OXFORD JOURNAL
OF STUDENT
SCHOLARSHIP

Generating Electricity from Tuning Fork Resonance Using Electromagnetic Induction and Piezoelectricity

Aanshi Shah[1], Amrita Singh[2]
aanshi.p.shah@gmail.com, amrita.singh@colorado.edu

ABSTRACT

Sound, a free and readily available resource, is underutilized as a source of energy. This work describes the design of a novel prototype that utilizes sympathetic resonance and electromagnetic induction to generate electricity from the vibrations of a tuning fork.. A prototype was developed that consisted of resonating 440 Hz tuning forks, a ping-pong ball with attached N35 magnets in contact with one of them, and an insulated copper wire with 100 turns through which the magnets passed after the vibrations of the sympathetically resonating tuning fork set the ball into motion as a slow pendulum. Upon producing a peak current of 0.7 mA, this design was subsequently modified and tested for increased voltage production through the addition of either an additional set of repelling magnets or a piezoelectric disc at the base of the coil. The model using repelling magnets did not produce a measurable voltage. In the prototype incorporating piezoelectricity, the effects of the diameter of the ball, the diameter of the magnets, and the number of magnets on voltage production were measured and determined. With the incorporation of piezoelectricity, the modified prototype produced a maximum voltage of 9.2 mV. In conclusion, electricity can be produced from the vibrations of a tuning fork upon a hammer strike by combining sympathetic resonance, electromagnetic induction, and piezoelectricity. This reflects a promising outlook on the use of sound as a renewable source of energy.

INTRODUCTION

As per the International Energy Agency (2022), the "global demand for each of the fossil fuels shows a peak or plateau across all WEO (World Energy Outlook) scenarios" [1]. This could be reflective of a transition toward renewable, more available sources of energy. Around the world, renewable energy sources such as solar power, wind power, hydropower, geothermal energy, and biomass are being used [2]. However, such sources can be dependent on natural conditions: for example, in a region with large cloud cover or long periods of time without sunlight, solar energy would be impractical to utilize; varying wind speeds can pose challenges with wind power. An underutilized and readily available energy source is sound, or acoustic energy [3].

The majority of the energy carried by the ambient noise around us is dispersed and absorbed without being used as a source of power. At 60 dB SPL, the sound intensity of an average conversation, the intensity is about 10^{-6} W/m^2 [4]. Even at 100 dB, the intensity is 10^{-2} W/m^2. Compared to the average intensity of full sunlight, 1,360 W/m^2, sound has a low power density [5]. Historically, studies have

attempted to harvest energy from sound by amplifying it using a Helmholtz resonator, a rigid container with a cavity for air that acts as a mass-spring system [6, 7]. Garg et al. (2015) used a speaker and a transformer to convert sound into electrical energy [8]. Ge (2017) explored acoustoelectric transducing materials to capture the low-grade energy of sound and convert it to high-grade electrical energy [9]. Jean et al. (2024) studied the use of triboelectric nanogenerators to capture low-frequency sound waves and convert them to usable power [10]. While all these studies have been successful in utilizing acoustic energy as a source of power, a common trade-off is cost effectiveness for scalability, or vice versa. The feasibility of generating electricity from sound while considering cost-effectiveness and scalability was thus evaluated through the design and testing of a novel prototype.

The novel prototype design was driven by several fundamental physics principles, including sympathetic resonance, Faraday's law of electromagnetic induction, and piezoelectricity. Sympathetic resonance involves an object of a certain frequency vibrating and causing another object of the identical frequency to vibrate, thereby amplifying the sound [11]. Faraday's law states that "any change in the magnetic field or change in orientation of the area of the coil with respect to the magnetic field induces a voltage" [12]. The piezoelectric effect implemented in the prototypes in this work is defined as the "generation of electric charges on the surface of certain non-conducting materials in response to applied mechanical stress" [13].

MATERIALS AND METHODS

Four prototypes were created through an iterative design process (Table 1).

Table 1: Summary of the prototypes and main features.

Prototype name	Main features	Quantity measured
Drum Prototype (Figure 1)	• Salt on a thin plastic membrane • Water surrounding the drum divided into cells with copper and aluminum sheets partially immersed and connected through copper wires	0.0 mV
Electromagnetic Induction Prototype (Figure 2)	• Two tuning forks on resonance boxes • Ping-pong ball with attached magnets • Copper coil with 100 turns (6 cm diameter)	0.7 mA
Magnetic Repulsion Prototype (Figures 3 and 4)	• Electromagnetic Induction Prototype with additional repelling magnets within and/or outside the coil	0.0 mV
Piezoelectricity Prototype (Figure 5)	• Electromagnetic Induction Prototype with a piezoelectric disc behind the coil	9.2 mV

A WeePro Vpro850L digital multimeter was used to measure the current or voltage produced through each model (DC current, DC voltage). The multimeter was set to a range limit of 200mA for the Electromagnetic Induction prototype and 200mV for the Drum Prototype, Magnetic Repulsion Prototype, and Piezoelectricity Prototype.

The initial prototype (Drum Prototype) was designed to replicate a human eardrum. This prototype consisted of a drum with a thin tensile plastic membrane that would vibrate from the sound of a tuning fork. Grains of salt on top of this membrane vibrated as well and fell into cells containing water surrounding the drum. Copper and aluminum sheets partially immersed in this water were connected through copper wires (Figure 1). This completed the circuit that was activated through the redox reaction of aluminum and copper in salt water, forming a galvanic cell. However, the voltage produced through this prototype was below the minimum reading attainable by the multimeter and was not measurable, due to the concentration of salt in each cell being meager and the salt being unable to dissolve quickly.

