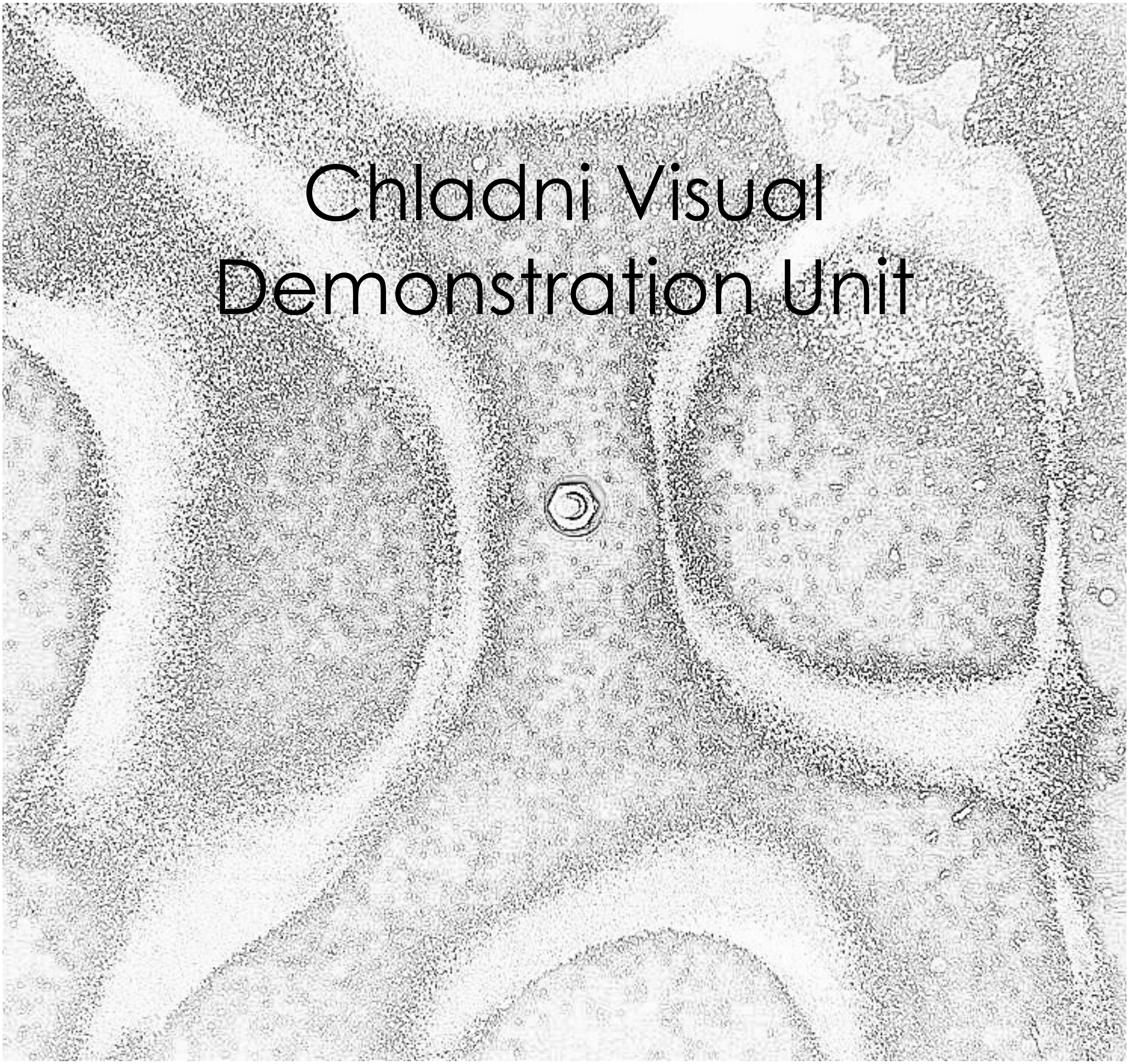
Chladni Visual Demonstration Unit



Resonauts

Designed by:
Thomas Minniti
Kelly Rodman
Robert Toledo III
Alyssa Virgil
Humboldt State University
ENGR215 “Introduction to Design” Fall 2015
Client: Zane Middle School, Ken Pinkerton

Table of Contents

1 Problem Formulation 1
  1.1 Introduction 1
  1.2 Objective 1

2 Problem Analysis and Literature Review 1
  2.1 Problem Analysis 1
  2.2 Introduction 2
  2.3 Specifications and Considerations 2
    2.3.1 Specifications 2
    2.3.2 Considerations 2
  2.4 Criteria 2
    2.4.1 Introduction 2
  2.5 Usage 3
  2.6 Production 3
  2.7 Literature Review 4
    2.7.1 Client Interview and Criteria 4
    2.7.2 Humboldt Math Festival 4
    2.7.3 Zane Middle School 5
    2.7.4 Education Code Violations 5
    2.7.5 Interactive Lecture Demonstrations 5
      2.7.5.1 Definition and Structure of an Interactive Lecture Demonstration 5
      2.7.5.2 Reason to Use an Interactive Lecture Demonstration 6
    2.7.6 Physics of Resonance 6
    2.7.7 Mathematical Applications of Resonance 8
    2.7.8 Applications in Science 9
      2.7.8.1 Electron Paramagnetic Resonance 9
      2.7.8.2 Magnetic Resonance Imaging 9
    2.7.9 Engineering applications of Resonance 10
    2.7.10 Applications in Music 12
      2.7.10.1 Sound 12
      2.7.10.2 Standing Waves 13
      2.7.10.3 Wave Impedance 13
      2.7.10.4 Tension and Density 14
      2.7.10.5 Beats 14
      2.7.10.6 Tuning Fork Demonstrations 15
      2.7.10.7 Guitar Strings 15
    2.7.11 Materials and Safety 16
      2.7.11.1 Wood (types, durability) 16
      2.7.11.2 Metal (types, characteristics) 16
      2.7.11.3 Chladni Plates 16
      2.7.11.4 Soldering 17
      2.7.11.5 Non-Newtonian Fluid (cornstarch and water) 17
      2.7.11.6 Sustainable Materials/ Recycling Materials 18
      2.7.11.7 Speakers 18

3 Alternative Solutions 18
  3.1 Introduction 18
  3.2 Brainstorming 18
  3.3 Alternative Solutions 18
    3.3.1 The Chladni Visual Demonstration Unit 19

3.3.2 The Guitar String Wave Lab 21
3.3.3 Head Scratcher 21
3.3.4 Levitation 23
3.3.5 Tuning Fork Sound Demonstration 26
3.3.6 Jiggle It 27
3.3.7 The Soprano 28
3.3.8 Barton's Pendulums 29

4 Decision Process 30
4.1 Introduction 30
4.2 Criteria Definitions 31
4.3 Decision Process 31
4.4 Delphi Matrix 32
4.5 Final Decision 33

5 Specification of Solution 33
5.1 Solution Description 33
5.1.1 Recycled Redwood Storage Box 34
5.2 Cost Analysis 35
5.2.1 Design Costs 35
5.2.2 Material Costs 36
5.2.3 Maintenance Costs 37
5.3 Implementation 38
5.4 Results 38

Appendix A - References ....a

Appendix B - Brainstorming ....d

Table of Figures

Figure 1-1 A black box diagram showing the state of Zane Middle School before and after the Resonaut's design is implemented. 1
Figure 2-1 2014 Poster for the 2014 Humboldt Math Festival ("Goals of the Humboldt Math Festival") 5
Figure 2-2 An image demonstrating the harmonic motion of a displaced spring. (http://hyperphysics.phy-astr.gsu.edu/hbase/shm.html) 7
Figure 2-3 The effects of damping on the resonance amplitude of an oscillator. (https://www.boundless.com/physics/textbooks/boundless-physics-textbook/sound-16/further-topics-132/forced-vibrations-and-resonance-473-1966/) 8
Figure 2-4 Differential equation for pure resonance (Dukes 2005). 8
Figure 2-5 Differential equation for practical resonance (Dukes 2005). 9
Figure 2-6 Conditions for practical resonance (Dukes 2005). 9
Figure 2-7 Electron Paramagnetic Resonance. Retrieved from: (https://upload.wikimedia.org/wikipedia/commons/d/d8/Animated_Rotating_Frame.gif) 9
Figure 2-8 MRI of Skull. Retrieved from:(https://www.flickr.com/photos/reighleblanc/3854685038/sizes/o/in/photostream/) 10
Figure 2-9 A picture of the inner workings of an MRI machine. Retrieved from: (http://hellobougeotte.blogspot.com/2015/02/inside-mri-machine.html) 11
Figure 2-10 The collapsing Tacoma narrows bridge. Retrieved from: (http://faculty.plattsburgh.edu/margaret.campion/seconded/second/Kent/Kent.html) 12
Figure 2-11 A Compressional Sound Wave and Its Representational Waveform. Retrieved from: (http://www.mediacollege.com/audio/images/loudspeaker-waveform.gif) 12
Figure 2-12 Sand Travelling to the Nodes of a Standing Wave (Lapp 2006) 13
Figure 2-13 A Wave Before and After Being Reflected by a Rigid Object (Lapp 2006) 13
Figure 2-14 A Wave Reflected After Encountering a Medium of Less Impedance: Note that the wave was not inverted (Lapp 2006) 14
Figure 2-15 Two Sound Waves of Different Frequencies Add Together to Create Volume Fluctuations. Retrieved from: (http://www.indiana.edu/~emusic/acoustics/phase.htm) 15
Figure 2-16 A Recently Stuck Tuning Fork Being Dipped in Water (Lapp 2006) 15
Figure 2-17 Tuning Pegs at the Head of a Guitar. Retrieved from: (http://upload.wikimedia.org/wikipedia/commons/5/50/Classical_guitar_head_gears_DSC06945.jpg) 16
Figure 2-188 Chladni plate with violin bow. Retrieved from: (http://www.hps.cam.ac.uk/whipple/explore/acoustics/ernstchladni/chladniplates/) 17
Figure 3-1 Drawing of the Chaldni Visual Demonstration Unit [A-fine sand/salt; B-metal rod; C-metal plate; D-riser; E-Magnetic coil; F-amplifier; G-arduino] 20
Figure 3-2 Drawing of the Guitar String Wave Lab [A-bridge and saddle; B-tuning pegs; C-bridge; D-guitar strings; E-guitar tuner] 21

Figure 3-3 The Head Scratcher has to sets of stainless steel prongs, where prongs of the same length resonate with each other. 22
Figure 3-4 Case to Base for Head Scratcher 23
Figure 3-5 Levitation Demonstration - Sound waves at alternating amplitudes levitate small objects by the pockets formed between the waves. 25
Figure 3-6 Tuning Fork Sound Demonstration 26
Figure 3-7 the Jiggle It (non-Newtonian fluid on a resonating plate) 27
Figure 3-8 The Soprano – Sound waves at specific frequencies (frequencies glass will resonate at) are passed through a wine glass, causing the glass to resonate (vibrate) and eventually shatter. 29
Figure 3-9 Barton's Pendulum – The amplitude and frequency of the swinging pendulums visually demonstrates the mechanism of sound waves. 30
Figure 5-1 Auto CAD drawing of the Chladni Visual Demonstration Unit's main components drawn by Kelly Rodman. 34
Figure 5-2 Auto CAD drawing of the Chladni Visual Demonstration Unit case with dimensions. Drawn by Robert Toledo III. 35
Figure 5-3 Pie Chart of time needed to design, test, and build the Chladni Visual Demonstration Unit. A combined time of all individual team members' time. 36
Figure 5-4 Humboldt County Students visiting the demonstration unit at the Humboldt County Math Festival April 25th, 2015. 38
Figure 5-5 Humboldt County Students interacting with the demonstration unit. The pattern shown occurs at 175 Hz. 39
Figure 5-6 Function Generator with analog controls (http://www.ebay.com). 40
Figure 5-7 An image of patterns at specific frequencies generated by another mechanical wave driver. (http://pubs.sciepub.com/ajme/2/7/15/). 41
Figure 5-8 Humboldt County Math Festival at the Bayshore Mall in Eureka, CA. The pattern shown on the Chladni plate occurs at 215 Hz. 42

Table of Tables

Table 2-1 Criteria and Constraints considered for resonance project....................2
Table 4-1 Table of Weighted Criteria 32
Table 5-1 A table of retail costs of all materials, compared to the cost incurred in designing the demonstration. 37

1 Problem Formulation

1.1 Introduction

Section one of the document formulates an objective statement as well as a black box diagram for the project. The black box diagram in figure 1-1 shows a before and after state for Zane Middle School.

1.2 Objective

The objective of this project is to design a resonance demonstration unit for the students at Zane Middle School. The design must be portable, aesthetically appealing, and informative. The goal of the design is to provide a visual aid for the students to learn about the principles of resonance. The design should function as a safe and useful teaching tool.

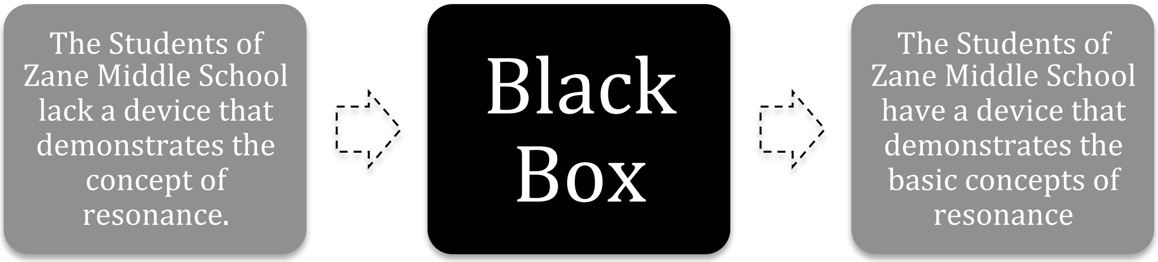


Figure 1-1 A black box diagram showing the state of Zane Middle School before and after the Resonaut's design is implemented.

2 Problem Analysis and Literature Review

2.1 Problem Analysis

2.2 Introduction

The problem analysis section contains specifications, considerations, criteria, usage, and production volume for the project. In table 1-1, the criteria and constraints of this project are defined.

2.3 Specifications and Considerations

Specifications and considerations for this particular project must be met based on the client's needs and the nature of this project. The specifications and considerations for the resonance project are described below.

2.3.1 Specifications

The specifications are the required components of the project. A specification for this project is the dimensions must be within 2 feet by 2 feet and a height that will fit inside a classroom, or of other dimensions that easily store in a classroom without obstructing pathways or causing distraction. The client wants a lifetime of at least 5 years for the project so sturdy materials are to be used for construction.

2.3.2 Considerations

A consideration for this project is it will have to be transported to the Humboldt Math Festival on April 25, 2015. The project will need to be completed before this date, so plans will be made accordingly. Another consideration is that the project must be light enough to transport easily.

2.4 Criteria

2.4.1 Introduction

Criteria and their constraints are given in table 2-1 which were established through an interview with the client.

Table 2-1 Criteria and Constraints considered for resonance project.

