Investigation Of Soundwaves For Potential Use In Fire Extinction

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Abstract

The goal of this research project is to demonstrate and understand the process of extinguishing a flame with sound waves. A device consisting of a speaker system and a waveform generator is used to create this effect. To gather data, we developed a device consisting of the MLX90614 infrared sensor and an array of electret microphones, operated through an adalogger device. Our investigation found that sound waves can be used to put out fires. Based on the data collected, our hypothesis that higher amplitude sound waves are more effective was supported. We also observed that square waves are clearly more effective than the other waveforms tested, and only frequencies under 60 Hz were viable for fire extinguishing.

Intro and Theory

When a fuel source has enough oxygen and heat, combustion begins and a fire starts. When a fire inadvertently starts, as is not uncommon, it is almost always necessary to extinguish it. The current methods to extinguish a fire takes away one of the three ingredients needed for combustion. We can remove the fuel source of a fire, such as conducting a controlled burn to remove flammable objects. We can remove a fire's access to oxygen by smothering the fire with blankets. Or we can remove the heat source by cooling the fuel source. As a novel method of fire extinguishing, we propose the following: depriving a flame of oxygen by utilizing a soundwave, which creates a pressure differential with respect to time, to physically separate the surrounding oxygen rich air from the flame. In layman's terms, the flame is suffocated as the air around it is pushed to a lower pressure, i.e. has less "air" (or oxygen, for our purposes) in it.

To explain why this is possible, allow us to briefly recap the fundamentals of sound waves. Sound waves, also known as acoustic waves, are what we call longitudinal waves, or waves which oscillate parallel to the direction they propagate energy. Energy is transmitted when particles within the medium of propagation "bump" into each other. When diagramed, a sound wave might look like Figure 1. Compressions and rarefactions, or places of high and low pressure, respectively, correspond to crests and troughs, both labeled below.

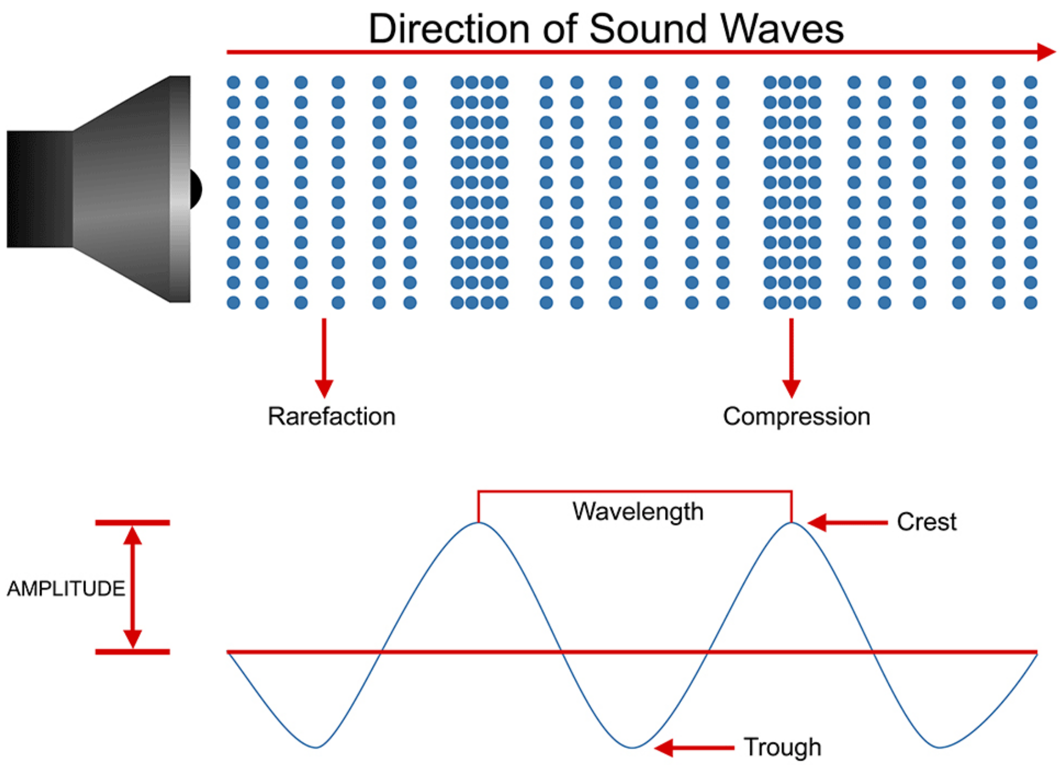

Figure 1. Diagram of an acoustic wave. One wave cycle is equivalent to one wavelength. [1]

To extinguish a fire most effectively, our theory indicates that we want a wave that maintains as large a low pressure area for as long as possible — this will allow the flame to be separated from its oxygen for long enough to be extinguished. In technical terms, this means we want a high amplitude, as this is the factor that determines the "size" of the low pressure area, and a low frequency. The frequency of a wave (or the "pitch" for the musically inclined), is determined by the waveform generator. The amplitude A of a sound wave is proportional to the intensity (or loudness) of a sound, as indicated by equation 1.

$$A^2 \propto I \tag{1}$$

This intensity can be defined as the power P (measured in Watts) per unit Area *a* (measured in meters^2) in the wave, i.e.

$$I = \frac{P}{a} \tag{2}$$

Recalling that power is a measure of energy over time, we see that Intensity, and by extension Amplitude, is a measurement of the energy of a wave over time and space. Intuitively, it seems reasonable that a wave with more energy would have more effect on the world around it. We'll take this as a sanity check that higher amplitude is the right direction. To manipulate the amplitude of our wave, we need only produce a high power wave, something to be kept in mind when selecting parts for our wave source. When it comes to setting the amplitude, there is one more important relationship we must establish: the relationship between input voltage and output power.

$$P = \frac{V^2}{R} \tag{3}$$

We see that in a system where the resistance is known and the input voltage is an independent variable, the output power can be calculated. Because of this relationship and the correlation between power and intensity, we can thus use input voltage as a metric of amplitude.

Before entirely moving on from the discussion of intensity, one more thing must be noted. The area A represents the spherical surface area affected by the wave source, and increases rapidly as the distance from the wave source goes up. This decrease in intensity follows what you might know as the inverse square law, and results in a natural phenomenon called attenuation. Attenuation, the weakening in the energy of the wave resulting from its scattering and absorption, is the physical cause for the diminished intensity. Seeing as a large amplitude is desirable for the flame-conquering efficiency of our wave, it becomes necessary to find a way to prevent attenuation. The act of collimating a wave, commonly done with visible light and other electromagnetic waves (e.g. lasers), involves making multiple waves parallel to each other, so as to prevent scattering. A more detailed description of acoustic collimators can be found in the hardware section herein, for now it is sufficient to know that we will desire some kind of collimation as we go into curating our experimental set up.

Experimental Design

As described above, our theoretically ideal wave has a low frequency, high amplitude, and is collimated. We decided the most uniform measurement for measuring the effectiveness of a sound wave in putting out a flame was to determine:

A. Success or failure in completing the task: could this wave actually extinguish a flame?
B. Time required to do as such: how long must a fire be exposed to this wave before being terminated?
C. Effective distance: at what distance from the flame did this wave cease being effective?

To test these three points, we propose an experiment in which a candle is placed in front of a speaker emitting our sound wave. With the candle lit and the wave emission begun, we record the time it takes the wave to extinguish the fire (if at all). This simple test is then repeated at different distances from the speaker face. Our original intent was to perform this experiment for three independent variables: wave form, frequency, and amplitude. As we will see later, these plans changed as our analysis began and more pressing matters demanded investigation.

Method & Equipment

Our basic method requires a wave source and a timer. The wave source is composed of a speaker and the necessary components for powering and controlling the wave. The timer will measure the time elapsed between the emission of the wave and the suffocation of the fire. To do this systematically and without human error, we determined our timer would be composed of a sound sensor and a temperature sensor, recording the time elapsed between when the sound of the wave is first detected and when the temperature of the fire dips low enough to indicate it has gone out. A detailed discussion of this is found below.

Our equipment can be split into two categories: hardware and software. Hardware consists of the physical components needed to run the experiment — speaker elements, wave generators, arduino boards and sensors, and the like. Software consists of the programs run on our arduino and on our personal computers to collect data from the sensors and analyze it.

Hardware

Generating a sound wave such as the one desired requires several components, nominally:

- A speaker (subwoofer),
- Amplifier,
- Power source (for the speaker),
- Wave Function Generator, and
- An Oscilloscope.

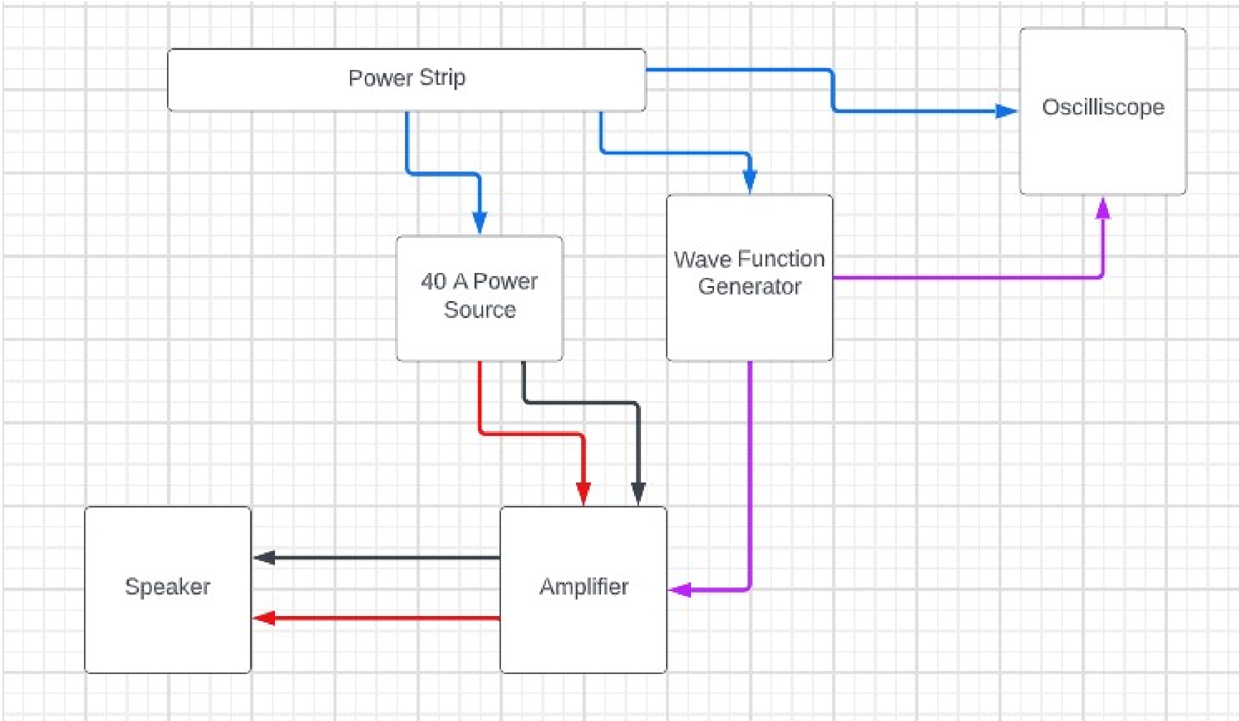

Figure 2. Speaker System Set Up. Red connection: Positive Lead. Black connection: Negative Lead, Purple Wires: Transmission Lines, Blue Connection: From Power Strip.

Speaker — our speaker is an Alpine W10S4, BassLine Series 10" 4-ohm subwoofer, as manufactured by Alpine. The speaker (or driver) is responsible for driving the wave itself, based on input from the waveform generator.