The next prototype (Electromagnetic Induction Prototype) incorporated sympathetic resonance and Faraday's law. This prototype consisted of a pair of tuning forks of the same frequency (either 128, 440, 512, or 528 Hz) mounted on their individual resonance boxes facing each other and a suspended ping-pong ball with attached 5 mm x 3 mm (diameter x thickness) N35 magnets in contact with the resonating tuning fork. When one tuning fork was struck, the other resonating fork in contact with the ping-pong ball would vibrate, causing the ball with attached magnets to pass in and out of an insulated 22 AWG copper coil (Figure 2). This generated a measurable current only through the use of 440 Hz resonating tuning forks.

Despite this, the generated current was quite low. As such, two more prototypes were developed with an aim to maximize the current or voltage produced. For this, magnetic repulsion (Magnetic Repulsion Prototype) and piezoelectricity (Piezoelectricity Prototype) were incorporated into the existing prototype (Figures 3, 4, and 5). In the Piezoelectricity Prototype, in addition to the magnets moving in and out of the coil upon vibrations from the resonating tuning forks, the magnets also activated the piezoelectric disc transducer at the other end of the coil, thereby producing additional voltage that was measured independently of electromagnetic induction (Figure 5).

The basic unit of the Piezoelectricity Prototype used tuning forks of 440 Hz with a 5 cm distance between the resonance boxes. Each unit also consisted of 100 turns of insulated 22 AWG copper wire (coil diameter of 6 cm; resistance ~1Ω) to be used for electromagnetic induction. The other materials used for the prototypes included ping-pong balls with diameters of 25 mm and 40 mm, 6 mm x 3 mm (diameter x thickness) and 5 mm x 3 mm (diameter x thickness) N35 magnets, a 20 mm piezoelectric disc transducer, and a multimeter to measure the mV produced. For the Piezoelectricity Prototype, the disc at the base of the coil generated a piezoelectric current whenever the magnets that were set in motion by the resonating tuning fork traveled through the coil and tapped on the disc at the far end of each swing.

For the Magnetic Repulsion Prototype, a set of magnets in an insulated copper coil and another set attached to a ping-pong ball, with similar poles facing each other in order to generate magnetic repulsion, were used. Once the magnets on the moving ping-pong ball were set in motion from the vibrations of the resonating tuning fork, the repulsion force caused the magnets inside the coil to move back and forth, hypothetically generating a voltage. The back-and-forth motion of the magnets within the coil was facilitated either by gravity or by another set of repelling magnets at the other end of the coil (Figures 3 and 4).

The impact of different variables, such as the size of the ball (25 mm or 40 mm), the size of the magnets (6 mm x 3 mm (diameter x thickness) or 5 mm x 3 mm (diameter x thickness)), and the number of magnets, on the production of electricity was recorded over 10 trails per combination of conditions and analyzed for each prototype. For the Piezoelectricity Prototype, the number of magnets was varied from 6 to 10, as a stack of 1 to 5 magnets could not come in contact with the piezo at the end of the coil.

