USING ENGINEERING AS A CONTEXT AND PEDAGOGICAL STRATEGY FOR ENGAGING STUDENTS IN MATHEMATICAL MODELING, COMPUTATIONAL THINKING, AND DESIGN

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APPROVAL OF THE DISSERTATION

This dissertation, *Using Engineering as a Context and Pedagogical Strategy for Engaging Students in Mathematical Modeling, Computational Thinking, and Design*, has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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DEDICATION

This dissertation is dedicated to my loving wife and my daughter who waited three weeks past her due date until I had defended to be born. I would also like to dedicate this dissertation to my parents, who gave me the love, support, and freedom to pursue my own journey in life.

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Overview and Conceptual Links

When the topic of engineering comes up in education, it is usually done so in the context of science, mathematics, and technology; the so-called STEM subjects. Advocates for engineering education often cite the critical role these subjects will be to the U.S.'s future success in competing in a global economy and solving complex issues in society (Katehi, Feder, & Pearson, 2009; PCAST, 2010). As a result, engineering education has received more attention from researchers over the past decades. This increased awareness has led to K-12 engineering education initiatives, such as *Engineering is Elementary* and *Project Lead the Way*. However, engineering remains enigmatic to school teachers and absent from teacher preparation programs. While school administrators may be excited by the prospect of including engineering programs in schools, teachers may not be well-prepared or confident in their ability to integrate engineering into their respective content areas.

STEM Integration

When engineering is included in K-12 schools, it is often integrated with the other STEM subjects (i.e., science and mathematics). The *International Technology and Engineering Education Association* (ITEEA) defines Integrative STEM Education as "the application of technological/engineering design based pedagogical approaches to *intentionally* teach content and practices of science and mathematics education through the content and practices of technology/engineering education." (Wells & Ernst, 2012/2015). Similarly, the National

Academy of Engineering (NAE, 2010) reported: "…limited but intriguing evidence suggests that engineering education can stimulate interest and improve learning in mathematics and science as well as improve understanding of engineering and technology." This is said to provide a more authentic "real-world" context which can make STEM subjects more relevant than learning the same subjects in isolation. Some of the touted benefits include improved student motivation, interest, and achievement, all of which have important distal outcomes. NGSS (2013) has gone as far as to say that science instruction should integrate engineering into the classroom.

While these groups see engineering as providing opportunities for students to learn mathematics, Carr, Bennet, and Strobel (2012) reported that of 41 states including "engineering content in their educational standards," only one referred to engineering in their mathematics standards. Thus, there appears to be a lack of actual integration of engineering with the other STEM subjects, especially within mathematics (English, 2017). When engineering does get integrated with STEM subjects, it is done in one of three ways. Schools included engineering in the curriculum as 1) ad-hoc integrated units into pre-existing courses, 2) stand-alone elective courses, or 3) informal learning opportunities such as clubs or summer camps. (Carr, Bennet, & Strobel, 2012; Katehi, Feder, & Pearson, 2009; Purzer, Strobel, & Cardella, 2014). In the subject-focused courses of middle school and high school, STEM *integration* usually refers to the use of engineering (or engineering design process [EDP]) as a pedagogical strategy for teaching science concepts or as a context to engage students in a new subject. Moore et al. (2014) assert this type of integration is rooted in an old theoretical model for learning proposed by John Dewey and is also line with the contemporary theory of constructivism.

Similar to ITEEA, the NGSS also include engineering design concepts as core knowledge for students to learn in school. In contrast, the National Council of Teachers of Mathematics (2000) does not explicitly promote the integration of engineering into the classroom, but advocates for mathematical modeling in authentic contexts. Despite these calls for integration, little research has been done to characterize and describe what successful integration looks like. If the benefits of STEM integration are to be fully realized in the classroom, a better understanding of how engineering can be integrated with other subjects is needed.

STEM and Computing

In addition to engineering, computing has also received more attention lately and is being promoted to be included in the K-12 curriculum by organizations such as the National Science Foundation, National Research Council, and the US Department of Education. In fact, NSF's STEM + C funding program is dedicated to the integration of computing with the STEM subjects. Virginia's Department of Education recently passed new educational standards that include computer science, computing, and computational thinking throughout K-12. Research that looks at the integration of computing with engineering and other STEM subjects is lacking, and more work should be done to better understand how computing can be integrated into the classroom.

Middle School

Middle school is a critical transitional period for students (Richards, Hallock, & Schnittka, 2007). Researchers have demonstrated that middle school is a time when girls' consideration of future occupations and career identities are formed (Sadler, Coyle, & Schwartz, 2000). Interestingly, girls and boys express almost equal interest in science, medicine, and engineering as future careers at the time of middle school (Cummings & Taebel, 1980). However, by the time students reach high school, many are struggling with mathematics and science, and girls interest in STEM begins to wane (Lemke, Sen, Pahlke, Partelow, Miller, Williams, Kastberg, & Jocelyn, 2004). Yet, these are the two subjects that are most needed in order for students' to pursue engineering or other STEM-related college majors. Finding new ways to support students' mathematics and science education before high school may address some of these issues. Integrating STEM subjects through engineering at the middle school level may be one way of doing so (Cogger & Miley, 2012). This dissertation looks at engineering education through the lens of STEM integration to better understand how students can be supported in the critical years of middle school.

Dissertation Overview

The focus of this dissertation is on the role of engineering in K-12 schools in three different contexts. The goal is to understand better how teachers can leverage engineering as a context-rich subject as well as a pedagogical strategy for supporting students' learning. The first manuscript explores engineering as a context for engaging middle school students in a challenging mathematical modeling activity that involves non-linear relationships. The second manuscript explores engineering as a context for engaging middle school students in physical computing activities and evaluating their computational thinking. Results of this study report on what computational thinking students demonstrate in this context. Finally, the third manuscript explores the pedagogical strategies implemented within an engineering design context. That is, this study focuses on how engineering can be used as both a context and pedagogical strategy for supporting students through the design process. These three studies offer insight into how engineering can be used in formal and informal K-12 settings to support students in a variety of ways. The table below illustrates the specific focus of each manuscript.