Important specifications:

- power handling: 50-250 watts RMS
  - This metric tells us how much power we can push through the speaker for long periods of time without damaging it.
- peak power: 750 watts
  - This metric tells us how much power we can push through the speaker for a moment without damaging it. Seeing as our experiment requires prolonged emittance of a wave of uniform power, we aren't too worried about the maximum power. We will try to stay within the RMS power handling range.
- frequency response: 24-200 Hz
  - Like any subwoofer, this speaker has a low frequency range, which is ideal for our experiment. For reference, the human range of hearing ends at about 20 hz.
- resistance: 4-ohm

Figure 3. Alpine W10S4, BassLine Series 10". [2]

Amplifier — Rockville dB11 1400w Peak/350w RMS Mono 2-Ohm Amplifier.
Important specifications:

- RMS Power Ratings:
    - 2 Ohm: 700 Watts x 1 Channel
    - 4 Ohm: 440 Watts x 1 Channel
- Peak Power Ratings:
    - 2 Ohm: 1400 Watts x 1 Channel
    - 4 Ohm: 880 Watts x 1 Channel
- Frequency Response: 15 Hz - 250 Hz

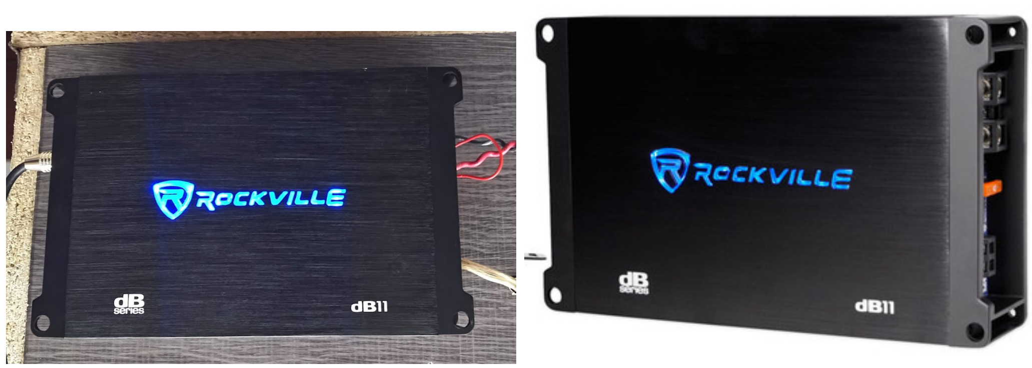

Figure 4. Rockville Amplifier. [3]

Power Supply — 12 Volt, 40 Amp

Wave Function Generator — Tektronix CFG253 3 MHz function generator
Important specifications:

- Outputs - Square, sine, and triangular waves
- Frequency range - 0.3 Hz - 3.0 MHz
- Output amplitude - 0 - 20 Volts peak-to-peak
- Square response - <= 100 ns rise/fall time maximum output into 50 ohm load

This device allows us to set the voltage, frequency, and waveform the speaker outputs.

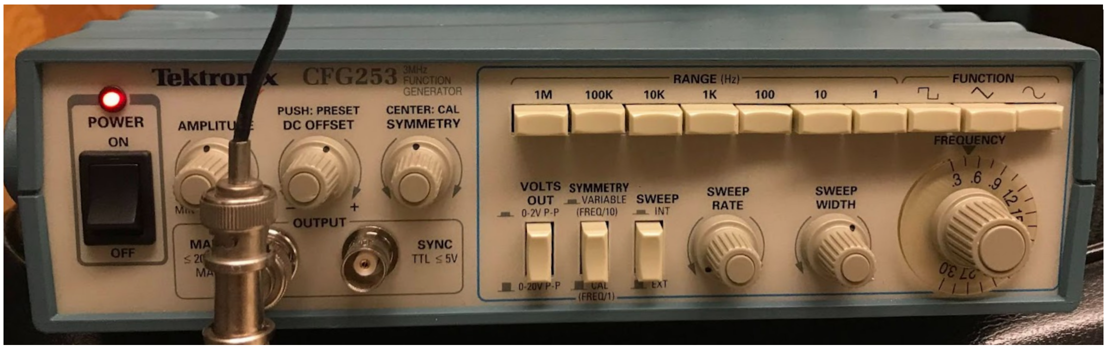

Figure 5. Tektronix Waveform Generator. [4]

Oscilloscope — Tektronix TDS 224 Digital Real-Time Oscilloscope

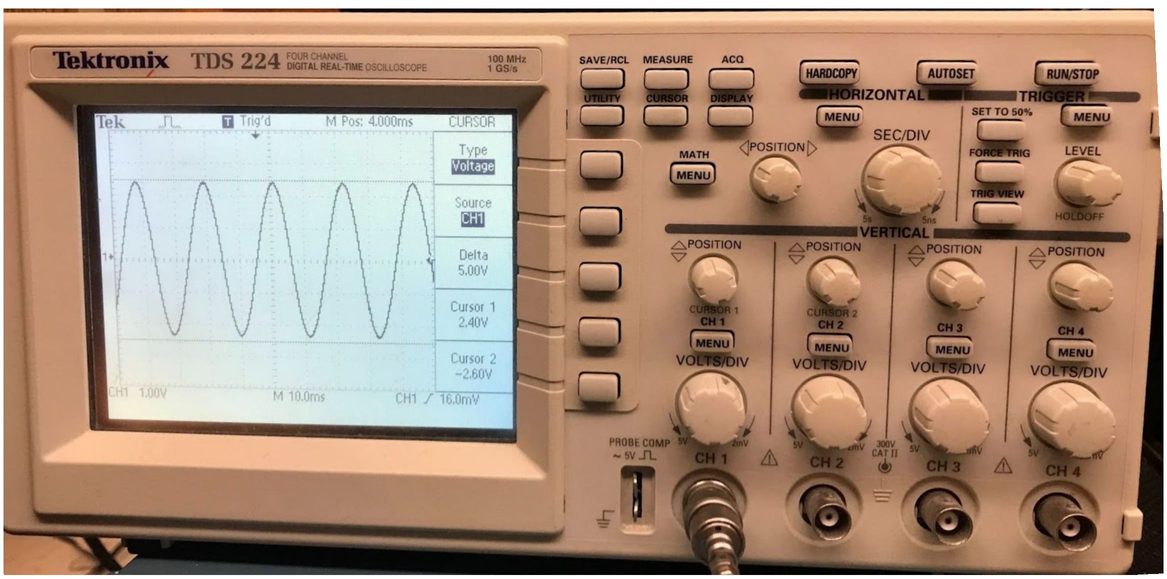

Figure 6. Tektronix Oscilloscope [5]

With our speaker assembled, we are ready to make some noise. There is, however, one critical piece still missing: the collimator. Collimation of waves is a well populated field, as demonstrated by every type of collimated light out there, e.g. lasers. Collimation of *acoustic* waves, however, is much less researched. Some have proposed planar collimators (citation for images found below), such as those pictured below. In fact most existent methods of acoustic collimation (especially those feasible in an experiment such as this) mimic a method of electromagnetic wave collimation, such as a Luneberg lens or a Winston Cone.

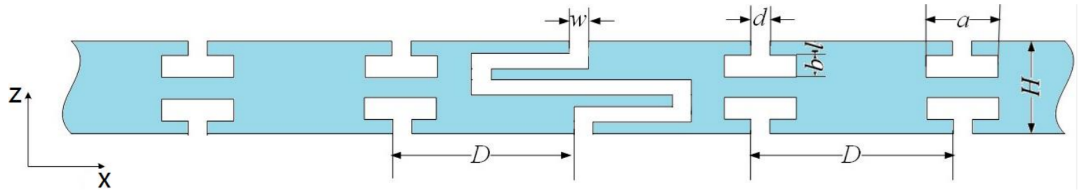

Figure 7. The schematic diagram of the proposed 2D ultra-thin planar structure for producing the high efficiency collimated acoustic beam transmitting through the zigzag aperture in the center. [6]

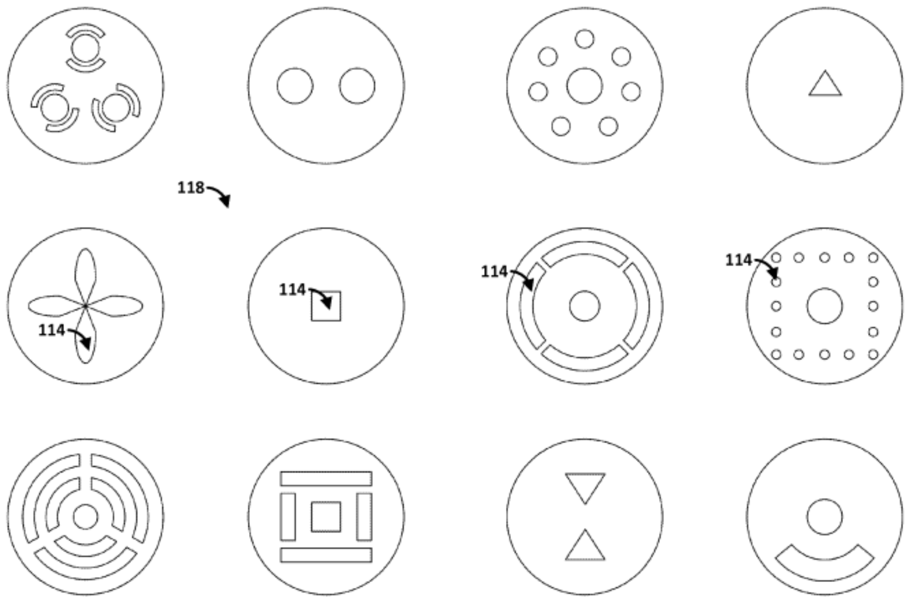

Figure 8. Acoustic collimator designs identified in U.S. Patent no. 10,569,115 B2, Tran et al, *METHODS AND SYSTEMS FOR DISRUPTING PHENOMENA WITH WAVES* . [7]

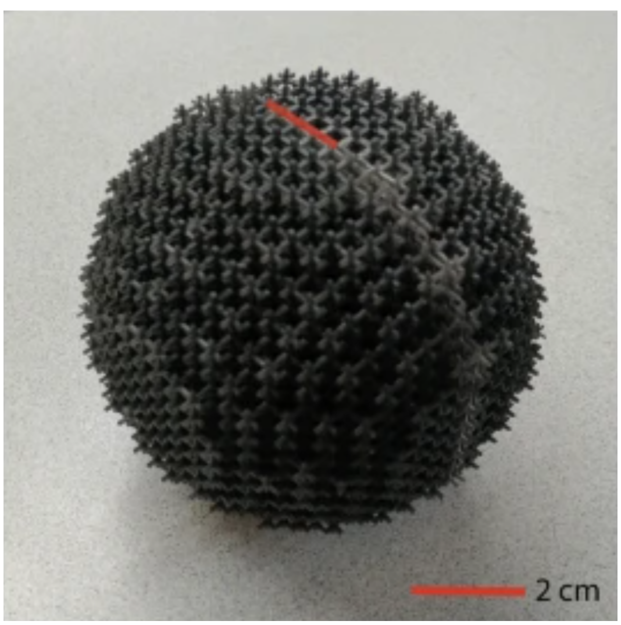

Figure 9. 3D printed acoustic Luneberg lens, a spherically symmetric lens containing a gradient of refractive indexes. Each refractive index refracts the wave to the same point on the opposite side of the sphere, focusing it.

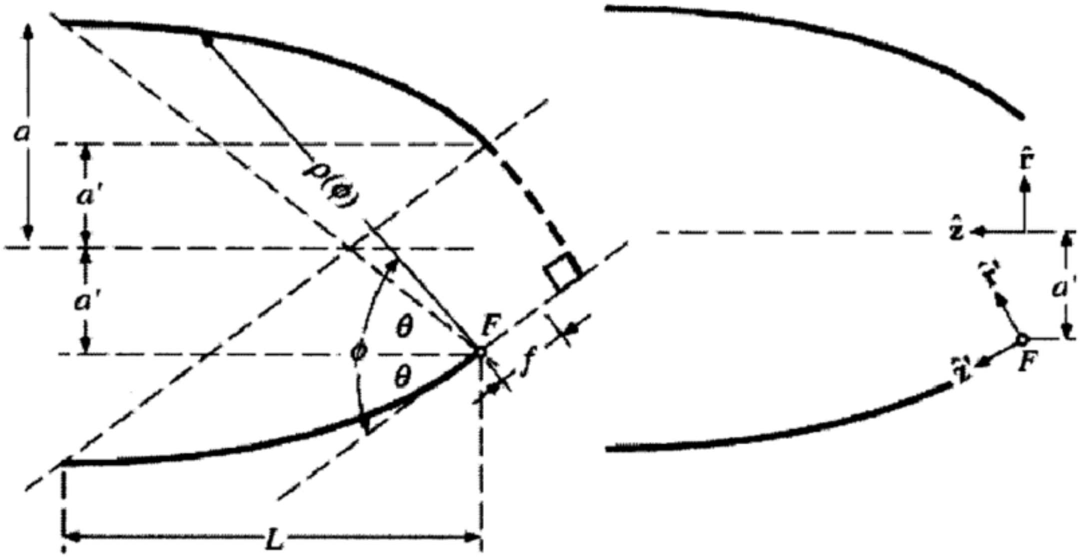

Figure 10. Baseline design specs for a Winston Cone, an optical collimating device. This diagram shows the p between entrance aperture, exit aperture, and acceptance angle, which are not discussed in detail in this paper. [8]

For feasibility, we opted to 3D print a Winston Cone, matching the entrance aperture to the diameter of the speaker. Our cone, 3D printed in two pieces and glued together, is shown below.