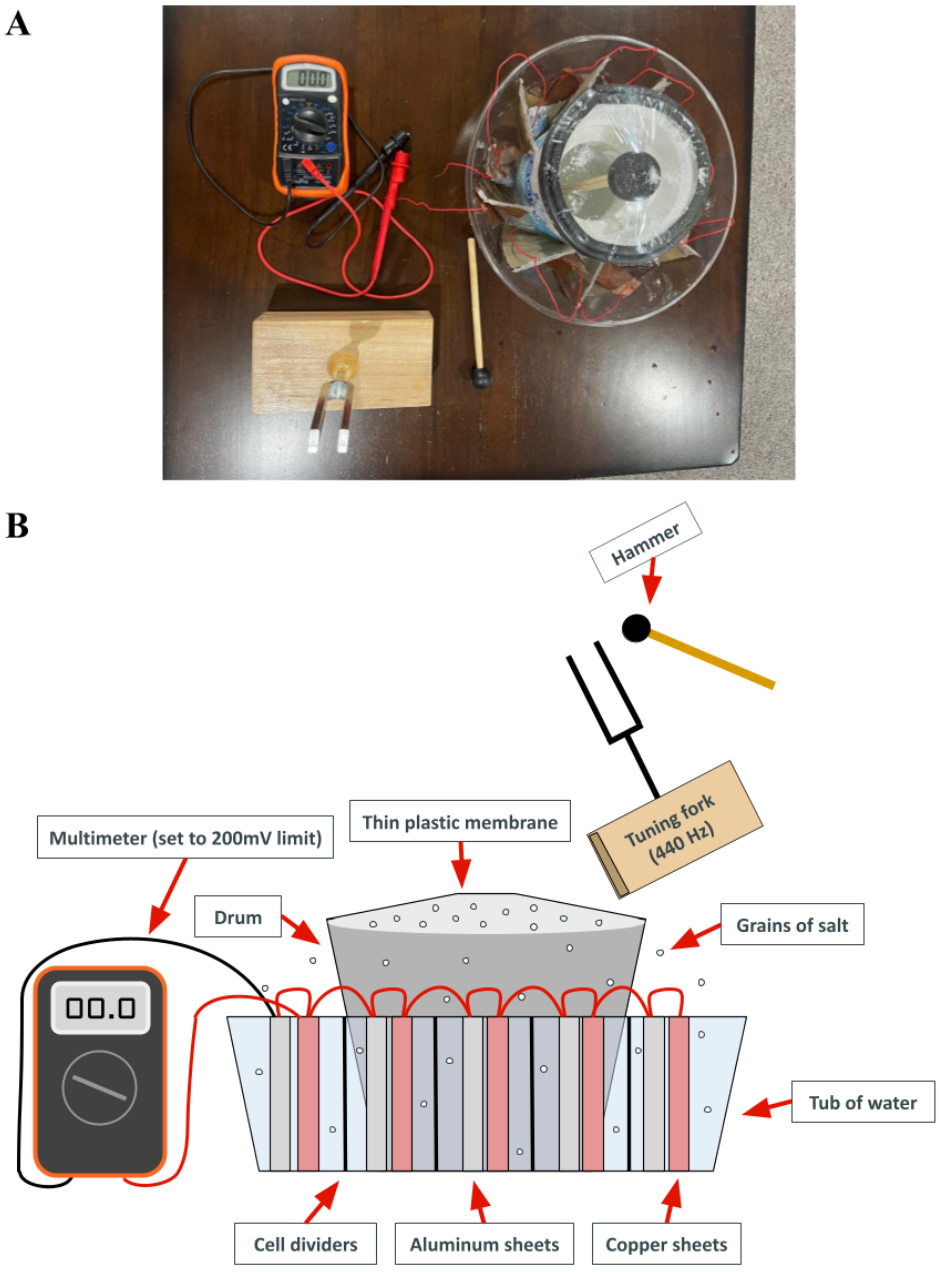


Figure 1: Drum Prototype photo (A) and schematic (B).

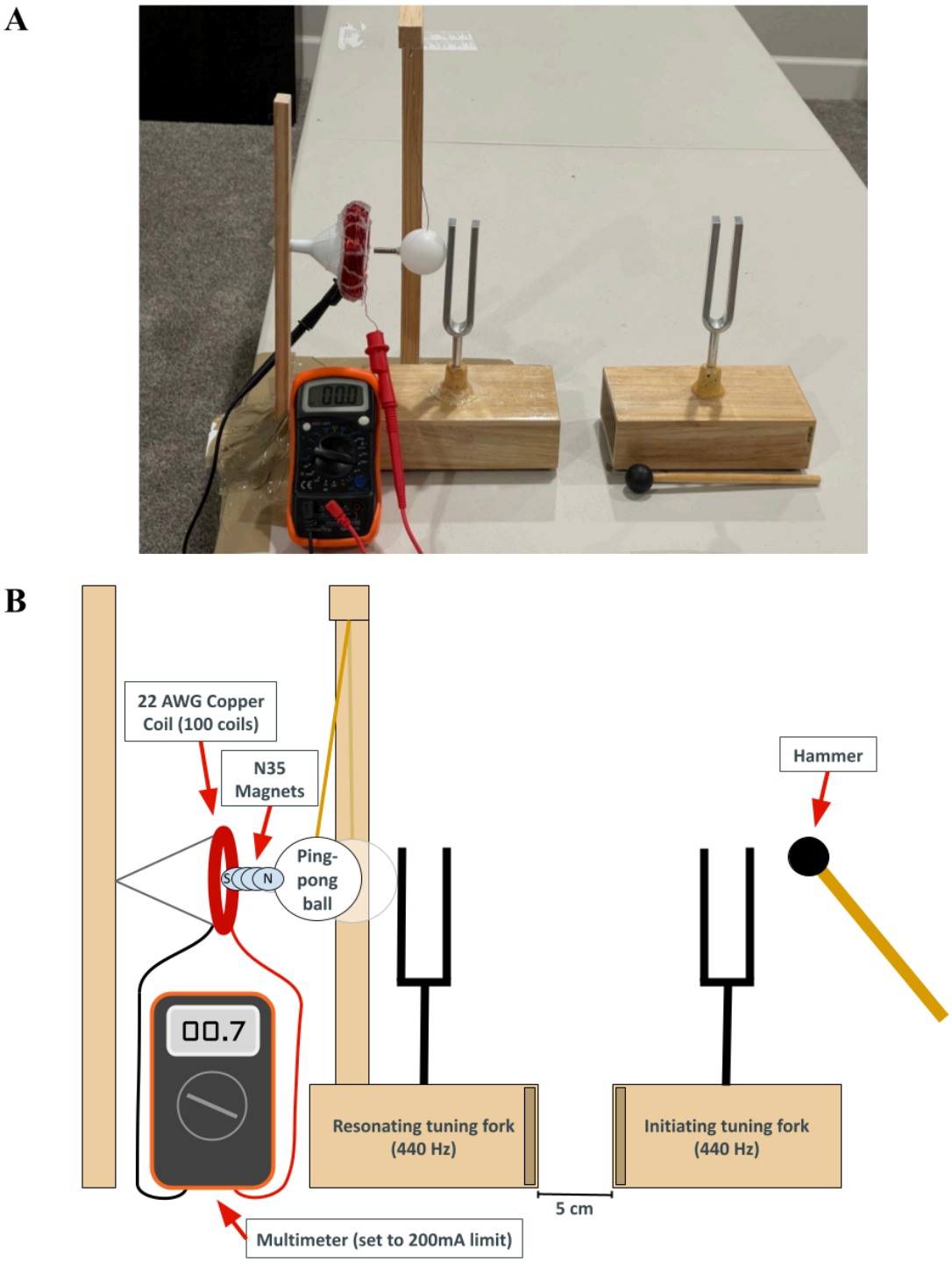


Figure 2: Electromagnetic Induction Prototype photo (A) and schematic (B).