Criteria	Constraints
Safety of demonstration unit	Must follow common sense safety practices.
Educational value	The more the students understand resonance, the better.
Aesthetic appeal	A well-polished aesthetic is desirable as this will be a presentation unit.
Ability to grab and audience's attention	It should easily draw attention of passersby at the math Festival.
Portability	The unit must be portable, and occupy a 2' x 2' base up to 4' tall.
Ease of use	The less reset time between demonstrations the better.
Cost	Must stay within a budget of $400.00.
Durability	Must last at least five years and the more longevity the better.

2.5 Usage

The resonance demonstration unit will be presented and used at the Math Festival. It will then reside in Ken Pinkerton's classroom as a demonstration tool for students attending his classes at Zane Middle School in Eureka. The demonstration unit will be used in the Math Festival for multiple years.

2.6 Production

Since this is a demonstration unit for use by a single educator, only one will be produced by this design group. The demonstration unit will be easy for others to reproduce if they so desire.

2.7 Literature Review

This literature review supplies background knowledge about the topic of resonance as it applies to a demonstration unit for the Humboldt Math Festival and Zane Middle School classroom use. The review includes several topics including safety, current demonstration models, the learning pedagogy of Middle School age Children, possible materials, the physics of resonance, and applications of resonance. All citations for reference materials are given in appendix A in ASCE format.

2.7.1 Client Interview and Criteria

The client, Ken Pinkerton, is the science, technology and engineering teacher at Zane Middle School in Eureka California. A meeting with Mr. Pinkerton was held Friday, February 6, 2015, to discuss the criteria and expectations of the resonance demonstration. The two main criteria conveyed for the project are an April 25th deadline for the Eighth Annual Humboldt Math Festival and durability against middle school students.

2.7.2 Humboldt Math Festival

In addition to being a teacher, Mr. Pinkerton is also the coordinator of the Humboldt Math Festival, the goal of which is to celebrate the richness of mathematics in a hands-on community event. The Humboldt Math Festival is also designed to inspire and engage students, parents and community members in thinking about mathematics and its interconnectedness with the world around us ("Goals of the Humboldt Math Festival").

HUMBOLDT
Math Festival
April 5, 2014
Bayshore Mall · Eureka
10:00 a.m.
2:00 p.m.

A Community Celebration of Mathematics
Fun for All Ages – Activities, Games, Contests, Puzzles,
Career Information, Computers & Calculators,
Displays of Student Art, and Math History

For more information visit
humboldtmathfestival.org
or call 725-6980

SPONSORED BY

Figure 2-1 2014 Poster for the 2014 Humboldt Math Festival ("Goals of the Humboldt Math Festival")

2.7.3 **Zane Middle School**

The curriculum that Zane Middle School uses is known as the common core standards. The California State Board of Education has set curriculum standards in English, mathematics, language arts, science, social studies, and the visual and performing arts (California Department of Education). According to Eureka City Schools Student and Parent handbook, Eureka City Schools are continuing to transition to these common core standards (Eureka City Schools 2014-2105 Student and Parent handbook).

2.7.4 **Education Code Violations**

Sharp objects, or objects that could inflict injury are not permitted on school grounds (Eureka City Schools 2014-2105 Student and Parent handbook). This should be considered during the design process.

2.7.5 **Interactive Lecture Demonstrations**

In a classroom setting, demonstrations are a useful learning tool that serves to supplement a lecture topic and reinforce the students' understanding of a certain concept. When conceiving of a teaching demonstration, certain guidelines need to be kept in mind to produce an effective and relevant understanding in students.

2.7.5.1 Definition and Structure of an Interactive Lecture Demonstration

An Interactive Lecture Demonstration is a carefully planned activity such as a classroom experiment, a survey, a simulation, or an analysis of data (Laws 1999). The purpose of these demonstrations is to present a concept in an impactful and memorable way, requiring students to review any of their previous knowledge of the subject and then to contrast it with what they observe in the demonstration. This prepares them to learn in a follow up lecture (Laws 1999).

The three sections of an Interactive Learning Demonstration are: Predict, Experience, Reflect (Laws 1999).

During the Prediction phase, after explaining the demonstration, the teacher should ask students to articulate their understanding of the subject being demonstrated, even if they do not have a full understanding of it. This can be done by having them make a prediction about the results of the demonstration, explaining their guess to another student, and then taking a poll of the students' predictions (Laws 1999).

The Experience phase contains the main activity of the demonstration, where students will observe events or data that the teacher hopes will clearly illustrate the concept being taught. It can be carried out by the teacher in front of the whole class, or by students in small groups. The Experience can include student data, a simulation, a lab experiment, or an analysis of data from a secondary source (Laws 1999).

The Reflection phase is the most likely to be skipped over in a rush to end a class meeting, but is very important in solidifying understanding of the concepts being presented. During the Reflection, students are asked to record and report the results of the demonstration, and then compare and contrast the results with their prediction (Laws 1999).

2.7.5.2 Reason to Use an Interactive Lecture Demonstration

In the 2012 paper titled *Using Interactive Lecture Demonstrations to Improve Conceptual Understanding of Resonance in an Electronics Course,* Mazzolini, Daniel, and Edwards state that active learning techniques promoting student engagement are more effective than traditional lecture methods at correcting student misconceptions in areas related to science and engineering. This is found to be especially true when teaching physics. The SERC website gives certain specific reasons why a teacher should use an Interactive Lecture Demonstration. It states that the technique of intentionally addressing student's pre-existing conceptions before demonstrating a concept is more effective at reinforcing the correct idea if the results of the demonstration are a surprise to the student (Merritts).

2.7.6 Physics of Resonance

Resonance is a form of harmonic motion. Simple harmonic motion is often exemplified by the motion of a spring, since a spring will oscillate once displaced until it is restored to its original position (Knight 2013). This can usually be visually represented by the sinusoidal waveform, which is shown in figure 2-2. The principle demonstrated by the spring model can be applied to most types of harmonic motion in most types of systems, including the vibration of airplane wings, the ringing of a crystal goblet, the vibration of a tuning fork and many other examples. The idea is that when a system at rest, and under forces that hold the system in a resting state is disturbed or acted upon by an outside force, the system oscillates in a predictable way until it returns to its normal resting state (Knight 2013).

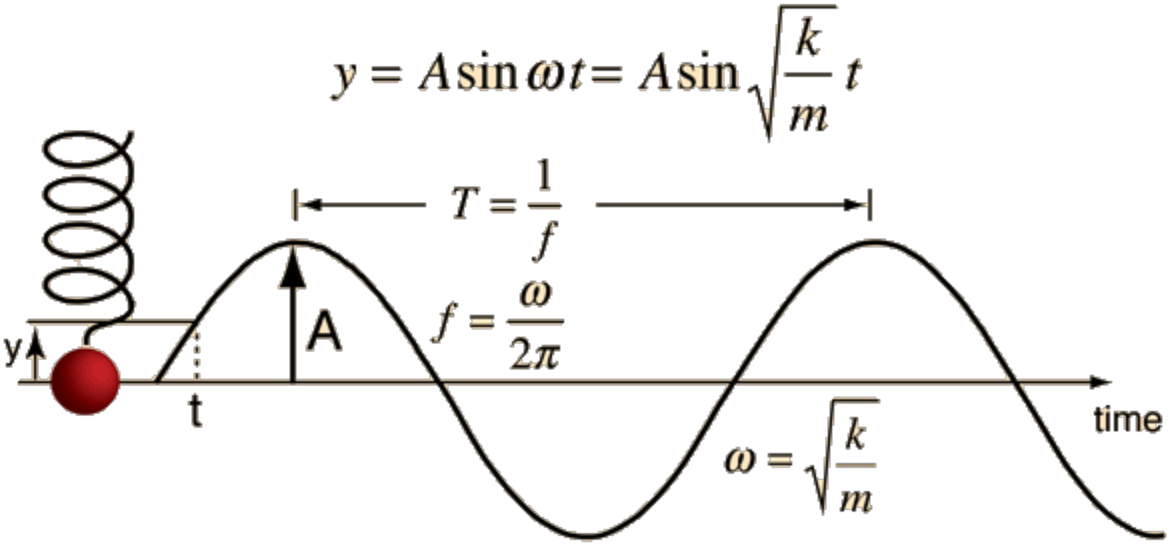


Figure 2-2 An image demonstrating the harmonic motion of a displaced spring. (http://hyperphysics.phy-astr.gsu.edu/hbase/shm.html)

The variables shown above in figure 2-2 apply to most forms of harmonic motion. In this model, the function y is a function of time; A is the amplitude, or maximum/minimum value the wave reaches; T is the period of the wave; and □ is the angular frequency measured in radians per second, with one oscillation per second or 1Hz corresponding to an angular frequency of 2□ rad s^{-1}(MIT).

An oscillator, or any material capable of periodic motion, can undergo resonance if subjected to a periodic (wave) or external force. Resonance is what occurs when an object or substance/material having a given natural frequency, or resonant frequency, encounters an external force (physical, electrical or magnetic) with a frequency that closely matches its natural frequency (Knight 2013). For example, the magnetic coil in the back of a speaker causes a magnetic periodic force, which creates vibrations of the speaker cone, sending out sound waves from the speaker.

Different factors like the damping in the system, which depends on the viscosity of the air or fluid surrounding the system, as well as the shape of the object, causes the vibrations or resonance within the object to last longer or quiet down more quickly (MIT). Systems of one degree of freedom, like a spring, only have one frequency at which resonance occurs. More complex systems with more than one degree of freedom, like coupled pendulums, can have resonance at multiple frequencies. Some things like organ pipes, quartz crystals and laser rods can resonate from vibrations within them at millions of resonant frequencies and are called resonators (Hyperphysics).

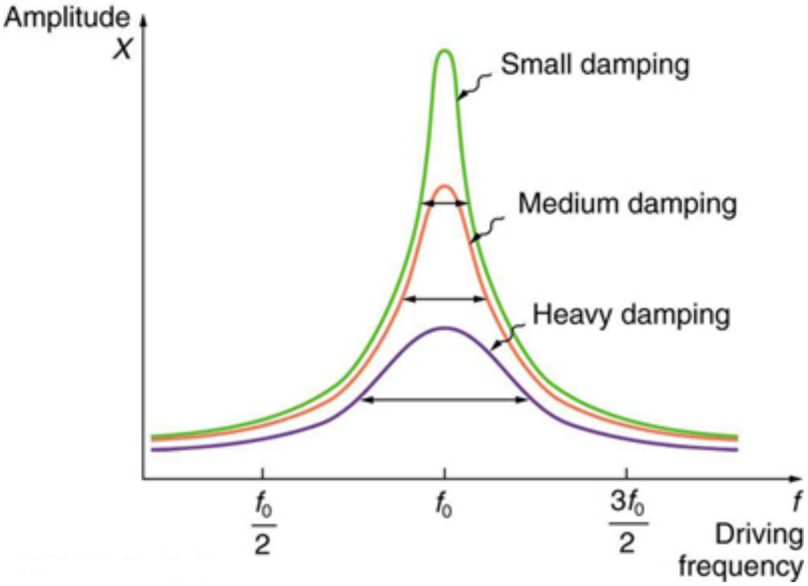


Figure 2-3 The effects of damping on the resonance amplitude of an oscillator. (https://www.boundless.com/physics/textbooks/boundless-physics-textbook/sound-16/further-topics-132/forced-vibrations-and-resonance-473-1966/)

People interact with environments to cause resonance in surrounding objects by creating a force on a system which has the ability to oscillate. The most common ways that this is accomplished involve creating a movement of air (as through wind instruments, vocalizations or whistling), striking, plucking or hitting, and rubbing, scraping, or bowing on and object in our environment (Cook 2002).

2.7.7 **Mathematical Applications of Resonance**

The differential equation behind pure resonance is shown in Figure 2-4. Pure resonance occurs when the natural internal frequency matches the natural external frequency of the object. The effects of damping and other forces that interfere with natural frequency are left out, which is why the equation in figure 2-4 is unbounded as it approaches infinity. Damping is the loss of energy that occurs in a resonating structure. If damping was taken into account, the equation would have limits as it approaches infinity, as shown in figure 2-5. Practical resonance will occur when the conditions in figure 2-6 are met, with w being external frequency and c as the coefficient for the effect of damping (Gustafson 2009).

$$x''(t) + \omega_0^2 x(t) = F_0 \cos(\omega t)$$

Figure 2-4 Differential equation for pure resonance (Dukes 2005).

$$mx''(t) + cx'(t) + kx(t) = F_0 \cos \omega t.$$

Figure 2-5 Differential equation for practical resonance (Dukes 2005).

$$\omega = \sqrt{k/m - c^2/(2m^2)} \text{ and } k/m - c^2/(2m^2) > 0.$$

Figure 2-6 Conditions for practical resonance (Dukes 2005).

2.7.8 Applications in Science

2.7.8.1 Electron Paramagnetic Resonance

Electron paramagnetic resonance (EPR) is a method of measuring distance in biological systems. One important aspect of EPR is its ability to detect the small number of unpaired electrons in a system, which can convey the structural layout of environments (Berliner, 2007). Further applications of EPR include studying the arrangement of proteins in membranes, studying protein folding and studying the structure of protein in intact biological systems (Berliner, 2007).

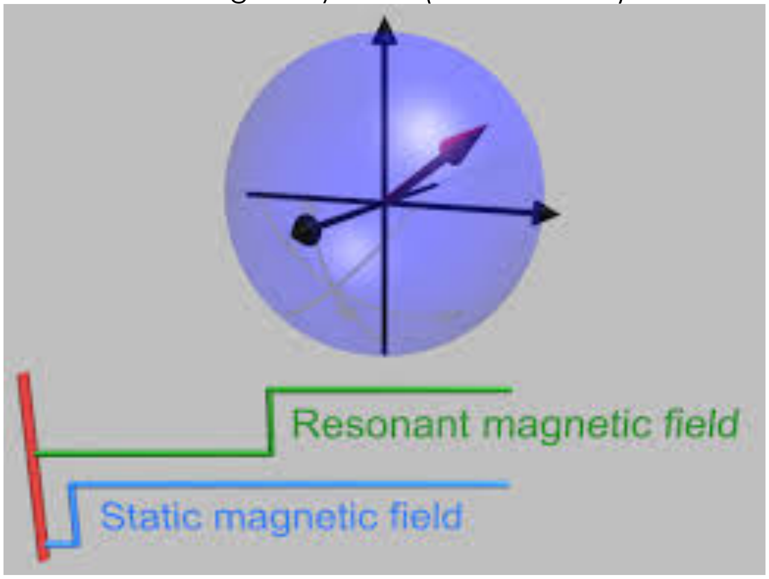


Figure 2-7 Electron Paramagnetic Resonance. Retrieved from: (https://upload.wikimedia.org/wikipedia/commons/d/d8/Animated_Rotating_Frame.gif)

2.7.8.2 Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) is a form of nuclear magnetic resonance that detects the directional and energetics change of protons found in water. This is used in accordance with a radio frequency current to stimulate the protons. MRI is non-invasive technology and can produce a detailed, three dimensional image of tissue. One advantage is that it does not use radiation or x-rays. A disadvantage of MRI is that it is a more expensive alternative to other tissue imaging techniques (National Institute of Biomedical Imaging and Bioengineering).