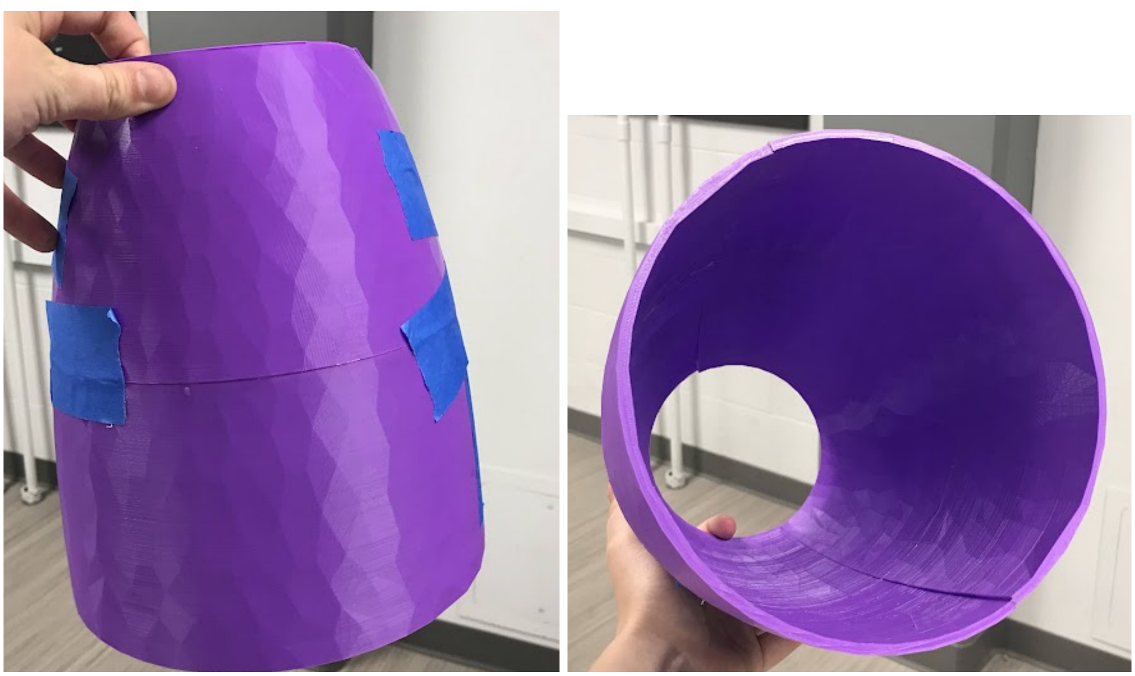

Figure 11. Our Winston Cone, 3D printed.

Using a Winston Cone for acoustic collimation is a novel concept, so we needed to determine if this would collimate the sound enough to be worth using in our experiment. We tested this experimentally by using the electret mic (discussed in detail below) to measure the Root Mean Square (RMS), a metric that provides an average distance from a midpoint (set as zero), or in other words, an approximate amplitude of our wave. Because this is a comparison test, we have omitted any proportionality constants that would be needed to convert from an RMS value to a true amplitude measurement, and see it sufficient to use RMS alone. By measuring the RMS at multiple positions we can create maps of the sound intensity relative to the center of the speaker from. Comparative sound maps (speaker with and without collimator) showed that the collimator effectively increased the distance the sound traveled before attenuating, though one can observe that the cone does not seem to focus the wave after it exits, rather it merely prevents attenuation within the length of the cone. Our data also showed a severe influence from the wall that was ~20cm to the right of the speaker (positive y direction), which prompted us to move our experimental set up to a new position in the room. Sound maps showing the difference caused by the collimator and the wall are shown below.

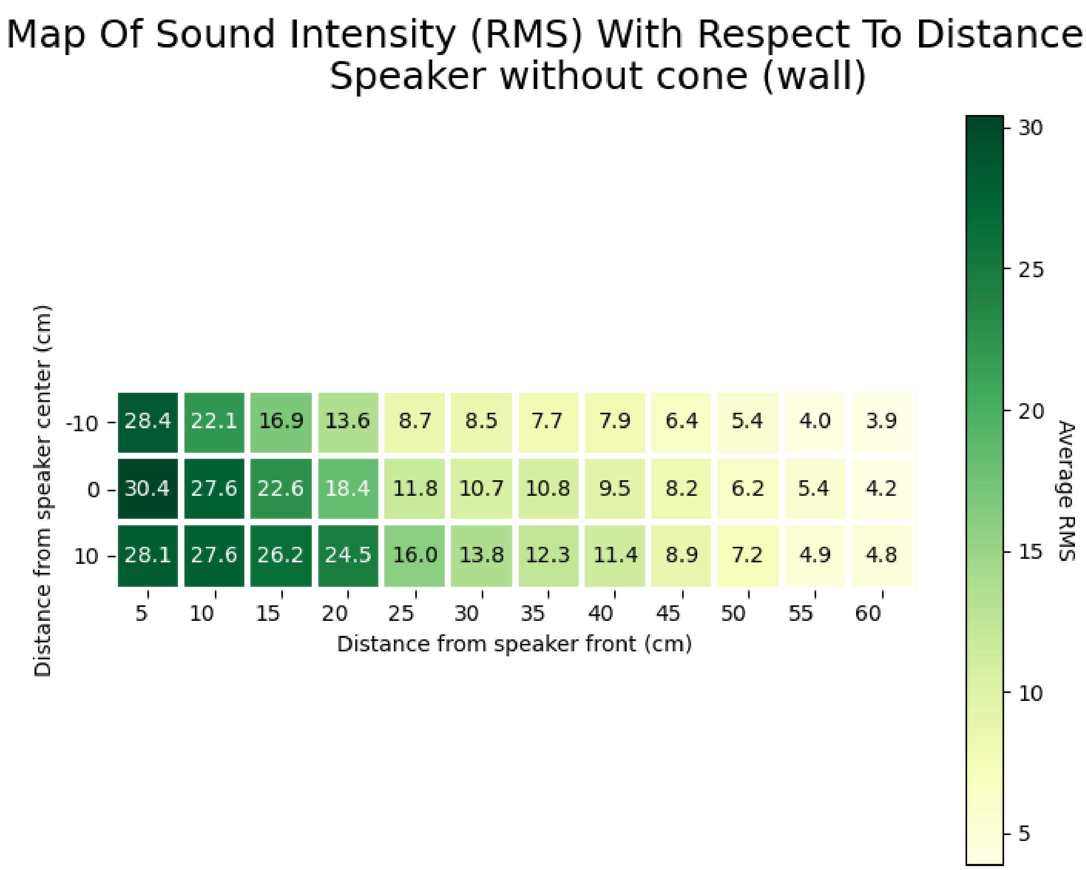

Figure 12. This sound map shows the average RMS with reference to the speaker front, the center of which is located at 0 cm in the y direction. This test has no collimator and is located next to the wall, hence the visible asymmetry.

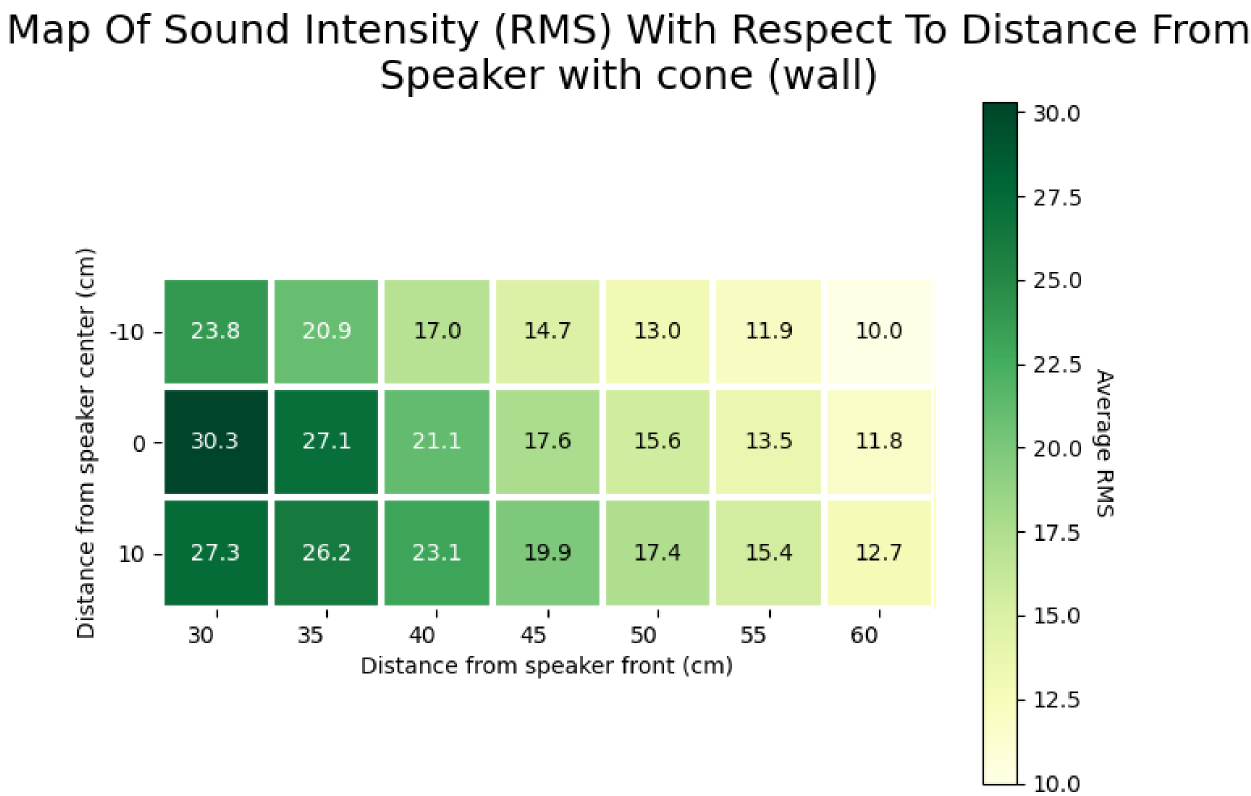

Figure 13. This sound map shows the average RMS with reference to the speaker front, with the Winston Cone collimator attached. X measurements (with respect to the front of the speaker) begin at the edge of the edge of the cone, around 30 cm from the speaker itself. This test is also skewed by the presence of the wall.

