vibrate the air molecules near them with massive amounts of energy. This energy is transferred to adjacent molecules in a longitudinal wave to the audience. The energy is so great that the air around the body is being violently oscillated causing the skin to detect changing air pressure. Longer wavelengths (bass) allow for more detection time between drastic pressure changes, therefore allowing these to be the most "felt" sounds.

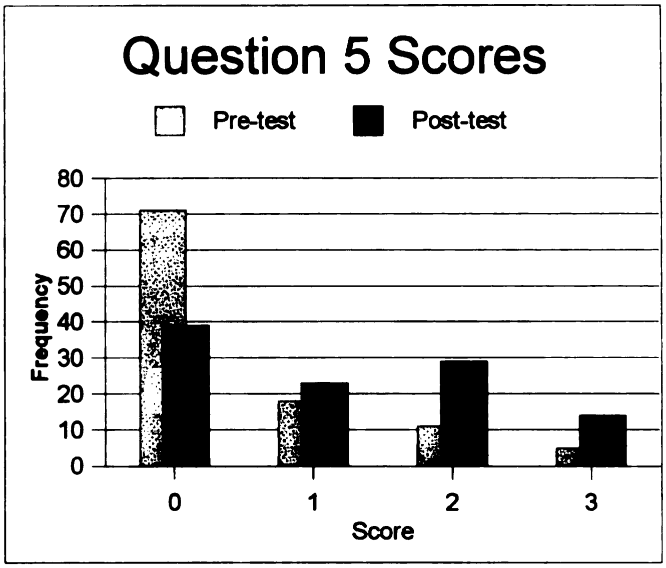


**Figure 10:** Histogram of Pre-test and Post-test Scores for Question 5.

"Sara", a senior female, had some thoughts about how you feel sound. Her pre-test response was, "When one attends a rock concert he can feel the music because there is energy being released from the instruments and coming out of the speakers. The energy is moving through them, or vibrating through them. It does not go around them, some of it might, but a little of it goes through them because a body can not block all of it out. Therefore, a person is able to feel it because the energy is actually going through them." "Sara" earned one point on the pre-test. After the sound unit, "Sara" thought this about feeling sound, "I can feel the music at a rock concert because the sound impulses vibrate out of the musical instruments, and the frequency of the music carries through the air and does not stop when it comes in contact with humans. Therefore, sound waves travel much like water waves in a rhythm-like manner. Since the sound waves are traveling in a rhythm like motion they are then able to permeate through most mediums including humans. Because of air molecules bouncing into a human's molecules the human feels the sound waves vibrate through him." This response, while still showing a connection with humans being a medium through which sound waves travel, was worthy of three points on the rubric scale. Figure 11 shows a histogram of scores earned on question number six. The total test group improved their performance on this question by 0.736 points - this change represented the greatest improvement by students in this study.

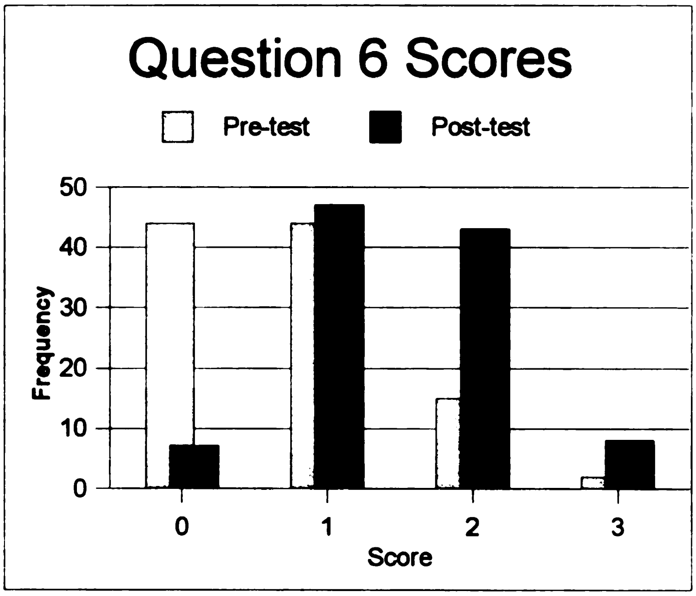


**Figure 11:** Histogram of Pre-test and Post-test Scores for Question 6.

**Qualitative Data**

Some students didn't improve their score as the above may indicate, because they were already proficient. "Joe", a senior male, answered the question about mechanical energy transfer correctly on both tests. Pre-test: "The closest thing I can come to relating to this is a hockey player hitting the boards. The player has energy. When he hits the boards, his kinetic energy is transferred to them. This causes them to "wave." The wave runs down the boards away from the point of impact. I see each board like a molecule. When one is disrupted, it bumps into its neighbor which hits its neighbor and so on. So transferring energy to one point propagates it to the whole." Post-test: "I guess you could say that a vibrating string would have mechanical energy. As the string vibrates, it bumps against air molecules on either side. So the string is doing work on the molecules. These disturbed molecules then bump into other molecules creating a wave that moves out from the source, in this case the string. That's how mechanical energy can be responsible for wave propagation." "Joe" used different examples to illustrate his understanding of the concept. He did, however, use a recent example of the vibrating string - an experiment in the unit - to explain his understanding.

Other students weren't proficient and didn't improve on their scores. Some, in fact, gave entirely different but still incorrect responses for both the pre and post-test. For example, "Katy" - a senior female - answered the question about transverse and longitudinal waves in two ways. Pre-test: "Longitudinal waves are straight. Transverse waves are curvy." Post-test: "Transverse waves are in the direction of motion. Longitudinal waves are perpendicular to direction of motion." "Katy" was incorrect on both tests, but on the right track. When I questioned her responses in a later discussion she gave a more complete answer. In an attempt to defend herself, she said, "I just didn't want to write all of that down. I thought (what I wrote) was enough."

"Mike" is another example of students who did not improve. This senior male originally thought of constructive and destructive interference this way: "Constructive interference helps in the transmission of a wave. It adds to the wave. Whereas destructive interference causes small breaks in the wave and makes transmission difficult." On his post-test "Mike" said, "When listening to an AM radio we hear destructive interference quite often. Destructive interference occurs when something blocks the transmission of the wave or there is a break in that wave. Constructive interference on the other hand is something that adds to the quality of the wave. It helps to make the transmission of the wave better." "Mike" was not alone in using a definition for constructive which means "to be helpful." Students have heard teachers tell them to "do something constructive and stop fooling around" for years. The word destructive has also had a similar use, that led many students to think of destructive interference as something which stops a wave's motion. In discussions with some of the students about this vocabulary mix-up, several responses showed that the students didn't know the vocabulary so used a learned contextual technique to "dissect" the word's parts for meaning.