Table 1. Three Manuscript Overview

Manuscript	*Focus*
1 – Mathematical Modeling in the Context of Engineering	Students' mathematical modeling patterns of behavior
2 – Computational Thinking in the Context of Engineering	Students' computational thinking patterns of behavior
3 – Design Thinking in the Context of Engineering	Teachers' pedagogical strategies to support students' design

Manuscript 1 – Engineering and Mathematics

The *National Council of Teachers of Mathematics* (NCTM) stresses the importance of developing students' mathematical modeling skills throughout their formal education (2000). They recommend providing students with opportunities to explain and predict real-world phenomenon through modeling activities. Mathematical modeling within the context of engineering is a method for representing the problem or system in a useful way that can inform design decisions made throughout the engineering design process (Crismond & Adams, 2012). This process is nuanced and complex but may provide unique opportunities for students' to develop these essential skills (National Mathematics Advisory Panel, 2008; Carberry & McKenna, 2014). However, a survey of engineering education found mathematical modeling to be absent from the curriculum (Katehi, Pearson, & Feder, 2009). It is crucial to understand better ways in which engineering may provide a useful context for supporting students' mathematical modeling.

An interpretive case study was conducted to investigate the use of engineering projects to provide a context for engaging middle school students in mathematical modeling eliciting activity. Students constructed their own speaker and then explored the relationship between an audio amplifier's voltage and the speaker's loudness. Students learned about logarithmic relationships by the end of the activity and thus extended their experience in mathematical modeling beyond linear relationships. This study demonstrates how engineering projects can be utilized in the mathematics classroom to introduce new and challenging concepts.

Manuscript 2 – Engineering and Computational Thinking

Engineering in today's digital world often involves the use of code to program computers or microcontrollers and is an essential part of both robotics and mechatronics. These two prominent fields of study require professionals to combine *mechanical engineering, electrical engineering,* and *computer science.* Most engineering programs, whether it be mechanical or electrical, require students to learn some form of programming. Therefore, when the discussion of engineering education comes up, it most often involves some dimension of computer programming or *computational thinking.*

Computational Thinking (CT), a term coined and promoted by Wing (2006), but had long been discussed prior during the digital revolution (Papert, 1980). It has received more attention by educators in the past decade in hopes to prepare current students for a future generation of digital thinkers and problem solvers. While there remains some disagreement around how CT should be defined, it is mostly considered to be a problem-solving process that has several key characteristics. However, only preliminary research has been conducted to explore how CT can be adequately measured and supported in the K-12 classroom.

CT has most frequently been explored within the context of computer science. However, as discussed above, CT exists in other domains. One potential area that appears promising is the use of physical computing, similar to the field of robotics but with broader applications and examples. The use of robotics to teach students computer programming has already been well documented in the literature (Beer et al., 2000; Mauch, 2001; Moore, 1999; Papert, 1980; Rogers & Portsmore, 2004), and has been shown to help teach scientific and mathematic principles through experimentation with robots. Given that the use of robotics has been well-established, it may also be prudent to explore alternative, non-robotics, pathways to developing CT and other STEM-related learning outcomes.

The second study was conducted to explore how engineering can provide a useful context for developing students' computational thinking. This mixed-methods study explored how students were able to engage in computational thinking within a physical computing unit, which made use of the Arduino computing platform. Eighth-grade students completed a performance assessment in which their CT was evaluated and analyzed through quantitative and qualitative measures. Findings suggest a number of differences between high, medium, and low performing CT students. Factors such as gender and prior experience with algebra seem to be related to students' performance. Further, students demonstrated their level of CT through components of CT (e.g., abstraction, generalization, and debugging). Arduino and open-ended engineering projects may provide a useful and possibly more gender-neutral context for students to engage in CT.

Manuscript 3 – Engineering and Design

More schools are encouraging the integration of engineering design into the science curriculum. The Next Generation Science Standards (NGSS, 2013) includes engineering design as an essential component to include within science education. An integrated science classroom may draw upon the scientific method of inquiry to develop knowledge on a topic in science, and then apply that knowledge using engineering design to produce an informed design (Crismond & Adams, 2012). Because middle school is when science courses are first taught, it is also likely to be students' first experience with engineering. Students at this level are novice designers are will ultimately require unique scaffolds that school teachers may not be prepared to provide. For this reason, it is essential that teachers understand how to best students through the complex process of design.

This final case study was conducted to investigate middle school engineering design in greater detail. Middle school students participated in a two-week summer enrichment program and were engaged in an intensive engineering design challenge. Findings suggest there are a number of scaffolds that teachers can employ to support and guide students toward successful designs. These pedagogical strategies are described in the results of this study.

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Manuscript One

Engineering Projects as a Context for Learning Mathematics: Middle School Students' Modeling of the Relationship between Voltage and Sound Pressure Level

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Abstract

This study explores how students' draw upon their prior knowledge and develop strategies for completing a model-eliciting activity. Middle school students' who had previously designed and constructed a speaker modeled and described the logarithmic relationship between the output voltage of the sound source and the sound pressure level of a speaker. The findings demonstrated that with persistence and occasional scaffolding, students were able to develop and describe an appropriate graphical non-linear model of their collected data. We conclude that engineering projects, such as designing a speaker, can provide useful contexts for exploring challenging mathematical relationships. We also provide several recommendations for implementation.

Introduction

STEM education has been identified as being important for our future ability to compete in a global economy (PCAST, 2010). As a result, much attention is now being placed on engineering education in K-12 schools. The *Next Generation Science Standards* (NGSS), the *National Academy of Engineering* (NAE), and the *National Research Council* (NRC) are promoting the inclusion of engineering in school curricula, asserting the synergetic relationship among science, engineering, and mathematics for learning opportunities (Katehi, Pearson, & Feder, 2009; NGSS, 2013). The pedagogical and content connections between these areas are emphasized by the *International Technology and Engineering Education Association* (ITEEA) in their adapted definition of *Integrative STEM Education*:

> "Integrative STEM education refers to technological/engineering design-based learning approaches that intentionally integrate the concepts and practices of science and/or mathematics education with the concepts practices of technology and engineering education" (Sanders & Wells, 2006, p.12).