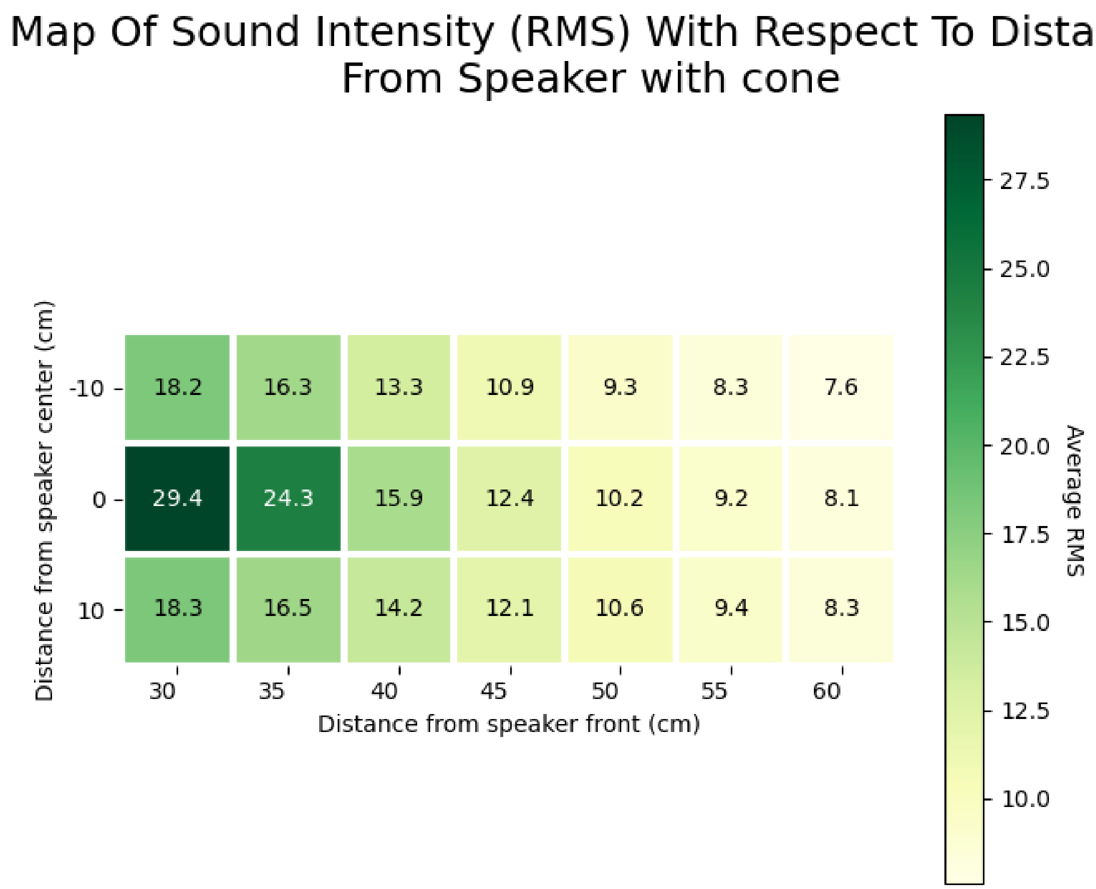

Figure 14. This sound map shows the average RMS with reference to the speaker front, with the Winston Cone collimator attached (as in Figure 13). The experimental set up has been moved away from the wall, as demonstrated by the increased symmetry.

Based on this data, we determined that even though the Winston Cone had a comparatively worse attenuation over increased distance, the benefit of having a sizable space between the flame and the speaker itself (a damageable object) was worth using the cone.

With the sound wave produced and collimated, we next needed equipment to time our experiment and take other measurements on the environment.

The components of the device that we developed to gather data are the following:

- A processor (1)
- An infrared sensor (2)
- Three microphones (3)
- A liquid crystal display, or LCD (4)
- A candle (tea lights, for uniformity)

Processor - An Adafruit Adalogger Feather M0 [9]

Important specifications:

- 48 MHz processor, fast enough to read from the three microphones and the IR sensor.
- Built in MicroSD card, to easily write data to.

Infrared sensor - MLX90614 Contactless Infrared (IR) Digital Temperature Sensor [10]

Important specifications:

- Measuring range of -70℃ to 382.2℃
- Accuracy: 0.02℃

The positioning of the IR sensor was changed multiple times while developing the setup. To get consistent readings of the temperature of the flame, the distance and angle of the sensor is important. Originally, the IR sensor was set up on the side of the candle, looking at the base of the flame, perpendicular to the speaker front. The issue with this placement is that the flame flickers away from the speaker, and leaves the field of view of the sensor. This causes the sensor to produce readings indicating that the candle is out, while it is visually on fire. To solve this problem, the sensor was moved to face the speaker front. This put the IR sensor in line with the flickering, yielding much more consistent results.

Candle - Tea lights

The use of tea lights allowed for more consistency in flame height and position. It was convenient to replace the candles as they burned down, as opposed to adjusting the sensor positions as a larger candle changed height and shape.

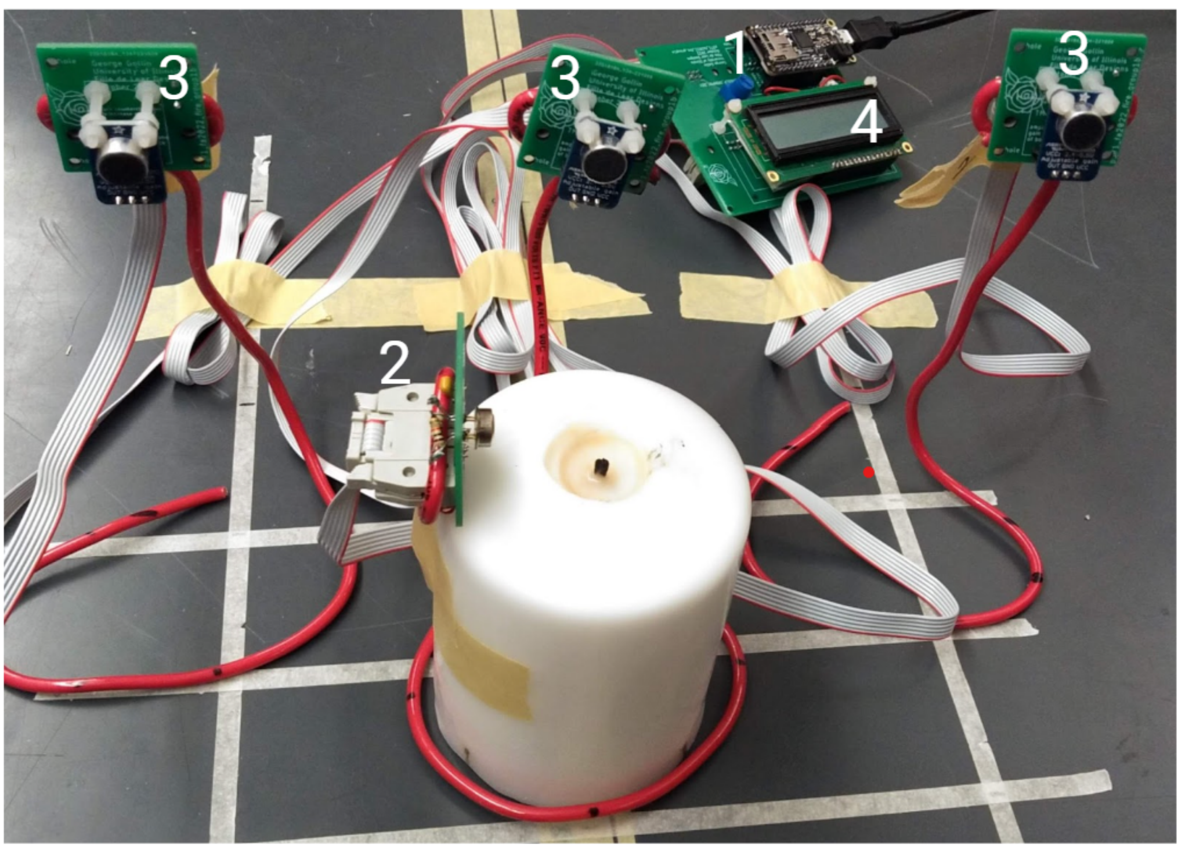

Figure 15. Adalogger Feather 0, Sensor Suite, and Candle

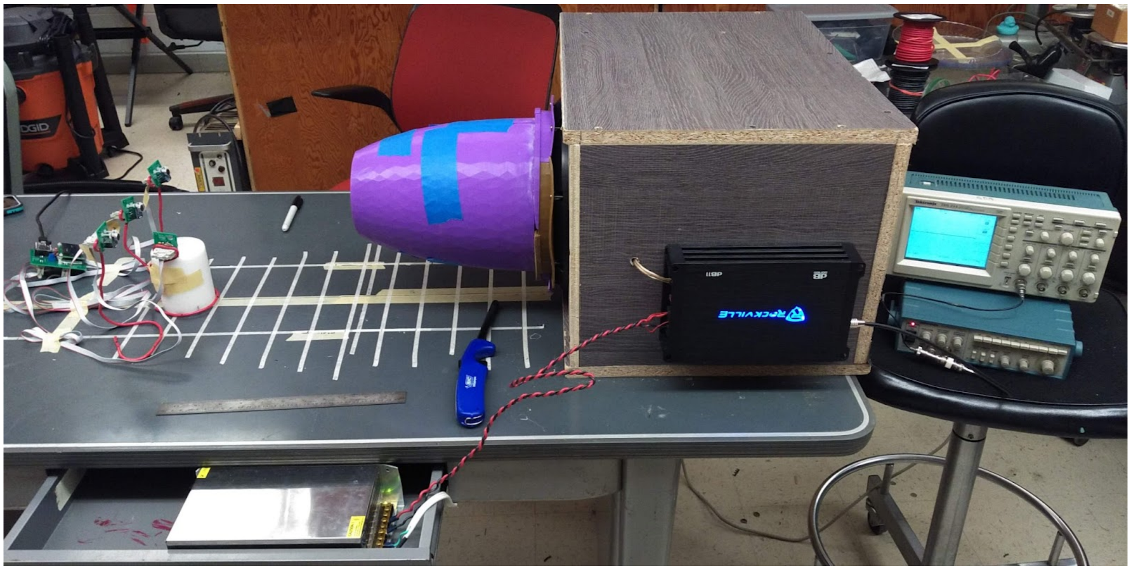

Figure 16. Complete Setup

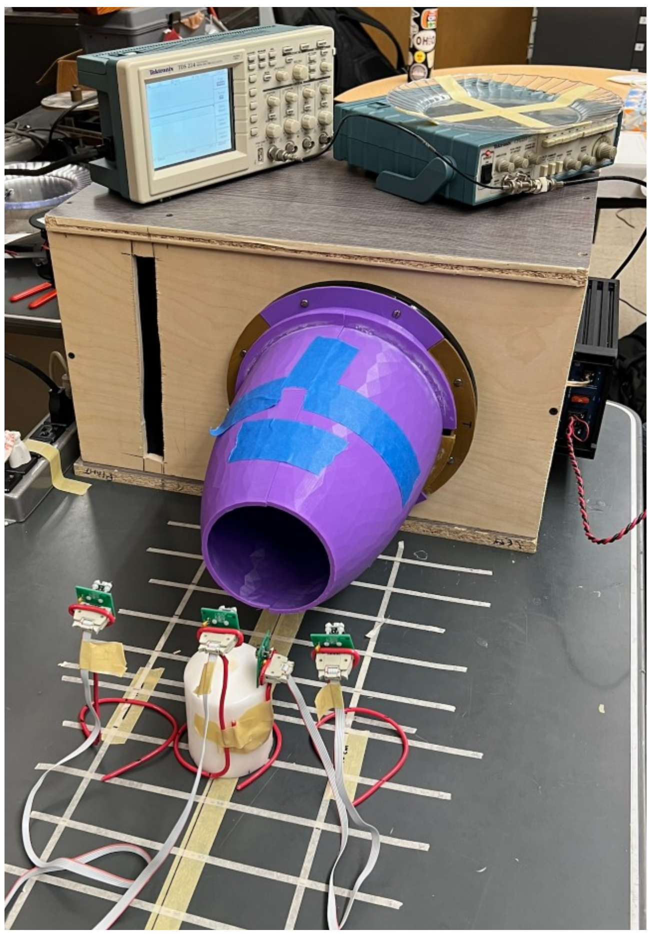

Figure 17. Complete Setup

Software/Program

Basic Algorithm

Our arduino program measured raw ADC values from the three microphones, as well as temperature from the IR sensor. Using the ADC values, the program was able to determine an RMS value for each microphone during a time interval. For each trial, we first lit up the candle and then turned on the speaker after the program setup was finished. The program started timing as soon as it detected a sufficiently large increase in the RMS values. After the candle was blown out (ie. the temperature from the IR sensor was sufficiently low), the program stopped timing. The time taken and the average RMS during this time interval were recorded into the SD card.

RMS value

To prevent overflow, the program determines a baseline value by calculating the average ADC values of the first 1000 samples. For subsequent measurements, this value was subtracted. Moreover, all raw ADC values are scaled down by a factor of 10. Then, for every 1000 samples, a root mean square (RMS) value is calculated by adding up all the amplitudes squared and taking the square root of the average over time. All three microphones use the same algorithm for determining an RMS.