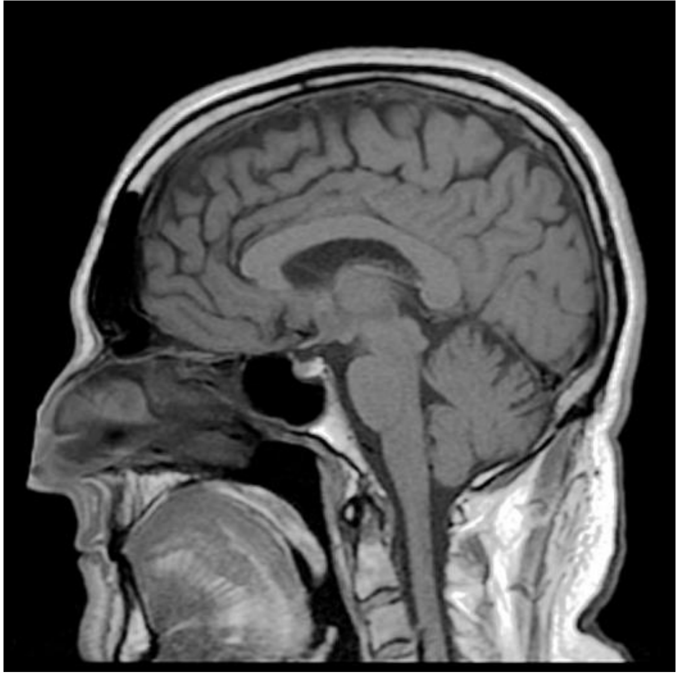


Figure 2-8 MRI of Skull. Retrieved from:(https://www.flickr.com/photos/reighleblanc/3854685038/sizes/o/in/photostream/)

2.7.9 Engineering applications of Resonance

The principles behind oscillations and resonance are applied in engineering to many different fields. This includes, but is not limited to: biomedical engineering, energy and power, fluid dynamics, communications, network sciences, and physical chemistry (Perseh 2013). Biomedical applications for engineers include many different devices, the most familiar of which is Magnetic Resonance Imaging technology. Resonance also plays a role in biomedical and computer science engineering of brain computer interface devices for robotics, prosthetics, etc. (Perseh 2013). The mathematical principles of these sorts of applications are well beyond the scope of understanding of middle school students, but it is interesting to note the variety of areas to which wave harmonics apply in engineering, science and technology.

Figure 2-9 A picture of the inner workings of an MRI machine. Retrieved from: (http://hellobougeotte.blogspot.com/2015/02/inside-mri-machine.html)

Bridges and structures are also influenced by the effects of resonance from outside forces like wind and earthquakes, and must be engineered to withstand these forces so they do not fail. A classic example of this, mentioned in several physics textbooks, is the collapse of the Tacoma Narrows Bridge in 1940 due to resonance with wind. The wind theoretically provided an external frequency that matched the mechanical frequency of the bridge and thus caused its collapse (Billah 1991). The effects of resonance on structures and building materials is therefore of some consequence in civil and architectural engineering.

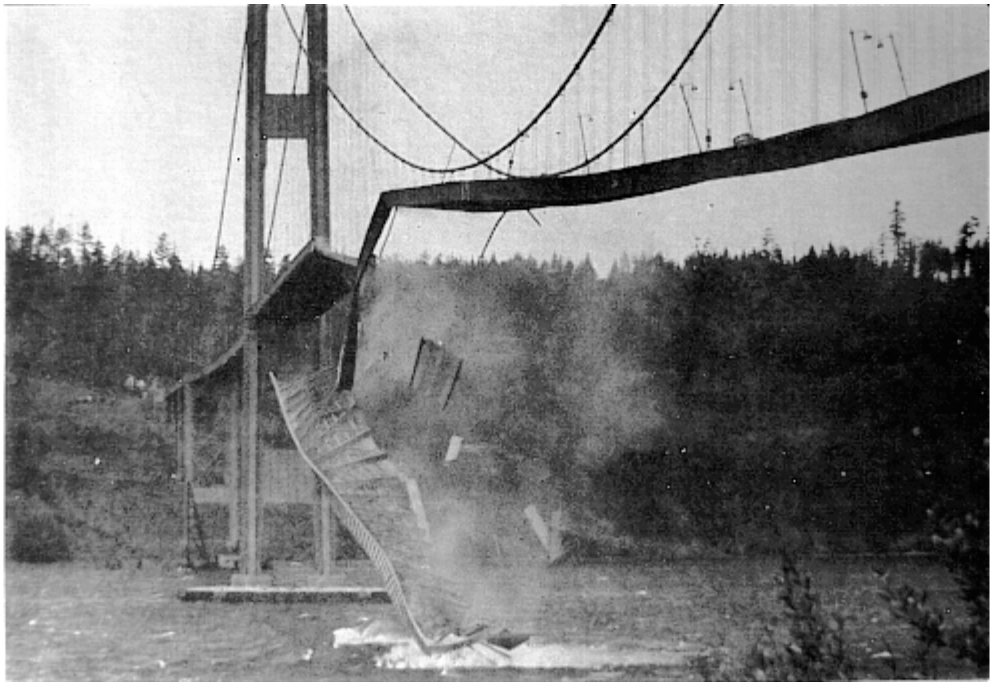


Figure 2-10 The collapsing Tacoma narrows bridge. Retrieved from: (http://faculty.plattsburgh.edu/margaret.campion/seconded/second/Kent/Kent.html)

2.7.10 Applications in Music

The concept of resonance can be applied to music by thinking of music in the context of sound waves, frequencies, and vibrations.

2.7.10.1 Sound

Sound is comprised of compressional waves originating from a vibrating object and moving through air molecules. When the compressional waves hit a person's eardrum, it vibrates the eardrum at the same frequency of the vibration of the source of the sound waves. The person's brain then interprets this as a specific tone (Lapp 8).

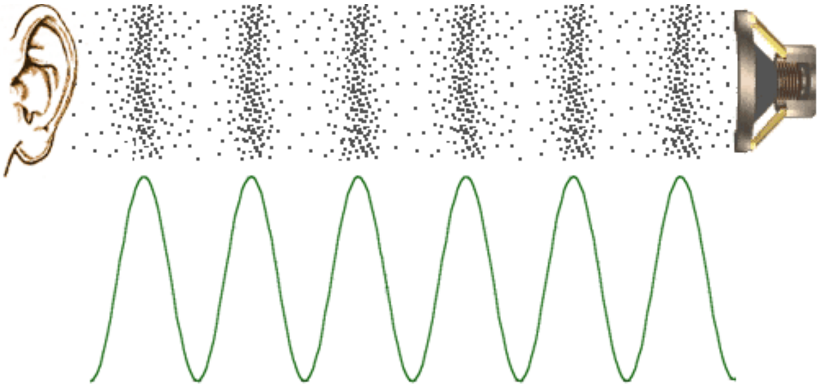


Figure 2-11 A Compressional Sound Wave and Its Representational Waveform. Retrieved from: (http://www.mediacollege.com/audio/images/loudspeaker-waveform.gif)

2.7.10.2 Standing Waves

Standing waves appear when two waves of equal frequency are acting in the same system, and end up reinforcing one another. With sound, standing waves tend to occur when a sound wave has the same resonant frequency as an object that it is acting upon. When someone builds an instrument, much of the design and choice of materials is chosen to maximize this effect (Lapp 2006).

A standing wave can be created in a flat metal plate by applying a vibration to the center of the plate at one of its natural resonant frequencies. A large speaker secured below the plate, and outfitted with some sort of tone generating device, could produce these frequencies. Because the plate vibrates too quickly for the human eye to see, sand is poured onto the plate as a visual aid. When a standing wave is achieved, the sand settles in the nodes of the wave, where the plate is not moving up and down, and forms striking geometrical patterns (Lapp 2006).

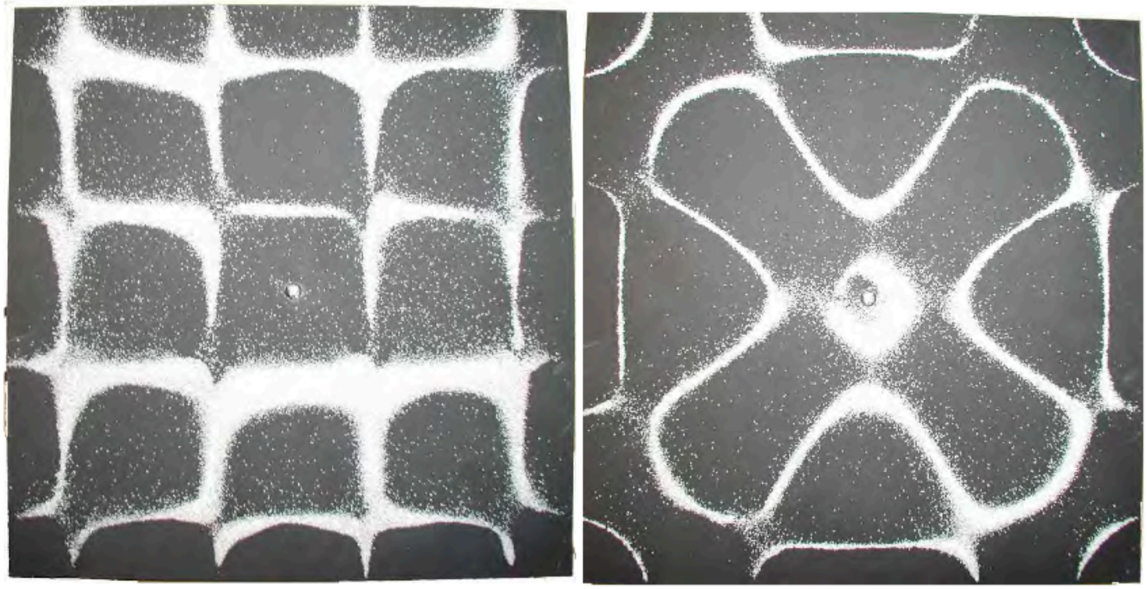


Figure 2-12 Sand Travelling to the Nodes of a Standing Wave (Lapp 2006)

2.7.10.3 Wave Impedance

One way to create standing waves in a musical instrument is by incorporating wave impedance. This is most easily observed in string instruments. When a string on a guitar is plucked, sinusoidal waves travel through the string and eventually run into the bridge or the nut. These rigid components bounce most of the energy of the wave back along the string to sustain the standing wave condition (Lapp 2006).

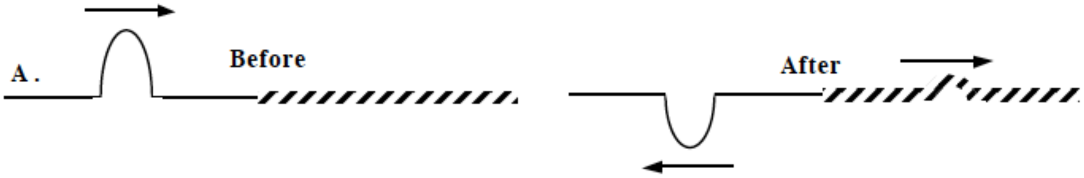


Figure 2-13 A Wave Before and After Being Reflected by a Rigid Object (Lapp 2006)

The small portion of the wave that the bridge absorbs is sent into the wooden body of the guitar, which vibrates and amplifies the tones created by the vibrations of the strings. Wave reflection can also be caused by a wave suddenly encountering a medium that has much less impedance than the one it was previously traveling through. When a wave travelling through the thin brass tube of a trumpet reaches the end of the instrument and finds a wider opening, the wave suddenly expands and much of it is sent back into the instrument, helping to sustain a standing wave (Lapp 2006).

Figure 2-14 A Wave Reflected After Encountering a Medium of Less Impedance: Note that the wave was not inverted (Lapp 2006)

2.7.10.4 Tension and Density

In string instruments and percussion instruments, two factors that affect frequency are tension and density. A guitar string and a drumhead both have to be pulled tightly across the resonating body of their respective instruments. This tension allows the instruments to create a frequency that will cause ideal resonance. The denser a string is, the more it tends to resist changes in motion, and therefore vibrates at a lower frequency. According to Lapp, the equation for the fundamental frequency of a stringed instrument is represented by the calculation:

$$f_1 = \frac{\sqrt{\frac{T}{\mu}}}{2L}$$

T=tension
□=density
L=length of string (Lapp 2006)

2.7.10.5 Beats

When two sound waves of different frequencies are moving through the same air space at the same time, they will create constructive interference, as well as destructive interference. Constructive interference is when the antinodes of both waves are lined up for a period of time, causing both sounds to amplify each other. Destructive interference is caused when the antinode of one wave is aligned with the node of the other, making the volume of both frequencies quieter, or even silent. If the frequencies are close enough together, they can cycle through these two types of interference fast enough to create an audible beat (Lapp 2006).

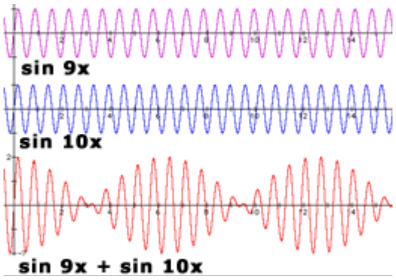


Figure 2-15 Two Sound Waves of Different Frequencies Add Together to Create Volume Fluctuations. Retrieved from: (http://www.indiana.edu/~emusic/acoustics/phase.htm)

2.7.10.6 Tuning Fork Demonstrations

A number of demonstrations can be done with tuning forks. Since the vibration of a tuning fork is so small and rapid, it is essentially invisible. A demonstration that clearly shows observers that the tuning fork is vibrating, is done by dipping the vibrating prongs of the tuning fork into a bowl of water, which causes the water to violently splash about (Lapp 2006). Acoustic resonance can be displayed, with two tuning forks of the same pitch, by striking one, dampening it with your hand, and observing that the other tuning fork has started ringing. Also, two tuning forks can demonstrate how two slightly different tones can create very audible beats.

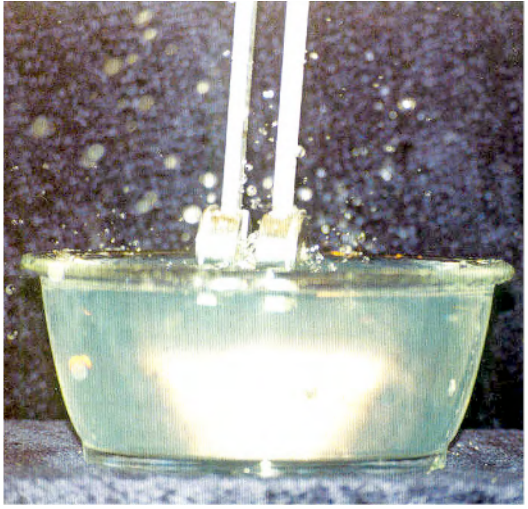


Figure 2-16 A Recently Stuck Tuning Fork Being Dipped in Water (Lapp 2006)

2.7.10.7 Guitar Strings

Guitar strings connected to tuning pegs could easily illustrate how tension affects the natural resonance of a string. If two strings are incorporated, they could also be used to create beats, and illustrate how the beats get faster as the two strings are tuned further away from each other.

Figure 2-17 Tuning Pegs at the Head of a Guitar. Retrieved from: (http://upload.wikimedia.org/wikipedia/commons/5/50/Classical_guitar_head_gears_DSC06945.jpg)

2.7.11 Materials and Safety

The types of materials used for this design project and the safety procedures for using each of these materials will be reviewed in this section.