This definition is consistent with our view that engineering design projects can provide unique opportunities for students to further explore related topics in science and mathematics. Indeed, we have used engineering projects as springboards to engage students in mathematical thinking in ways that extend beyond traditional curricular expectations (Corum & Garofalo, in press).

Engineering design requires mathematical knowledge and skills (Katehi, Pearson, & Feder, 2009). More specifically, "mathematical analysis and modeling are essential to engineering design" (p. 8). In a review of the state of K-12 engineering education, Katehi, Pearson, and Feder (2009) analyzed the ways mathematics was incorporated into engineering curricula and found the role of mathematics to be limited. The most typical uses of mathematics were to measure and collect variable data, construct and organize graphs, and look for patterns to inform design decisions. The most perplexing finding was the absence of mathematical modeling as a way in which to inform the engineering design process.

While modeling often refers to constructing physical or digital prototypes, Crismond and Adams (2012) acknowledge that *mathematical modeling* can “represent the problem or potential solutions and act as cognitive devices to enable thinking” (p. 759). Such modeling is nuanced, complex, and important for students to develop over the span of their formal mathematics education (National Council of Teachers of Mathematics [NCTM], 2000; National Mathematics Advisory Panel, 2008; Carberry & McKenna, 2014). The NCTM’s Principles and Standards for School Mathematics (2000) recommend providing students opportunities to explain and predict real-world phenomenon through modeling activities and, furthermore, those nonlinear relationships be included in modeling situations.

In this article, we report on middle school students’ approaches to constructing a mathematical model of the nonlinear relationship between two scientific variables. We developed an activity that exposed students to a logarithmic relationship, one that does not conform to their prior experiences with linear relationships. This modeling activity was a natural extension of an engineering design project the students had previously completed through the use of our *Speaker Invention Kit*. This is one kit from our *Make to Learn Invention Kit* initiative.

Background: Make to Learn Invention Kits

The *Make to Learn Invention Kits* are digital resource packages containing 3D models of inventions from the Smithsonian collections, instructional guides, historical primary and secondary sources, and support materials for teachers and students. The goal for the student is not to create exact physical replicas of inventions, but to reinterpret and reinvent fully-functioning devices using low-tech and advanced manufacturing technology. Each successive invention kit provides scaffolding and progressively builds upon the previous. The main goals of this initiative are to 1) foster the spirit of innovation in American youth, 2) provide historically situated projects, and 3) support students in building a foundation of STEM principles (Slykhuis, Martin-Hansen, Thomas, & Barbato, 2015).

The development of the *Make to Learn Invention Kits* began in 2014 leveraging collaboration among the University of Virginia, Princeton University, and the National Museum of American History. To date, there are six invention kits developed, one centered on each of the following: 1) solenoid, 2) motor, 3) generator, 4) telegraph, 5) telephone, and 6) speaker. In addition to helping students develop engineering and manufacturing expertise, the use of the invention kits can lead to students' development of mathematical and science knowledge. One preliminary study demonstrated students' improved conceptual understandings of electricity and magnetism (Standish, Christensen, Knezek, Kjellstrom, & Bredder, 2016) using the kits in a middle school engineering classroom. Another study (Corum & Garofalo, in press) demonstrated middle school students' ability to develop a mathematical model of Ampere's Law using the *Solenoid Invention Kit*. The present activity was developed to be used with the *Speaker Invention Kit*, a project in which students design and fabricate their own speakers.

Literature Review

Mathematical Modeling

The *International Technology and Engineering Association* (ITEEA) identifies mathematical modeling as a process essential to engineering design (ITEEA, 2000). Engineers use mathematical modeling as a way in which to make informed design decisions (Carberry & McKenna, 2014; Magnani, Nersessian, & Thagard, 1999). Models allow students to make sense of their designs. However, modeling is complex and challenging for students to fully understand and appreciate (Carberry & McKenna, 2014). Lesh, Hoover, Hole, Kelly, and Post (2000) provide a comprehensive definition of a mathematical model.

> A model is a system that consists of (a) elements; (b) relationships among elements; (c) operations that describe how the elements interact; and (d) patterns or rules, such as symmetry, commutativity, or transitivity, that apply to the relationships and operations...To be a model, a system must be used to describe another system, or to think about it, or to make sense of it, or to explain it, or to make predictions about it (p. 609).

Additionally, modeling can be represented as a cyclical process, in which students are constantly forming new interpretations of the relationship or phenomenon. It involves “a series of iterative testing and revision cycles in which competing interpretations are gradually sorted out or integrated or both—and in which promising trial descriptions and explanations are gradually revised, refined, or rejected” (Lesh & Lehrer, 2003, p. 109). Students engaged in modeling activities form various interpretations of problems and phenomena and develop their own descriptions, explanations, and solutions (Lesh et al., 2000). This iterative and interpretive process can be represented in the following diagram.

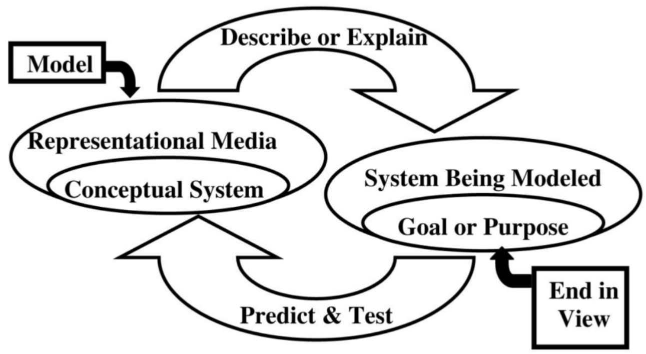

Figure 1. The modeling cycle (Lesh et al., 2000).