**Analysis of Data**

The distribution of scores on the pre- and post-tests shows an improvement as well. As is shown in Figure 12, the highest half of scores on the post-test was higher than the highest quarter of scores on the pre-test. Not only were the range of scores larger in the post-test, the mean and median scores were increased as well. The average score on the pre-test was 4.63 points and on the post-test 8.48 points. The median score - the score which shows the

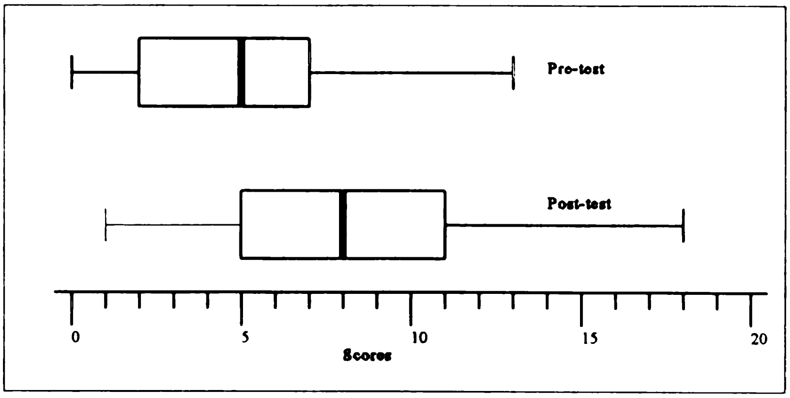



**Figure 12:** "Box and Whiskers" plot showing the distribution of scores. Each segment represents 25% of the scores.

middle of the distribution of scores - improved from 5 points to 8 points. All scores assigned to student responses for both the pre-test and post-test are listed on Table 1 in Appendix C.

This improvement was across the board. Only three of the one-hundred-five showed a decrease in score from pre-test to post-test with an equal number improving their scores by more than four points, an equivalent of 22% improvement. Figure 13 indicates that over three quarters of the subjects improved by up to seven points on their total rubric score.

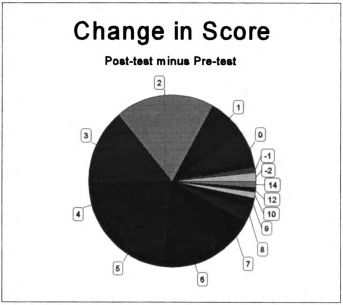



**Figure 13:** Pie Chart Representing the Changes in Score. Each Area Represents the Number of Students Whose Score Changed by the Amount listed.

It was found through taking average pre-test and post-test scores, that students improved their scores an average of 0.648 points out of three possible points or approximately 22 percent. Table 2 shows average scores for test items. On the pre-test, subjects scored an average below one point per item. On the post-test, students improved their average score to nearly one and one half points.

Since female performance in the "hard sciences" in general and physics in particular is an issue of discussion among many pedagogues, I decided to look at this issue using the results of this study. Some analysis of data separated into gender groups shows little deviation from the group as a whole. A comparison of the sixty-three males' scores found an improvement average of 0.651 points or just over 21 percent. The group of forty-two females averaged a little more than 20 percent improvement or 0.615 points out of the three possible. A similar comparison of male and female pre- and post-test data was also made. As is apparent in Table 3 and Table 4, there was a small difference in performance between males and females on the assessment. On the average pre-test items, females were 0.233 points lower than the males, the equivalent of a 7.8% difference. On the post-test,

**Table 2:** Average Pre- and Post-test Scores for All Students

| Question | Pre-test points earned | Post-test points earned | Change in score |
|---|---|---|---|
| 1 | 0.657 | 1.314 | 0.657 |
| 2 | 0.771 | 1.467 | 0.696 |
| 3 | 1.248 | 1.733 | 0.485 |
| 4 | 0.619 | 1.295 | 0.676 |
| 5 | 0.524 | 1.162 | 0.638 |
| 6 | 0.762 | 1.495 | 0.733 |
| Average | 0.764 | 1.411 | 0.648 |

**Table 3:** Average Pre- and Post-test Scores for Female Subjects

| Question | Pre-test points earned | Post-test points earned | Change in score |
|---|---|---|---|
| 1 | 0.690 | 1.167 | 0.477 |
| 2 | 0.786 | 1.500 | 0.714 |
| 3 | 1.095 | 1.714 | 0.619 |
| 4 | 0.429 | 0.905 | 0.476 |
| 5 | 0.190 | 0.810 | 0.620 |
| 6 | 0.619 | 1.405 | 0.786 |
| Average | 0.635 | 1.250 | 0.615 |

males averaged 0.269 points better than females (9.0%). Interestingly, however, both groups showed average increases which differed by only one percent. The females improved more than the males on three of the six questions. On the other three questions, the males had a greater improvement. Therefore, contrary to many assertions, gender differences do not affect student performance; at least within the scope of this study's population and content.

**Table 4:** Average Pre- and Post-test Scores for Male Subjects

| Question | Pre-test points earned | Post-test points earned | Change in score |
|---|---|---|---|
| 1 | 0.698 | 1.397 | 0.699 |
| 2 | 0.778 | 1.444 | 0.666 |
| 3 | 1.380 | 1.762 | 0.382 |
| 4 | 0.746 | 1.540 | 0.794 |
| 5 | 0.746 | 1.413 | 0.667 |
| 6 | 0.857 | 1.556 | 0.699 |
| Average | 0.868 | 1.519 | 0.651 |

## Conclusion

Perhaps the most effective aspects of the sound unit (as with any unit) were the class discussions which followed and supported the demonstrations, experiments and worksheets. There was some predictability in the questions students asked and responses students gave, but occasionally, a student epiphany would drive the discussion beyond its intended boundaries. It was during the discussion periods that students' understanding was evaluated and clarified. Unfortunately, in class discussions, only the participating members can be evaluated. All students who pay attention to the discussions, however, can benefit from the discourse. The important thing for leading the discussions was to concentrate on topics to which students could relate and maintain interest.

Many high school students are quite focused on music, as it is a major part of their lives and is somewhat fascinating to the students. This fact supports the benefit in using music in the discussions. Unfortunately, since discussion was the major way of promoting understanding of the concepts, keeping the students' interest wasn't very simple. No practical and affordable methods of showing students the relationships between frequencies and harmonies were found other than diagrams and calculations. There were no easy and tangible tools to allow the students to conceptualize the alliance of music and physics. Perhaps, an economically priced computer program, or musical keyboard would provide greater opportunities for understanding these concepts.

It was also difficult to teach the physics of music to a group with varying levels of musical background. Some students were well-versed in music theory, and brought a higher level of understanding to the discussions. Others seemed happy to remember the order of notes on a treble clef. The variety of backgrounds for this unit was much greater than for any other unit in the course. The heterogeneity of this particular conceptual category was not a problem, as few students had studied music in relationship to the frequency values and the mathematics involved which helped close the gap. In addition, mathematics was a fairly common experience for all students.

With any extended study, students tend to gain a greater understanding of the basic concepts. With the sound unit, the purpose was for students to increase their understanding of wave mechanics. An additional but less emphasized reason for teaching this unit was to further expose students to the physics found in everyday events. This unit appears to have proven effective in its goals. The theory that "less is more" seems to be true here. Students were not overwhelmed with many different concepts, they were exposed to a variety of events dealing with waves which have varying degrees of complexity. It is this eclectic approach which made the concepts understandable on different levels by different students.