2.7.11.1 Wood (types, durability)

Wood is a naturally durable and convenient building material. It does, however, degrade over time. Chemical and physical factors affect the durability of wood. Extreme conditions of temperature or humidity can shorten the lifespan of wood (Forde 2010).

2.7.11.2 Metal (types, characteristics)

Metal is a strong, durable material for building. The main environmental condition that affects metal is humidity, which could cause rust in ferrous metals (Goodheart Wilcox Co.).

2.7.11.3 Chladni Plates

A Chladni plate is a square metal plate that is used to show the nodes, or points of no displacement, of the metal plate. The location of the nodes depends on the natural frequencies of the plate. Sand is placed on the top of the plate and when certain vibrations are induced on the plate, a standing wave pattern forms with the sand settling in the location of the nodes. A standing wave pattern is the pattern of the location of the nodes and anti-nodes. Originally, a violin bow was used to create the vibrations on the plate which can be seen in figure 2-18 Now machines can be hooked up to the plate to create those frequencies more precisely like that of the plate in figure 2-19 (Physics Classroom).

Figure 2-188 Chladni plate with violin bow. Retrieved from: (http://www.hps.cam.ac.uk/whipple/explore/acoustics/ernstchladni/chladniplates/)

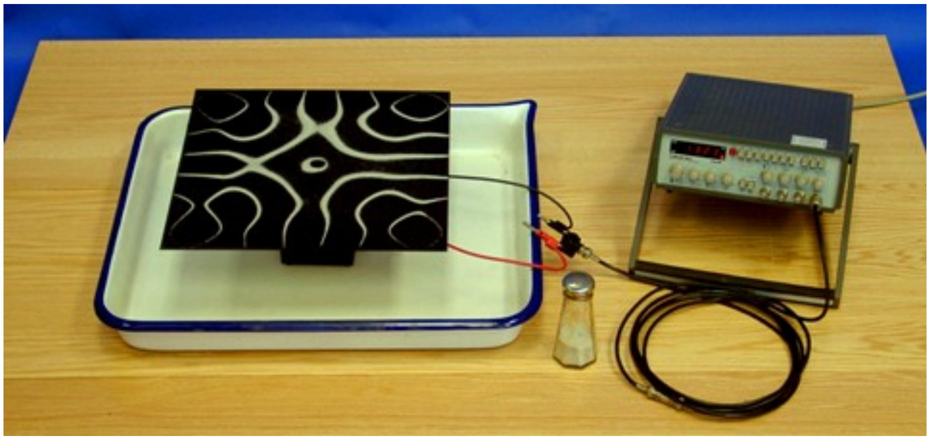


Figure 2-19 Chladni plate with machine. Retrieved from: (http://www.mediateletipos.net/archives/5679)

2.7.11.4 Soldering

When soldering, one should never touch the tip of the soldering iron. The soldering gun should always be returned to the holder or stand when it is not in use. The wires that need to be soldered should be held with tweezers and the cleaning sponge should always be kept wet. To work safely with solder: wear eye protection, use lead free solder, keep cleaners (flux) in bottles to reduce inhalation, and wash your hands after soldering. Lead exposure is dangerous. During soldering exposure can be created by absorption through skin or inhalation. To avoid inhalation work in a ventilated space. To avoid contact with skin wear non-flammable, long-sleeved shirts and long-legged pants (CMU 2013). Lead and silver solder waste should be placed in a covered, labeled container for reuse. Used sponges and any contaminated objects must be discarded as hazardous waste (Stony Brook University 2009).

2.7.11.5 Non-Newtonian Fluid (cornstarch and water)

Non-Newtonian fluids do not follow the rule that layers of fluid sliding twice as fast over each other will produce a resisting force that is twice as large, as the resistive force from the fluid sliding at the original speed. Non-Newtonian fluids will have a resisting force that is more or less than twice the original. For example, both gravy and quicksand have a proportionally higher resistive force when the speed of their layers moving past one another increase (Senese 2010). Cornstarch and water mixed together in an approximately one-to-one ratio create a non-Newtonian fluid (SEP). When using cornstarch, proper ventilation is needed to reduce risk of inhalation (SIRI 1985).

2.7.11.6 Sustainable Materials/ Recycling Materials

Sustainable materials are materials that are made without reducing non-renewable resources and negatively affecting the environment (Rutgers 2010). Many plastics and metals are reusable and recyclable. Sustainable material is either reused in its original form, or melted down to take on new forms (EPA 2014).

2.7.11.7 Speakers

Some resonance experiments include the use of speakers to create vibrations at certain frequencies that can transfer to other objects. Speakers create longitudinal sound waves that travel through the air (UMD).

3 Alternative Solutions

3.1 Introduction

The Alternative Solutions section describes the alternative solutions team Resonauts brainstormed for demonstrating resonance. Included is an explanation of the brainstorming process used and descriptions with corresponding diagrams of the alternative solutions.

3.2 Brainstorming

Our group spent an hour period of time brainstorming ideas for the resonance demonstration unit at Zane Middle School. We had discussed several ideas prior to this final brainstorming session, but stayed open to improving upon those ideas and developing new ideas. Our brainstorming notes are attached in appendix B. We first wrote down any and all ideas and topics or design components that any group member thought of for half an hour. During the second half hour of the brainstorming session, we force fit ideas together, crossed out irrelevant ideas, and grouped ideas and components together by type to form cohesive ideas. We then split up the design elements (two per team member) and developed the ideas.

3.3 Alternative Solutions

Through the brainstorming and planning process, the following eight designs were developed for educational aids in resonance demonstration in the classroom of Ken Pinkerton at Zane Middle School and at the Math Festival:

- The Chladni Visual Demonstration Unit
- The Guitar String Wave Lab
- Head Scratcher
- Levitation
- Tuning Fork Sound Demonstration
- The Jiggle It
- The Soprano
- Barton's Pendulums

3.3.1 The Chladni Visual Demonstration Unit

The Chladni Visual Demonstration unit is based on ideas from German Physicist Ernst Chladni, who developed the Chladni plate as a way to research sound and acoustics. He used a bow from a stringed instrument to cause his plates to vibrate. The alternative demonstration unit would not use a violin or bass bow, but instead has an Arduino (possibly a touch screen unit), which would contain a program loop to generate various sound waves at G on figure 3-1. Sound waves would go to the amplifier at F and then be transferred through the speaker wires to the modified speaker cone and magnetic coil at E where the sound would transfer to the metal plate C, causing it to vibrate. The metal plate is attached at the center with a metal rod at B to the riser D on top of the speaker coil. A very fine light colored sand would then migrate over the plate to rest in patterns that corresponded to the nodes and antinodes generated by the sound waves. Middle school students could experiment with programming the Arduino to change amplitudes and frequencies of the sound wave program and see how those changes effect the patterns shown by the sand on the metal plate. The tray H catches any sand that falls from the plate. The components are stored in a redwood carrying case for transport and storage.

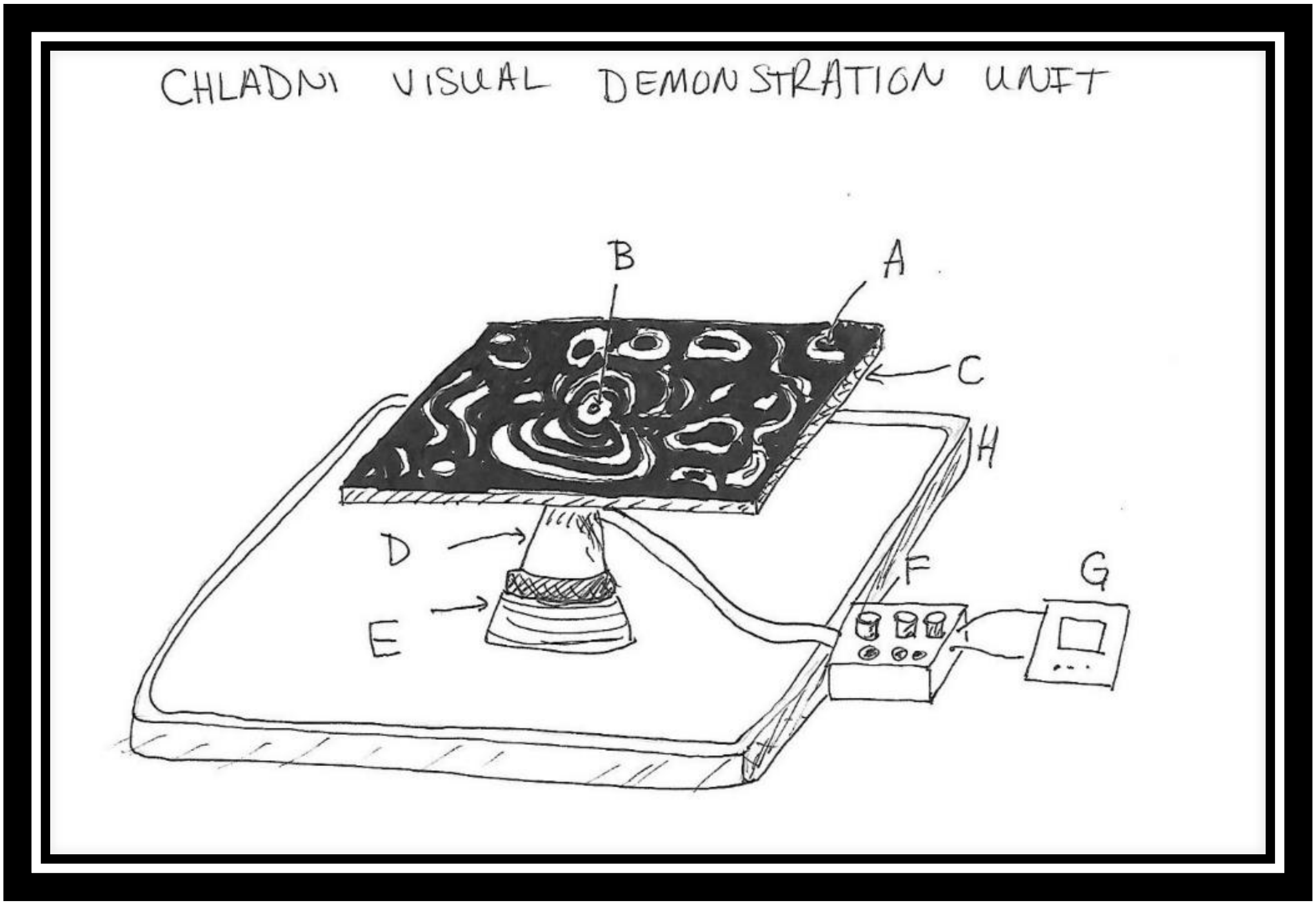


Figure 3-1 Drawing of the Chaldni Visual Demonstration Unit [A-fine sand/salt; B- metal rod; C-metal plate; D-riser; E-Magnetic coil; F-amplifier; G-arduino]

3.3.2 **The Guitar String Wave Lab**

The Guitar string wave lab is an interactive unit, which allows middle school students to explore the different frequencies generated by causing a string to vibrate with a harmonic wave. The hands on demonstration unit could easily be placed on a table in the classroom or at the Math Festival for students to explore. The stand will be made of a decorative wood, most likely salvaged scrap redwood. The bridge and saddle assembly, A of figure 3-2, holds one end of the guitar strings fixed in place. The strings are elevated across the table and run over the bridge at C, then be wrapped around the tuning pegs at B. Students will be able to tune the strings by turning the pegs. Turning the pegs shortens or lengthens the strings, thereby changing the frequency of the sound generated when a student plucks the strings. The guitar tuner at E shows the frequency in Hertz and lights up when a particular note is struck. The guitar string wave lab packs into a case for transport and storage.

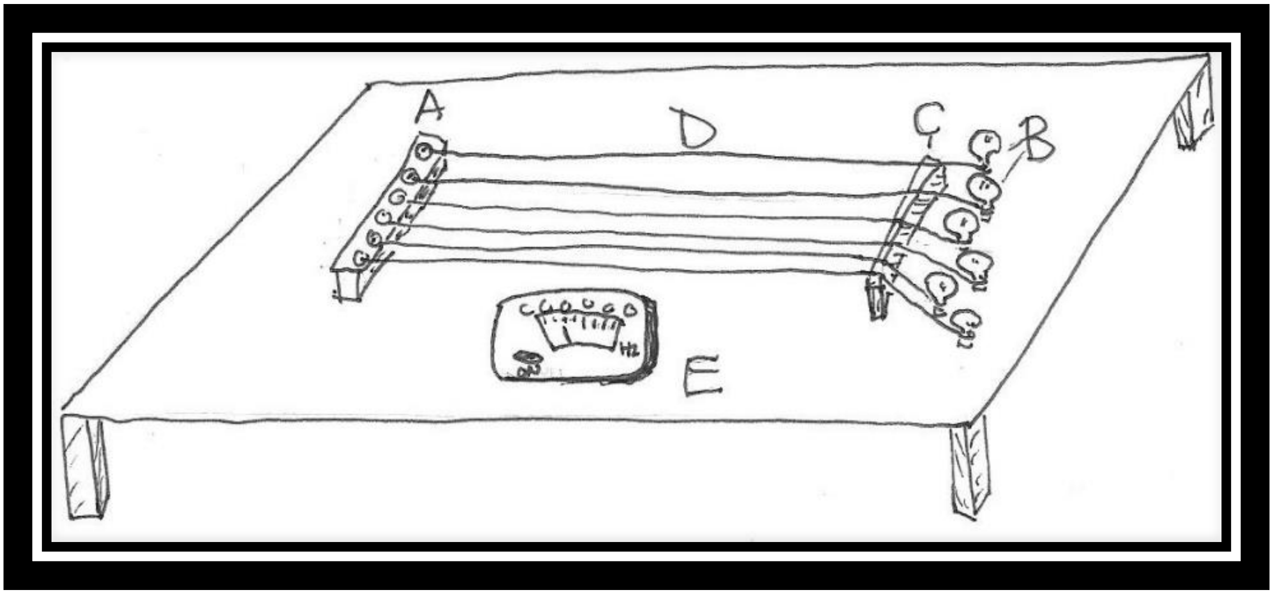


Figure 3-2 Drawing of the Guitar String Wave Lab [A-bridge and saddle; B-tuning pegs; C-bridge; D-guitar strings; E-guitar tuner]

3.3.3 **Head Scratcher**

The Head Scratcher solution shown in figure 3-3 is constructed with stainless steel and is connected to a redwood base. Redwood is also used to construct the case in figure 3.3-4. The stainless steel fingers on the Head Scratcher alternate between two different lengths, each resonating at different frequencies. The short fingers resonate with other short members, while the long fingers resonate do the same with their corresponding members. All fingers connect to the same stainless steel handle, which also connects to a redwood. The platform of the Head Scratcher fits into a carved out portion of the case, allowing the case to transform into a base that firmly holds down the Head Scratcher with interlocking clips. The large mass of the redwood case holds the Head

Scratcher stable for proper demonstration. Even though it is heavy, two roller wheels and two handles give the device portability which make it easy enough for a child to transport. The rectangular, sturdy shape of the redwood case is functional for multiple storing positions.

