INTRODUCTORY-LEVEL PROJECTS DESIGNED TO TEACH FUNDAMENTAL MATH AND PHYSICS CONCEPTS TO ELEMENTARY SCHOOL STUDENTS

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Abstract – (This paper falls within the Research to Practice category.) It is an undeniable fact that U.S. students, across all educational levels, lag behind their peers in countries considered major global competitors in thof mathematics and physics. This gap has negatively affected higher education institutions' ability to recruit, retain, and graduate qualified engineers to meet the growing demands for the modern world. Addressing this issue requires more than efforts of higher education alone; it is a systemic challenge. High schools, middle schools, and even elementary schools must work together to establish a closed-loop precollege engineering education system that offers consistent and meaningful learning experiences for U.S. students. This paper presents three introductory-level projects designed to instill fundamental math and physics concepts in elementary school students. Each project introduces key physical laws along with the associated mathematical skills. The first project involves building and measuring a mass-spring system to explore Hooke's law; the second focuses on understanding Ohm's law using an electric circuit closed with pencils; and the third entails building a catapult and calculating its projectile range. These projects were structured progressively and completed by an elementary student under parental guidance and are considered suitable for students in grades 2 through 5.

Keywords: Projects for elementary school students, precollege engineering education, Hooke's law, electric circuit, catapult physics

1. Background

SAE (Society of Automotive Engineers) International sponsored a report at the end of 2023 stating that the U.S. is already facing a shortage of engineers, and the problem is expected to worsen. According to the report, the U.S. needs 400,000 new engineers each year, yet one-third of engineering jobs go unfilled, a trend projected to continue through 2030. The report lists several reasons for the engineering shortfall, noting that perhaps the most significant reason is that most aspiring engineers never make it through the pipeline. Only 13% of high school students who express interest in becoming engineers ultimately graduate with a college degree in engineering.

A major contributing factor is that many U.S. students lack the strong math and physics foundation needed for success in college-level engineering studies. According to the National Center for Education Statistics (NCES), U.S. high school students generally score below the international average in both math and science compared to peers in other developed nations and this trend is particularly evident in the later years of high school [2]. The lead author's personal experience also supports this observation. He has 20 years of experience teaching a variety of mechanical engineering courses at both the undergraduate and graduate levels [3-13]. In his classes, many students have demonstrated significant deficiencies in math and physics fundamentals, such as free-body diagrams, partial different equations, and calculus, as well as an overreliance on computer problem-solving, calculation, and conceptual understanding. Consequently, class averages were often around 70 out of 100. Another indicator of this challenge is the retention rate of engineering students. At the author's current university, this rate is near or below 60%, significantly lower than the university-wide average of approximately 80%.

Clearly, the most effective way to address this challenge is to strengthen the math and physics foundations of U.S. high school students. This cannot be achieved by high schools alone, as the development of math and physics skills is a progressive process. In this regard, elementary, middle, and high schools must work together to create a cohesive, sustained learning environment that provides students with a complete, practical precollege engineering education. At the high school level, various camps and design competitions have been organized to inspire students' interest in different areas of engineering [14-16]. At the middle school level, outreach events such as "Parent Daughter Engineering Night" have been held to engage students – especially female students – in project design and problem-solving across a range of engineering disciplines [17, 18].

Compared with the middle and high school levels, relatively few educational tools or projects have been developed for elementary school students (grades 1 to 5) to spark early interest in math and science. As noted by Krajcik and Czerniak [19], project-based learning is an effective approach for teaching science and engineering in elementary schools. Tufts University's Center for Engineering Education Outreach has achieved significant success in designing and implementing a number of elementary-level projects using LEGO materials and the ROBOLAB software as the instructional toolset [20]. However, the lack of curriculum materials still remains a barrier to teaching engineering to elementary students [21]. To address this gap, this paper presents three introductory-level science projects designed by the author for elementary school students. Details of these projects are presented in the following sections.

All three projects involve experimental analysis in which students build an experimental setup, conduct experiments, collect and document data, perform analyses, develop an understanding, write a report, and create a poster. The goal of the first project is to introduce students to Hooke's law, the mass-spring system, and the concept of a linear relationship in mathematics, while also giving them an intuitive sense of the engineering phenomenon of vibration. The second project teaches students how to build an electric circuit and introduces key electrical parameters such as voltage, current, and resistance, as well as their relationships (Ohm's law). The third project demonstrates the working principle of catapults and explores the influence of various factors on projectile distance. The difficulty level of the three projects increases gradually, with Project 1 suitable for 2nd or 3rd graders and Project 3 suitable for 4th or 5th graders. Most of the kits required to build the experimental systems were purchased online.

2. Project 1: Understanding Hooke's Law and Vibration via a Mass-Spring System

<u>Summary</u>

The participant assembled a mass-spring system and studied its vibration behavior. Spring stiffness was calculated using Hooke's law, the system's natural vibration period was measured, and the effect of air damping on its vibration mode was observed.