The data indicate that students indeed showed an improvement in demonstrating understanding concepts demonstrated by the pre and post-test scores. Whether the improvement was due specifically to the activities in the sound unit or would have occurred merely with more time spent on experiments in the ripple tanks cannot be definitely determined by the nature of the study. However, the first attempt at teaching this sound unit was effective and will continue to be developed and taught.

With my experiences as a teacher in mind, I am very positive about this unit's effectiveness. The data support a conclusion that the unit was successful in its intended goal of improving student understanding of selected fundamental concepts. Sometimes an experiment or discussion just doesn't seem to have the desired effect and sometimes a vast majority of the students don't see the connections that the activity is designed to demonstrate. This unit had those moments, too. There were also the moments of epiphany and revelation which drove the student understanding to a more complex level. It is these moments which must be replicated for the unit to continue to be successful. Unfortunately, there is no real recipe for these "ah-ha" moments. There is a magical mix of students, teachers, environment, and discussion which makes the whole thing work. Given a different set of students, or a different teacher, this unit may have been more or less successful. It is, however, undeniable that the data supports the accomplishments of this unit, especially considering the relatively large population of subjects used in this study.

In a holistic sense, there is no reason to believe that this unit doesn't help students in these concepts which are also central in the State of Michigan Department of Education's essential goals for science. In a very real way and on many levels, this unit was successful. Not only did students show an improvement in conceptual understanding of topics to which they had previously been exposed, but they also were exposed to different experiences surrounding those ideas, thereby enriching their overall experience.

# APPENDIX A

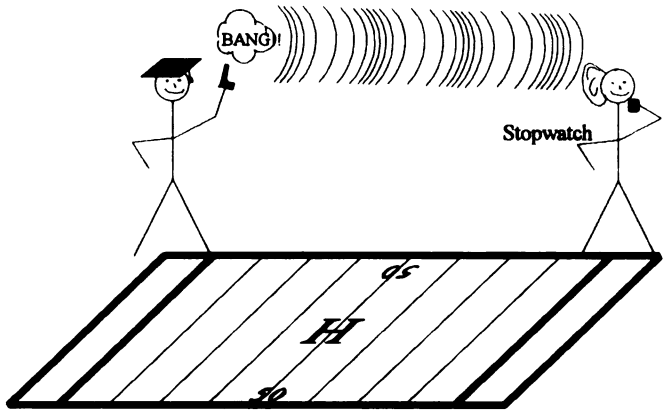
## Experiments and Activities

**Experiment #1** 

# Speed of Sound in Air

**Purpose:** To use our senses to determine the speed of sound.

**Theory:** Light has a speed of about $3.0 \times 10^8$ m/s. Sound moves much more slowly. We can see a distant event before we hear it. By timing the difference between seeing and hearing an event and measuring our distance from the event we can determine the speed of the sound.




**Procedures:**

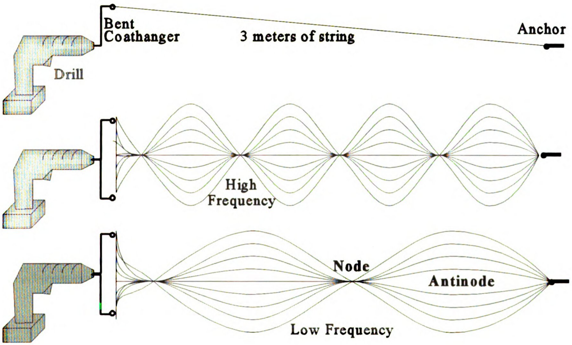
1. Get stopwatch, and proceed to the football field.
2. Stand on the opposite goal line as your teacher. The teacher will have a starter's pistol
3. When the teacher shoots the pistol, start the stopwatch when you see the puff of smoke. Stop the watch when you hear the gun.
4. Record the time and repeat.
5. Double the distance between students and teacher and repeat steps 3 and 4.
6. Record class data, calculate speeds, and class averages. Remember: 1 inch = 2.54 cm.

**Questions:**

1. Approximately how fast does sound travel in air?
2. About how far away is a thunderstorm if you hear thunder 3 seconds after seeing the lightning (1 mi = 1.61 km)?
3. Why might the people at the end of a long marching band be out of step with the front?
4. A spoken message from the moon (d = 240,000 mi) can reach the earth in about 1.3 seconds. How is this possible?
5. Sound waves travel 4 times faster in water than air. When sound leaves air and enters water, how are wavelength and frequency affected?

## Standing Wave Demonstration

Theory: Standing waves are formed when a wave reflects on itself. The superposition of the wave and its reflection create areas of constructive interference known as antinodes. Areas of destructive interference are known as nodes. When viewed from the side, a string being spun by an electric drill appears as a standing wave.



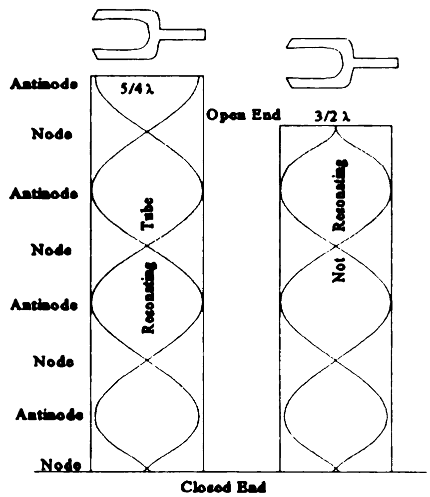

Questions:

1. What is the relationship between wavelength and frequency?
2. How much distance, in terms of wavelengths, is between nodes? Antinodes?
3. How is a node created? How is an antinode created?

## Experiment #2 Temperature and the Speed of Sound

**Purpose:** To measure the speed of sound of different frequencies in different temperatures of air

**Theory:** A standing wave will occur when a wave's reflection interferes with its incident path. The shortest column of air that can have a node (destructive interference) at the bottom and antinode (constructive interference) at the top is 1/4 $\lambda$. Resonance will occur when a tuning fork vibrates at the open end of a closed end tube in multiples of 1/4 $\lambda$.



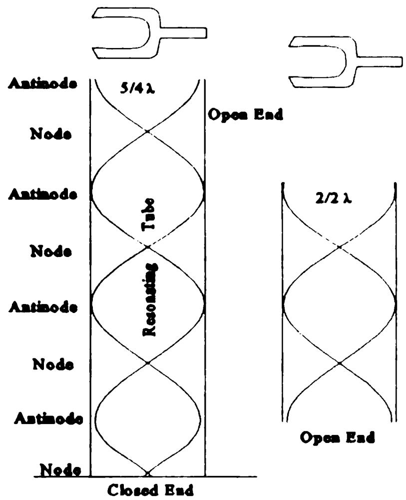

**Procedures:**

1. Place cylinders with hot water on one side of the classroom and ice water on the other side of the classroom.
2. Record the value of the frequency that is stamped on the tuning fork.
3. Wear goggles while using tuning forks next to the glass tubes. Strike a tuning fork to the palm of your hand.
4. Hold the tuning fork above the glass tube while you slowly raise the tube until the sound is amplified and is loudest.
5. Measure *l*, the distance from the water to the top of the tube, to the nearest .01 m.
6. Repeat steps 3 - 5 with the same fork but struck so that the tuning fork sound is quiet.
7. Hold a thermometer in the middle of the glass tube and measure the air temperature.
8. Trade places with another group on the other side of the room and repeat steps 3 - 7 using the same tuning fork.
9. Change the frequency and repeat.