Researchers have also identified several unique perspectives on modeling (Kaiser & Sriraman, 2006). For instance, the aim of *epistemological modeling* is to develop a theory within mathematics or science. In contrast, the aim of *realistic modeling* is to solve authentic problems situated within a science or industrial context. This more pragmatic perspective of modeling can be seen as applied mathematical modeling and thus is useful to the field of engineering. Realistic-based modeling within the context of engineering education has largely been implemented through the use of so-called *model-eliciting activities.*

Model-Eliciting Activities

To Lesh et al. (2000), the purpose of implementing a *model-eliciting activity* (MEA) is to expose students' thinking. These thought-revealing activities require students to develop their own mathematical interpretations of a problem or relationship. This construction process requires students to make sense of the phenomenon in terms of mathematical descriptions. Constructions can be expressed graphically, symbolically, or described qualitatively (e.g., written or spoken). MEAs should provide students with the ability to operate on and analyze information related to a problem. For example, a MEA might involve students collecting data on two or more variables, and then developing a graphical or algebra relationship between the variables. Additionally, students should have the ability to test their model by making predictions and assessing if their conclusion makes sense.

More recently, researchers have explored the benefits and challenges associated with MEAs (Carberry & Mckenna, 2014; Corum & Garofalo, in press; De Bock, Verschaffel, Janssens, Van Dooren, & Claes, 2003; Doerr, Delmas, & Makar, 2017). Corum and Garofalo (in press) reported that students successfully constructed an algebraic model to empirically derive Ampere's Law, $B = \mu\left(\frac{N \cdot I}{L}\right)$, a fundamental law of electricity and magnetism. Students measured the magnetic field strength on a set of solenoids, related strength to three independent variables (N, I, L), and derived the dielectric constant (μ). This finding is encouraging given that several studies found that students tend to struggle with modeling nonlinear relationships (De Bock, Van Dooren, & Verschaffel, 2011; De Bock et al., 2003; Ebershbach, 2008; Van Dooren, De Bock, Janssens, & Verschaffel, 2007).

Modeling Nonlinearity

When students are presented with nonlinear relationships, they tend to apply their prior knowledge of linearity to make sense of them. Students' over-reliance on linearity when modeling non-proportional relationships has been well documented (De Bock et al., 2011; De Bock et al., 2003; Ebershbach, 2008; Van Dooren et al., 2007). De Bock et al. (2011) provide a common example of this in geometry. For instance, students are likely to assume that the relationship between the area of a figure and the length of its sides is directly proportional.

Overall, De Bock et al. (2003) demonstrated that students generally perform better on proportional tasks than non-proportional tasks.

While students' performance on non-linear tasks generally improves over time, there has been limited success in developing authentic and contextual activities for students to experience non-linear relationships. Moreover, few have documented the ways in which students apply prior mathematical conceptual understanding to make sense of nonlinear MEAs, especially within the context of science. By learning more about how students make sense of such activities, educators may be able to design appropriate MEAs that enhance engineering design projects and support the learning of difficult concepts.

The goal of our study was to explore how students engage in a nonlinear MEA within an engineering design project. We designed an MEA that was intended to complement the *Make to Learn Speaker Invention Kit.* Specifically, the activity had middle school students explore the logarithmic relationship between *sound pressure level* and *voltage*. Logarithmic relationships are useful for understanding other STEM topics (e.g., earthquakes, pH, and acoustics). For this activity, students collected data from a speaker and amplifier and made sense of this relationship, which was unknown to them.

Research Questions

The following questions guided the research conducted in this study:

1) What strategies do middle school students in a summer engineering enrichment program employ to collect data? What difficulties do they experience when collecting this data? How are their strategies and difficulties related to their prior mathematical knowledge and experiences?

2) What strategies do middle school students employ to develop a mathematical model of a nonlinear relationship previously unknown to them and what difficulties do they experience? How are their strategies and difficulties related to their prior mathematics knowledge and experiences?

Methodology

This study used a multiple-case design to describe and evaluate student performance on a mathematics extension of one of the *Make to Learn Invention Kits*. A case study approach was useful for exploring and describing student actions because it allowed us to take an in-depth look at their work to make argumentative claims about what students were doing and learning. Using a multiple-case study design allowed us to collect more data for generating robust assertions (Yin, 2018). Studying students' behaviors and actions while working on the activity required us to take an interpretive perspective on the research.

Interpretive educational research (Erickson, 1986) is appropriate for describing a specific occurrence in an educational setting and interpreting the meaning-perspectives of the actors involved, taking into account contextual factors as part of the analysis. In this study, the researchers utilized observations, interviews, and document analysis as sources of data. This triangulation process helps to establish the credibility of the findings. Along with multiple sources of data, this study used multiple researchers to strengthen the assertions made. The researchers are the primary instruments to collect and analyze data. Hence, interpretations of student behavior are filtered through the researchers' lens.

Participants

The participants in this study were students enrolled in a two-week summer engineering program. The students were from a range of grade levels, spanning grades eight through twelve. In the program, the older students served as mentors to the younger students and assisted with their engineering projects. Students volunteered to be in this study and were scheduled to work on the mathematics activity outside the normal hours of the engineering program. Three cases or instances of the activity were completed. Within each case, multiple students worked together to complete the activity. The students completed an introductory engineering course during the previous academic year, where they constructed a speaker. The table below displays the student participants in each case.

Table 1. Student participants by case.

	Student	*Grade*	*Completed Math Courses*
Case 1	Emily	Rising 9^{th}	Algebra I, Geometry
	Melissa	Rising 8^{th}	Algebra I
Case 2	Jonah	Rising 8^{th}	Algebra I
	Henry	Rising 8^{th}	Algebra I
Case 3	Lily	Rising 9^{th}	Algebra I, Algebra II
	Max	Rising 9^{th}	Algebra I, Geometry
	Nicole	Rising 9^{th}	Algebra I, Geometry

Activity Description

Recall that the participants in this study had previously constructed a speaker in their engineering course. The goal of the activity is to introduce students to a mathematical relationship (i.e., logarithmic) that was previously unknown to them. We were interested in seeing how students draw upon their prior mathematical knowledge to work through the activity.