Temperature

We can find a temperature readout directly using mlx.readObjectTempC()

Timing and average RMS value during this time

We discovered that every time the speaker is on, the RMS value exceeded 1. Therefore, we decided to use 1 as our threshold RMS value: the program starts timing once it detects an RMS value above 1. We also discovered that the temperature is about 30 degrees Celsius when the fire is out. The program stops timing when the temperature reaches 30 degrees Celsius. After the program starts timing, the sum of RMS values is calculated for each microphone. When timing stops, this sum is averaged over the number of RMS measurements. The average RMS for each microphone and the time measurement are written into the SD card.

Issues faced

The Adalogger device that we ran the code on had a limited amount of memory to store readings, and run calculations. If our trials sampled for too long, or we calculated numbers that were too large, the code outputs not-a-number (nan). To fix this, we had to decrease the rate of sampling, and manipulate the types of calculations required.

Another big issue we encountered is that the minimum time the device could measure is 658 ms. This value shows up if timing starts before everything is set up. To solve this problem, we added a delay of 10 seconds. That is, we turned on the speaker 10 seconds after the program was uploaded and the set up code had run.

Terminating the program is also a hard part of coding. We initially used "exit(0)", but we later found that "exit(0)" does not exist in Arduino because there is no operating system. We used a "while(1){}" loop to stop the program.

Conducting the Experiment

Our experiment was composed of multiple mini experiments, each testing the effect of a different aspect of the wave on its ability to extinguish the flame, and each requiring its own procedure.

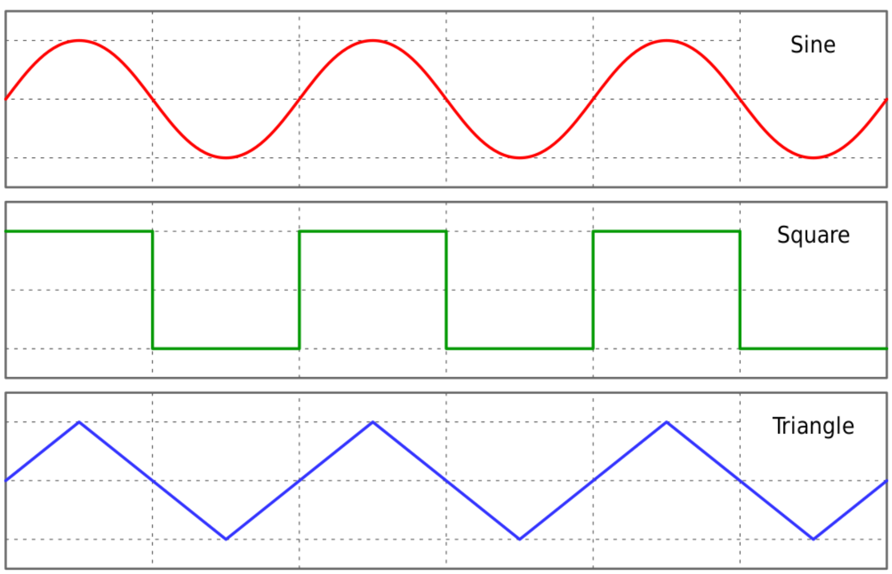

Figure 18. Graphic depicting Sine, Square, and Triangle waves. [11]

Experiment 1 - Waveform vs. Time and Distance

This experiment tested the comparative abilities of Sine, Square, and Triangle waves to extinguish a flame. Switching between waveforms was done by changing the wave input to the speaker by the oscilloscope. All three waveforms were provided the same voltage (3 volts) and operated at the same frequency (45Hz). To conduct the experiment, the candle was placed at the appropriate distance, surrounded by the sensor suite. We would begin running our data acquisition code, light the candle, and then, when everything had processed, turn on the speaker. When the speaker was detected by mic 2 in the sensor suite, the adalogger's timer would begin, ending when the IR sensor determined the flame was out. This simple test was repeated 5 times at each distance, and was performed at 35, 40, 45, 50, 55, and 60 cm away from the face of the speaker (along the perpendicular axis).

Experiment 2 - Frequency vs. Time and Distance

This experiment tested the comparative abilities of a 21Hz, 25Hz, 35Hz, 45Hz, and 55 Hz sine wave, serving to test our theory that a lower frequency wave would perform better. The chosen frequency range was determined by performing a qualitative test. The wave was set to a 3V sine wave, starting from a frequency far above what would be usable — 120Hz. The frequency was then decreased until the flame began to be visibly affected. Our general observations were as follows:

- ➔ 120Hz: Flame is entirely unaffected.
- ➔ 105Hz: Flame has begun to quiver, but burns as brightly as before.
- ➔ 90Hz: Flame has begun to flicker.
- ➔ 75Hz: The flicker of the flame has become notably intense.
- ➔ 60Hz: Flame is diminished.
- ➔ 50Hz: Flame is extinguished.

From this, we selected an upper bound for interesting frequency testing, and chose frequencies that spanned the range of the speaker's lower limit to this upper bound. All tests were performed with 3 volts, following the same sequence as Experiment 1. Unlike Experiment 1, however, only 35 and 45 cm distances were tested.

Experiment 3 - Amplitude vs. Time

This experiment tested the comparative abilities of a 1, 3, 5, and 7 volt wave. All tests were performed with a 45 Hz sine wave, following the same sequence as Experiment 1. Only a 35 cm distance was tested.

Experiment 4 - Voltage vs. RMS of Sine and Square Wave

Wanting to investigate why the square wave had performed so much better in Experiment 1, we concocted a test that investigated the actual intensity of each wave, and how the difference in waveform affected the shift from input voltage to output RMS. This test focused only on sine and square waves and did not require actually timing the flame, so the procedure of this experiment was different from the previous ones. Initially, we intended to find the different voltage values that produced identical (within reasonable error) RMS measurements for both waveforms, but we found that the RMS measurements were too sporadic to match them, even when the voltage was maintained. Instead, we opted to determine the minimum voltage required to extinguish the candle for each waveform (determined by starting at a minimum voltage and slowly increasing the voltage until the flame was affected enough to face extinction). Once this minimum voltage was determined, we ran the experiment, taking note of the average RMS values of the center mic for each run.

Data and Analysis

Experiment 1 - Waveform vs. Time and Distance

This experiment, being the only experiment completed at the full range of distances, allows us to not only compare the effectiveness of a waveform in extinguishing a fire, but also to create sound intensity maps. Figures 19, 20, and 21 show the sound maps for all three waveworms, each compared to a universal RMS value of 3. (NOTE: These RMS values have been scaled down to prevent overflow in our adalogger system. As such, they are not fit for comparison to the earlier sound maps, but are sufficient for comparison between each other.) Bearing in mind that all three waveforms were provided with 3 volts, one can note that the square wave has a comparatively higher RMS across the board. Considering the physical shape of the wave alone, this makes sense. A square wave oscillates between two extremes — assuming zero as the midpoint, with the extreme being +/- the amplitude, it checks out that the square wave will have a higher RMS value than its sine and triangle counterparts, both of which will spend less of their existence at their extreme values. We might also attempt to understand this occurrence by contemplating the production of such a wave as a square wave: a linear combination of multiple sine waves, constructively and destructively interfering to create the desired shape. This combination, known as a Fourier Series, is composed of several waves, each having its own energy. It seems reasonable to conclude that multiple waves with several energies will sum to a wave with a greater energy, and by extension, a greater RMS. It should be noted, however, that the triangle wave is also composed via Fourier Series, and has a lower RMS than the sine wave, on average. Further investigation into the sine/square wave discrepancy is found in Experiment 4.

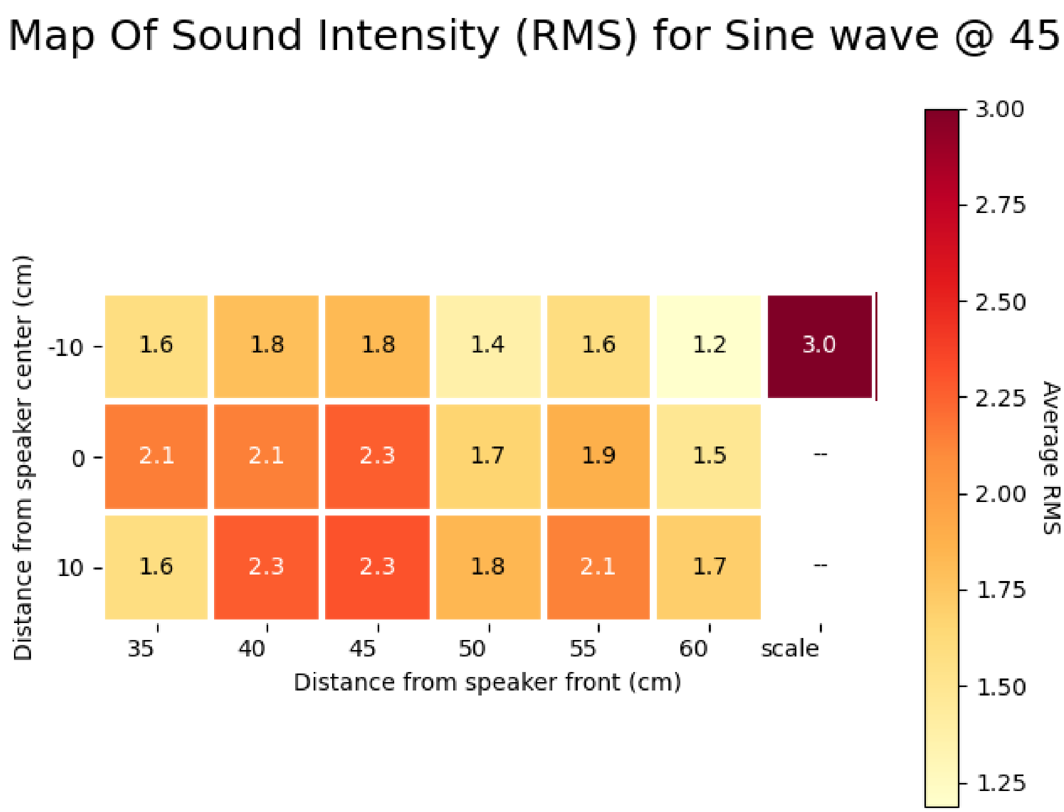

Figure 19. Sound map of the RMS of a 45 Hz sine wave, with reference to the speaker front. A scale patch (3.0) is included for comparison between waveforms.

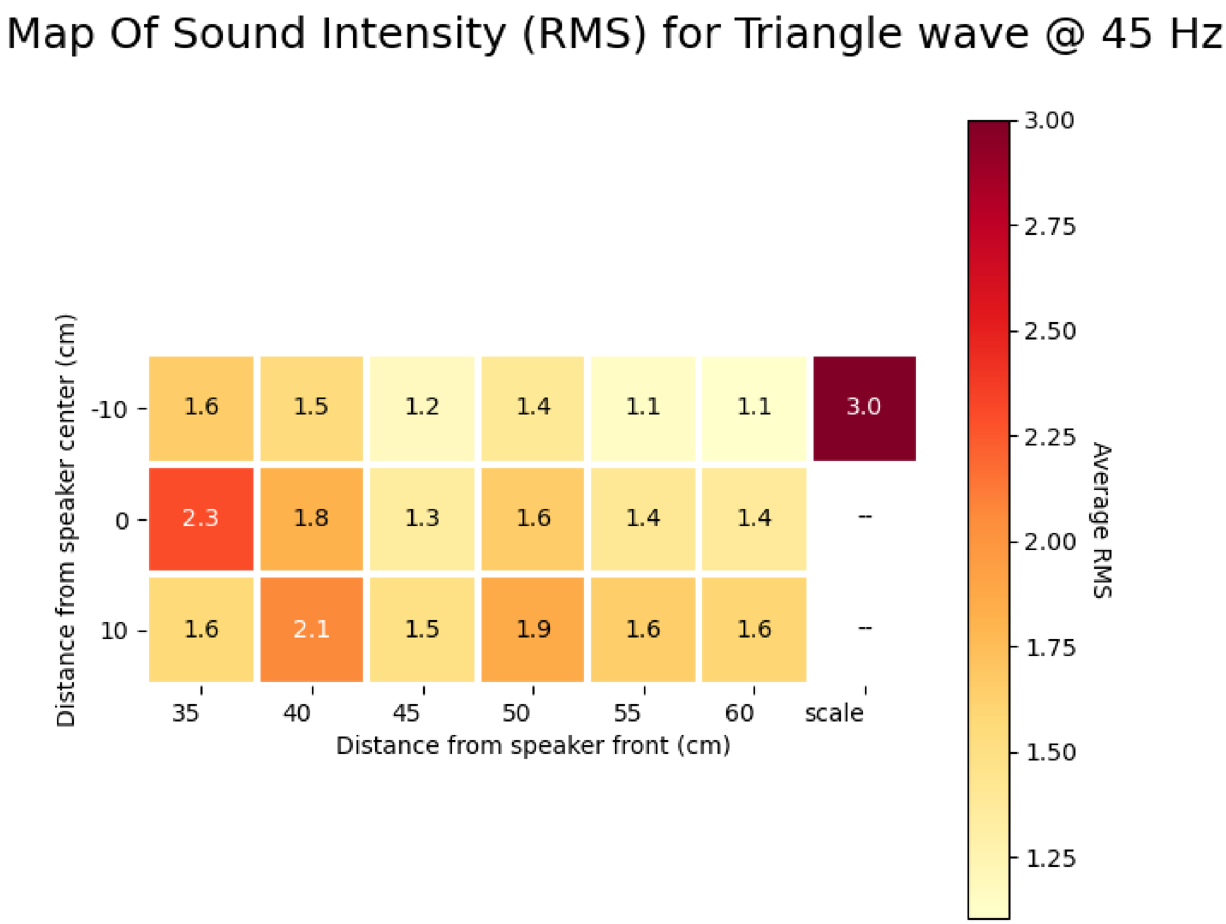

Figure 20. Sound map of the RMS of a 45Hz triangle wave, with reference to the speaker front. A scale patch (3.0) is included for comparison between waveforms.