**Questions:**

1. Are the values of "*l*" different for loud and soft sounds?
2. How are the values for "*l*" different for hot or cold air?
3. Write a general statement describing how the speed of sound depends on loudness.
4. Write a general statement describing how the speed of sound depends on frequency.
5. What would an orchestra sound like if the higher frequencies traveled at a different rate than lower frequencies?

## **Resonance Worksheet #1** *The Air Column*




When the air inside a tube is made to vibrate, the tube can also vibrate. When this occurs, the tube is said to be resonating with the oscillating air pressure. The reflection of the sound waves traveling through the tube will interfere with the incident waves and cause standing waves. In a standing wave, two nodes (or antinodes) are separated by $\frac{1}{2}\lambda$.

When the tube has a closed end, the first (fundamental) resonant length or harmonic is $\frac{1}{4}\lambda$, the second resonant length is $\frac{3}{4}\lambda$, and so on in odd multiples of $\frac{1}{4}\lambda$. When the tube has an open end, the tube resonates with the vibrating air at $\frac{1}{2}\lambda$ (fundamental), $1\lambda$, and so on in even multiples of $\frac{1}{2}\lambda$.

PLACE THE CORRECT RESPONSE IN THE SPACE BELOW EACH PROBLEM. SHOW WORK ON ATTACHED SHEET OF PAPER.

1. A tuning fork with a frequency of 400 Hz causes resonance in a 20°C air column which is 43.0 cm long. What is the speed of sound in that temperature air?

2. A sound wave in a fluid medium (water) is reflected at a barrier so that a standing wave is forced. The distance between nodes is 3.8 cm and the speed of propagation is 1500 m/s. Find the frequency.

3. Determine the length of an open organ pipe that emits middle C (262 Hz) when the temperature is 20°C (see question #1).

4. A flute is designed to play middle C (262 Hz) as the fundamental frequency when all the holes are covered. Approximately how long should the distance be from mouthpiece to the far end of the flute (v = 343 m/s)?

5. How far from the end of the flute (from question #4) should the hole that must be uncovered to play D above middle C (294 Hz)?

6. The speed of sound changes 0.60 m/s per degree centigrade - colder is slower. What frequency will be sounded if a flutist attempts to play middle C in 10°C weather without "warming up" her flute?

7. A pipe has a length of 2.46 m. Determine the frequencies of the first three harmonics if the pipe is open at each end. Let 335 m/s be the speed of sound in air.

8. What is the lowest possible frequency if the pipe from question #7 is closed at one end?

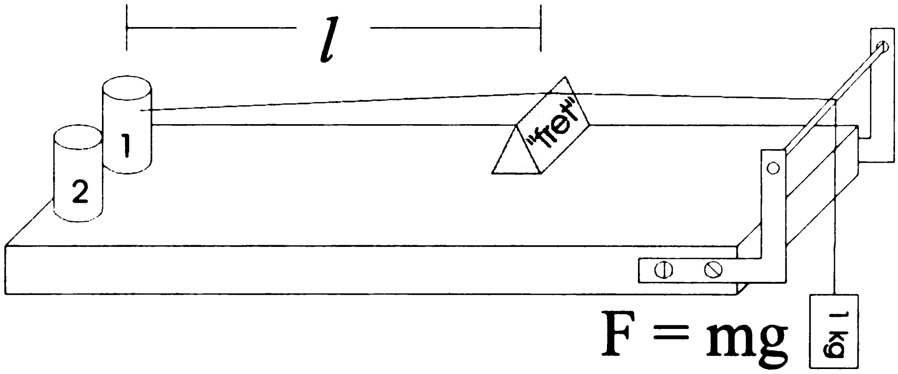
**Experiment #3** **Vibrating Strings**

**Purpose:** To see how tension and length affect the frequency of a vibrating string

**Theory:** When drawn tight with some constant force (tension), a length of string will only vibrate at a specific *fundamental frequency*. A guitar player will change the length of the vibrating strings by pressing them at various ridges (called frets) which lie beneath the strings. S/He can also adjust the pitch of a string by changing the tension to get it "in tune."

**Procedures:**

1. Cut 1.5 m of high test fish line. Tie string through hole in peg #1. Make a loop at the free end of the string.

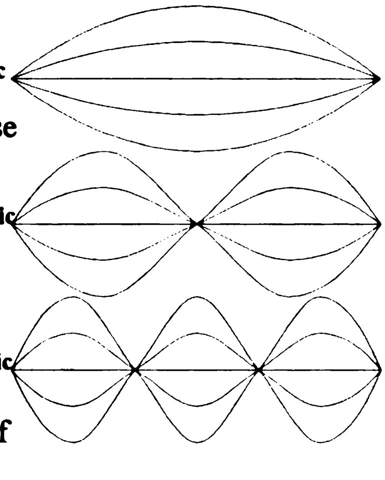



2. Repeat for peg #2 and clamp the board to the lab bench with the other end hanging over the edge.
3. Hang 25 N from line #1, adjust the fret to a length of 1.0 m.
4. On line #2, hang 20, 15, 10, and 5 N. Adjust the fret length to produce an equal pitch as line #1 - use your ear to make this as accurate as possible.
5. Graph length ($l$) vs tension (F).

**Questions:**

1. Does pitch increase or decrease when the vibrating string's length is increased.
2. How does pitch change with increased tension?
3. What is the specific relation between $l$ and F?
4. Frequency is indirectly proportional to string length and directly proportional to the square of its tension. How must the tensions compare if string two has twice the length of string one in order to maintain equal pitch? Try it to be sure.
5. How much tension must a 1.5 m piano wire (m = 0.0005 kg/m) have to produce the standard pitch $A_{440}$ ($f = (2l)^{-1}(F/m)^{½}$)?

## Resonance Worksheet #2 *The Vibrating String*




If stretched string is fixed at both ends, waves travelling along the string will reflect at these fixed ends causing waves travelling in both directions. These waves will interfere with each other causing standing waves. Points of destructive interference are nodes and are stationary, points of constructive interference are antinodes and move at a maximized amplitude.

The fundamental frequency (first harmonic) for a string is a function of its length L, mass per unit length (density) μ, and the tension F on the string.The subsequent harmonics are found to be multiples of this fundamental frequency

$$f=\frac{v}{\lambda} \;;\quad 2l=\lambda \;;\quad \sqrt{\frac{F}{\mu}}=v \quad \therefore \quad f=\frac{1}{2l}\sqrt{\frac{F}{\mu}}$$

PLACE THE CORRECT RESPONSE IN THE SPACE BELOW EACH PROBLEM. SHOW WORK ON ATTACHED SHEET OF PAPER.

1. The G string on a violin has fundamental frequency of 196 Hz. The length of the vibrating portion is 32 cm and has a mass of 0.55 g. Under what tension must the string be placed?

2. An unfingered guitar string is 0.70 m long and is tuned to play E above middle C (330 Hz). How far from the end of the string must the finger be placed to play A above middle C (440 Hz)?