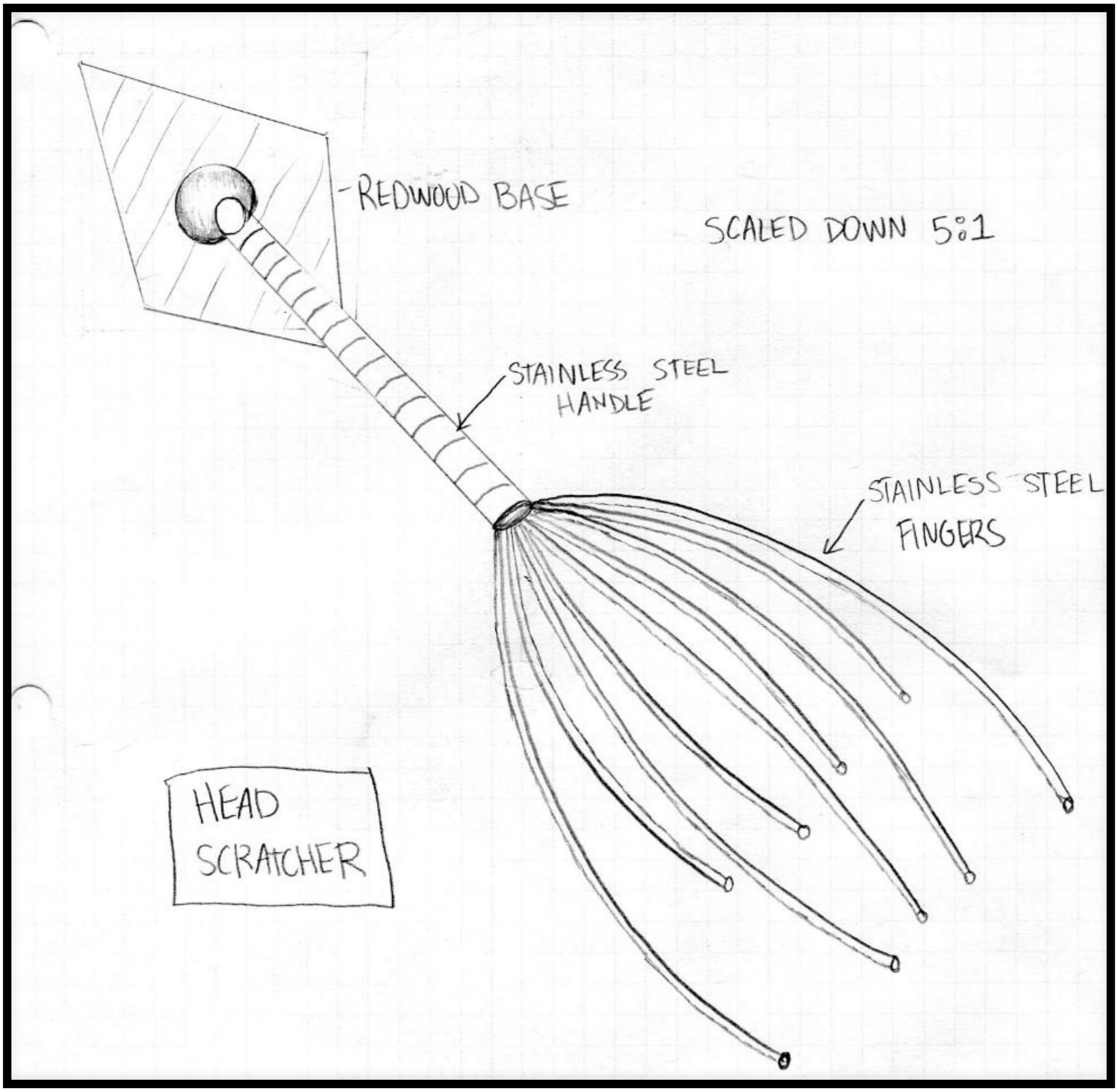


Figure 3-3 The Head Scratcher has to sets of stainless steel prongs, where prongs of the same length resonate with each other.

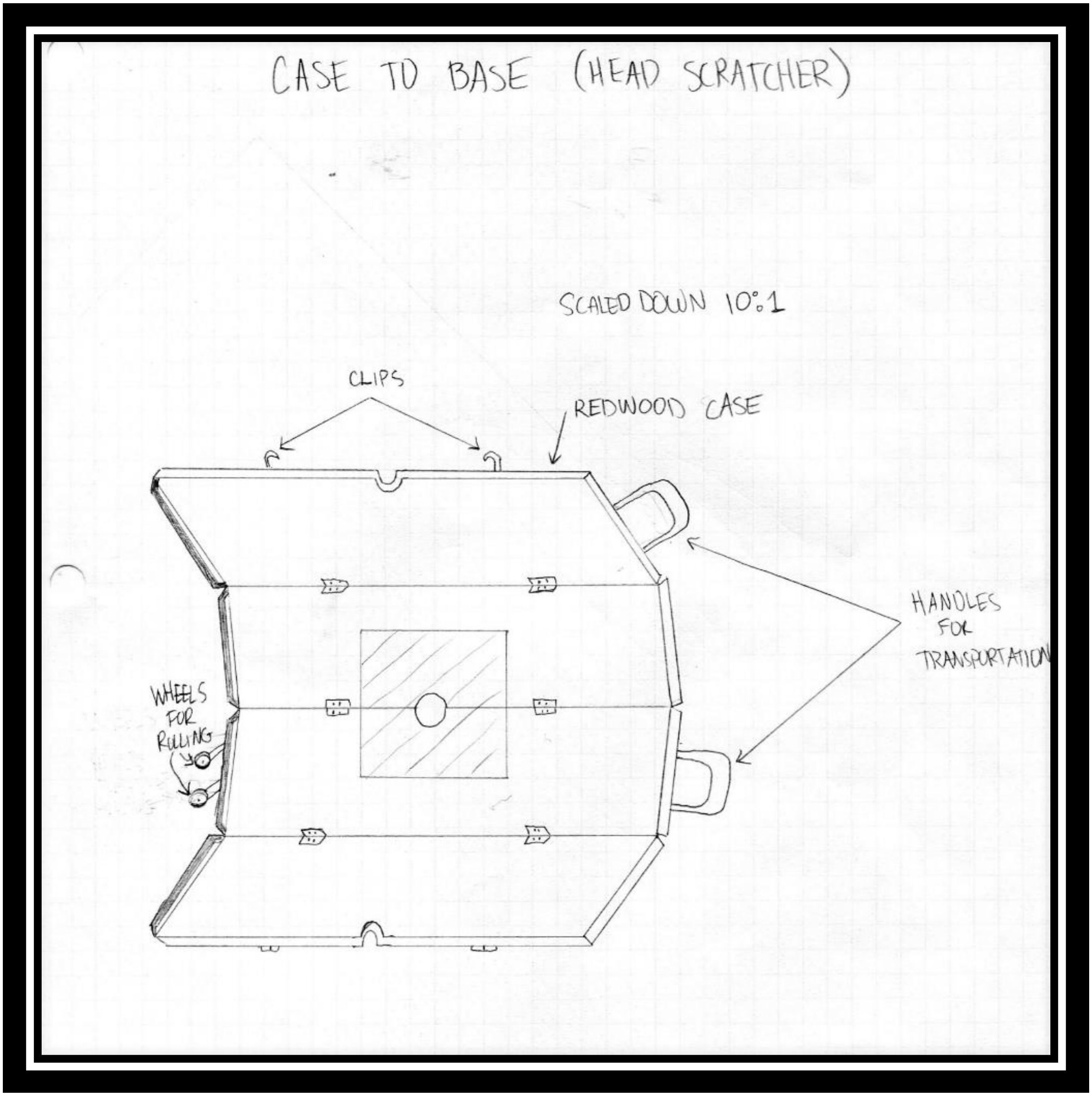


Figure 3-4 Case to Base for Head Scratcher

3.3.4 **Levitation**

The Levitation solution shown in figure 3-5 is constructed from a speaker, redwood and stainless steel. The speaker is situated at one end across from a stainless steel plate. The speaker and stainless steel plate are both parallel to each other and orthogonal to the redwood base. The distance between the speaker and stainless steel plate are set so that the period of the sound wave generated from the speaker meets with the plate at any half-period. The sound waves that bounce off the plate and back towards the speaker are at opposite amplitudes, which [The nP+1/2 rate] produces an encompassing effect that holds small objects in place, trapped between alternating sound waves, producing the visual effect of levitation. A power source is used for this demonstration. A cellular phone with a sound frequency application is also used to monitor and control the frequency emitted from the speaker. The device is contained in a redwood case. The redwood case is used as a stand for the Levitation device during demonstration and a box for storage when not in use. The levitation demonstration is stored upside down in the redwood case with extra room available for extension cords.

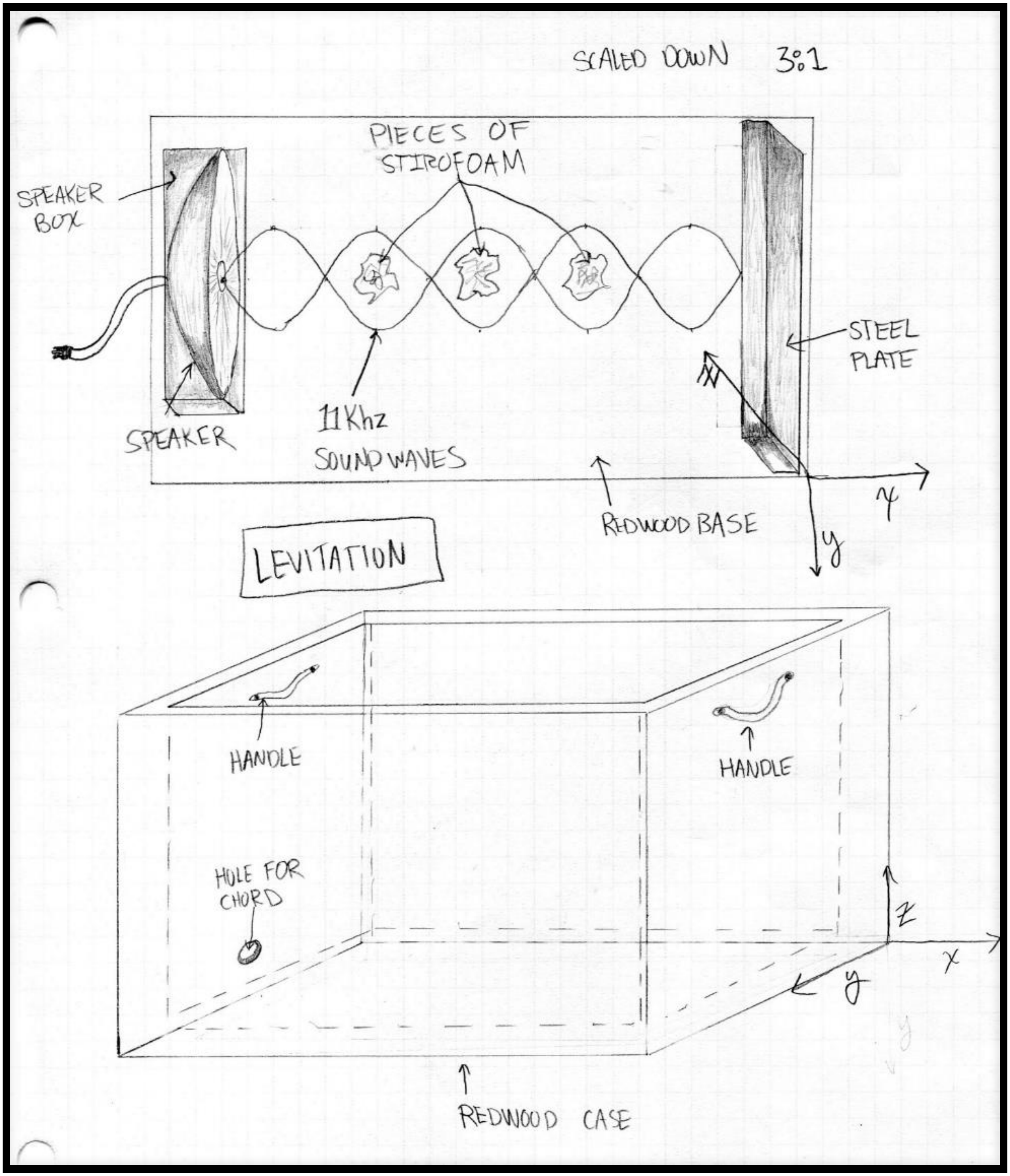


Figure 3-5 Levitation Demonstration - Sound waves at alternating amplitudes levitate small objects by the pockets formed between the waves.

3.3.5 **Tuning Fork Sound Demonstration**

The Tuning Fork Sound Demonstration is a collapsible, rotating tuning fork resonance demonstration. It is a classic tuning fork demonstration, but includes multiple tuning forks showing resonance works between metals with the same natural frequencies. Different lengths in tuning forks affect the natural frequencies; so two tuning forks of different lengths do not resonate with each other. The other pair of tuning forks will be in location D in figure 3-6. The tuning forks are placed in sockets that are mounted on a metal (or some other material) rod, part C in figure 3-6, so they rotate and fold down into the project. The wooden base the metal rod rests in, shown as A in figure 3-6, can also rotate, so the tuning forks face each other. To enhance the sound of the tuning fork, a sound box is placed over the base and the tuning fork is placed through the sound box attachment and into the socket. The tuning forks and their bases are located inside case E, which can be closed and transported.