<u>Apparatus</u>

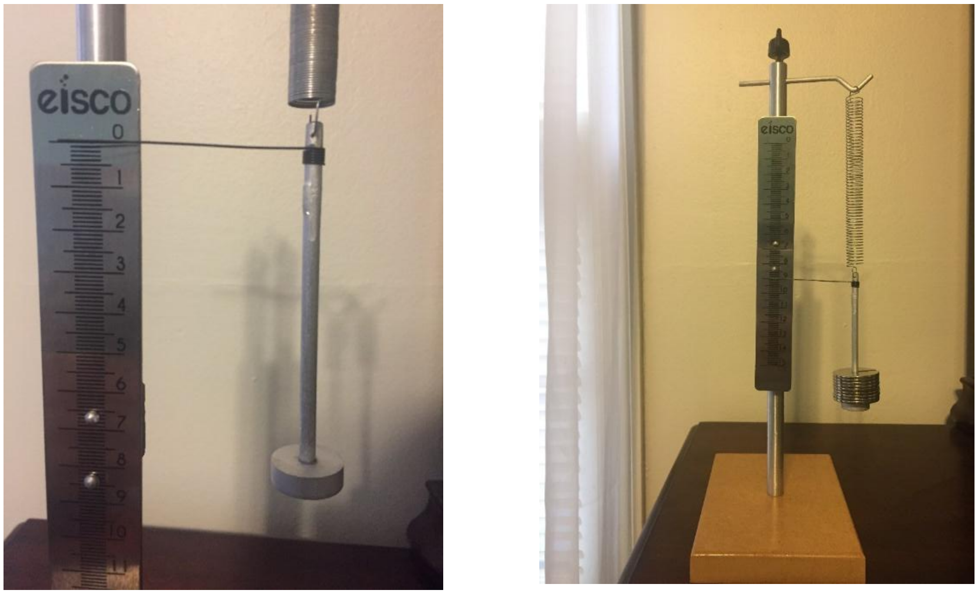
Fig. 1 displays all components of this apparatus (any standard stand and coil spring can be used), and Fig. 2 shows the participant assembling this system. The assembled mass-spring system consisted of a spring mounted on a stand and a pointer moving in front of a metal scale marked from 0 to 15 cm, read from the top down. Nine weights, each 10 g, were provided for the experiments.

Figure 1. Components for the mass-spring system

Figure 2. Fixing the stand to the wood base using a screwdriver

<u>Determine Spring Stiffness</u>

The objective of this step is to test Hooke’s law and use it to determine the spring stiffness. Hooke’s law states that the force needed to extend or compress a spring is directly proportional to the displacement. In other words, the ratio between the force and the displacement is constant, and this constant is the spring stiffness. As illustrated in Fig. 3, the initial position of the point was set to zero, and the weights were added one by one. For each added weight, the spring displacement was recorded as the reading on the scale, as listed in Table 1.



(a) (b)

Figure 3. Pointer position when the weight was (a) 0 and (b) 90 g

Table 1. Weights and spring displacements

Weight	10 g	20 g	30 g	40 g	50 g	60 g	70 g	80 g	90 g
Distance	1 cm	2 cm	3 cm	4 cm	5 cm	6 cm	7 cm	8 cm	9 cm

As shown in Table 1, for each pair of weight and distance, the ratio between them is constant, with values such as 10 g/1 cm, 20 g/2 cm, …, and 90 g/9 cm all equal to 10 g/cm. This observation reflects Hooke's law. According to the law, the spring stiffness can be obtained by converting the constant value 10 g/cm to the standard unit, resulting in 9.8 N/m.

Determine Natural Vibration Period

To measure the natural vibration period of the system, the mass (weighing 90 g) was pulled down to its maximum displacement and released. The mass then vibrated under the force of the spring, allowing the participant, under the author's guidance, to observe the vibration behavior and understand the concepts of cycle and period. Because the vibration was too fast to precisely measure the duration of one cycle (the period), the author assisted the participant in measuring the time for 20 cycles, which was 12.22 seconds. The natural period was then calculated as 12.22/20 = 0.611 seconds.

Although the following part is beyond the scope for 2^{nd} or 3^{rd} grade students, the tutor may choose to explain that the vibration period can be calculated using the equation $T = 2\pi\sqrt{\frac{m}{k}}$, where m is the mass and k is the spring stiffness. The calculated period can then be used to validate the measured value. In this experiment, the mass is 90 g = 0.09 kg, and the spring stiffness was previously measured as 9.8 N/m. Using the equation, the period is calculated as 0.602 seconds, which closely matches the measured value. The small difference between the measured and theoretical periods arises because the mass of the holder was ignored in the theoretical calculation, but even a small additional mass can affect the actual period.

The Effect of Air Damping

Students should understand that in a vacuum, once the mass begins to vibrate, it would never stop because there is no force to stop the vibration. However, in this experiment, the vibrating mass eventually stopped after 8 minutes 16 seconds. This was because of the air. It is the friction between the mass and the air that reduced and eventually stopped the vibration, known as the effect of air damping. This effect is too small to detect but it can be observed from the phenomenon that the mass eventually stopped vibrating after a certain amount of time.

Outcomes

Through this project, students can gain an understanding of the following physics and math concepts: Hooke's law, spring stiffness, linear relationships, natural period, vibration cycles, and the effect of air damping. Additional outcomes of this project include a final report and a poster (Fig. 4).