3. Find the speed of waves on a 0.80 g violin string 22 cm long if the frequency of the fundamental is 920 Hz? What is the tension on the string?

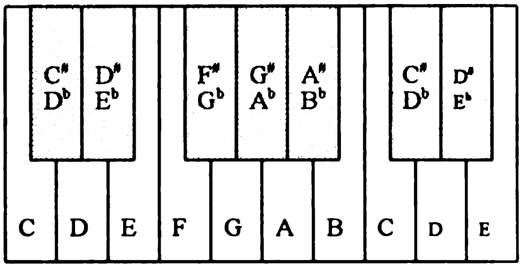
4. If a cello string is tuned to a certain note, by how much must the tension be increased if it is to emit a note of double the original frequency (1 octave higher)?

5. A certain violin string is 30 cm long between its fixed ends and has a mass of 2.0 g. The string sounds an A note (440 Hz) when played without fingering. Where must one put one's finger to play a C (528 Hz)?

6. The highest key on a piano corresponds to a frequency about 150 times that of the lowest key. If the string for the highest note is 5.0 cm long, how long would the string for the lowest note need to be if it were the same mass per unit length and under the same tension?

7. Find the first four harmonics of a string 1.0 m long if the string has a mass per unit length of $2 \times 10^{-3}$ kg/m and is under a tension of 80 N.

## **Music Worksheet #1** *The Notes*




The Musical Scale is based on frequencies. An octave is the progression through one whole range of notes so that the frequency is doubled. For example, in the diagram at the right the "C" which is farthest left will give a frequency of 264 Hz and the "C" which is closest to it on the right will be at 528 Hz. Octaves are usually measured from "C" to "C." The standard reference pitch, or frequency, is an "A" note with a frequency of 440 Hz. This standard pitch is often called "A" above middle "C." Middle "C" has a frequency of 264 Hz. From middle "C" the next highest non-sharp/flat note frequency is 9/8 times as large, next is 5/4, then 4/3, 3/2, 5/3, 15/8 and 2/1 will end at the next "C" note (all multiples of the original 264 Hz).

1. Based on the previous statement, completely fill in the rest of this table:

| Scale Note | C | D | E | F | G | A | B | C |
|---|---|---|---|---|---|---|---|---|
| Scale Ratio | 1/1 | | | | | | | 2/1 |
| Frequency (Hz) | 264 | | | | | 440 | | |
| Voice Note | Do | Re | Mi | Fa | So | La | Ti | Do |

2. What note would have a frequency of 220 Hz?

3. What is the frequency difference between F and G in the middle octave (see above)?

Since there are some frequencies between the whole step notes, we use what are called sharps and flats. A sharp for a note has a frequency which is higher than its own, and a flat was a frequency which is lower. For example, a "$C^{\#}$" (said "C-sharp") will have a frequency between the "C" and the "D." There are two different scales for dealing with sharps and flats. The *chromatic scale* says that each sharp is 25/24 times the frequency of its note, and the flat is 24/25 times that note's frequency. The *equal tempered scale* uses 440 Hz as the standard pitch and divides the octave into 12 equal ratio intervals with each semitone being 1.0594 times the frequency of its previous note. In the equal tempered scale, a "$C^{\#}$" and a "$D^{b}$" are the same note.

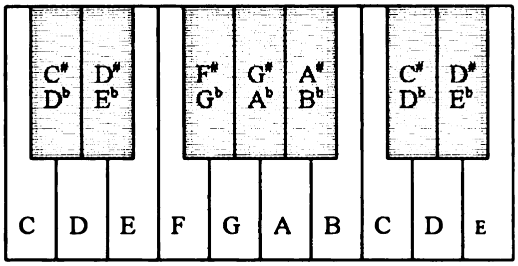
4. On the chromatic scale, what is the frequency for "$F^{\#}$" above middle "C" and what is "$G^{b}$" in that octave?

5. Answer question #4 for the equal tempered scale.

**Musical Scale for 4 Octaves**

| Note | Freq. (Hz) | Note | Freq. (Hz) |
|---|---|---|---|
| C | 132.0 | C | 528.0 |
| C♯/D♭ | 140.0 | C♯/D♭ | 560.0 |
| D | 148.5 | D | 594.0 |
| D♯/E♭ | 140.3 | D♯/E♭ | 561.0 |
| E | 165.0 | E | 660.0 |
| F | 176.0 | F | 704.0 |
| F♯/G♭ | 187.0 | F♯/G♭ | 748.0 |
| G | 198.0 | G | 792.0 |
| G♯/A♭ | 209.0 | G♯/A♭ | 836.0 |
| A | 220.0 | A | 880.0 |
| A♯/B♭ | 233.8 | A♯/B♭ | 935.0 |
| B | 247.5 | B | 990.0 |
| C | 264.0 | C | 1,056.0 |
| C♯/D♭ | 280.5 | C♯/D♭ | 1,122.0 |
| D | 297.0 | D | 1,188.0 |
| D♯/E♭ | 313.5 | D♯/E♭ | 1,254.0 |
| E | 330.0 | E | 1,320.0 |
| F | 352.0 | F | 1,408.0 |
| F♯/G♭ | 374.0 | F♯/G♭ | 1,496.0 |
| G | 396.0 | G | 1,584.0 |
| G♯/A♭ | 418.0 | G♯/A♭ | 1,672.0 |
| A | 440.0 | A | 1,760.0 |
| A♯/B♭ | 467.5 | A♯/B♭ | 1,870.0 |
| B | 495.0 | B | 1,980.0 |

## **Music Worksheet #2** *The Harmonies and chords*




Harmony occurs when two or more frequencies sound pleasing together. This occurs when the frequencies exist in a small whole number ratio. The smaller the whole numbers giving the ratio between frequencies of the two notes the more harmonious is the resultant. These are so important to music that each ratio has been given a name. Here the frequency ratios are listed in decreasing harmony:

2:1 is an octave, 2:3 is a fifth, 3:4 is a fourth, 4:5 is a major third, 5:6 is a minor third, 3:5 is a major sixth, and 5:8 is a minor sixth.

1. If these harmonies are sensed due to superposition of the waves, draw a picture representing the wave overlap (interference) created with an octave harmony.

2. Name the frequency which would make a fourth with 440 Hz.

3. What note will make a major third with “B” above middle “C” (495 Hz)?

4. What name would you give the harmony of “F” and “$B^b$?”

Triads or chords are formed by 3 separate notes. Each note must be harmonious with the other two while the highest and lowest notes are less than an octave apart. There are only six of these, their frequency ratios are: 4:5 5:6, 3:4 4:5, 5:6 4:5, 5:6 3:4, 4:5 3:4, and 3:4 5:6.

5. What ratios exist in a chord with a major third followed by a minor third?

6. If the chord from question 4 has 264 Hz as its lowest frequency, what are the frequencies for the other two notes?

7. What ratios exist between “F,” “A,” and “C?”

8. A chord called “A minor” has “A” as it’s middle note and frequency ratios of a fourth followed by a 5/8 ratio. What are the three notes and their frequencies for this triad?