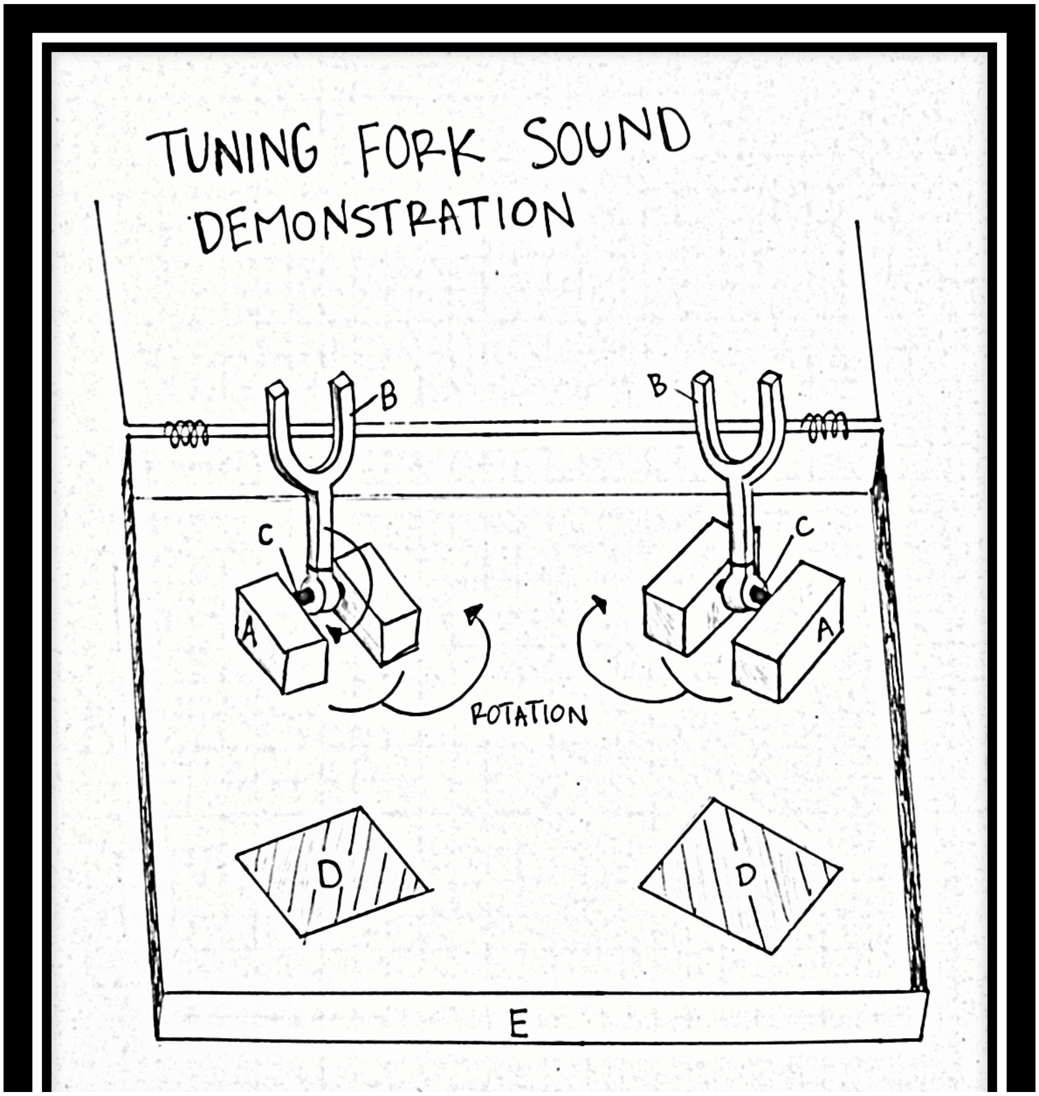


Figure 3-6 Tuning Fork Sound Demonstration

3.3.6 **Jiggle It**

The Jiggle It is a resonance demonstration with two plates made of different metals and non-Newtonian fluid. The metal plates, shown as B in figure 3-7, force the vibrations of the natural frequency of the metal plates on to the non-Newtonian fluid, A in figure 3-7. The differences between the natural frequencies of the two different metals are shown in the standing wave patterns that form in the non-Newtonian fluid. This is similar to demonstrations done with sand on Chladni plates. The metal plates are detachable for cleaning up and the non-Newtonian fluid is thrown away at the end of the demonstration. These parts are relatively flat so they are stored in a compact container.

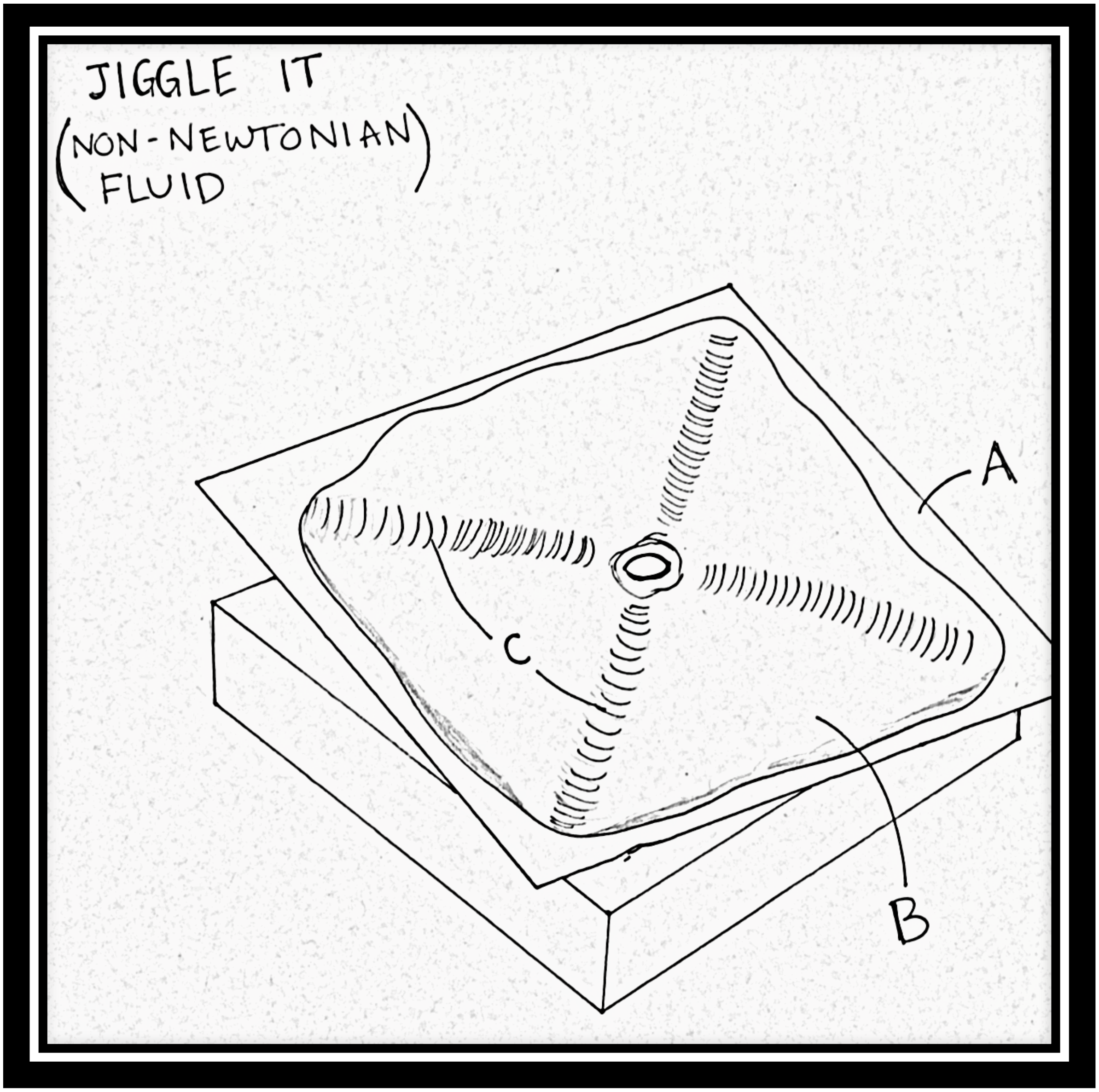


Figure 3-7 the Jiggle It (non-Newtonian fluid on a resonating plate)

3.3.7 **The Soprano**

The Soprano is a demonstration device that shows how resonance may be acting violently on an object even though the human eye may not be able to see it. This design takes the familiar trope of an opera singer breaking glass with his or her voice, and mechanizes it for optimum destructive efficiency. It consists of a speaker, tone generating technology, and a wine glass. First, the wine glass is set directly in front of the speaker. The operator of the demonstration then flicks or taps the glass for an idea of the pitch of the glass's natural frequency. Next, the Soprano is used to generate that tone at very high amplitude until the glass shatters. The reason this demonstration is possible is because the sound waves produced by the speaker are causing the wine glass to flex and unflex extremely rapidly. At the right frequency, one of the compression waves hits the glass at a point on the rim, causes the glass to flex inward at that point, the glass then produces a corrective force outward at that point, overcorrects, and just as the glass starts to naturally pull that point back in, another sound wave hits it and combines with the corrective force of the glass to drive its oscillation even more forcefully.

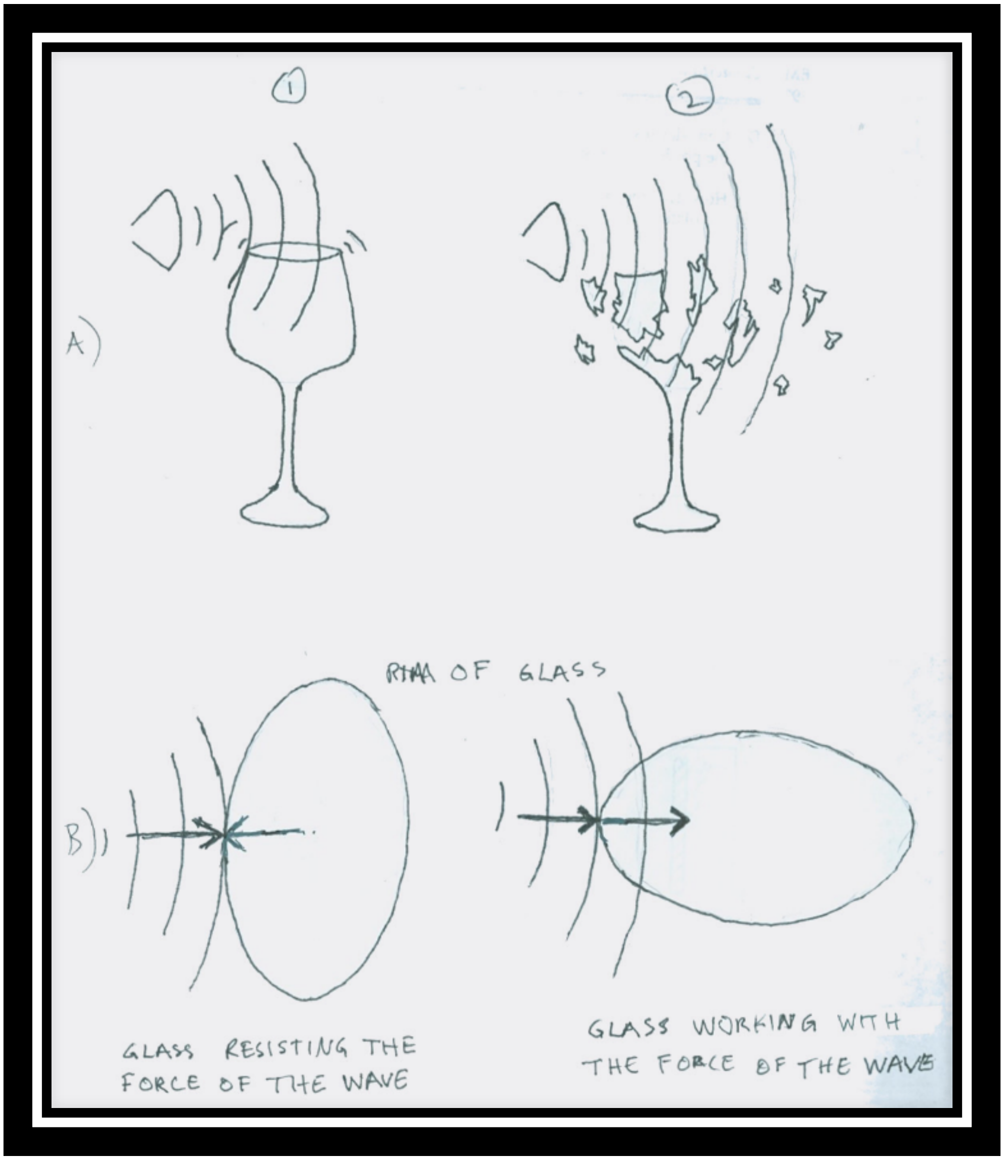


Figure 3-8 The Soprano – Sound waves at specific frequencies (frequencies glass will resonate at) are passed through a wine glass, causing the glass to resonate (vibrate) and eventually shatter.

3.3.8 **Barton's Pendulums**

Barton's Pendulums are a system that is commonly used to demonstrate the physical phenomenon of resonance. It consists of a set of five to ten pendulums of different lengths that are hung from different points on the same horizontal string. One of the pendulums is much heavier than the rest, which causes it to drive the whole system. This pendulum is referred to as the driver. When the driver is set in motion and oscillates the system at its own resonant frequency, an observer can see that some of the pendulums swing in larger arcs due to them having natural frequencies that are closer to the driver's. The further away a pendulum's resonant frequency is from the driver's, the less it moves. The factor that determines each pendulum's resonant frequency is the length of the pendulum arm that it is hanging on (which is usually a string).

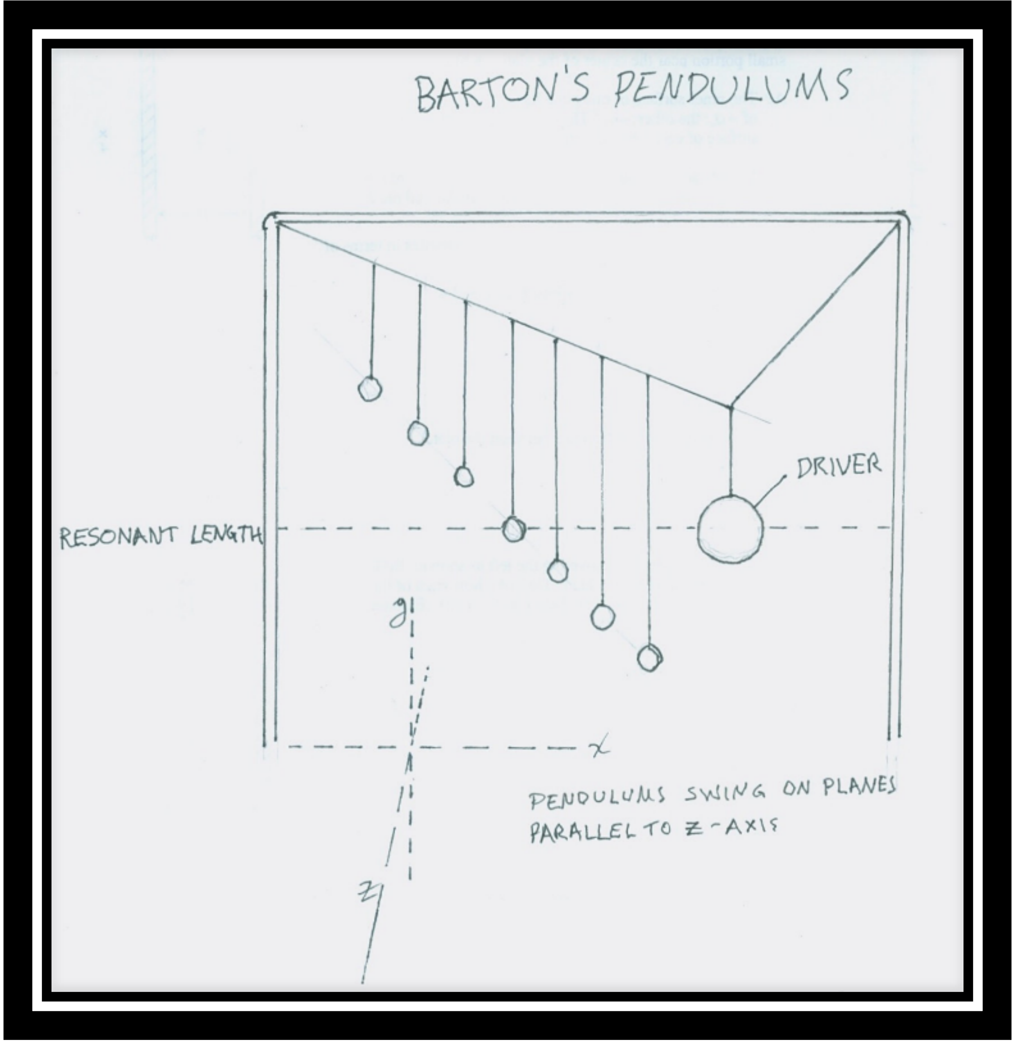


Figure 3-9 Barton's Pendulum – The amplitude and frequency of the swinging pendulums visually demonstrates the mechanism of sound waves.