During the activity, the students were asked to explore the relationship between the *voltage* applied to the coil of a speaker and the resulting *sound pressure level* produced by the speaker. This is a natural occurrence of a logarithmic relationship. Ultimately, the goal of the activity is for the students to discover that the relationship between voltage (V) and sound pressure level (SPL) is *nonlinear* and logarithmic. Because these students had not been exposed to logarithmic functions and graphs, we considered students to have successfully reached the goal when they were convinced that the relationship was not linear and could describe it qualitatively or graphically.

Setup. A visual representation of the activity setup is shown below in Figure 2. Students were given an electronic amplifier with a *voltmeter* connected to the voltage of the output, a speaker connected to the amplifier, a *sound pressure level* (SPL) meter pointing at the speaker cone, and a tone generator connected to the input of the amplifier. The tone generator used was an online application (http://www.szynalski.com/tone-generator/) played on an iPad device. The groups also had access to the paper, a laptop with Excel, and a graphing calculator.

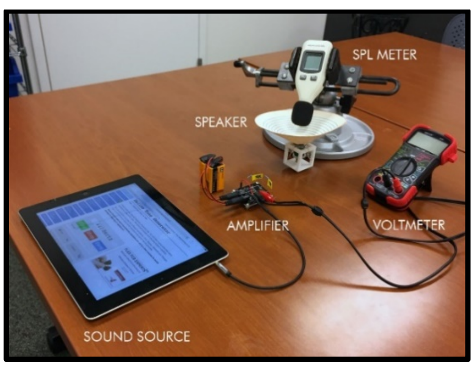

Figure 2. Physical setup of the activity

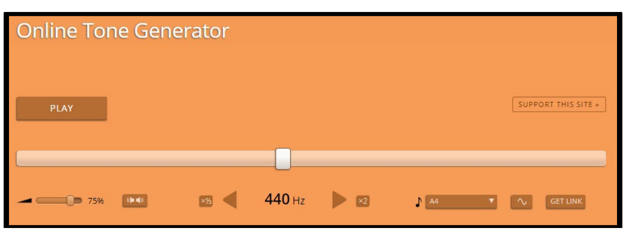

Figure 3. The online tone generator (http://www.szynalski.com/tone-generator/)

Activity Prompt. The students worked at a table with the setup, while the researchers sat across the table to introduce the activity and observe them working on it. The researchers explained to the students that their activity was to explore the relationship between a speaker's *SPL* and the *voltage* applied to the speaker's coil by the amplified signal from the iPad. Specifically, the students were asked to find a way of relating the voltage coming out of the amplifier to the number of decibels of sound coming out of the speaker by manipulating the tone generator's volume slider on the iPad (as a percentage) and noting both the voltage and the decibel readings. One brief demonstration was done to show how adjusting the volume control on the tone generator affected the voltage being applied to the speaker, and another to show how to take accurate readings from an SPL meter.

Pilots. This activity was piloted three times prior to the actual study in order to improve the flow of the activity. Pilot 1 was with one rising 9^{th}-grade student, pilot 2 with one rising 11^{th}-grade student, and pilot 3 with two rising 12^{th}-grade students. The selection of these participants was both convenience and purposive. The older students had knowledge of logarithms and could provide feedback to the researchers about difficulties with the activity. During these pilots, the students struggled with several aspects of the activity. In the first pilot, the student ignored the voltage reading from the voltmeter and instead used the volume percentage from the sound source to compare with the speaker's SPL reading. In the second pilot, the student collected SPL, voltage, and volume but only related SPL to volume. As a result, the activity prompt was modified to emphasize that voltage and not the sound source volume should be related to the SPL. Finally, a step was added to improve the quality of the speaker data. Students were directed to first measure the noise floor (the ambient noise level of the room).

Data Collection

Data was collected over the course of a two-week summer engineering program for middle school students at a public university. Students were asked to participate in a mathematics activity as an extension of the program. Each instance of the activity was scheduled for a two-hour block of time in a lab at the university and facilitated by the authors of this paper, a graduate research assistant and a mathematics education faculty member. A total of six instances of the activity were completed, three of which functioned as the pilots noted above. Students were given an open-ended prompt to explore the relationship between SPL and voltage. The researchers provided scaffolding to the students as needed to progress through the activity.

Observations. After delivering the activity promptly, the two researchers observed the students interacting with each other and with the activity. The researchers were positioned across the table from the participants and took notes while the students worked together on the activity. Aside from brief moments of scaffolding, the students worked together as a group, independent of the researchers. The observational notes served as a basis for questioning during the debriefing interview. An audio recording and transcription of the students' discussion were made for each of the three cases.

Interviews. The researchers conducted a post-activity debriefing interview with the students for approximately 15 minutes immediately after the activity had been completed. This process involved asking the students to explain their problem-solving processes and strategies and ask any clarifying questions. Some of the questions were generated based on observational notes during the activity. Each interview was audio recorded and transcribed verbatim.

Documents. Finally, documents that the students created as part of completing their activity were collected as part of the data corpus. These documents included the graphs, charts, mathematical work, and notes all associated with the activity. Students primarily used paper and pencil to generate their documents but were also given the opportunity to use a graphing calculator or Excel as a way to collect and chart data. All digital and paper documents were collected.

Data Analysis

The observational field notes, post-activity debriefing interviews, and student work documents were integrated to create a complete case description of the participants' experience with the modeling activity. This process was completed for each of the three cases prior to analysis and provided a more comprehensive perspective on the students' behaviors and strategies employed throughout the activity.