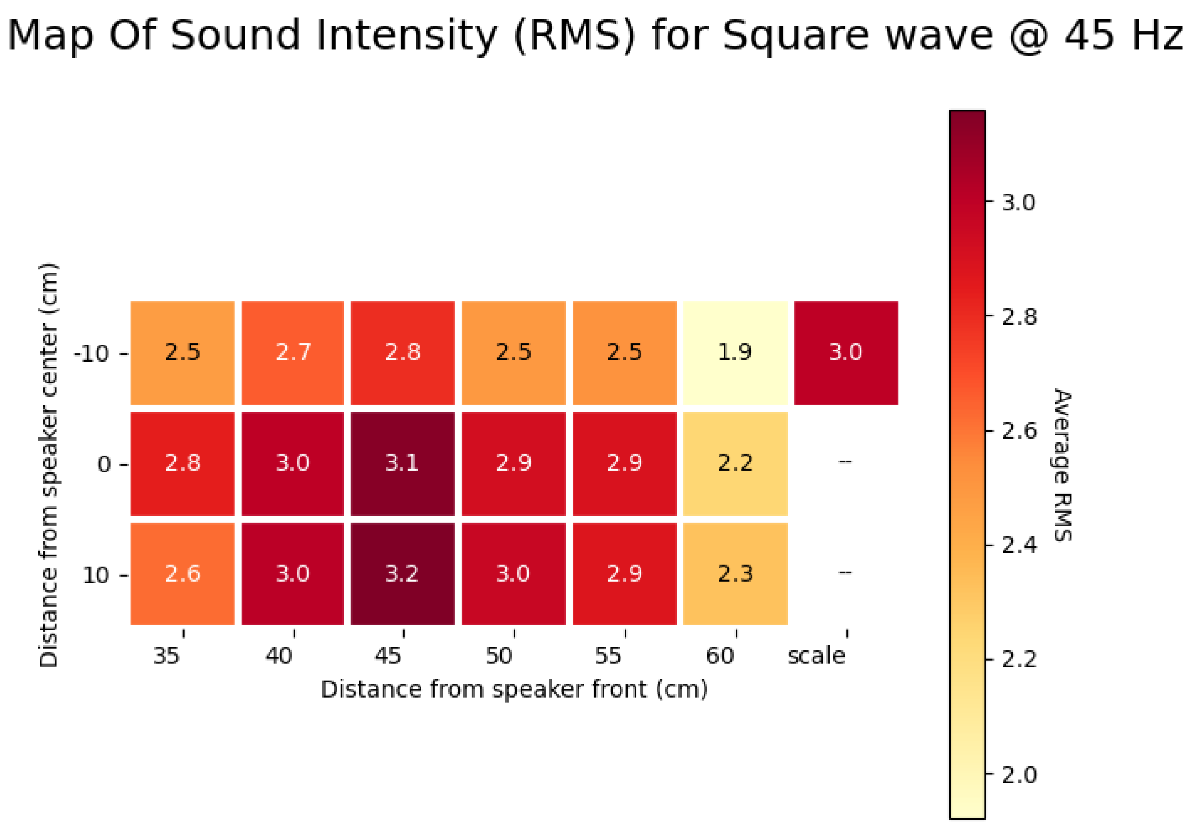

Figure 21. Sound map of the RMS of a 45 Hz square wave, with reference to the speaker front. A scale patch (3.0) is included for comparison between waveforms.

Seeing these sound maps, one can predict that the square wave would have more success in extinguishing the flame, following our hypothesis that a higher amplitude would be more effective. Looking at the average time to extinction for each waveform, we can see that the predicted is indeed observed. The square wave's time to extinction stays consistently low, whereas sine and triangle both increase drastically over distance.

Waveform comparison (45Hz) - avg time (ms) to extinction v. distance (cm)						
	Distance from speaker front (cm)					
Waveform	**35**	**40**	**45**	**50**	**55**	**60**
Sine	1733.60	761.40	1292.20	1564.20	3712.40	799.40
Triangle	1823.60	1560.00	4007.40	11068.40	12998.00	13885.20
Square	687.20	731.80	765.20	783.00	676.40	689.60

Figure 22. Table showing average times for each waveform. Full values are found in appendix 1.

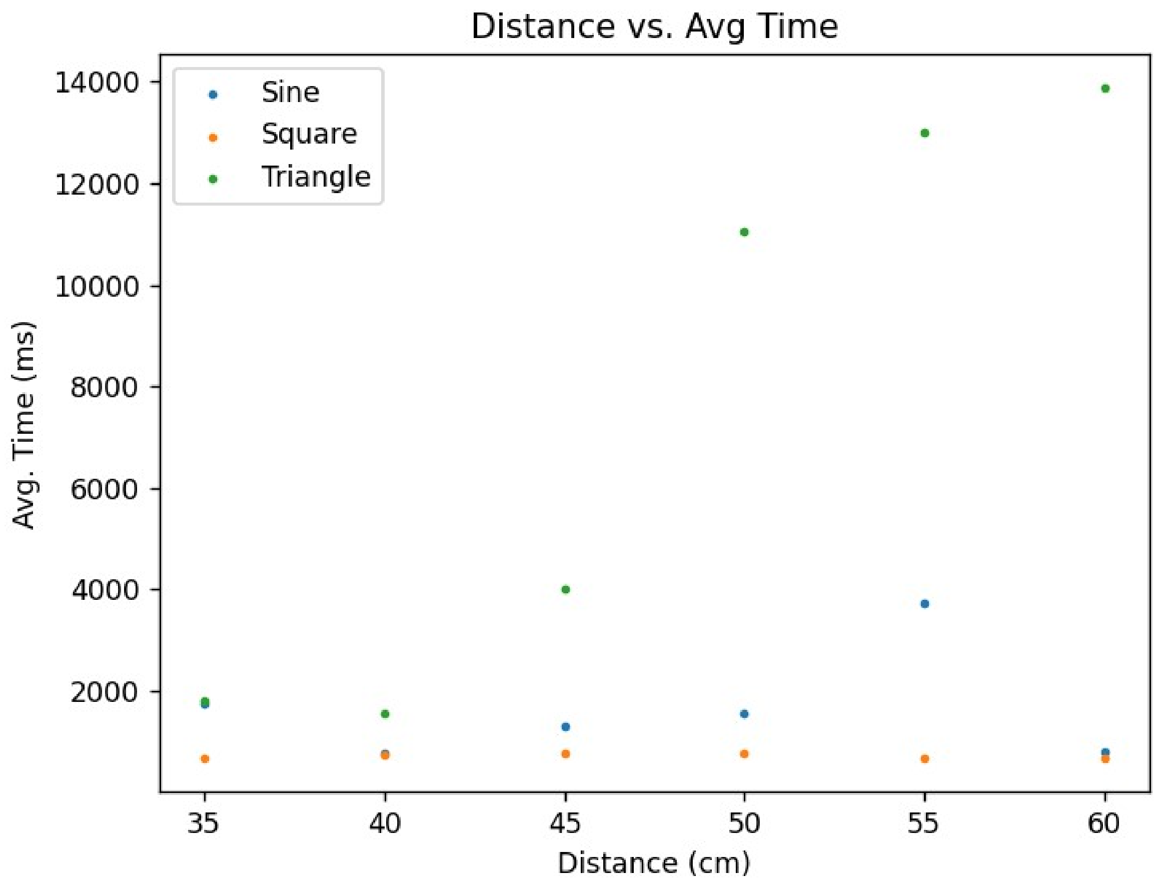

Figure 23. This plot shows the average time to extinction of each waveform at each distance.

Experiment 2 - Frequency vs. Time and Distance

This experiment served to test our hypothesis that lower frequencies would be more effective in extinguishing the fire. Our data indicates that the 45Hz wave performed the best, which contradicts our hypothesis. One possible reason for this is that, while the frequency rating on both our amplifier and speaker technically spans all the way down to 20Hz, it is not uncommon for speakers to have significantly reduced performance at these low frequencies.

Time to Extinction v. Distance (cm)					
	Frequency				
Distance	21hz	25hz	35hz	45hz	55hz
35cm	-	14355.00	1813.80	1733.60	3198.80
45cm	-	-	4647.20	4007.40	5235.60

Figure 24. Table showing average time to extinction values for various frequencies.

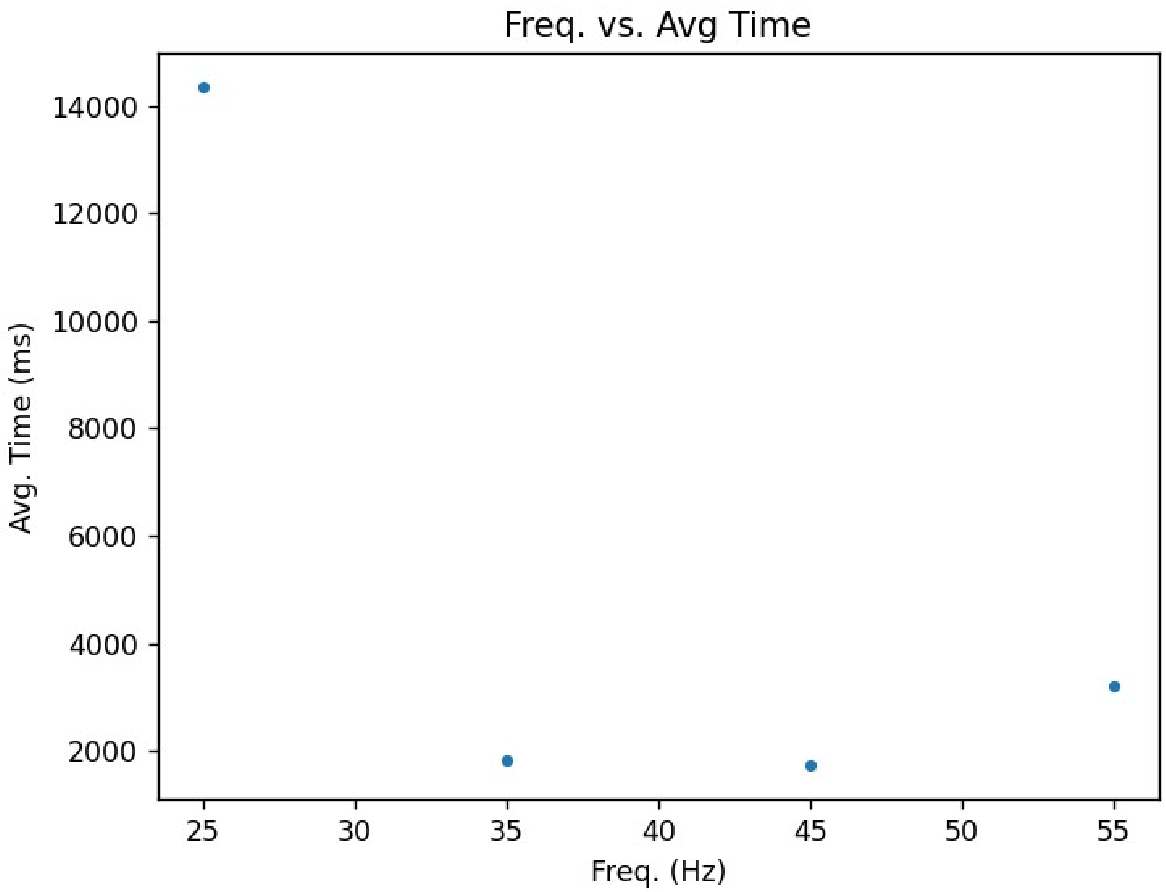

Figure 25. This plot shows the effect frequency had on the average time to extinction at 35cm.