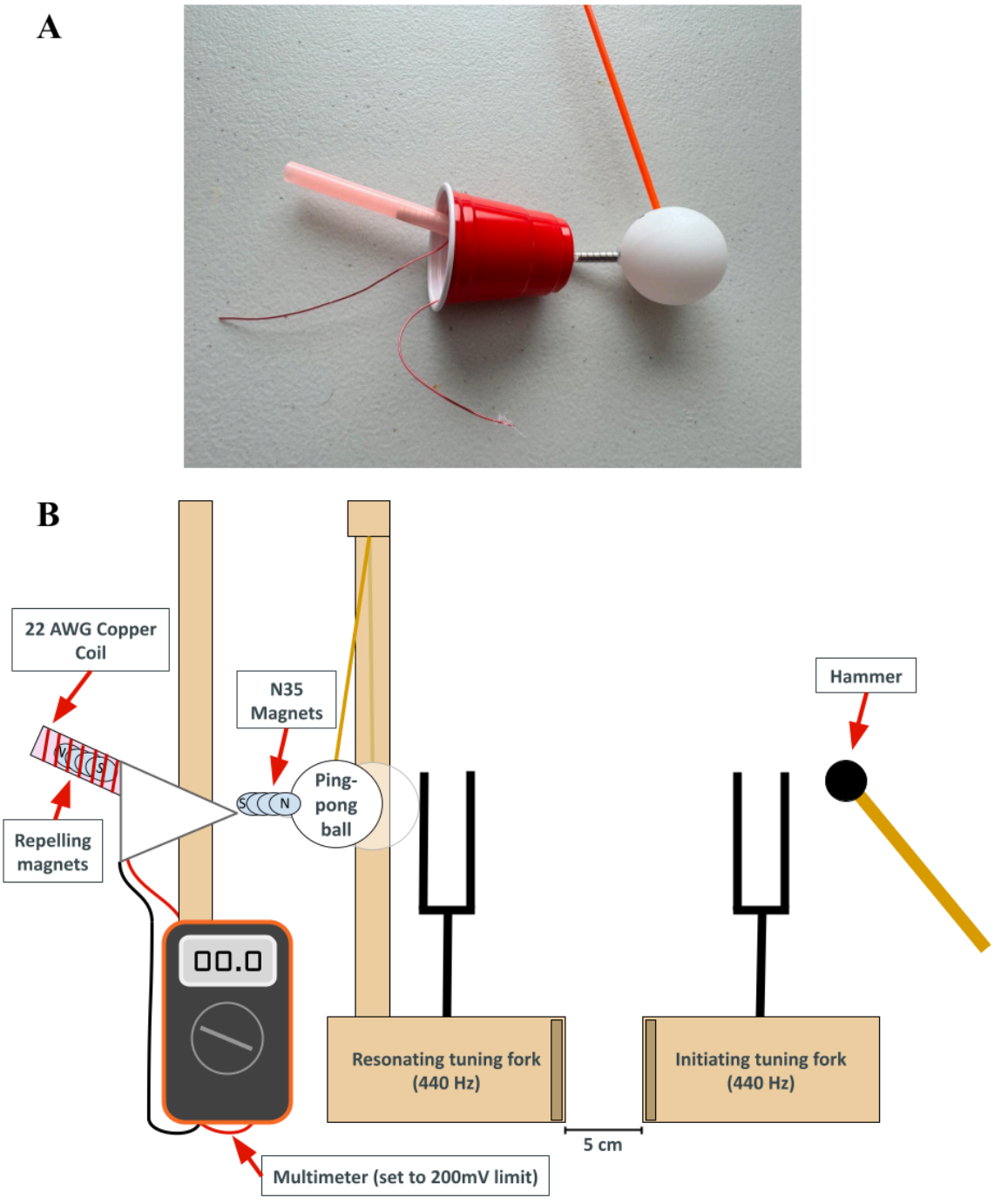


Figure 3: Magnetic Repulsion prototype, version 1 photo (A) and schematic (B).