## Sound and Music Quiz

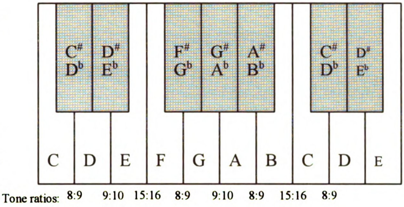
**Multiple Choice: 2 points each. Circle the letter of the best answer.**

1. *As a steel strip vibrates from left to right, it:*
   a) does work on gas molecules on the right,
   b) transfers energy from the gas molecules on the right,
   c) does work on the gas molecules on the left side,
   d) transfers energy to the gas molecules on the left side.
2. *Sound waves are:*
   a) longitudinal waves in space
   b) longitudinal waves in matter
   c) transverse waves in space
   d) transverse waves in matter
3. *Sound travels at a speed which is:*
   a) faster than light
   b) the same as light
   c) slower than light
   d) 200 m/s at 100°C
4. *The speed of sound in air:*
   a) decreases with a rise in temperature
   b) is constant
   c) increases at 0.6 m/s per °C
   d) is about 200 m/s at 100°C
5. *Resonance is:*
   a) the vibration of air molecules
   b) a frequency of vibrating glass
   c) two or more substances vibrating at the same frequency
   d) the length of an air column vibrating with water below
6. *The slide on a trombone changes:*
   a) the pressure of the vibrating air column
   b) the length of the vibrating air column
   c) the temperature of the vibrating air
   d) the intensity of the vibrating air
7. *A string of a certain density will vibrate:*
   a) twice as fast with twice the tension
   b) half as frequent with twice the tension
   c) twice as fast with quadruple the tension
   d) half as frequent with quadruple the tension
8. *Harmonics are:*
   a) multiples of the fundamental frequency
   b) the difference between two frequencies
   c) frequencies which occur in whole number ratios greater than ½ with each other
   d) sympathetic vibrations caused by an oscilloscope
9. *Some pairs of tones sounded together are pleasing; these tones:*
   a) are harmonious
   b) are discordant
   c) may have frequencies between 10 and 50 Hz
   d) may have frequencies which differ by 68 Hz

**Questions/Problems:**

10. What range of vibrations (frequencies) can most humans hear? (2 points)

11. At room temperature (20°C) sound travels at 342 m/s. What range of wavelengths can humans hear? (3 points)




12. The *equal tempered scale* uses A (440 Hz) as the standard pitch and an octave is divided into 12 equal ratio intervals. If A above middle C is 440 Hz, what is $D^\#$ above middle C? (5 points)

13. The *chromatic scale* uses A (440 Hz) as the standard pitch and each sharp ($^\#$) or flat ($^b$) frequency is in a 25:24 ratio of its primary note. Find $D^\#$ above middle C **and** $E^b$ above midle C. (6 points)

14. A bass guitar string is 90 cm long and is tuned to A (110 Hz). To what length must it be "fingered" in order to produce B in the same octave? (6 points)

15. An open vertical tube is filled with water and a tuning fork vibrates over its mouth. As the water level is lowered in the tube, resonance is heard when the water level has dropped 17 cm and again after 51 cm of distance exists from the top of the tube to the mouth of the tube the temperature is 20°C. What is the frequency of the tuning fork? (3 points)

16. A slide whistle has a length of 27 cm. If you want to play a note one octave higher, how long should the whistle be if the temperature is 20°C? (3 points)

17. One open organ pipe has a length of 810 mm. A second pipe should have a pitch one major third higher (frequency ratio of 4:5). How long should this pipe be at 20°C? (4 points)

# APPENDIX B

## Assessment Rubric

**Waves Assessment grading rubrics**

**How is mechanical energy transfer responsible for wave propogation?**

0. No or totally incorrect response.
1. Vibrating air molecules bounce off one another.
2. Vibrating molecules of the medium of propogation collide causing a periodic wave to form.
3. Energy is transfered by particles in the medium colliding in a periodic fashion. The vibrating source moves the molecules of the medium immediately adjacent to it. These molecules move the adjacent molecules and the energy is transfered until the energy is "used up" or lost to external forces.

**Explain the difference between transverse waves and longitudinal waves.**

0. No or totally incorrect response.
1. Transverse waves have amplitudes which are vertical and longitudinal waves have amplitudes which are horizontal.
2. Transverse waves are like sine waves and have disturbances which are perpendicular to the direction of motion ***OR*** longitudinal waves are compression waves which vibrate in the direction of motion.
3. A transverse wave causes the particles of the medium to vibrate in a direction that is perpendicular to the direction the wave is moving. A longitudinal wave causes the particles of the medium to vibrate in a direction parallel with the direction of the wave.

**How does a wave's speed relate to its frequency? Its wavelength?**

0. No or totally incorrect response.
1. $v = f\lambda$.
2. Speed varies directly with frequency and wavelength.
3. With a constant wavelength, the wave's speed is directly related to its frequency. With a constant frequency, a wave's speed is directly related to its wavelength. $v = f\lambda$.

**Explain constructive and destructive interference.**

0. No or totally incorrect response.
1. Constructive interference is making big waves, destructive is making small or no waves.
2. Constructive interference makes bigger waves, destructive interference makes no waves because of superposition.
3. The principle of superposition allows for the adding of the displacement of individual waves at a particular position in the medium to form one displacement. Constructive interference occurs when the wave displacements are in the same direction, destructive interference occurs when two waves -of equal displacement- overlap to result in zero disturbance of the medium.

**How does a standing wave "stand?"**

0. No or totally incorrect response.
1. By creating nodes and antinodes through destructive and constructive interference.
2. Reflecting a wave so that it interferes with itself causes nodes and antinodes.
3. A standing wave is the result of identical waves moving in opposite directions. The reflection of one periodic wave source is a possible method of producing standing waves. The areas of maximum displacement - due to constructive interference - are called antinodes. The areas of total non-disturbance - due to destructive interference - are called nodes.

**Explain how you can "feel" the music at a rock concert.**

0. No or totally incorrect response
1. They turn up the volume causing the air to vibrate around the audience.
2. High energy output of the speakers vibrates the air causing longitudinal waves. The air around the audience is constantly vibrated - the skin detects this vibration allowing the sound to be "felt."
3. The speakers vibrate the air molecules near them with massive amounts of energy. This energy is transfered to adjacent molecules in a longitudinal wave to the audience. The energy is so great that the air around the body is being violently oscillated causing the skin to detect changing air pressure. Longer wavelengths (bass) allow for more detection time between drastic pressure changes, therefore allowing these to be the most "felt" sounds.