The first author analyzed the data by looking at each case individually, and then all three cases holistically for emergent themes and patterns. Each of the cases was described in terms of students' 1) strategies for data collection, 2) strategies for model development, 3) application of prior knowledge, 4) use of technology, and 5) challenges. These dimensions were then compared across each case for converging and diverging themes. Initial findings were made and then presented to the second author, who independently read through them, subsequently asked for clarification and supporting data to warrant the findings, and raised interpretation issues to resolve. The two authors met numerous times to discuss the data and findings, regularly going back to sections of the students' written work and excerpts of the transcriptions to reanalyze the data and revise their interpretations, until no new interpretations emerged.

Findings

Case 1 – Emily and Melissa

Activity Introduction. After the students introduce themselves, James initiates the activity with the prompt described in the previous section (methods). Emily and Melissa start by taking two measurements to determine the noise floor. They then ask a couple of clarifying questions about what they can use during the activity (e.g., paper and calculators) and then begin working.

Getting Evenly-Spaced Voltage Intervals. Melissa and Emily quickly exchange ideas on how to start. Melissa asks, "Do you want to do extremes or do you want to just—." Emily jumps in and suggests, "Let's just bump it up, I guess. Because it's [zero percent]." Melissa is asking if they should record the maximum and minimum values of the voltage to start, while Emily suggests they should start making incremental changes to the voltage, increasing the volume on the iPad from zero percent.

Emily and Melissa make an incremental adjustment to the volume and observe the voltmeter. The voltmeter display reads, "0.012V" (volts) and Melissa comments, "that's gnarly," as if to imply that the value is messy data. The students adjust the volume percentage on the iPad and spend a minute trying to get the voltmeter to read exactly 0.1V, but the volume adjustment (slider) was not precise enough to dial it in. They settle on their first value of 0.012V and move to observe the SPL meter.

They continue to work together to record and collect the data; Melissa adjusts the volume on the iPad until Emily is satisfied with the value displayed on the voltmeter. They work patiently on this process for the next 20 minutes to collect their data before Joe checks in with them.

Joe: What are you trying to do?

Melissa: What we're trying to do is attempting to go .01, .02, .03, .04, etc. all the way down. We got other numbers that…because you can't find it perfectly, then what we're going to do is find the change in [voltages], which would be .01, corresponding to the change in the decibels for each of them and find out what that would be.

Melissa and Emily are trying to increase the volume to get evenly spaced voltage values (0.01V, 0.02V, etc.). This strategy would provide them with a consistent change in voltage to compare to the changes in SPL values, making the pattern detection process easier. However, due to the imprecision of the volume slider, the students are not able to get perfectly spaced data. Emily attributes these imperfections to “faulty data collection.” This incremental and equally-spaced data is shown in Figure 4.

Dealing with Inconsistent SPL Readings. Emily and Melissa shift their focus to the SPL meter and look for the reading corresponding to 0.012V. They observe that the SPL meter is displaying slightly different readings for the same voltage value. Due to the sensitive nature of the SPL meter, the numbers would fluctuate by fractions of a decibel. As a result, Emily decides to record multiple SPL values for each voltage level and calculate the midpoint between the minimum and maximum values observed. She states that this will make their data more accurate. They take a minute to find and record the minimum and maximum data points for 0.012V (39.8dB and 40.5dB). This process is shown in Figure 4.

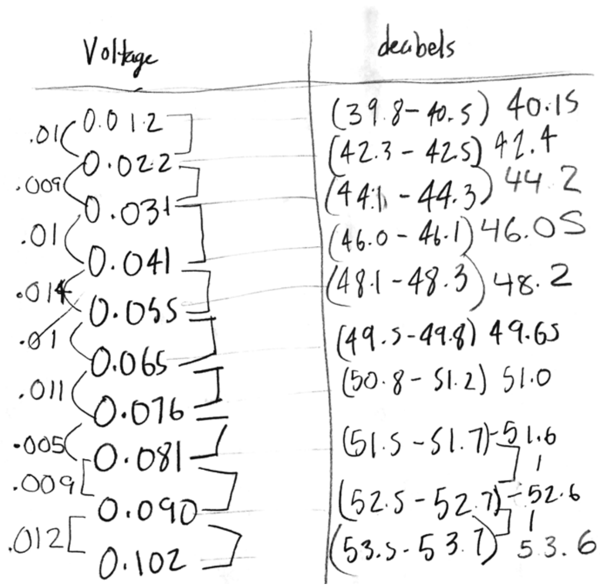

Figure 4. Emily and Melissa's data collection strategy.

Looking for a Linear Relationship. After collecting more data, the students fall silent and appear to be confused, as if unsure what to do next. Joe asks them to explain what they are trying to do and initiates the following discussion:

Melissa:	We were thinking if the voltage were to change .01... (Melissa trails off)
Emily:	Volts, yeah, 0.01 volts. Then it should correspond to the change between with the decibels. Is there a change like if I move the voltage up, this should move up with it at a steady rate? I'm calculating human error into it. Which isn't working out perfectly.
Joe:	So, what you were trying to do is look at the change in voltage and the change in decibels?
Emily:	Yeah, there's some correlation between the change in voltage and the change in decibels.
Joe:	Okay what is leading you to think that they would go up in a steady rate?
Melissa:	We just want to see if they would. To see if the voltage has an effect on this.
Emily:	It has a steady—
Melissa:	Yeah, like a mathematical formula.
Emily:	I mean technically you have like parabolas and stuff that could make it go down before it goes up. So, it's not technically not mathematical. It's not just a steady line though.

Melissa: So, then we tried to do the change in decibels and then change in voltage and comparing them, then we ended up with some wonky numbers. It's like a change .01 volts resulted in three different numbers showing that it wouldn't be a straight line.

Emily observes that there appears to be a relationship between voltage and SPL. She recognizes that that SPL is not increasing at a “steady rate” with an increase in voltage. Melissa adds that their numbers are “wonky” and states that the relationship would not resemble a straight line. They both seem to expect or at least be looking for a linear relationship, but they both agree that the data does not support this expectation. However, they identify the human error and faulty data collection as the source of the problem.