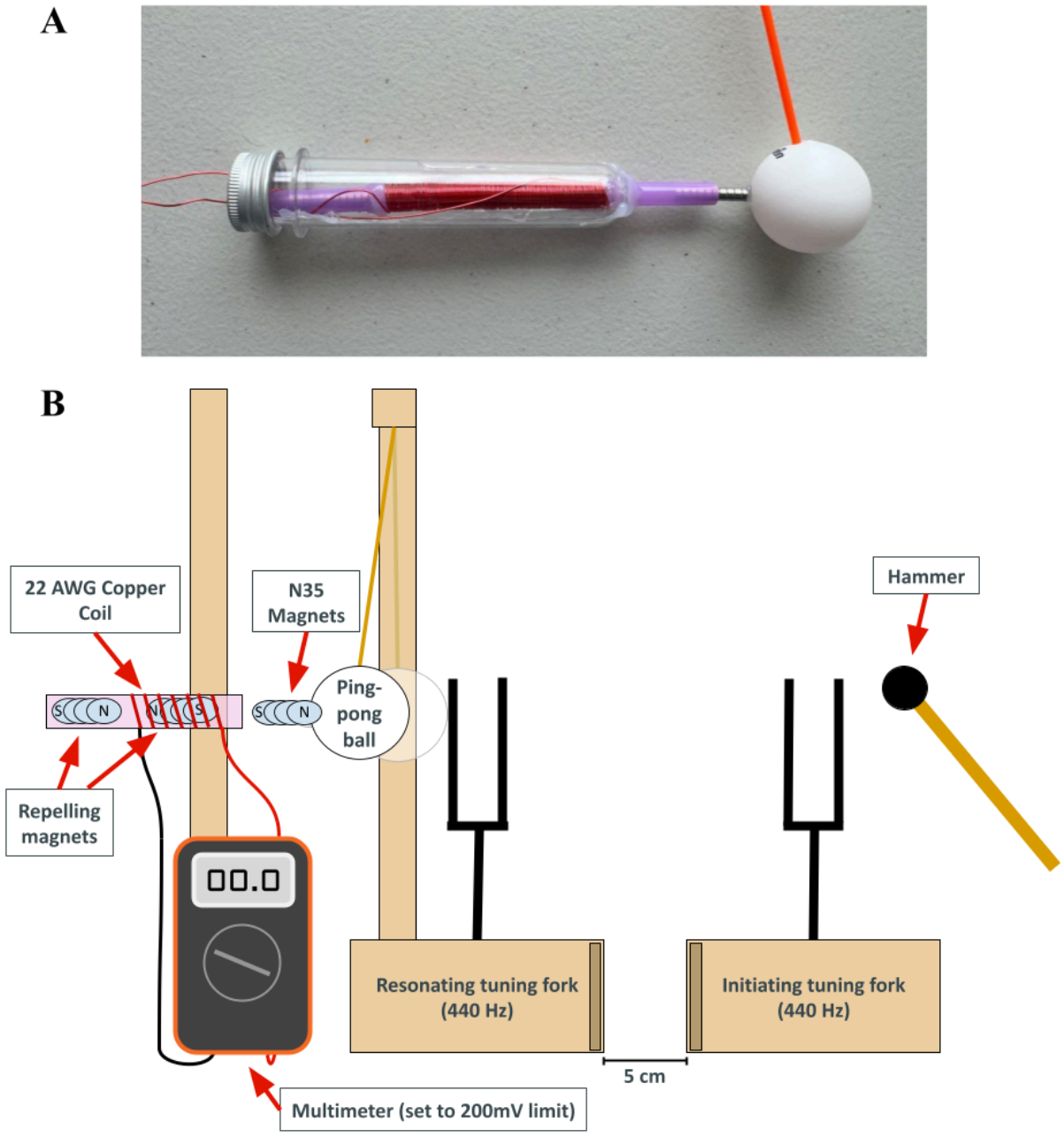


Figure 4: Magnetic Repulsion Prototype, version 2 photo (A) and schematic (B).

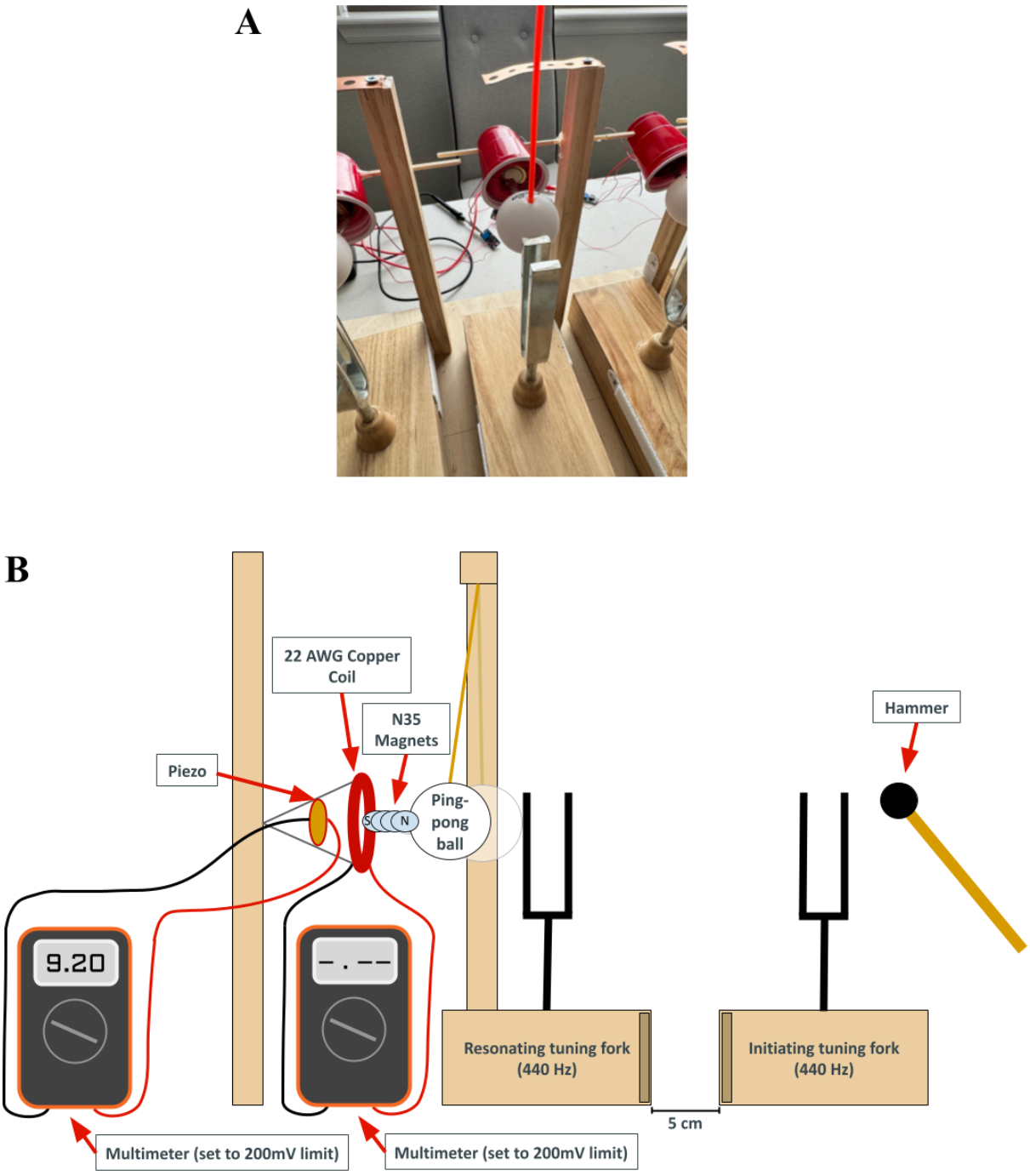


Figure 5: Piezoelectricity Prototype photo (A) and schematic (B).

RESULTS

Controls including forks of differing frequencies, a barrier between the resonance boxes to isolate vibrations carried through the table, and measurements without an initial tuning fork strike were tested for voltage production. 0 mV were produced through all controls.