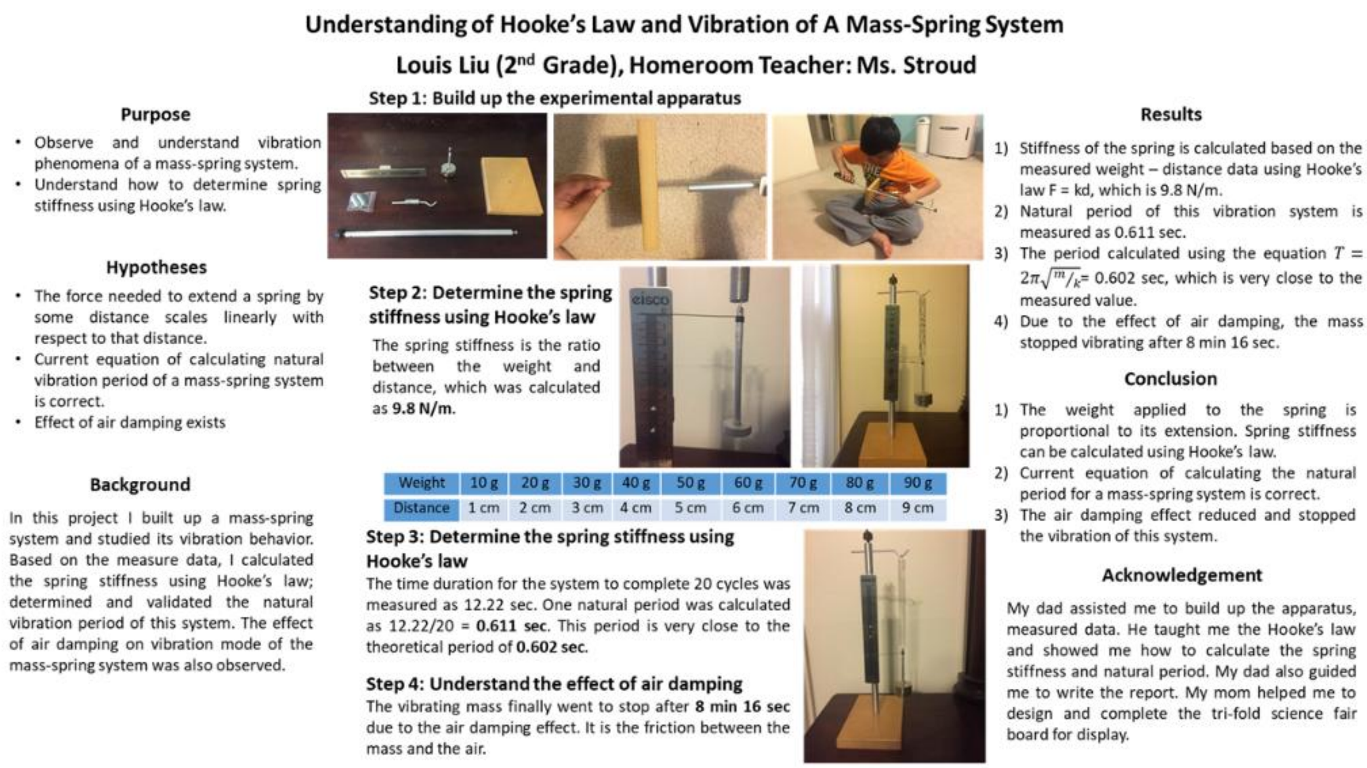


Figure 4. Poster created based on the results of Project 1

3. Project 2: Understanding Voltage, Current, and Resistance via an Electric Circuit with Pencils

Summary

The participant set up an electric circuit including a lightbulb using pencils. Pencils of different lengths were used as resistors to explore the relationship between their length and the bulb's brightness. Through this project, the participant learned the fundamentals of electric circuits and developed an understanding of Ohm's law based on the experimental observations.

<u>Experimental Procedure</u>

The electric circuit was first set up using the components shown in Fig. 5. Five used pencils of lengths 7 cm, 9 cm, 12.4 cm, 14.3 cm, and 16.5 cm were used for this experiment (Fig. 6), with both ends sharpened. First, the exposed metal ends of the red and black alligator clips were connected, and the lightbulb's brightness was recorded; at this point, the pencil length was considered "0". Next, the clips were attached to both ends of the shortest pencil, and the bulb's brightness was recorded when the pencil length was 7 cm. This procedure was repeated for all pencils. A scale from 0 to 5 was used to indicate the bulb's brightness, where 0 represents "off" and 5 represents "very bright". Fig. 7 shows the bulb's brightness for different pencil lengths, and Table 2 lists the observed brightness values alongside the corresponding pencil lengths. As shown in that figure and observed from the experiment, the lightbulb became less bright as the pencil length increased.

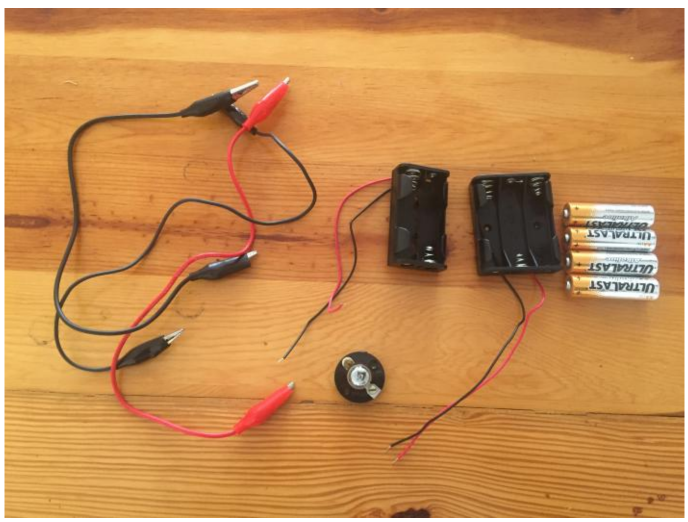
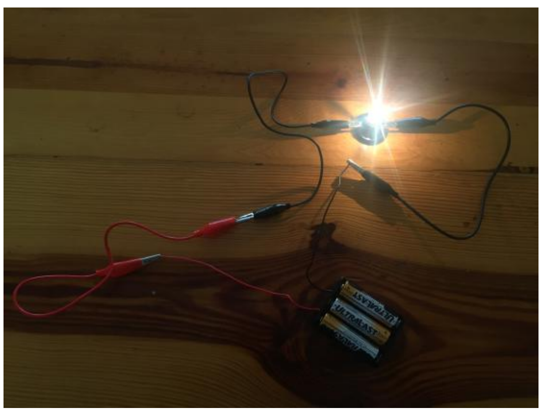