Emily and Melissa continue to struggle through the meaning-making process. Melissa states, “There is something wrong with this [data]. We’re trying to look for a direct relationship between all the lines but there isn’t one.” She explains that she is trying to calculate the differences between data points and divide by the change in decibels, as if to find the slope but seems confused. Eventually, she concedes, “What I don’t understand is what we’re doing now because if we know that it doesn’t fit function in a straight line.” She is cut off by Emily, “No, it could though, if the straight line was really steep.” Emily tries to rationalize the situation and explain how a straight line could make sense, and Melissa agrees that it is possible. She says, “That’s true, our data is so messed up, I can’t tell.” She remains open to the possibility that it could be a line because the data is untrustworthy.

Melissa created the chart below to track and compare the change in voltage to the change in decibels. This illustrates the lack of a linear or direct pattern in the data, which continued to confound the students. Melissa then suggests that they graph the points using their graphing calculator.

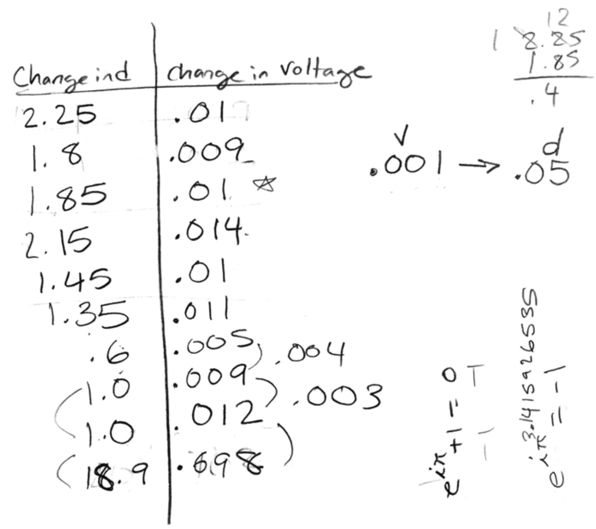

Figure 5. Melissa and Emily's change in SPL versus voltage chart.

Describing the Non-Linear Relationship Graphically. Melissa spends the next couple of minutes entering the data points shown in Figure 5 into her graphing calculator to create a scatterplot. She then makes an interesting observation about the graph. This cues James to join the discussion.

Melissa: So, I've graphed everything…it looks like it could be half a parabola.

Emily: A very wiggly parabola.

Melissa: That continued on.

Emily: Yeah, but it wouldn't go down.

James: What do you think? (The students look at the entire scatterplot on their calculator).

Emily: Yeah, that doesn't make sense because it's like a pretty drastic jump between each .01…from .01 to .1, it's 20. But then from .1 to .8, it's also about 20. I think it was 15 and 19. So it wouldn't make sense for it to go ... the curve to like slowly flatten out yeah.

Emily accurately describes the relationship between SPL and voltage, but something is not making sense to her. She asks if they can find the "line of best fit" but Joe asks them to revisit their scatterplot.

Joe: So, what does [the graph] look like?

Emily: It's a curve, it's not going to be a parabola, right because it wouldn't go down.

Melissa: It just comes ... there must be some kind of formula.

Joe: Okay, tell us more about what you think is happening.

Emily: The curve is just flattening out. The change is becoming less drastic between each point.

Emily's qualitative description of the logarithmic relationship satisfies the goal of the activity. Joe then reminds them how to find the line of best fit using a graphing calculator. Melissa and Emily try fitting a linear equation to the data but it is obvious to them that the line does not fit the data well. They also ruled out a quadratic. Joe explains that there is a function that may fit the data better, and so they enter parameters to graph a logarithmic curve. This curve fits the data more accurately than the straight line. The students seem satisfied as if they are relieved by this new information. Joe concludes the activity by leading a brief discussion on logarithms.

Case 2 – Henry and Jonah

Activity Introduction. After the students introduce themselves, James initiates the activity with the prompt. The students immediately begin exploring the amplifier and discussing its properties. It is clear they are familiar with these devices.

Looking for a Linear Relationship. Jonah and Henry begin exploring the speaker and amplifier by setting low-volume values on the iPad. Shortly after, Henry says to Jonah, "Okay, let's start pretty low like 40 [percent volume]." They set the volume to 40 percent and observe the SPL and voltage meters. Henry notices, "Well, obviously the higher the volume gets the more voltage it uses." He continues, "There's probably an equation for this like that relates [SPL] to the amount of voltage."

After a few minutes of observing, the students each grab a piece of paper and start writing down the data. Henry suggests that they check the maximum volume; they record an SPL value of 64 dB and a voltage of 0.858V. Jonah adjusts the position of the SPL meter with respect to the speaker. They record the SPL value (66.1dB) for this new meter position and decide to keep it pointed at the center because it gives the maximum reading. They also take an SPL reading at 0% volume. They spend a few minutes writing down their data and making some calculations (shown below). This is followed by a discussion on direct and indirect variation.

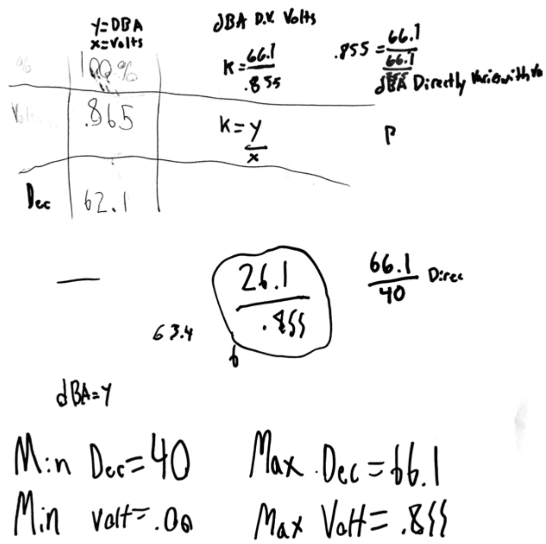

Figure 6. Jonah and Henry's initial data and calculations.

Henry: The decibels vary with the volts...What's the equation for direction variation again? It's X times Y divided by K. K equals— (He is talking out loud as if to communicate his thought process to Jonah).