The Magnetic Repulsion Prototype prototype had two variants, distinguished by how the magnetic repulsion was facilitated. In the variant of the Magnetic Repulsion Prototype using gravity to facilitate repulsion (Figure 3), the magnets attached to the ping-pong ball were repelled by the second set of magnets before they could reach the coil. In the variant using two sets of repelling magnets (Figure 4), the magnets' low power resulted in insufficient movement of the magnets through the coil. Because of this, the Magnetic Repulsion Prototype did not produce a measurable voltage.

The data from the Electromagnetic Induction Prototype did show that it was able to generate a measurable voltage. Data was collected on the following variables: the frequency of the tuning fork, the distance between the resonance boxes, the number of magnets, and the number of times the tuning fork was struck. Using the results from analysis of this data through linear regression, the number of magnets that could produce the most electric current were determined. The results showed that 9 magnets produced the strongest electric current of 0.7 mA when the resonance boxes were placed at a distance of 5 cm apart.

The data for the impact of the size of the ball, the size of the magnets, the number of magnets, and the use of a piezoelectric disc transducer on the electricity produced by the Piezoelectricity Prototype were obtained through a series of experiments and analyzed subsequently. To determine the validity of the results from this analysis, the Statistical Package for the Social Sciences (SPSS) software was used to conduct univariate and multivariate linear regression analysis of variance for the data. A multivariate linear model was fitted to determine the effect of the variables on voltage production. The unstandardized coefficients for the variables, which reflect the rate at which voltage increases depending on the change in value of the individual variables, were determined (Table 2).

Table 2: Unstandardized coefficients (with standard errors) showing the effect of modifying variables in the Electromagnetic Induction and the Piezoelectricity Prototype.

Model	Unstandardized coefficient	Coefficient standard error
Diameter of ball (mm)	0.039	0.005
Diameter of magnet (mm)	0.743	0.081
Number of magnets	0.216	0.016

DISCUSSION

The maximum voltage was produced by the unit with a large ball (40 mm diameter) that facilitates the collision of 9 magnets of size 6 mm x 3 mm (diameter x thickness) against a piezoelectric transducer. This worked best with the resonance of two tuning forks of 440 Hz frequency, both mounted on their individual resonance boxes with a distance of 5 cm between them, as determined in the Electromagnetic Induction Prototype. All the variables had a significant effect on the electricity produced through electromagnetic induction, as reflected by the R^2 value of 0.892 that was obtained through the tests of between-subjects effects, along with the defined trend in the box plots with few outliers (Figure 6). In contrast, a similar impact of these variables on the voltage produced through piezoelectricity was not observed (Figure 7).

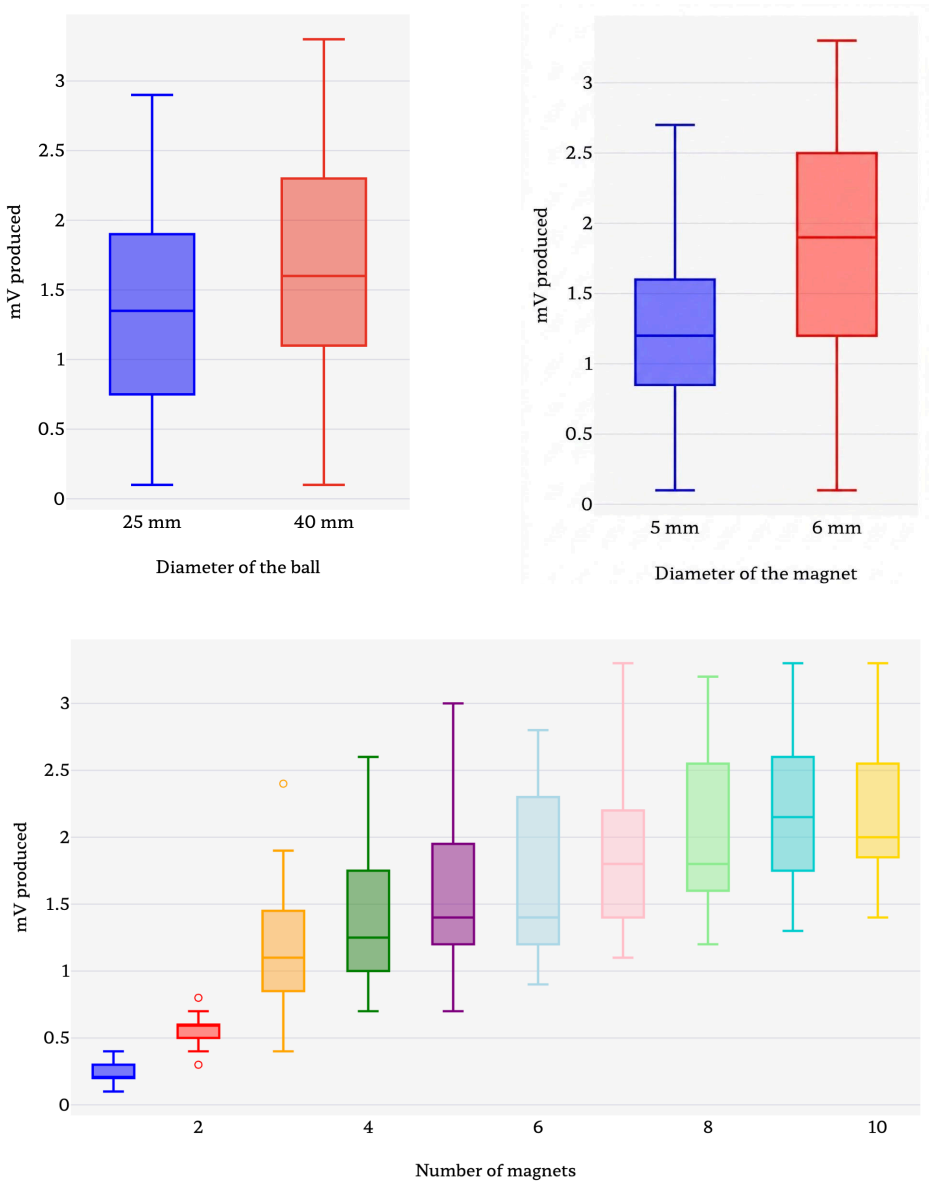


Figure 6: Impact of diameter of the ball, diameter of the magnets, and number of magnets on voltage produced through the electromagnetic induction component of the Piezoelectricity Prototype. 10 trials were conducted per combination of conditions. Whiskers extended to ±1.5 IQR. Max output was 3.3 mV.