4 Decision Process

4.1 Introduction

This section describes the process employed by Team Resonauts to compare the alternative solutions and make a final decision for the design of the resonance demonstration unit for Zane Middle School. Definitions of the criteria for the demonstration unit are provided. A description of the Delphi matrix, used for making the final decision, is also included. The last subsection is an explanation for the final decision.

4.2 Criteria Definitions

The following criteria are used for the decision making process. These criteria provide a means to quantify and compare the quality of the alternative solutions and arrive at a final decision.

Safety: Defined as the ability to prevent injury of any kind to anyone using the demonstration unit.
Educational Value: Defined as the ability of the demonstration to visually demonstrate resonance to observers and educators in teaching the principles of resonance.
Cost: Defined as the total time in hours and money spent in dollars to develop and build the final demonstration unit.
Durability: Defined as the time the demonstration unit will last without breaking or needing repairs and its ability to withstand normal wear and tear.
Aesthetics: Defined as the designs visual appeal and ability to draw positive attention to itself.
Portability: Defined as the ease with which the demonstration can be packed up and moved between locations and its ability to be easily stored.
Ease of use: Defined as the accessibility of the demonstration unit to any educator without having to spend a lot of time learning how to operate the demonstration.
Solutions: Defined as the final decision took into consideration the following eight solutions. Refer to Section 3 for more detailed information about these solutions. The considered solutions are listed below.

- The Chladni Visual Demonstration Unit
- The Guitar String Wave Lab
- Head Scratcher
- Levitation
- Tuning Fork Sound Demonstration
- The Jiggle It
- The Soprano
- Barton’s Pendulums

4.3 Decision Process

The first step of our decision process was to brainstorm ideas for potential alternative solutions. We then chose the best ideas from our brainstorm session and refined them to give us a clearer idea of what the building process for each design would entail. After receiving feedback from the client, we used a Delphi Matrix to assign numerical ratings to each solution based on specific weighted criteria in table 4-1. The results of the Delphi Matrix were the primary influence on our final decision.

Table 4-1 Table of Weighted Criteria

Criteria	**Weight**
Safety	8
Educational Value	10
Cost	9
Durability	9
Aesthetics	6
Portability	8
Ease of Use	7

4.4 Delphi Matrix

We used a Delphi matrix for our decision process. In a Delphi matrix weights are assigned to each of the criteria based on the values of the client. Each alternative solution is graded from 0-50 on each criteria, with 50 being the highest score. The weight assigned to each criteria and the score given to each alternative solution for the criteria are then multiplied, and that value is summed into the final score for each alternative solution. The alternative solution with the highest cumulative score meets the criteria the best.

Table 4-2 The Delphi method weights the criteria based on importance. The alternative solutions are given a score for how well they meet the criteria. These scores are multiplied by the weights and the scores are summed for a final score of each alternative.

		Alternative Solutions (0- 50) high							
Criteria	**Weight (0-10) high**	Chladni Visual Demo	Guitar String Wave Lab	Head Scratcher	Levitation	Tuning Fork Demo	Jiggle It	The Soprano	Barton's Pendulums
Safety	8	45 360	35 280	40 320	40 320	45 360	45 360	30 240	45 360
Educational Value	10	50 500	35 350	35 350	30 300	50 500	40 400	40 400	45 450
Durability	9	35 315	35 315	40 360	35 315	45 405	35 315	30 270	40 360
Aesthetics	6	40 240	25 150	35 210	40 240	40 240	40 240	40 240	45 270
Portability	8	45 360	45 360	40 320	30 240	45 360	40 320	40 320	35 280
Ease of Use	7	45 315	45 315	50 350	10 70	50 350	35 245	30 210	45 315
	Total	**2090**	**1770**	**1910**	**1485**	**2215**	**1880**	**1680**	**2035**

4.5 Final Decision

The final decision is based off of the Delphi Matrix in table 4-2 and the client's decision with Team Resonauts. The decision came to a tie between the Chladni Visual Demonstration and the Tuning Fork Sound Demonstration. Both demonstrations will be built and displayed at the Math Festival. The client and Team Resonauts decided that it is best to have more than one demonstration to increase the learning capacity at the Math Festival. In the end, Team Resonauts decided against building the tuning fork demonstration because of how common the tuning fork demonstration is and the scarcity of tuning forks with sound boxes for sale locally. All effort was then put into the Chladni Visual Demonstration Unit to make sure it clearly showed resonance in a way middle school students could understand.

5 Specification of Solution

The purpose of the solution specification is to present the specific components of the final design that was stated in the last section. The information in this section includes details about the physical design structure, total design hours, materials, cost analysis, results of the design implementation at the Humboldt Math Festival, and instructions for use.

5.1 Solution Description

The Chladni Visual Demonstration Unit is a portable visual demonstrations of resonance, which is implemented for the final solution in order to provide client Ken Pinkerton with a classroom resonance demonstration aid for his curriculum. The Chladni Visual Demonstration unit shown in figure 5-1 functions by using an up-cycled 4-Ohm subwoofer speaker, along with an amplifier and a sound wave generator to create mechanical vibrations in a metal plate. These vibrations match the frequency of the sound waves being generated and create patterns in salt sprinkled uniformly on top of the metal plate.

The vibrations are transferred to the plate by a threaded metal rod attached through the exact geometric center of the metal plate shown in figure 5-1. The central threaded metal rod has a rubber stopper with a hole drilled in it attached to the bottom where it is taped onto the speaker diaphragm in order to prevent damage to the speaker. As the speaker diaphragm moves up and down with the frequency the sound wave generator creates, it transfers that into the up and down motion of the metal rod. The mechanical energy created by the motion transfers into a vibration at the same frequency as the sound in the metal plate. As the plate vibrates, it has standing wave patterns form throughout the metal and cause the salt to move. The salt is moves off sections where the metal is vibrating and into non-vibrating areas, where is can rest calmly. The vibrating and non-vibrating regions on the steel plate shown in figure 5-7 cause the salt to form patterns on the plate. The salt patterns are different for a wide range of frequencies.

Two metal plates, one made of aluminum and one made of steel, so that students may see how the different metals react to different frequencies. Both of the metal plates are thirteen-inch square plates. The plates are painted red with falcon for the Zane Middle School Falcons, and in order to create a contrast so the white salt patterns are more easily visible on the plate.

A plexiglass triangle is bolted to the speaker with metal rods and holds the central rod that attaches to the plate stable so that it can move freely up and down, without any side-to-side motion. The illustration of the Chladni Visual Demonstration Unit is shown in figure 5-1, with the dimensions of the components.

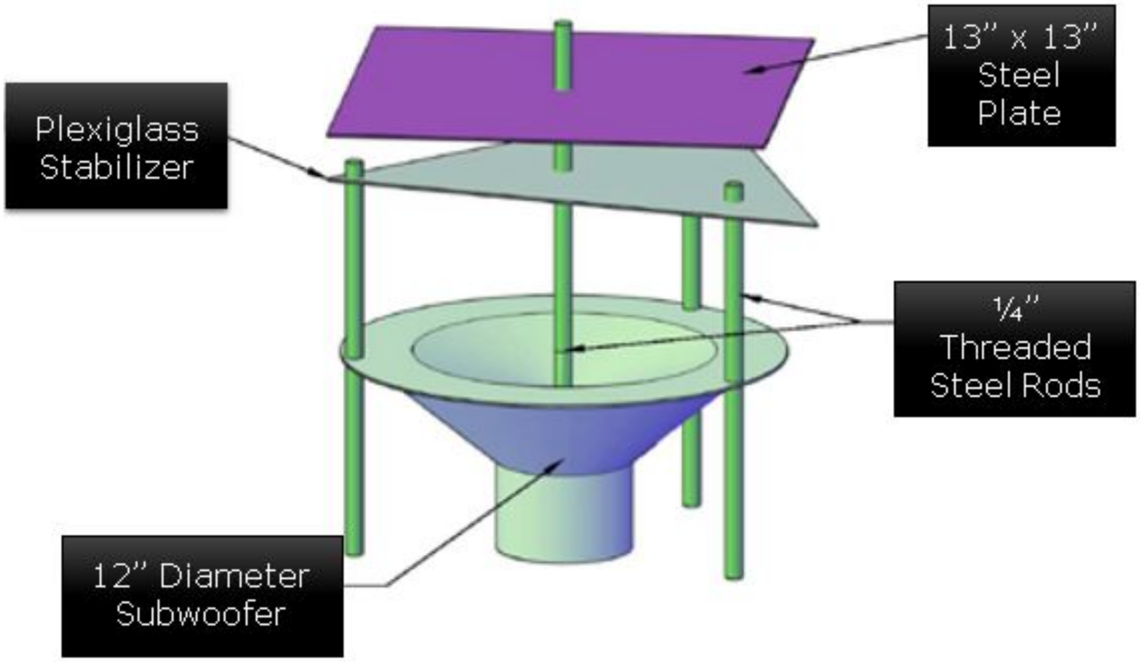


Figure 5-1 Auto CAD drawing of the Chladni Visual Demonstration Unit's main components drawn by Kelly Rodman.

5.1.1 Recycled Redwood Storage Box

The Chladni Visual Demonstration Unit is stored and transported in a redwood case made from recycled redwood boards, with carrying handles for increased portability. The speaker, amplifier, sound wave generator, metal plates and all other components fit inside the redwood case for storage. The lid of the Case closes around the Chladni Visual Demonstration Unit in order to dampen the sound and keep all of the wiring enclosed for safety. The case is shown in figure 5-2.

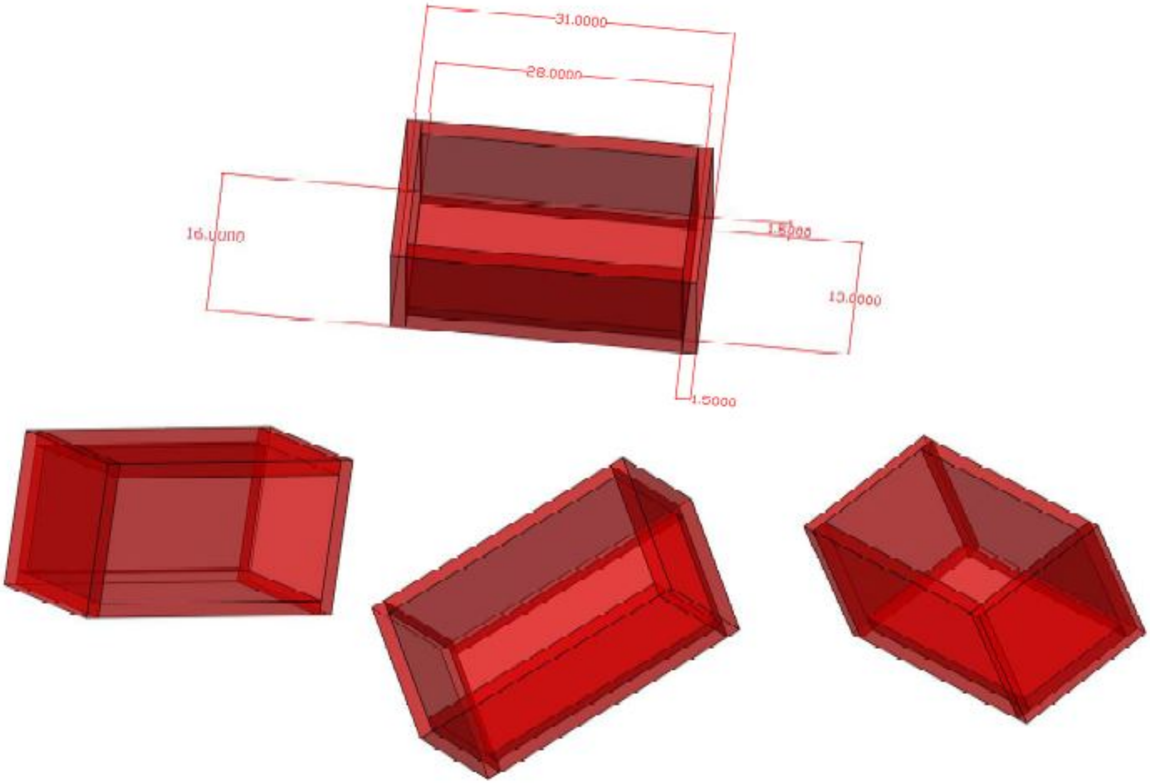


Figure 5-2 Auto CAD drawing of the Chladni Visual Demonstration Unit case with dimensions. Drawn by Robert Toledo III.

5.2 Cost Analysis

The cost analysis consists of design, material, and maintenance costs for the Chladni Visual Demonstration Unit.

5.2.1 Design Costs

The design costs for the Chladni Visual Demonstration are calculated as the number of hours spent on the project from all members of the Resonauts. The design costs are shown below in figure 5-3. A total of 162 hours was invested. The majority of time was used for testing and implementing the Chladni Visual Demonstration.

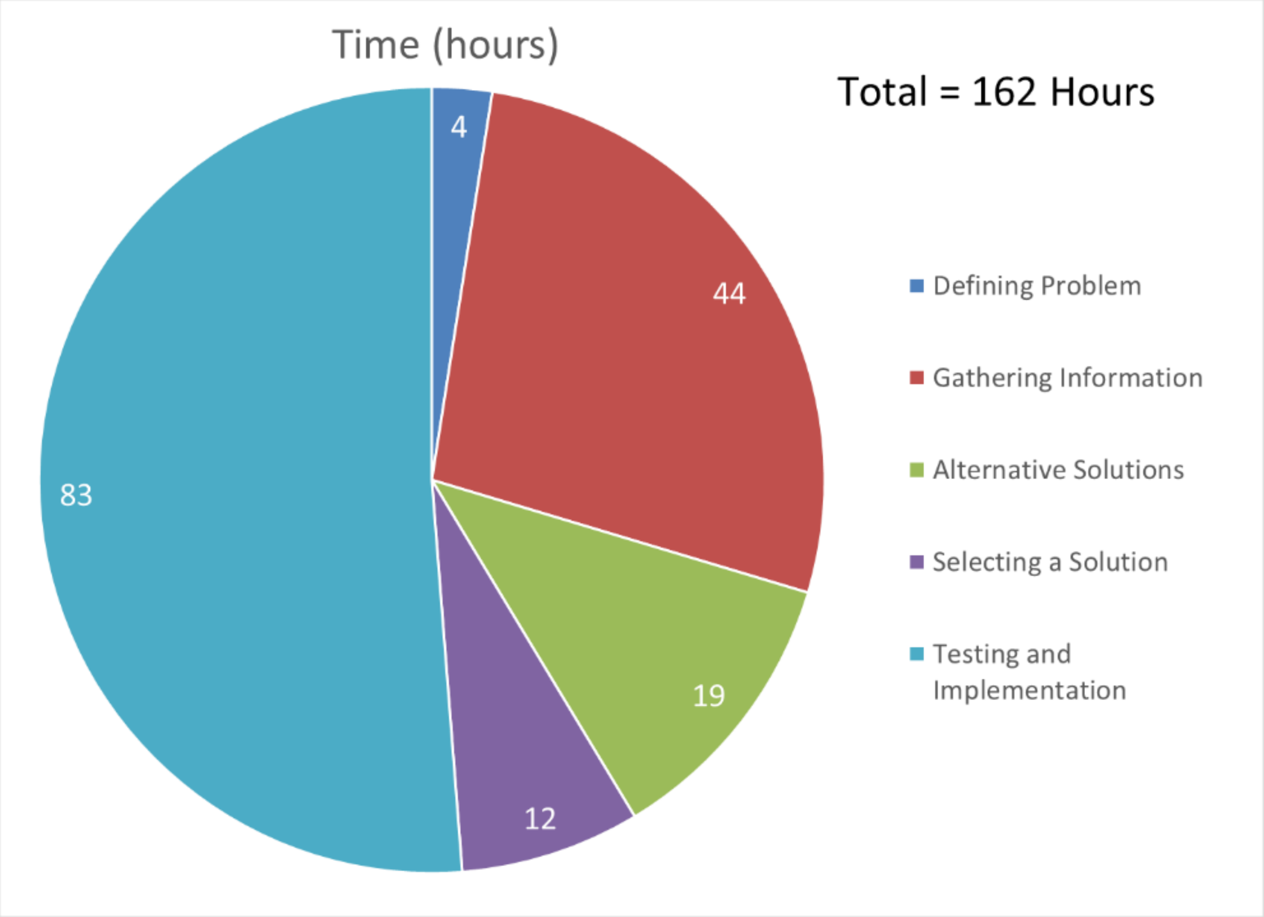


Figure 5-3 Pie Chart of time needed to design, test, and build the Chladni Visual Demonstration Unit. A combined time of all individual team members' time.