Experiment 3 - Amplitude vs. Time

This experiment serves only to experimentally prove what is intuitively obvious: that a wave with more energy (and by extension, higher amplitude) would be more effective. We also used this test to again show the correlation between input voltage and RMS, as seen in Figure 25.

Avg RMS vs Voltage				
Y position	**1V**	3V	5V	7V
-10 cm	-	1.582	2.648	3.858
0 cm	-	2.154	2.832	4.004
10 cm	-	1.576	2.756	4.032

Figure 26. Table showing the average RMS as measured by our 3 microphones, for each input voltage.

The predicted outcome was observed, with one other interesting occurrence — as the voltage increased, the consistency of our measurements also increased. We can quantify this with a standard deviation for our 5 sample data set. As seen in figure 28, we found that the 7 Volt amplitude had *one tenth* the standard deviation of the 3 V test.

Voltage v Standard Deviation (Sine at 45Hz, 35cm)	
Amplitude (Volts)	**Standard Deviation**
1	-
3	1095.94
5	158.43
7	10.57

Figure 27. Table showing the standard deviation of the amplitude trials.

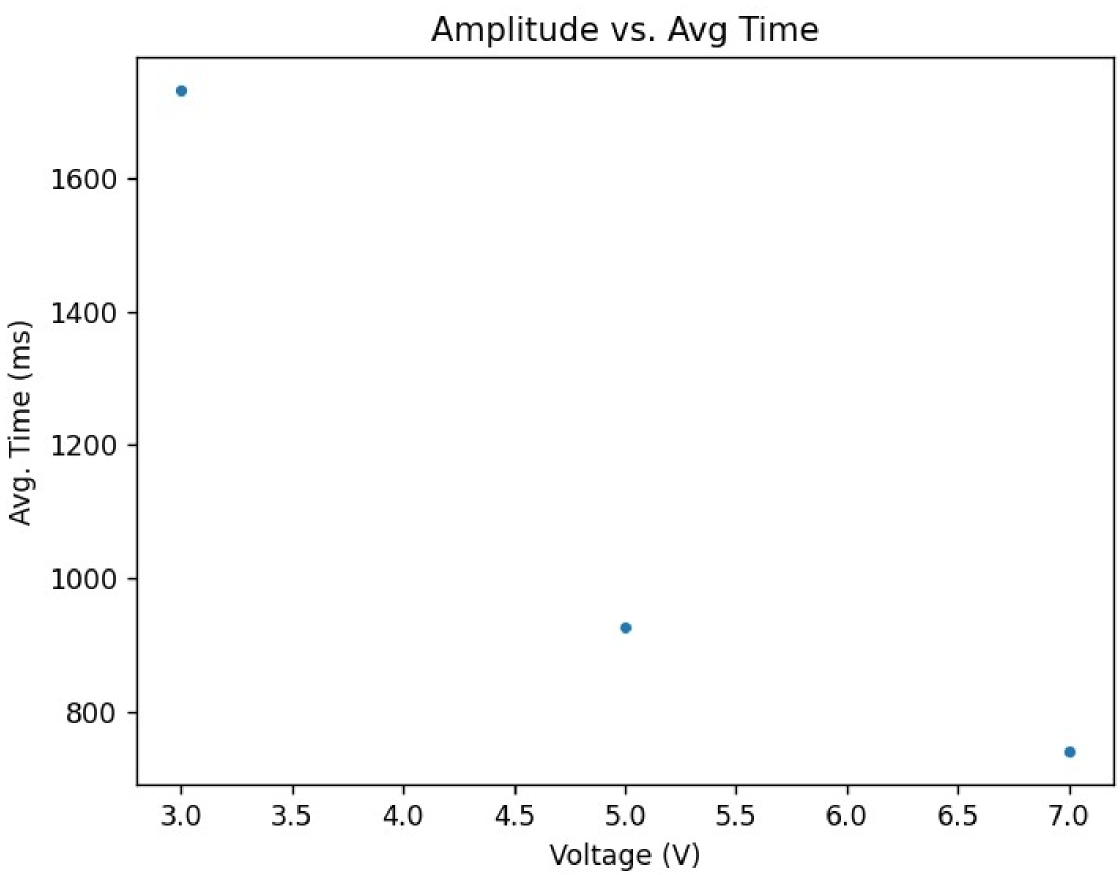

Figure 28. This plot shows the effect of increased input voltage on average time to extinction.

Upon further analysis, we can also see this pattern in the sine/square wave disparity from Experiment 1. Square waves, who have a higher RMS have an average standard deviation (standard deviation of each distance, averaged) of 81.4, while sine waves have an average standard deviation of 815.6. Triangle, even more inconsistent, clocked an average standard deviation of 7111.1. This seems to indicate a correlation between higher RMS and improved consistency.

Experiment 4 - Voltage vs. RMS of Sine and Square Wave

The purpose of this experiment was to test the claim prompted by Experiment 1: that square waves have a higher proportionality constant α than sine waves, given a relationship like the following:

$$V * \alpha \simeq RMS$$

Our experiment did find this to be true: Square waves with a lower voltage universally had a higher RMS value than their higher voltage sine wave counterpart.

	Minimum Extinction Voltage to RMS comparison (sine v square)						
Sine	**voltage**	2.12	2.12	2.12	2.12	2.12	2.12
	RMS	1.48	2.03	1.57	2.05	1.76	1.78
Square	**voltage**	1.84	1.84	1.84	1.84	1.84	1.84
	RMS	3.04	2.07	2.17	2.83	2.17	2.46

Figure 29. Table showing Sine/Square wave RMS comparison.

Error Analysis

There are many sources of error that contribute to possible inconsistency and accuracy within this experiment. The first and most influential of these sources is the candle flame itself. Fire is a plasma, a mass of ionized gas at high temperatures, and it behaves as such, ‘flickering’ and not reacting to force as a particle would. No two flames will burn identically, even when under the same conditions (same position in space, same candle, same lighter). This makes measuring things that pertain to fire an inherently inconsistent task, which is clearly seen in our data. Because of this it was necessary to perform numerous trials – we opted for 5 trials per test. This number was selected in the early stages of our project, when we were testing the Winston Cone. We found a standard deviation of less than or equal to 0.15 with 5 trials of our initial RMS tests. Deeming this sufficient, we used this number of trials for the rest of our experiments. Unfortunately our inconsistency increased as we transitioned into real data taking, as shown by the much larger standard deviations noted above. Due to time constraints, we were unable to perform more trials.

Another major source of error relates to both the nature of fire and to the sensitivity of our sensors. As you may imagine, a fire can get very small — nearly an ember — without actually extinguishing. Because of this, our IR sensor, though generally accurate, did not always correctly identify the fire as being out, resulting in errors in timing. While this was partially fixed by moving our sensor closer, and directing it to look more directly at the wick, this is still a source of inconsistency within our experiment, and could have thrown off some of our readings.

Continuing with the sensor failings, the electret mics have proven to be not very precise. For our purposes, the mics themselves are accurate enough, however complications with converting the ADC output from the mics to RMS resulted in variable RMS values, even when the wave itself was the same. To combat this, we took our RMS value as an average of several RMS readings over the time the timer was running. This helped to smooth our RMS readings, however one obvious limitation is that trials with much shorter times (i.e. ~700 ms) have less values to average over.

Speaking of errors associated with short times, we discovered that our system has a minimum time requirement for processing, meaning no run will ever clock in at less than 658 milliseconds. From observation, we know that some of the runs were legitimately faster than 658ms, and so in our data we must assume that any 658ms reading is really less than or equal to 658 ms.

Our physical setup also constitutes a source of error. The distance markings our set up was based around were accurate only to the centimeter. Our mounting frame for the microphones and IR sensor are made of shaped wire, meant to hold position but also be easily movable between distances. As such, they aren't perfectly aligned with each other, and can be off of the specific distances by slight amounts. We used a ruler and marker to more accurately place and move the mounting structures, but these methods are not perfectly accurate either. This could contribute to our inconsistent RMS readings. The candle we used can also be a cause of error. We tried to swap our candle out regularly, so as to avoid errors caused by the candle burning down and being a) further from the IR sensor or b) protected from the sound wave by being sheltered by the raised wax. On occasion the candle would burn farther down than acceptable, resulting in a handful of tests that would have a much higher time than they would have otherwise.

One last major source of error, again caused by the physical conditions of our space, is the wall brought up in the collimator tests. This wall caused major reflections of sound, which affected the RMS values. This same effect can be caused by a moveable wall-like object, such as a person. Having people in the way likely contributed to skews in our data that were not noticed until analysis.

Conclusions and Next Steps

We determined that our novel method of fire extinguishing is indeed possible — sound waves can be used to interrupt a burn. Our data clearly agrees with our hypothesis that a higher amplitude would be more effective, as seen in Experiment 3. Our data from Experiment 2 suggests that 45Hz is the highest performing frequency, however due to potential limitations of the speaker, we cannot conclude that one frequency is more effective than another. However, we can reasonably claim that frequencies higher than ~60Hz are not effective. Our data clearly indicates a superiority of square waves over other waveforms, which we understand as being linked to the increased RMS of square waves when compared to sine or triangle waves of the same input voltage.

Furthering this experiment, our next step (qualitatively begun but with no quantitative data to formally analyze) would be to investigate the relationship between actual wave shape and the effect on the flame. To do this, we intended to study skewed waveforms. Skewed waveforms have non-centered peaks or, in the case of a skewed square wave, have a disparity between the time spent at crest and trough. Analyzing the effect of a square wave skewed to the right such that the wave spent more time at its minimum value would help us understand the physics behind why this is possible.

To redo this experiment to obtain more concrete results, it would be necessary to reduce some of the systematic error caused by our equipment, i.e. have an apparatus more firmly fixed in space, away from outside influences, and with more precise measurement equipment. This experiment could also be furthered with a more detailed investigation into collimation, i.e. producing a collimator that prevents attenuation beyond the exit of the collimator itself.