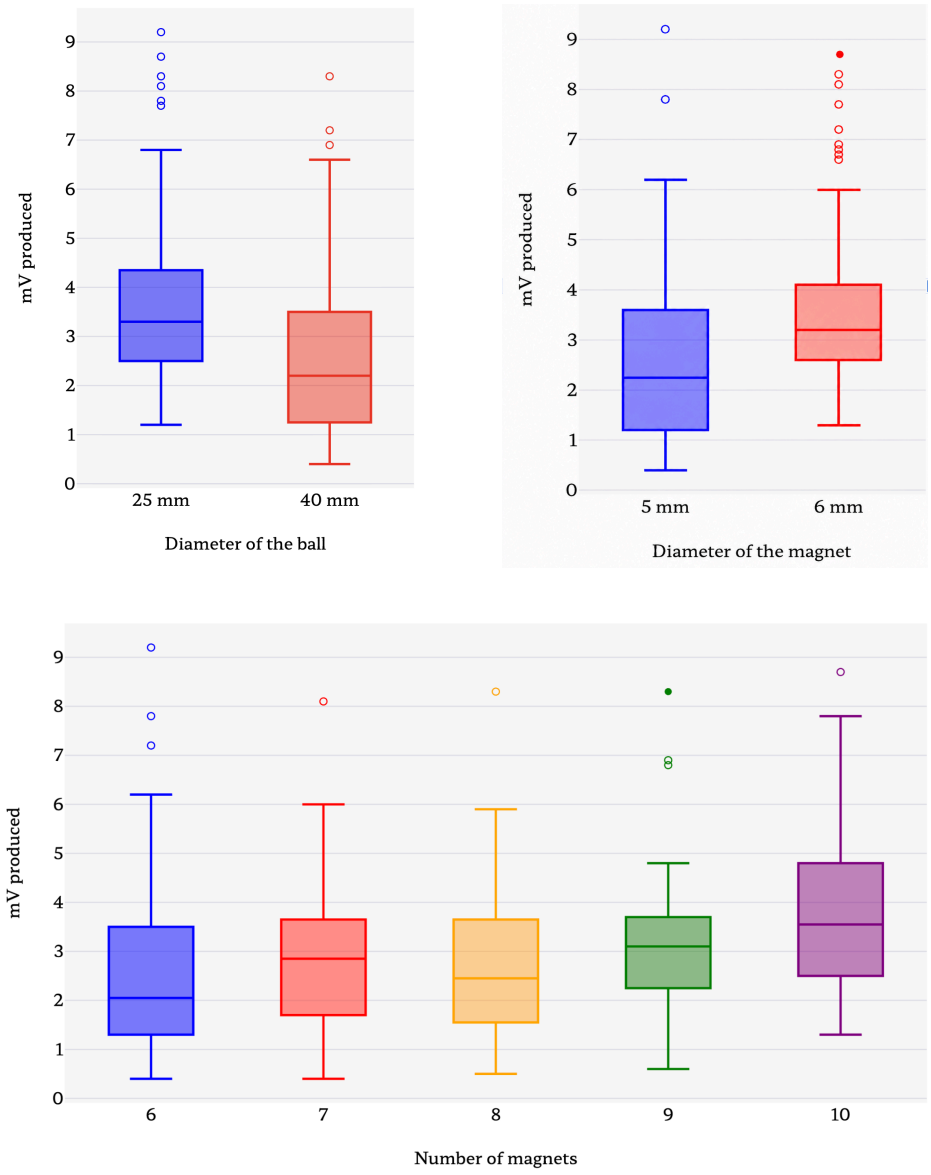


Figure 7: Impact of diameter of the ball, diameter of the magnets, and number of magnets on voltage produced through the piezoelectricity component of the Piezoelectricity Prototype. 10 trials were conducted per combination of conditions. Whiskers extended to ±1.5 IQR. Max output was 9.2 mV.

As seen in Figures 6 and 7, the Piezoelectricity Prototype, incorporating resonance, electromagnetic induction, and piezoelectricity, produced a stronger voltage than through electromagnetic induction alone. The success of low-cost materials in the production of this prototype reflects the feasibility of implementing this prototype on a grand scale. The results show that the prototype can be optimized in future experiments to generate more voltage. Additionally, the electricity produced through the

piezoelectric component, when combined with the electricity produced through electromagnetic induction, can increase the total voltage of this prototype.

Magnetic repulsion, although appearing to be a principle that could potentially generate electricity, had its shortcomings. The vibrations from the tuning forks were not strong enough to generate the force required to overcome the repulsion of the magnets, which led to the inability to generate significant motion of magnets through the coil.

The unstandardized coefficients were positive for all three variables, which reflects that by increasing the diameter of the ball, the diameter of the magnets, and the number of magnets, the voltage can increase significantly. However, there is a limit on the maximum number of magnets that can be used in one prototype unit, as the weight of the magnets would eventually start inhibiting the movement of the ball.