# APPENDIX C

## Student Data

**Table 1:** All data gathered from pre-test and post-test

| Student | Pre-test Scores | | | | | | | Post-test Scores | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | 1 | 2 | 3 | 4 | 5 | 6 | Total | 1 | 2 | 3 | 4 | 5 | 6 | Total |
| 03007 | 3 | 1 | 1 | 0 | 0 | 1 | 6 | 2 | 2 | 1 | 2 | 0 | 2 | 9 |
| 03020 | 0 | 0 | 2 | 0 | 0 | 1 | 3 | 2 | 2 | 1 | 0 | 0 | 2 | 7 |
| 04005 | 3 | 2 | 1 | 1 | 1 | 2 | 10 | 3 | 1 | 3 | 2 | 3 | 3 | 15 |
| 08005 | 3 | 0 | 1 | 0 | 1 | 2 | 7 | 3 | 2 | 3 | 1 | 2 | 2 | 13 |
| 08006 | 2 | 0 | 3 | 2 | 3 | 1 | 11 | 3 | 0 | 3 | 3 | 3 | 1 | 13 |
| 08007 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 1 | 4 |
| 08010 | 2 | 1 | 2 | 2 | 1 | 0 | 8 | 2 | 1 | 3 | 3 | 1 | 3 | 13 |
| 08027 | 1 | 0 | 2 | 2 | 3 | 1 | 9 | 2 | 2 | 1 | 2 | 0 | 2 | 9 |
| 08032 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 1 | 0 | 1 | 2 | 0 | 1 | 5 |
| 08043 | 0 | 0 | 2 | 0 | 0 | 1 | 3 | 0 | 1 | 1 | 0 | 0 | 1 | 3 |
| 16005 | 0 | 0 | 3 | 2 | 1 | 1 | 7 | 2 | 2 | 3 | 3 | 1 | 2 | 13 |
| 16007 | 1 | 0 | 0 | 2 | 1 | 1 | 5 | 2 | 2 | 3 | 3 | 2 | 2 | 14 |
| 16020 | 1 | 1 | 2 | 0 | 1 | 0 | 5 | 0 | 2 | 3 | 0 | 1 | 1 | 7 |
| 16039 | 1 | 0 | 1 | 2 | 0 | 0 | 4 | 3 | 2 | 3 | 3 | 2 | 1 | 14 |
| 16040 | 0 | 1 | 2 | 1 | 0 | 1 | 5 | 0 | 2 | 1 | 1 | 1 | 1 | 6 |
| 16042 | 1 | 1 | 2 | 2 | 2 | 0 | 8 | 3 | 3 | 2 | 2 | 3 | 2 | 15 |
| 16048 | 0 | 0 | 2 | 1 | 3 | 1 | 7 | 1 | 3 | 3 | 2 | 2 | 2 | 13 |
| 16073 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 2 | 3 |
| 16103 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 3 | 0 | 2 | 0 | 1 | 1 | 7 |
| 19439 | 2 | 2 | 3 | 2 | 0 | 3 | 12 | 3 | 0 | 2 | 0 | 1 | 1 | 7 |
| 19452 | 0 | 3 | 2 | 0 | 1 | 1 | 7 | 1 | 2 | 2 | 0 | 2 | 1 | 8 |
| 19500 | 0 | 0 | 2 | 1 | 2 | 0 | 5 | 3 | 0 | 3 | 3 | 3 | 2 | 14 |
| 19505 | 1 | 0 | 0 | 1 | 0 | 1 | 3 | 1 | 3 | 2 | 0 | 0 | 2 | 8 |
| 19512 | 0 | 1 | 2 | 0 | 0 | 0 | 3 | 0 | 0 | 2 | 0 | 0 | 2 | 4 |
| 19637 | 0 | 0 | 3 | 2 | 0 | 1 | 6 | 2 | 2 | 0 | 2 | 0 | 2 | 8 |
| 19658 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 0 | 2 | 2 | 6 |
| 19662 | 0 | 0 | 1 | 2 | 1 | 0 | 4 | 1 | 2 | 1 | 2 | 3 | 2 | 11 |

**Table 1:** Continued

| Student | Pre-test Scores | | | | | | | Post-test Scores | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | 1 | 2 | 3 | 4 | 5 | 6 | Total | 1 | 2 | 3 | 4 | 5 | 6 | Total |
| 19672 | 1 | 2 | 0 | 0 | 2 | 1 | 6 | 3 | 2 | 2 | 1 | 3 | 1 | 12 |
| 19673 | 0 | 1 | 1 | 0 | 0 | 1 | 3 | 3 | 3 | 2 | 0 | 2 | 1 | 11 |
| 19674 | 2 | 1 | 0 | 1 | 1 | 0 | 5 | 3 | 0 | 3 | 2 | 3 | 2 | 13 |
| 19686 | 2 | 1 | 1 | 2 | 1 | 1 | 8 | 2 | 2 | 3 | 2 | 2 | 3 | 14 |
| 19691 | 0 | 2 | 1 | 2 | 1 | 1 | 7 | 1 | 1 | 3 | 2 | 2 | 2 | 11 |
| 19702 | 0 | 1 | 3 | 0 | 0 | 0 | 4 | 0 | 3 | 3 | 2 | 1 | 2 | 11 |
| 19716 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 19719 | 1 | 2 | 1 | 2 | 3 | 2 | 11 | 1 | 0 | 2 | 2 | 3 | 2 | 10 |
| 19724 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 3 |
| 19728 | 0 | 2 | 1 | 0 | 0 | 0 | 3 | 1 | 2 | 0 | 2 | 1 | 2 | 8 |
| 19731 | 0 | 3 | 0 | 3 | 0 | 1 | 7 | 1 | 1 | 2 | 3 | 0 | 2 | 9 |
| 19757 | 0 | 0 | 3 | 1 | 0 | 0 | 4 | 1 | 0 | 1 | 1 | 1 | 1 | 5 |
| 19758 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| 19770 | 1 | 2 | 1 | 0 | 0 | 0 | 4 | 2 | 2 | 2 | 3 | 0 | 1 | 10 |
| 19771 | 0 | 1 | 1 | 0 | 2 | 1 | 5 | 1 | 2 | 2 | 2 | 2 | 2 | 11 |
| 19776 | 1 | 0 | 1 | 0 | 3 | 3 | 8 | 2 | 0 | 2 | 0 | 1 | 1 | 6 |
| 19777 | 1 | 1 | 1 | 0 | 0 | 1 | 4 | 1 | 2 | 2 | 0 | 0 | 1 | 6 |
| 19782 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 1 | 3 |
| 19788 | 3 | 0 | 0 | 0 | 0 | 0 | 3 | 3 | 1 | 0 | 1 | 0 | 1 | 6 |
| 19846 | 0 | 1 | 2 | 0 | 0 | 1 | 4 | 1 | 0 | 1 | 1 | 0 | 1 | 4 |
| 19869 | 1 | 2 | 2 | 0 | 2 | 1 | 8 | 2 | 2 | 2 | 2 | 2 | 2 | 12 |
| 20072 | 0 | 1 | 1 | 2 | 0 | 1 | 5 | 0 | 0 | 2 | 1 | 0 | 3 | 6 |
| 20076 | 3 | 1 | 1 | 2 | 0 | 2 | 9 | 3 | 3 | 2 | 3 | 3 | 2 | 16 |
| 20127 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 2 | 1 | 0 | 0 | 0 | 1 | 4 |
| 20140 | 1 | 3 | 1 | 2 | 1 | 0 | 8 | 3 | 2 | 2 | 2 | 2 | 2 | 13 |
| 20146 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 1 | 5 |
| 20232 | 1 | 1 | 1 | 0 | 0 | 0 | 3 | 2 | 2 | 0 | 3 | 1 | 3 | 11 |