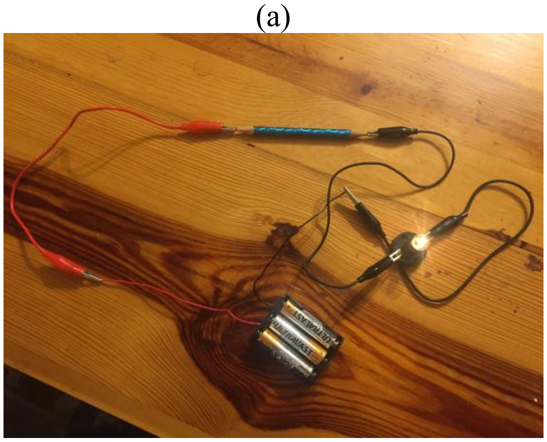
Figure 5. Components of the electric circuit

Figure 6. Used pencils of various lengths sharpened at both ends

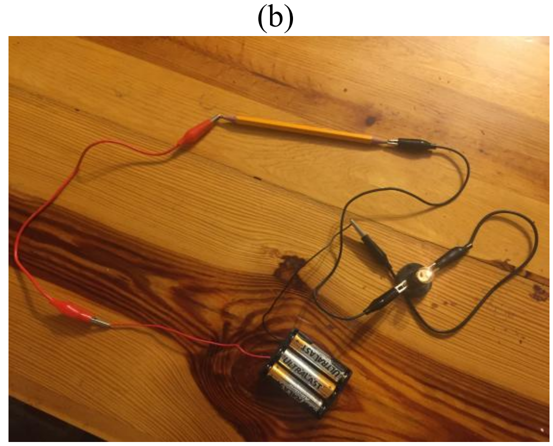


(a)

(b)



(c)



(d)

Figure 7. Bulb's brightness for different pencil lengths: (a) 0; (b) 7 cm; (c) 12.4 cm; (d) 16.5 cm

Table 2. Lightbulb's brightness values at different pencil lengths

Pencil length	0	7 cm	9 cm	12.4 cm	14.3 cm	16.5 cm
Brightness	5	4	3	2	1	1

Theoretical Background

After completing the experiment, elementary students should be able to understand the following concepts about electric circuits: voltage (V), current (I), resistance (R), conductor, resistor, and Ohm's law ($I = V/R$ or $V = IR$). In this experiment, since voltage is provided by the batteries and remains constant, the current is inversely proportional to the resistance. The lightbulb is brightest when the red and black clips are connected directly, because the overall resistance is at its minimum, indicating that the current flowing through the lightbulb is at its maximum. As the pencil length increases, the resistance increases, causing the brightness to decrease, which indicates a decrease in the current flowing through the lightbulb.

Make a Dimmer Switch with One Pencil

Building on what he had learned from the experiment, the participant created a variable resistor that could provide a continuous range of resistance, eliminating the need for multiple pencils of different lengths. With the advisor's help, he whittled away the wood on one side of a pencil to expose its graphite core, which is a good conductor. He then clipped the free end of one alligator clip to the tip of the pencil and used the other clip as a "slider" by pressing it onto the graphite core to make a dimmer switch. The brightness of the lightbulb could be controlled by moving the slider along the graphite core, as shown in Fig. 8.

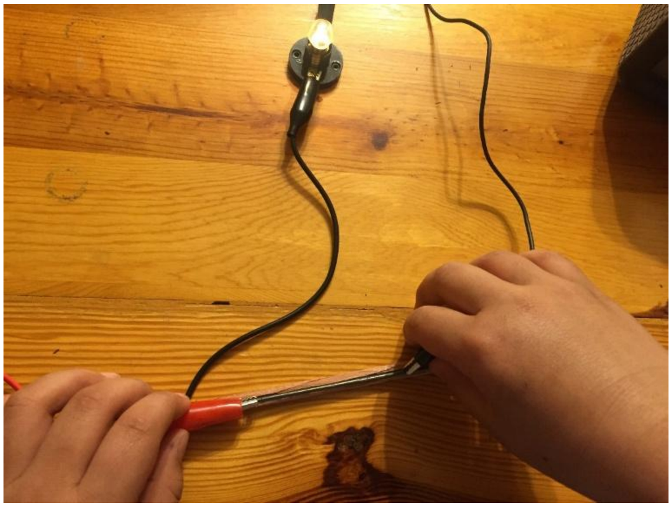


Figure 8. Control the lightbulb's brightness using the self-made dimmer switch

Outcomes

Through this project, students can gain an intuitive understanding of electric circuits, key electrical parameters, and Ohm's law. The participant summarized his activities and outcomes in a report and a poster (Fig. 9).