The lack of variability in the current produced through piezoelectricity under various operating conditions could be due to the low collision pressure of the magnets with the disc. In the Piezoelectricity Prototype, the electricity produced with the disc was independent of the electricity produced through electromagnetic induction. This could potentially reflect an opportunity to increase voltage produced when these two principles are combined, which will be tested through future work.

In this work, electricity was measured through both current and voltage. Power was not measured due to the lack of a known load resistor. In future work, the resistance will be held constant and power will be calculated to determine the true measure of electricity production through each mechanism of the Piezoelectricity Prototype.

There are still certain limitations of this study that will be addressed in future experimentation. Despite keeping the testbed stationary, variations in environmental conditions, such as temperature, pressure, relative humidity, and ambient noise, may have impacted the results. Additionally, the initiating tuning fork was struck manually, which could have led to inconsistencies in sound intensity. Future work will use a fixed, repeatable striker or a consistent sound source to minimize human error.

It would be interesting to see how multiple prototypes, when combined in series, could affect the ultimate voltage produced. Finally, converting the alternating current that is produced through this prototype to a direct current using a rectifier is a fundamental obstacle that is currently being addressed through further research and experimentation. Once a direct current is produced from one unit, multiple prototypes will be connected in series and tested for production of maximum electricity from a single vibrating tuning fork (eventually, a single sound source), similar to the methods of power production through a series of solar panels. The goal will be to store this cumulative direct current for future usage.

In conclusion, the Piezoelectricity Prototype, which is based on sympathetic resonance, Faraday's law, and piezoelectricity together, can be used to generate electricity from the vibrations of a tuning fork

without a battery in the harvesting circuit. This can mark a significant first step towards the use of sound as a renewable source of energy.

In the future, we plan to continue working on connecting prototype units in series to generate a greater voltage output, as well as modify the prototype to be able to harvest sound from any frequency, thereby making ambient sound a renewable source of energy. This cost-effective, scalable prototype has the potential to transform sound from a bothersome noise to a renewable source of energy.

ACKNOWLEDGEMENTS

We would like to express our deepest gratitude to Dr. James Nabity at the University of Colorado Boulder for the resources and encouragement he provided.

DATA AVAILABILITY

The data and analysis code supporting the findings of this study are permanently archived on Zenodo at https://doi.org/10.5281/zenodo.23985946.

AUTHOR CONTRIBUTIONS

Aanshi Shah: conceptualization, formal analysis, investigation, methodology, visualization, writing — original draft, writing — review and editing. **Amrita Singh:** supervision, writing — review and editing.

REFERENCES

[1] "World Energy Outlook 2022 shows the global energy crisis can be a historic turning point towards a cleaner and more secure future," International Energy Agency, Oct. 27, 2022. Accessed: Jan. 05, 2023. [Online]. Available: https://www.iea.org/news/world-energy-outlook-2022-shows-the-global-energy-crisis-can-be-a-historic-turning-point-towards-a-cleaner-and-more-secure-future

[2] "What is renewable energy?," United Nations. Accessed: Jan. 13, 2023. [Online]. Available: https://www.un.org/en/climatechange/what-is-renewable-energy

[3] M. Yuan, Z. Cao, J. Luo, and X. Chou, "Recent Developments of Acoustic Energy Harvesting: A Review," *Micromachines*, vol. 10, no. 1, p. 48, Jan. 2019, doi: https://doi.org/10.3390/mi10010048.

[4] "17.3 Sound Intensity," in *University Physics Volume 1*, vol. 1, 3 vols., in University Physics, vol. 1. , OpenStax, 2016.

[5] "Climate and Earth's Energy Budget," National Aeronautics and Space Administration, Jan. 2009.

[6] S. B. Horowitz, M. Sheplak, L. N. Cattafesta, and T. Nishida, "A MEMS acoustic energy harvester," *Journal of Micromechanics and Microengineering*, vol. 16, no. 9, p. S174, Aug. 2006, doi: 10.1088/0960-1317/16/9/S02.

[7] F. Liu *et al.*, "Acoustic energy harvesting using an electromechanical Helmholtz resonator," *The Journal of the Acoustical Society of America*, vol. 123, no. 4, pp. 1983–1990, Apr. 2008, doi: 10.1121/1.2839000.

[8] M. Garg, D. Gera, A. Bansal, and A. Kumar, "Generation of electrical energy from sound energy," presented at the 2015 International Conference on Signal Processing and Communication, Institute of Electrical and Electronics Engineers, Jul. 2015. doi: https://doi.org/10.1109/ICSPCom.2015.7150687.
[9] Q. Ge, "Prospect of electric generation using sound," *AIP Conf. Proc.*, vol. 1839, no. 1, May 2017, doi: https://doi.org/10.1063/1.4982415.
[10] F. Jean, M. U. Khan, A. Alazzam, and B. Mohammad, "Harnessing ambient sound: Different approaches to acoustic energy harvesting using triboelectric nanogenerators," *Journal of Science: Advanced Materials and Devices, Article 100805*, vol. 9, no. 4, Dec. 2024, doi: https://doi.org/10.1016/j.jsamd.2024.100805.
[11] H. von Helmholtz and A. J. Ellis, "Analysis of musical tones by sympathetic resonance," in *On the sensations of tone as a physiological basis for the theory of music*, Longmans, Green, and Co., 1895, pp. 36–49.
[12] "13.1 Faraday's Law," in *University Physics Volume 2*, vol. 2, 3 vols., in University Physics, vol. 2. , OpenStax, 2016.
[13] J.-F. Li, "Fundamentals of Piezoelectricity," in *Lead‐Free Piezoelectric Materials*, John Wiley & Sons, Ltd, 2021, pp. 1–18. doi: https://doi.org/10.1002/9783527817047.ch1.