5.2.2 Material Costs

The material costs for the Chladni Visual Demonstration is based on the United States dollar totaling at 131.39 USD. All materials necessary to construct the Chladni Visual Demonstration are available through various sources in the Arcata/Eureka area. The items used for construction as well as suggested and actual costs are given below in Table 5-1.

Table 5-1 A table of retail costs of all materials, compared to the cost incurred in designing the demonstration.

Item	Quantity	Suggested Cost (USD)		Actual Cost (USD)	
		Each	Total	Each	Total
Hardware	20	0.30	6.00	0.30	6.00
Hooks	10	0.20	2.00	0.20	2.00
Spray Paint	2	2.50	5.00	2.50	5.00
Super Glue	1	4.49	4.49	4.49	4.49
Shelf Bracket	1	7.99	7.99	7.99	7.99
Dowel (1"x48")	2	5.99	11.98	5.99	11.98
Threaded Rod (1/4"x24")	4	2.99	11.96	2.99	11.96
Adapters	2	7.99	15.98	7.99	15.98
Pyramid Amplifier	1	32.99	32.99	32.99	32.99
Function Generator	1	22.99	22.99	22.99	22.99
Chladni Plate	1	8.99	8.99	Donated	Donated
Redwood (3/4")	10 ft^2	9.99/ft^2	99.90	Donated	Donated
Subwoofer	1	49.99	49.99	Donated	Donated
SubTotal (USD)			280.26		121.38
Tax (8.25%)			23.12		10.01
Total (USD)			**280.26**		**131.39**

5.2.3 **Maintenance Costs**

Maintenance costs for the Chladni Visual Demonstration are low because when in use, the demonstration unit will be under instructor supervision. The Chladni plate speaker unit is relatively stable and will hold for years. The only maintenance to this piece of the demonstration will be tightening bolts as the vibrations loosen them, along with removing the salt or sand used on top of the plate from components of the demonstration unit in order to keep it in good working order. Cleaning the demonstration is accomplished by lifting it out of the box, emptying the box of material, and brushing material off the individual components.

5.3 Implementation

The implementation of the Chladni Visual Demonstration is relatively simple. The demonstration unit must first be connected to a power source. The amplifier and function generator both require electricity to work. A horizontally level surface is required so that the material being controlled by sound waves does not vibrate off of the Chladni plate. Due to the medium difficulty of setting up and running the demonstration unit, adult supervision is required to use.

5.4 Results

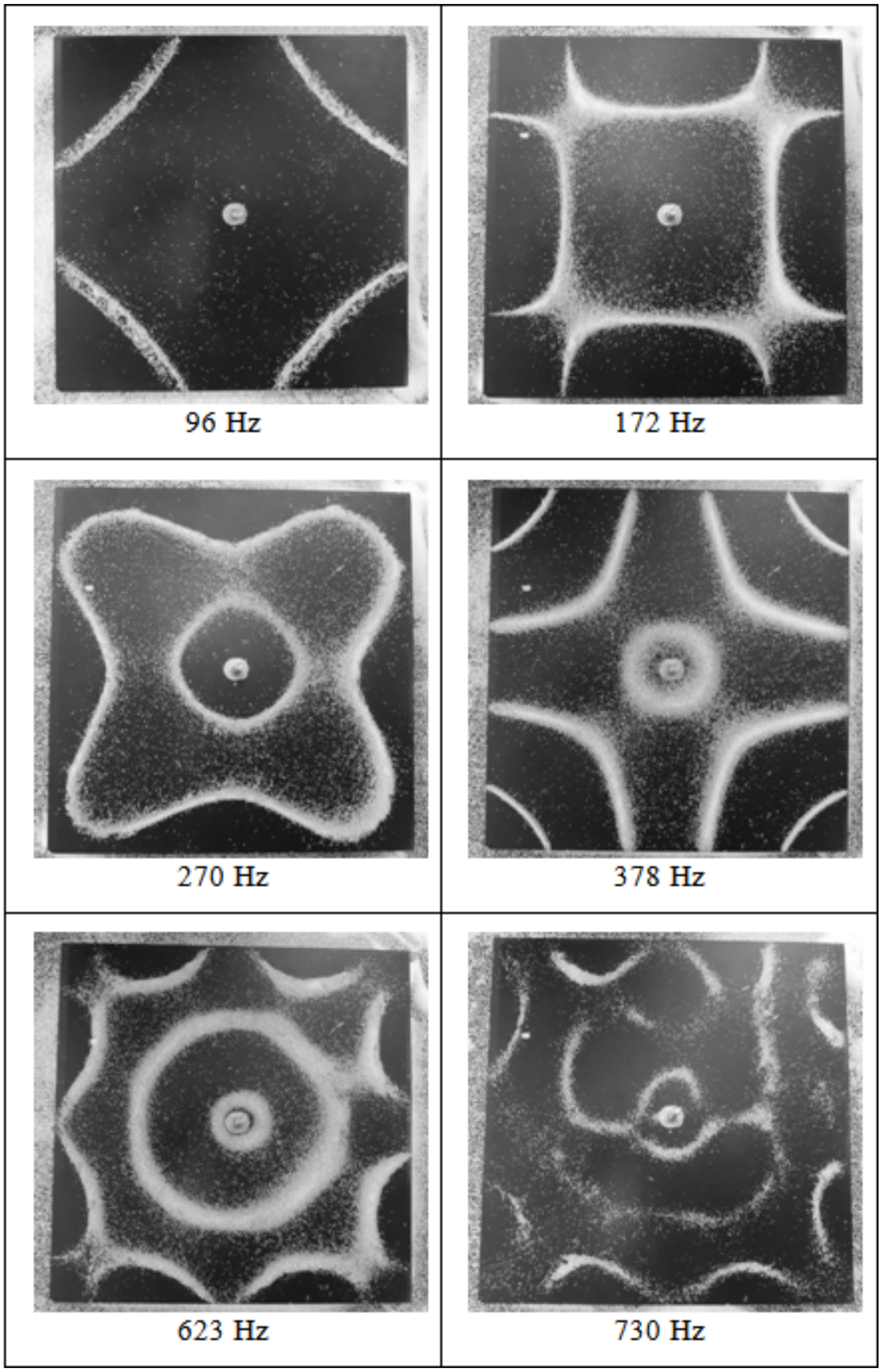
The Chladni Visual Demonstration has been tested and works according to design. A working design can be seen below in figure 5-5 and figure 5-7. Salt poured on the plate forms several different unique geometric patterns. The redwood box and lid have cut down on some of the excessive volume of the speaker. Team Resonauts have shown the design to Mr. Pinkerton who is enthusiastic about employing the demonstration for use in his classroom at Zane Middle School. The demonstration unit has been debuted with success at the Humboldt Math Festival at the Bayshore Mall in Eureka as seen in figures 5-4, 5-5, and 5-7.

Figure 5-4 Humboldt County Students visiting the demonstration unit at the Humboldt County Math Festival April 25th, 2015.

Figure 5-5 Humboldt County Students interacting with the demonstration unit. The pattern shown occurs at 175 Hz.

Through several days of testing, the team has been able to find a range of frequencies at which the Chladni Visual Demonstration functions best. The optimal operation is at frequencies between 75-350Hz. The frequencies generated by the Chladni Visual Demonstration Unit, while not the exact replicas of, are comparable to the patterns shown on other mechanical wave drivers at similar frequencies. The higher the frequency, as shown in figure 5-7, the more intricate and complicated the patterns formed in the salt on top of the steel plate. The tone generator in figure 5-6 allowed students to successfully change the frequencies on their own and see the patterns in the salt shift with very little instruction. The demonstration is durable, and able to withstand interaction with at least 150 individuals without any repairs being necessary.

Figure 5-6 Function Generator with analog controls (http://www.ebay.com).



96 Hz

172 Hz

270 Hz

378 Hz

623 Hz

730 Hz

Figure 5-7 An image of patterns at specific frequencies generated by another mechanical wave driver. (http://pubs.sciepub.com/ajme/2/7/15/).

Figure 5-8 Humboldt County Math Festival at the Bayshore Mall in Eureka, CA. The pattern shown on the Chladni plate occurs at 215 Hz.

Appendix A - References

Billah, Yusuf K. (1991). "*Resonance Tacoma Narrows Bridge Failure and Undergraduate Physics Textbooks", *American Journal of Physics Vol. 59 Biological Magnetic Resonance, Volume 19: Distance Measurements in Biological Systems by EPR (Berliner, Lawrence J., Eaton, Sandra S., Eaton, Gareth R. 2007).

Carnegie Mellon University (CMU). (2013). "Lead Soldering Safety Guidelines." <http://www.cmu.edu/ehs/chemical/Lead%20Soldering%20Safety%20Guidelines.pdf> (Feb. 20, 2015).

Cook, Perry R. (2002), "*Real Sound Synthesis for Interactive Applications*", AK Peters Natchick, Mass.

Dukes, Phillip. (2005). "An inexpensive resonance demonstration." *Journal of College Science Teaching*, *34*(4), 68-70. <http://www.nsta.org/publications/news/story.aspx?id=50119> (Feb. 20, 2015).

Environmental Protection Agency (EPA). "Common Recyclable Materials." *Recycling,* <http://www.epa.gov/smm/wastewise/pubs/commonmats.pdf> (Feb. 21, 2015).

Eureka City Schools 2014-2015 Parent and Student Handbook (Feb. 19, 2015).

Forde. (2010). "Bonding Strength of Wood Materials." *Construction and Building Materials*, 24(12), 2628-2632. <http://www.sciencedirect.com/science/article/pii/S0950061810002138> (Feb. 19, 2015).

"Goals of the Humboldt Math Festival." <http://humboldtmathfestival.weebly.com/goals.html> (Feb. 19, 2015).

Goodheart Wilcox Co. "Division 05 – Metals." *Construction Materials – Types and Uses,* <http://www.g-w.com/pdf/sampchap/9781590703472_ch10.pdf> (Feb. 20, 2015). *Pdf.*

Gustafson, Grant B. (2009). "Resonance." *In Engineering Math* (5.8). Retrieved from: <http://www.math.utah.edu/~gustafso/2250resonance.pdf> (Feb. 20, 2015). *Pdf.*

Harvard College. (2013). "Tuning Forks." *Simple Harmonic Motion,* <http://www.fas.harvard.edu/~scdiroff/lds/OscillationsWaves/TuningForks/TuningForks.html> (Feb. 20, 2015). *Pdf.*

Knight, Randall D. (2013) *Physics for Scientists and Engineers a Strategic Approach*, 3 Ed., Pearson

Lapp, D. (2006). *The Physics of Music and Musical Instruments* Wright Center for Science Education Tufts University, Medford, Massachussets, 8-38.

Laws, P., Sokoloff, D., and Thornton, R. (1999). "Promoting active learning using the results of physics education research." *UniServe Science News,* 13, 14-19.

Mazzolini, A. P., Daniel, S., and Edwards, T. (2012). "Using interactive lecture demonstrations to improve conceptual understanding of resonance in an electronics course." *Australasian Journal of Engineering Education*, *18*(1), 69.M <http://web.mit.edu/8.01t/www/materials/modules/chapter23.pdf> (Feb. 20, 2015). *Pdf.*

National Institute of Biomedical Imaging and Engineering. "Magnetic Resonance Imaging (MRI)." <http://www.nibib.nih.gov/science-education/science-topics/magnetic-resonance-imaging-mri> (Feb. 20, 2015).

Perseh, Bahram; Kiamini, Majid. (2013). "Optimizing Feature Vectors and Removal Unnecessary Channels in BCI Speller Application." *Journal of Biomedical Science and Engineering*, 6, 973-981.

Physics Classroom. "Standing Wave Patterns." *Sound Waves and Music,* <http://www.physicsclassroom.com/class/sound/Lesson-4/Standing-Wave-Patterns>. (Feb. 21, 2015).

Rutgers. (2010). "What Are Sustainable Materials?" *Center for Sustainable Materials,* <http://sustain.rutgers.edu/what_are_sustainable_materials>. (Feb. 21, 2015).

Science & Health Education Partnership (SEP). "Oobleck." *SEP Lessons,* <http://seplessons.ucsf.edu/node/3465> (Feb. 18, 2015).

Senese, Fred. (2010). "What is a non-Newtonian Fluid?" *General Chemistry Online*, <http://antoine.frostburg.edu/chem/senese/101/liquids/faq/non-newtonian.shtml> (Feb. 21, 2015).

Stony Brook University. (2009). "Soldering Safety." *Environmental Health and Safety,* <http://naples.cc.sunysb.edu/Admin/HRSForms.nsf/pub/EHSD0348/$File/EHSD0348.pdf> (Feb. 20, 2015). *Pdf.*

Torlakson, Tom. "Common Core State Standards." <http://www.cde.ca.gov/> (Feb. 20, 2015).

University of Maryland (UMD). (). "Speaker and Candle." *Physics,* <http://www.physics.umd.edu/deptinfo/facilities/lecdem/services/demos/demosh1/h1-02.htm> (Feb. 20, 2015).

University of Salford, Manchester. (). "Damping." *Simple Harmonic Motion,* <http://www.acoustics.salford.ac.uk/feschools/waves/shm2.php#damping> (Feb. 20, 2015).

Vermont Safety Information Resources Inc (SIRI). (1985). "Materials Safety Data Sheet – Cornstarch." *Hazard,* <http://hazard.com/msds/index.php> (Feb. 18, 2015).

Appendices

Appendix B - Brainstorming