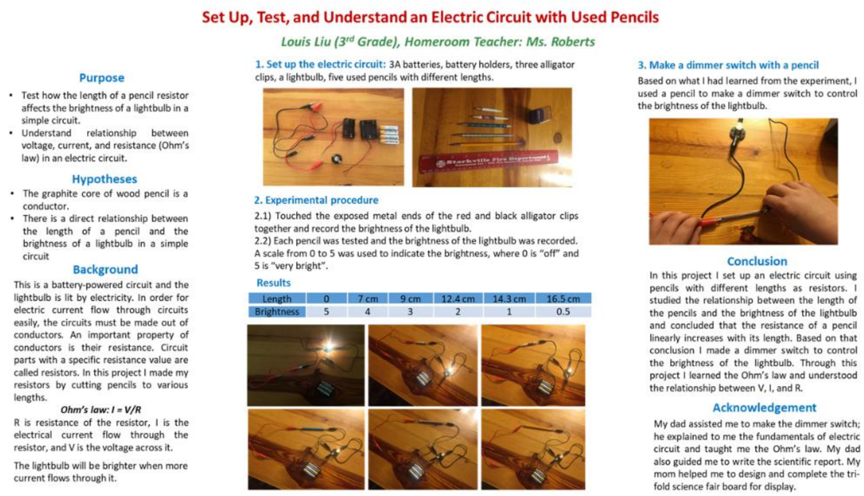


Figure 9. Poster created based on the results of Project 2

4. Project 3: Calculating the Projectile Range of a Catapult

Summary

In this project, the participant set up a catapult to launch small balls over varying distances by adjusting the launch angle, pull back angle, and number of rubber bands. Historically, catapults were used in the Middle Ages to hurl large stones to break down castle walls and proved to be highly effective weapons during ancient times, capable of causing significant damage. The goal of this project is to understand the physics of catapults and investigate how key parameters, such as launch angle and pull back angle, affect the travel distance of projectiles.

Experimental Setup

Components used for the catapult are shown in Fig. 10, including a catapult arm (with a black base) and a clamp. The black catapult base was secured to the edge of a worktable using the clamp. Next, a locking pin was inserted into the hole disc to set the launch angle. One rubber band was then attached to the pins by threading it through the hole in the catapult's disk. The fully assembled catapult is shown in Fig. 11.

Figure 10. Components of the catapult

Figure 11. The assembled catapult launching a ping pong ball

Experimental Procedure

Four factors that might affect the ball's travel distance were considered: ball type, number of rubber bands, launch angle, and pull-back angle. Two types of ball were tested in this experiment, an orange ping pong ball and a hollow ball. The number of rubber bands was either one, two, or three. The launch angle, which determines the ball's direction upon release, was set to five values: 0°, 15°, 30°, 45°, and 60°. The pull-back angle, which determines how far the launch arm is drawn back before release, was set to three values 20°, 40°, and 60°. Both launch and pull-back angles were measured using the markings on the disc (Fig. 12). By varying the ball type, number of rubber bands, and the launch and pull-back angles, a total of 90 (2 × 3 × 3 × 5 = 90) combinations of experimental settings were obtained.

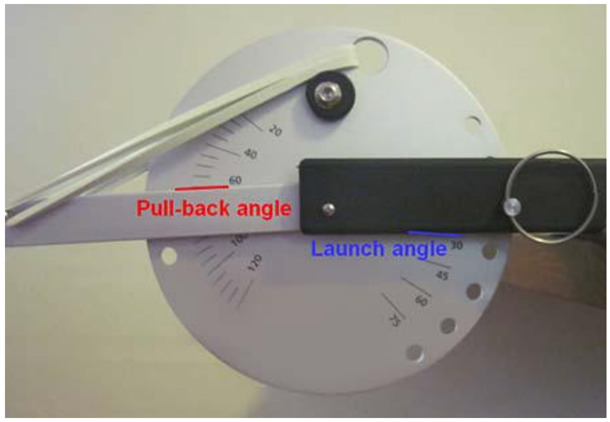


Figure 12. Measure the launch and pull-back angles

For each combination, both the ping pong ball and hollow ball were launched, and their travel distances were measured and recorded. In some cases, due to the launch direction and high initial velocity, the ball hit the ceiling before reaching the ground. Travel distances for those cases could not be measured and were recorded as "N/A".

Results and Discussion

Data recorded from the experiment were then processed in Excel to generate line charts illustrating the effects of various factors on the balls' travel distances. The participant was a 5th grade student at the time, so this step was completed by the author. However, the participant was old enough to understand the process of entering data and generating charts using Excel. Fig. 13 shows how the launch and pull-back angles affect the travel distance; Fig. 14 illustrates the influence of the number of rubber bands; and Fig. 15 compares the travel distances of the two ball types. Across all three figures, the travel distances at launch angles 15°, 30°, and 45° were generally similar and greater than those at 0° and 60°. In most cases, travel distance increased with launch angle from 0° to 30° or 45°, then decreased. Fig. 13 also indicates that for all cases, as the pull-back angle increased, the travel distance increased as well. Fig. 14 confirms that travel distance increased with the number of rubber bands in all cases.

The travel distance also depends on the launch angle and speed. The launch angle is defined as the angle between the launch direction and the horizontal plane. In theory, a ball should travel the farthest when launched at 45°, but this was not always observed in this experiment. The discrepancy arises from the launch position. As the catapult was secured to a worktable, so the balls were released at a height above ground level, and the travel distances were measured as the horizontal distance between launch and landing points. In contrast, the theoretical calculation assumes the catapult is positioned on the ground, with both the launch and landing points at ground level.

Fig. 13 also shows that, in all cases, travel distance increased with the pull-back angle. Fig. 14 confirms that travel distance also increased with the number of rubber bands. This is because travel distance also depends on launch speed, which in turn depends on the energy transferred to the balls from the rubber bands. In this project, the catapult stored energy in the stretched rubber bands; the greater the pull-back angle and the more the bands were stretched, the more energy is stored. Similarly, adding more rubber bands increased the total stored energy. Thus, increasing the pull-back angle or the number of rubber bands increased the stored energy, which was transferred to the ball, resulting in a higher launch speed and farther travel distance.