**Table 1:** Continued

| Student | Pre-test Scores | | | | | | | Post-test Scores | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | 1 | 2 | 3 | 4 | 5 | 6 | Total | 1 | 2 | 3 | 4 | 5 | 6 | Total |
| 20268 | 1 | 1 | 1 | 0 | 0 | 0 | 3 | 3 | 2 | 1 | 1 | 0 | 1 | 8 |
| 20650 | 3 | 2 | 2 | 1 | 0 | 2 | 10 | 1 | 2 | 2 | 3 | 0 | 2 | 10 |
| 21184 | 1 | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 2 | 2 | 0 | 3 | 2 | 9 |
| 21433 | 1 | 2 | 1 | 0 | 2 | 1 | 7 | 0 | 1 | 1 | 3 | 3 | 2 | 10 |
| 21575 | 0 | 2 | 2 | 0 | 0 | 1 | 5 | 1 | 1 | 3 | 0 | 1 | 1 | 7 |
| 21592 | 0 | 1 | 2 | 1 | 0 | 2 | 6 | 1 | 2 | 1 | 3 | 1 | 1 | 9 |
| 21646 | 0 | 0 | 1 | 0 | 1 | 1 | 3 | 0 | 0 | 3 | 2 | 2 | 1 | 8 |
| 21792 | 1 | 0 | 1 | 0 | 0 | 1 | 3 | 3 | 2 | 3 | 3 | 2 | 2 | 15 |
| 22149 | 0 | 1 | 2 | 0 | 1 | 0 | 4 | 2 | 1 | 3 | 1 | 2 | 1 | 10 |
| 22337 | 0 | 1 | 2 | 0 | 0 | 1 | 4 | 1 | 0 | 2 | 0 | 0 | 1 | 4 |
| 22456 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 2 | 2 | 7 |
| 22509 | 0 | 2 | 1 | 0 | 0 | 1 | 4 | 0 | 2 | 1 | 0 | 0 | 1 | 4 |
| 22512 | 1 | 2 | 3 | 3 | 0 | 0 | 9 | 1 | 2 | 3 | 3 | 2 | 1 | 12 |
| 22513 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 2 | 1 | 2 | 0 | 0 | 0 | 5 |
| 22654 | 2 | 3 | 1 | 1 | 0 | 0 | 7 | 2 | 2 | 3 | 3 | 0 | 2 | 12 |
| 22689 | 2 | 1 | 2 | 0 | 2 | 0 | 7 | 0 | 2 | 1 | 0 | 2 | 0 | 5 |
| 22728 | 0 | 0 | 1 | 0 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 1 | 5 |
| 23339 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 3 | 1 | 0 | 0 | 0 | 4 |
| 26008 | 0 | 0 | 3 | 2 | 0 | 1 | 6 | 1 | 2 | 2 | 3 | 1 | 2 | 11 |
| 26009 | 1 | 1 | 1 | 0 | 0 | 0 | 3 | 1 | 2 | 0 | 0 | 1 | 1 | 5 |
| 26042 | 2 | 2 | 1 | 0 | 1 | 0 | 6 | 1 | 1 | 2 | 3 | 3 | 2 | 12 |
| 26063 | 0 | 1 | 1 | 0 | 0 | 1 | 3 | 1 | 1 | 1 | 0 | 0 | 1 | 4 |
| 27066 | 0 | 0 | 1 | 0 | 1 | 1 | 3 | 1 | 1 | 2 | 0 | 1 | 1 | 6 |
| 37010 | 0 | 0 | 1 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 | 0 | 1 | 4 |
| 37015 | 2 | 0 | 3 | 2 | 2 | 2 | 11 | 2 | 2 | 0 | 3 | 3 | 2 | 12 |
| 37021 | 0 | 0 | 1 | 0 | 0 | 2 | 3 | 1 | 1 | 3 | 1 | 0 | 1 | 7 |
| 37026 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 4 |

**Table 1:** Continued

| Student | Pre-test Scores | | | | | | | Post-test Scores | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | 1 | 2 | 3 | 4 | 5 | 6 | Total | 1 | 2 | 3 | 4 | 5 | 6 | Total |
| 37032 | 0 | 0 | 1 | 0 | 0 | 1 | 8 | 1 | 0 | 2 | 0 | 2 | 1 | 12 |
| 47001 | 0 | 0 | 2 | 0 | 0 | 1 | 9 | 3 | 1 | 2 | 0 | 2 | 1 | 15 |
| 47004 | 3 | 3 | 3 | 0 | 0 | 2 | 17 | 3 | 3 | 2 | 3 | 0 | 3 | 20 |
| 47006 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 1 | 2 | 3 | 0 | 1 | 1 | 8 |
| 47009 | 1 | 0 | 1 | 0 | 0 | 2 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 18 |
| 47068 | 1 | 2 | 1 | 0 | 0 | 2 | 6 | 0 | 3 | 3 | 3 | 0 | 1 | 10 |
| 48075 | 0 | 1 | 2 | 1 | 0 | 0 | 4 | 1 | 2 | 1 | 1 | 2 | 1 | 8 |
| 74016 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 3 | 1 | 0 | 0 | 2 | 6 |
| 81053 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 1 | 1 | 0 | 2 | 1 | 5 |
| 81055 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 0 | 2 | 0 | 0 | 1 | 1 | 4 |
| 82112 | 0 | 0 | 2 | 3 | 2 | 1 | 8 | 1 | 3 | 0 | 3 | 2 | 1 | 10 |
| 82123 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 3 |
| 82152 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 0 | 1 | 1 | 6 |
| 83103 | 3 | 2 | 2 | 0 | 2 | 2 | 11 | 3 | 2 | 3 | 1 | 2 | 2 | 13 |
| 83199 | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 2 | 0 | 1 | 2 | 7 |
| 83207 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 2 | 1 | 6 |
| 83243 | 0 | 0 | 0 | 2 | 0 | 2 | 4 | 1 | 2 | 2 | 0 | 0 | 2 | 7 |
| 83273 | 0 | 1 | 1 | 1 | 1 | 1 | 5 | 1 | 3 | 2 | 2 | 0 | 2 | 10 |
| 84109 | 0 | 1 | 1 | 0 | 0 | 1 | 3 | 1 | 2 | 2 | 0 | 2 | 2 | 9 |
| 85157 | 0 | 1 | 2 | 2 | 0 | 0 | 5 | 2 | 2 | 2 | 2 | 0 | 1 | 9 |
| 92002 | 0 | 2 | 1 | 0 | 1 | 0 | 4 | 0 | 1 | 1 | 0 | 2 | 2 | 6 |
| 94014 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 2 | 0 | 0 | 3 |
| 94016 | 3 | 0 | 3 | 3 | 2 | 2 | 13 | 3 | 2 | 3 | 3 | 2 | 2 | 15 |
| 94018 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 3 | 0 | 0 | 8 |
| Average | 0.7 | 0.8 | 1.3 | 0.7 | 0.7 | 0.9 | 4.61 | 1.3 | 1.5 | 1.8 | 1.3 | 1.3 | 1.6 | 8.35 |

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