Appendix 1 - Waveform Experiment Full Data

Raw Data and additional Graphs

Experiment 1 - Waveform Comparison (Sine, Square, and Triangle wave at 45Hz and 3V, versus Time to extinction and Distance)

Averaged times

Waveform comparison (45Hz) - avg time (ms) to extinction v. distance (cm)						
	Distance from speaker front (cm)					
Waveform	**35**	**40**	**45**	**50**	**55**	**60**
Sine	1733.60	761.40	1292.20	1564.20	3712.40	799.40
Triangle	1823.60	1560.00	4007.40	11068.40	12998.00	13885.20
Square	687.20	731.80	765.20	783.00	676.40	689.60

Raw

Distance from speaker front (cm)	**Waveform comparison (Sine, Square, and Triangle at 45Hz, 3V)**						
Sine		**test 1**	**test 2**	**test 3**	**test 4**	**test 5**	**avg**
35 (cm)	**mic 1 (RMS)**	1.01	1.60	1.11	2.11	2.08	1.58
	mic 2 (RMS)	1.96	1.99	1.58	2.54	2.70	2.15
	mic 3 (RMS)	1.37	1.50	1.06	1.98	1.97	1.58
	time (ms)	2872.00	1452.00	2905.00	728.00	711.00	1733.60
40 (cm)	**mic 1 (RMS)**	1.22	1.92	2.22	1.91	1.66	1.79
	mic 2 (RMS)	1.48	2.34	2.64	2.25	1.99	2.14
	mic 3 (RMS)	1.51	2.46	2.80	2.42	2.18	2.27
	time (ms)	705.00	746.00	683.00	958.00	715.00	761.40
45 (cm)	**mic 1 (RMS)**	1.71	1.76	1.56	2.22	1.86	1.82
	mic 2 (RMS)	2.11	2.19	1.99	2.79	2.23	2.26
	mic 3 (RMS)	2.19	2.26	1.96	2.75	2.35	2.30
	time (ms)	811.00	723.00	2877.00	726.00	1324.00	1292.20
50 (cm)	**mic 1 (RMS)**	1.18	1.00	1.70	1.72	1.24	1.37

	mic 2 (RMS)	1.46	1.22	2.08	2.07	1.51	1.67
	mic 3 (RMS)	1.55	1.38	2.28	2.27	1.69	1.83
	time (ms)	672.00	2865.00	1397.00	772.00	2115.00	1564.20
55 (cm)	**mic 1 (RMS)**	1.58	1.53	1.87	1.73	1.23	1.59
	mic 2 (RMS)	1.86	1.85	2.29	1.99	1.41	1.88
	mic 3 (RMS)	2.15	2.11	2.53	2.28	1.60	2.13
	time (ms)	1699.00	1716.00	2843.00	7192.00	5112.00	3712.40
60 (cm)	**mic 1 (RMS)**	1.25	1.14	1.29	1.04	1.22	1.19
	mic 2 (RMS)	1.59	1.43	1.62	1.27	1.49	1.48
	mic 3 (RMS)	1.83	1.63	1.83	1.49	1.74	1.70
	time (ms)	658.00	762.00	658.00	1261.00	658.00	799.40
Triangle		**test 1**	**test 2**	**test 3**	**test 4**	**test 5**	**avg**
35 (cm)	**mic 1 (RMS)**	1.70	1.54	1.63	2.15	1.22	1.65
	mic 2 (RMS)	2.38	2.13	2.26	2.95	1.73	2.29
	mic 3 (RMS)	1.67	1.46	1.52	2.01	1.19	1.57
	time (ms)	952.00	1561.00	2813.00	905.00	2887.00	1823.60
40 (cm)	**mic 1 (RMS)**	1.54	1.62	1.44	1.55	1.57	1.54
	mic 2 (RMS)	1.75	1.93	1.65	1.82	1.91	1.81
	mic 3 (RMS)	2.03	2.17	1.87	2.08	2.18	2.07
	time (ms)	1867.00	1555.00	2847.00	798.00	733.00	1560.00
45 (cm)	**mic 1 (RMS)**	1.51	1.01	1.08	1.08	1.19	1.17
	mic 2 (RMS)	1.75	1.15	1.24	1.20	1.37	1.34
	mic 3 (RMS)	1.88	1.32	1.39	1.35	1.52	1.49
	time (ms)	2826.00	5148.00	3029.00	4985.00	4049.00	4007.40
50 (cm)	**mic 1 (RMS)**	1.34	1.37	1.55	1.40	1.29	1.39
	mic 2 (RMS)	1.62	1.61	1.83	1.65	1.54	1.65
	mic 3 (RMS)	1.83	1.81	2.09	1.88	1.68	1.86
	time (ms)	7914.00	16098.00	11481.00	16763.00	3086.00	11068.40
55 (cm)	**mic 1 (RMS)**	1.31	1.22	1.06	1.07	1.04	1.14
	mic 2 (RMS)	1.57	1.53	1.28	1.33	1.27	1.40
	mic 3 (RMS)	1.83	1.73	1.53	1.59	1.53	1.64
	time (ms)	1624.00	22927.00	35430.00	737.00	4272.00	12998.00
60 (cm)	**mic 1 (RMS)**	1.00	1.07	1.16	1.16	1.13	1.10

	mic 2 (RMS)	1.18	1.29	1.44	1.48	1.48	1.37
	mic 3 (RMS)	1.40	1.53	1.74	1.66	1.65	1.60
	time (ms)	5281.00	3211.00	45700.00	658.00	14576.00	13885.20
Square		**test 1**	**test 2**	**test 3**	**test 4**	**test 5**	**avg**
35 (cm)	**mic 1 (RMS)**	2.01	2.51	3.75	2.61	1.45	2.47
	mic 2 (RMS)	2.34	2.91	4.20	3.00	1.73	2.84
	mic 3 (RMS)	2.13	2.68	4.01	2.76	1.54	2.62
	time (ms)	657.00	698.00	658.00	658.00	765.00	687.20
40 (cm)	**mic 1 (RMS)**	1.35	3.38	3.48	2.90	2.20	2.66
	mic 2 (RMS)	1.57	3.76	3.81	3.28	2.56	3.00
	mic 3 (RMS)	1.55	3.79	3.90	3.28	2.52	3.01
	time (ms)	935.00	659.00	657.00	658.00	750.00	731.80
45 (cm)	**mic 1 (RMS)**	2.13	3.41	1.60	3.43	3.40	2.79
	mic 2 (RMS)	2.51	3.80	1.82	3.81	3.78	3.14
	mic 3 (RMS)	2.47	3.84	1.83	3.86	3.82	3.16
	time (ms)	992.00	658.00	766.00	699.00	711.00	765.20
50 (cm)	**mic 1 (RMS)**	1.86	2.03	2.81	2.83	2.92	2.49
	mic 2 (RMS)	2.24	2.41	3.32	3.34	3.28	2.92
	mic 3 (RMS)	2.27	2.45	3.37	3.40	3.31	2.96
	time (ms)	940.00	847.00	753.00	658.00	717.00	783.00
55 (cm)	**mic 1 (RMS)**	2.01	2.80	2.39	2.70	2.67	2.51
	mic 2 (RMS)	2.30	3.15	2.74	3.18	3.08	2.89
	mic 3 (RMS)	2.33	3.16	2.68	3.13	3.09	2.88
	time (ms)	658.00	750.00	658.00	658.00	658.00	676.40
60 (cm)	**mic 1 (RMS)**	1.38	1.38	2.55	2.56	1.74	1.92
	mic 2 (RMS)	1.62	1.63	2.90	2.92	2.13	2.24
	mic 3 (RMS)	1.70	1.67	3.05	3.05	2.14	2.32
	time (ms)	700.00	745.00	658.00	658.00	687.00	689.60

Appendix 2 - Frequency Experiment Full Data

Experiment 2- Frequency Comparison (Sine at 21 Hz, 25Hz, 35Hz, 45Hz, 55Hz, at 3V versus Time to extinction and Distance 35 and 45 cm)

Averaged Data

Time to Extinction v. Distance (cm)					
	Frequency				
Distance	21hz	25hz	35hz	45hz	55hz
35cm	-	14355.00	1813.80	1733.60	3198.80
45cm	-	-	4647.20	4007.40	5235.60

Raw Data

frequency	**Frequency comparison (Hz) - Sine @ 3V**						
21hz	**mic 1 (RMS)**	1.58					1.58
35cm	**mic 2 (RMS)**	2.00					2.00
	mic 3 (RMS)	1.98					1.98
	time (ms)	-	-	-	-	-	-
25hz	**mic 1 (RMS)**	1.16	1.13	1.02	1.09	1.10	1.10
35cm	**mic 2 (RMS)**	1.50	1.38	1.30	1.36	1.40	1.39
	mic 3 (RMS)	1.00	0.80	0.73	0.82	0.80	0.83
	time (ms)	26341.00	10180.00	9212.00	24231.00	1811.00	14355.00
35hz	**mic 1 (RMS)**	1.40	1.21	1.05	1.53	1.26	1.29
35cm	**mic 2 (RMS)**	1.81	1.62	1.31	1.99	1.59	1.66
	mic 3 (RMS)	1.02	0.92	0.75	1.13	0.94	0.95
	time (ms)	1050.00	1281.00	1577.00	3419.00	1742.00	1813.80
45hz	**mic 1 (RMS)**	1.01	1.60	1.11	2.11	2.08	1.58
35cm	**mic 2 (RMS)**	1.96	1.99	1.58	2.54	2.70	2.15
	mic 3 (RMS)	1.37	1.50	1.06	1.98	1.97	1.58
	time (ms)	2872.00	1452.00	2905.00	728.00	711.00	1733.60
55hz	**mic 1 (RMS)**	2.60	3.29	3.42	3.93	1.04	2.86

35cm	**mic 2 (RMS)**	3.04	3.66	3.70	4.33	1.35	3.22
	mic 3 (RMS)	2.95	3.64	3.72	4.33	1.26	3.18
	time (ms)	4997.00	4950.00	1435.00	724.00	3888.00	3198.80
25hz	**mic 1 (RMS)**	1.62					1.62
45cm	**mic 2 (RMS)**	2.02					2.02
	mic 3 (RMS)	1.67					1.67
	time (ms)	-	-	-	-	-	-
35hz	**mic 1 (RMS)**	1.20	1.18	1.05	1.17	1.14	1.15
45cm	**mic 2 (RMS)**	1.39	1.46	1.26	1.39	1.38	1.38
	mic 3 (RMS)	0.95	0.99	0.89	0.97	0.93	0.95
	time (ms)	5704.00	783.00	6334.00	7547.00	2868.00	4647.20
45hz	**mic 1 (RMS)**	1.51	1.01	1.08	1.08	1.19	1.17
45cm	**mic 2 (RMS)**	1.75	1.15	1.24	1.20	1.37	1.34
	mic 3 (RMS)	1.88	1.32	1.39	1.35	1.52	1.49
	time (ms)	2826.00	5148.00	3029.00	4985.00	4049.00	4007.40
55hz	**mic 1 (RMS)**	3.44	4.02	2.94	2.62	4.24	3.45
45cm	**mic 2 (RMS)**	3.99	4.51	3.52	3.21	4.52	3.95
	mic 3 (RMS)	4.05	4.53	3.58	3.27	4.56	4.00
	time (ms)	5752.00	6216.00	7056.00	3570.00	3584.00	5235.60

Appendix 3 - Amplitude Experiment Full Data

Experiment 3 - Amplitude Comparison (Sine at 1V, 3V, 5V, 7V, at 45Hz, and 35cm versus Time to extinction)

Averaged Data

Avg Time to extinction (Sine at 45Hz, 35cm)	
Amplitude (Volts)	**Time (ms)**
1	-
3	1733.60
5	927.60
7	740.80

Voltage v Standard Deviation (Sine at 45Hz, 35cm)	
Amplitude (Volts)	**Standard Deviation**
1	-
3	1095.94
5	158.43
7	10.57

Raw Data

Amplitude	**Amplitude comparison (Sine at 45Hz, 35cm)**						
1V	**mic 1 (RMS)**						
	mic 2 (RMS)						
	mic 3 (RMS)						
	time (ms)	-	-	-	-	-	
3V	**mic 1 (RMS)**	1.01	1.60	1.11	2.11	2.08	1.58
	mic 2 (RMS)	1.96	1.99	1.58	2.54	2.70	2.15
	mic 3 (RMS)	1.37	1.50	1.06	1.98	1.97	1.58
	time (ms)	2872.00	1452.00	2905.00	728.00	711.00	1733.60

5V	**mic 1 (RMS)**	2.83	2.79	4.20	1.92	1.50	2.65
	mic 2 (RMS)	3.41	2.89	4.30	1.98	1.58	2.83
	mic 3 (RMS)	2.78	2.97	4.39	2.04	1.60	2.76
	time (ms)	1180.00	890.00	764.00	962.00	842.00	927.60
7V	**mic 1 (RMS)**	2.60	4.32	4.61	4.51	3.25	3.86
	mic 2 (RMS)	2.72	4.45	4.81	4.67	3.37	4.00
	mic 3 (RMS)	2.71	4.50	4.85	4.72	3.38	4.03
	time (ms)	740.00	750.00	731.00	730.00	753.00	740.80

Appendix 4 - Sine v Sqaure Voltage v RMS Experiment Full Data

Experiment 4 - Sine v Sqaure Wave (Minimum voltage for extinction to RMS Comparison, 45Hz, 35cm)

Raw Data

	Minimum Extinction Voltage to RMS comparison (sine v square)						
Sine	**voltage**	2.12	2.12	2.12	2.12	2.12	2.12
	RMS	1.48	2.03	1.57	2.05	1.76	1.78
Square	**voltage**	1.84	1.84	1.84	1.84	1.84	1.84
	RMS	3.04	2.07	2.17	2.83	2.17	2.46

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