Fig. 15 shows that, in most cases, the hollow ball traveled farther than the ping pong ball under the same conditions. This is likely because the hollow ball experienced less air drag due to its hollow structure.

Outcomes

Through this project, students can obtain clear insight into the working principles of catapults and how various factors affect a ball's travel distance, as well as gain experience of using Excel for data processing and charting. Fig. 16 shows a poster generated from the results of this project.

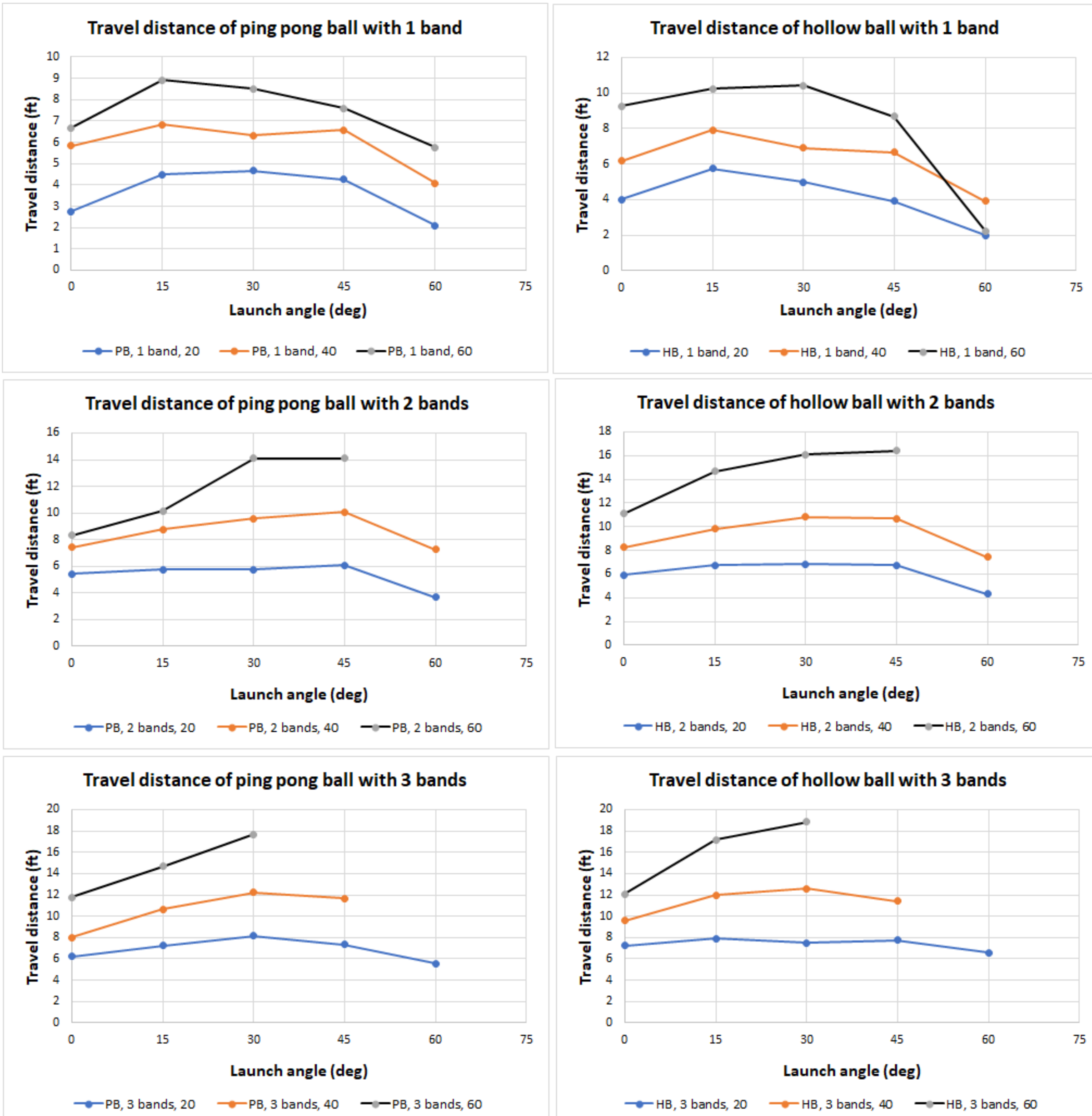


Figure 13. Effects of pull-back and launch angles on ball travel distance

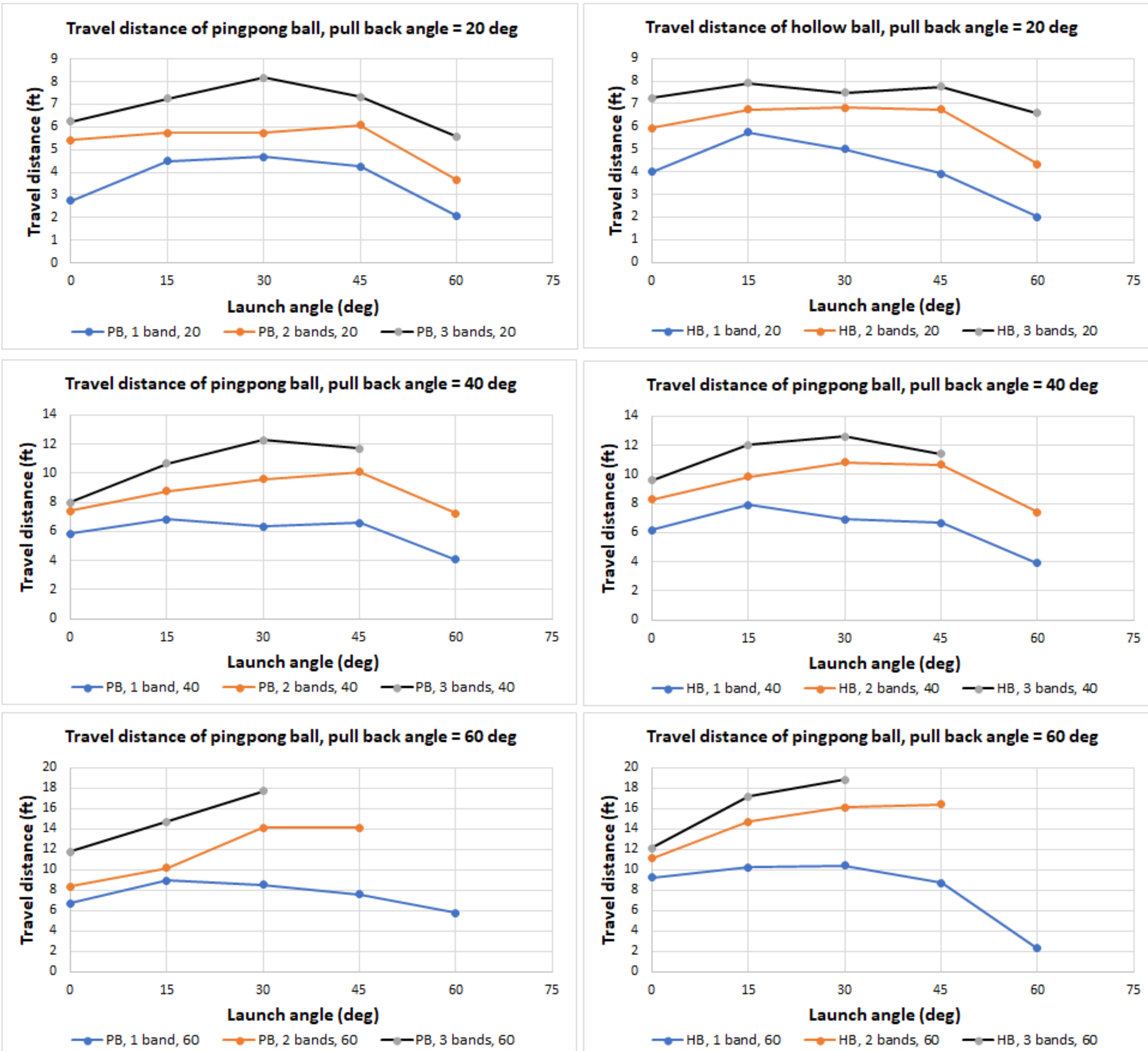


Figure 14. Effect of the number of rubber bands on ball travel distance

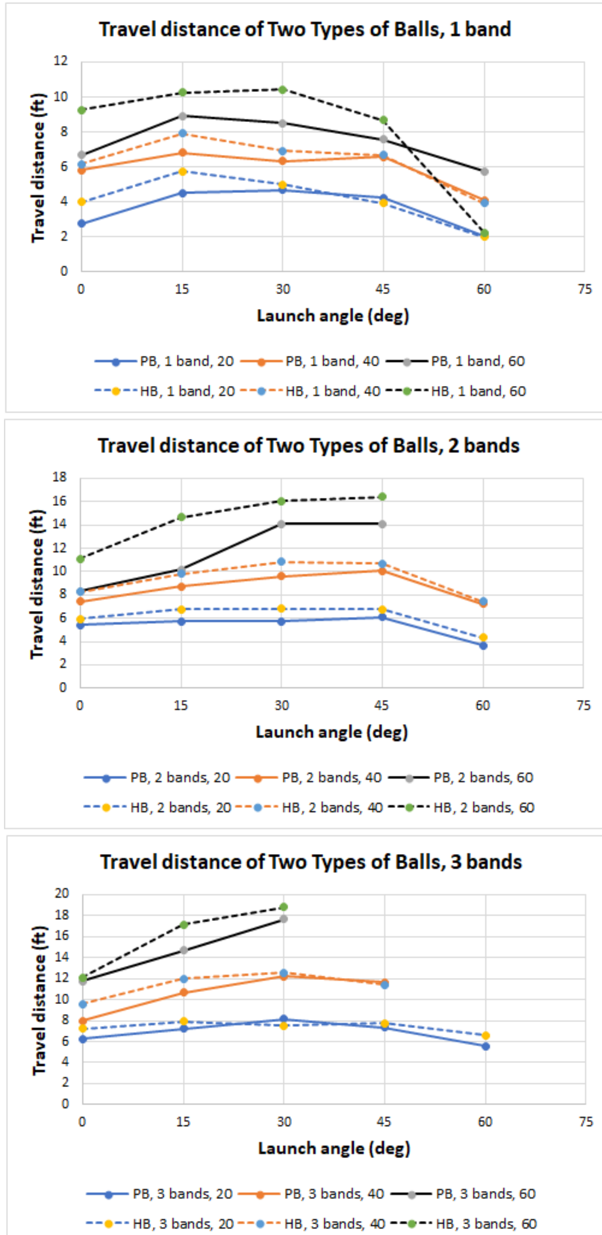


Figure 15. Travel distances of two types of balls

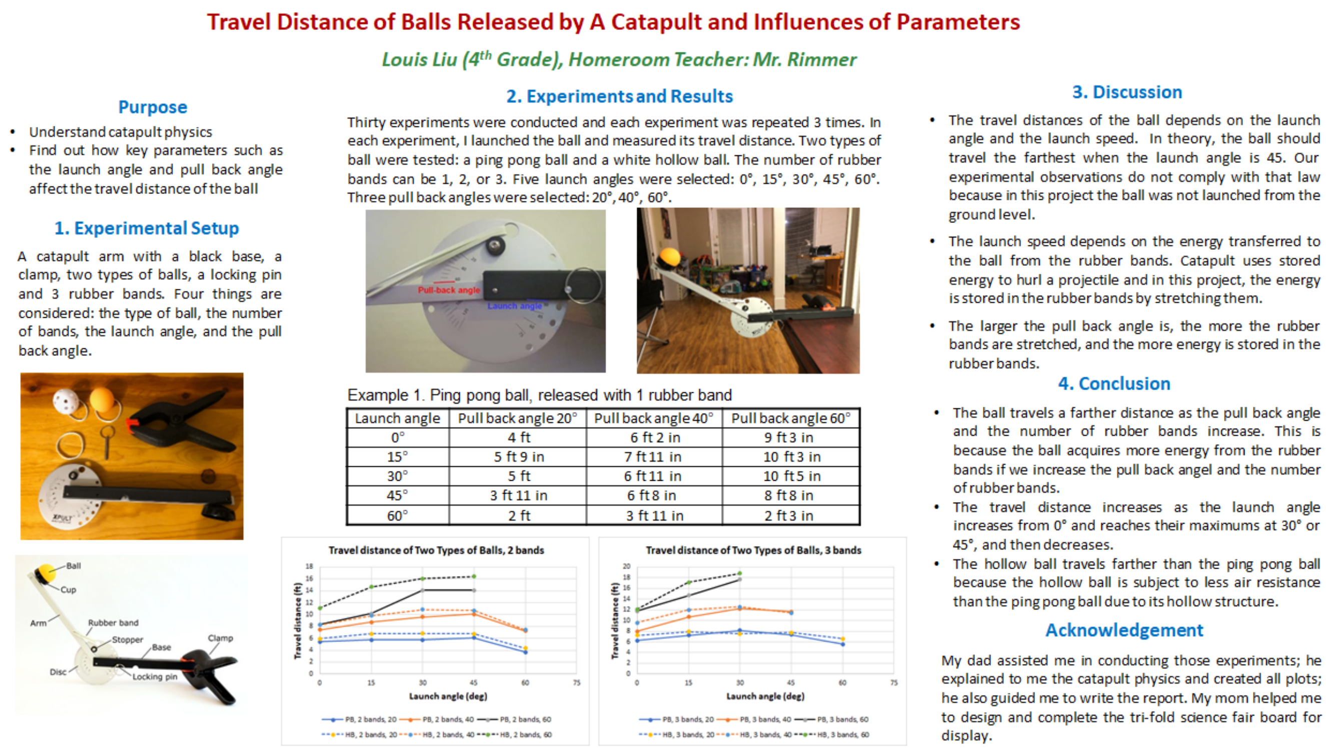


Figure 16. Poster created based on the results of Project 3

5. Discussion

The goal of the three elementary science projects is to give elementary students (2^{nd} to 5^{th} grade) a glimpse into physics and the role that mathematics plays in it. The principles demonstrated in these projects, such as Hooke's law, Ohm's law, and principles of parabolic motion, will later be taught in high school physics courses. Gaining hands-on experience and developing a fundamental understanding of these principles through these illustrative projects will help lay a strong foundation for future learning. This preparation can enhance students' likelihood of success in those courses and help foster a genuine interest in physics, which serves as a foundation for engineering. In fact, despite their fundamental nature, these principles are also introduced in engineering courses at higher-education institutions. For example, Hooke's law is discussed when teaching spring elements in the vibrations course; Ohm's law is a core topic in basic electrical engineering; and parabolic motion is illustrated with practical examples in dynamics. Therefore, the experience and knowledge gained from these projects can carry forward into students' college education, creating a lasting impact on their academic journey.

Since participants are expected to assemble the systems and complete the experiments largely independently, with only limited assistance from teachers and parents, the three projects were structured progressively based on the level of difficulty children may encounter in system assembly and in understanding the underlying theoretical principles. Therefore, the first project is more suitable for lower elementary students, as the mass-spring system is easy to assemble. In contrast, the second and third project are more appropriate for middle and upper elementary students, respectively, not only because the systems are more complex, but also because the power supply and electrical wires (Project 2), as well as the rubber bands (Project 3), may pose potential risks to younger students. Furthermore, Projects 1 and 2 exhibit linear relationships, whereas Project 3 involves a nonlinear, parabolic relationship, which is more appropriate for students in fifth grade and above.

6. Conclusions

This paper introduces three entry-level science and engineering projects designed for elementary school students in grades 2 through 5. The projects are progressively structured from simple to more complex in terms of the assembly process, data collection, and underlying engineering principles. With appropriate guidance and support from instructors, students should be able to follow the procedures outlined in the paper to complete these projects, present their findings, and develop an understanding of the relevant physical principles and mathematical concepts. The present work represents a modest effort to engage elementary school students in science and engineering and to spark their interest in these fields. Because engineering is inherently cumulative, students may find it considerably more challenging to complete an undergraduate engineering program without early exposure to foundational concepts and sustained academic development during their formative years. Given that U.S. high school students' performance in mathematics and physics remains below the international average, continued efforts are needed to strengthen proficiency in these subjects and to build a broader and more sustainable pipeline for the future STEM workforce. In the next phase, the author plans to develop a cyberinfrastructure to share more details about these projects, including information on where to obtain the components and parts. The author also aims to foster partnerships with regional school districts to support elementary school teachers in incorporating these projects into their curricula while ensuring alignment with relevant educational standards.

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