Jonah: Y times X. I am pretty sure.

Henry: I thought that was indirect?

Jonah: Ok, then Y divided by X.

Henry: Yeah, that sounds right…Y should be decibels. X should be volts.

Jonah: So, the constant K equals—is that on? (Referring to the tone generator.)

Henry: Yeah, it's on. Do you want me to turn this all of the way up?

Jonah: Sure.

Henry: Should say 66 decibels. You should solve for K first.

Jonah: Yeah, or you could solve for K—

Henry: Yeah, I mean simplify. I'll pull out the calculator and see if it has to simplify. Okay, so 66 divided by .855 equals. That's what K equals (pointing to the calculator).

Jonah: So then… (He pauses as if to stop and think about it). It doesn't make sense—

Henry and Jonah have just spent the past 10 minutes working together to find the constant K in the direct variation relationship between voltage and decibels. First, they divide the max decibels reading (66.1) by the max voltage reading (0.855) when the volume was set to 100%. Next, they take a second recording at the minimum volume setting (0%), this is recorded as 40dB, 0.00V. Then they subtract the maximum and minimum points to find the change in decibels over the change in voltage.

The students pause to review their work and are unsure what to do next. They ask Joe for help, and he responds by asking the students to show their work thus far. They explain their work and he points out that they only have two data points, one of which is the SPL value at 0% volume (i.e., the noise floor). The students calculated the slope of a line through the minimum and maximum points of their data. Joe suggests they collect data above the noise floor. The students then begin collecting more data.

Getting Evenly-Spaced Volume Intervals. Henry proposes that they collect data points at 20% volume intervals (i.e., 20%, 40%, 60%, and 80%). They spend several minutes testing each interval and collecting a second round of data. Joe inspects the data and suggests that Henry and Jonah collect some data below 20% volume. They decide to collect at every two percent from 0 to 20 and spend the next several minutes finishing their data collection. The students' final data is shown below in Figure 7.

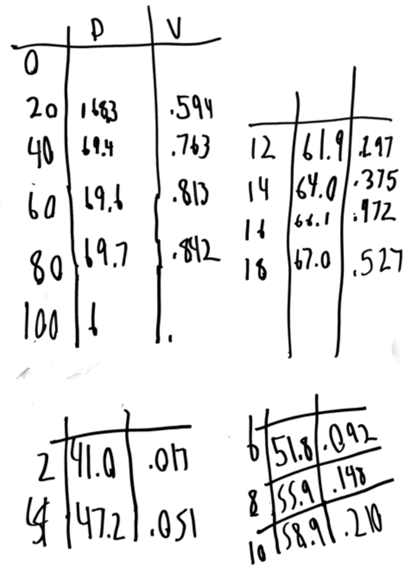

Figure 7. Jonah and Henry's final data.

Difficulties Graphing the Independent Variable. Jonah and Henry finish collecting their data, and Joe asks if they see a relationship between *voltage* and *SPL*. They agree that there is a relationship. Joe then asks them to describe it. The students do not provide a qualitative description of the relationship between *voltage* and *SPL*. Instead, Henry suggests that they make a graph to represent it.

At the onset of graphing the relationship, Henry decides that they should make two graphs, one of *voltage* versus *volume* and the other of *SPL* versus *volume*. They each decide to construct a graph separately and spend a couple of minutes working on this. Jonah rounds the SPL values to the nearest whole numbers, while leaving voltage as is, presumably to simplify the graphing process. The students both used volume along the X-axis, instead of plotting SPL versus voltage. Joe initiates the discussion.

Joe:	Okay, so let's remember what I said. What you want to look at is [volts] and [decibels].
Henry:	I can just change all these (volume percentages) to volts, should I do that?
Joe:	Volts and decibels.

Henry: Going to be a pretty easy fix.

Jonah and Henry begin constructing their new graph of voltage versus SPL. They do this by modifying the *SPL vs.* volume graph by merely erasing the volume values on the X-axis and replacing them with the corresponding voltages values. For example, they replace 20% volume with 0.594V and 40% with 0.763V. The students did not appropriately rescale the axis. Joe inspects their new graph and points out that they need a new scale along the X-axis to chart their voltage values.

Describing the Non-Linear Relationship Graphically. Jonah and Henry work through these issues and complete their graph. The final version is shown below in Figure 8.

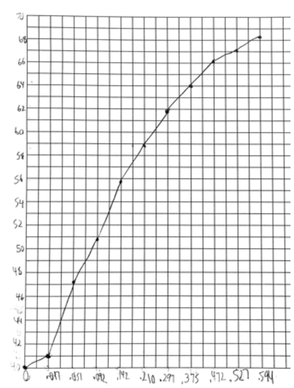

Figure 8. Jonah and Henry's final graph.

In the final phase of the activity, Henry and Jonah qualitatively describe the curve of their graph.

Henry: I mean I guess if we keep going it'll just go.

Jonah: It never goes back down

Henry: I mean the rest of the data...

Joe: What happens when you keep increasing the volts?

Jonah: It keeps going up until it stops. But it never comes down.

Henry: It'll just plateau.

Joe: So is that a parabola?

Henry: No…because it doesn't come down.

Henry acknowledges that it is not a parabola because the curve could not go back down. Later, during debriefing Jonah states that the curve “increases less” as you keep increasing the voltage, referring to the decibel output of the speaker. Henry points out that it resembles the square root curve, a non-linear relationship that they were taught in algebra. At this point, James and Joe are satisfied with their description of the relationship and end the activity. This is followed by a discussion on logarithms.

Case 3 – Lily, Max, and Nicole

Activity Introduction. After the students introduce themselves, James initiates the activity with the prompt. The students begin making adjustments to the online tone generator’s frequency control. They recognize that the default frequency, 440 hertz, is associated with the musical note, ‘A.’ Joe and James intervene by telling the students to keep the frequency fixed to 440 Hertz.

Getting Evenly-Spaced Volume Intervals. The students begin to adjust the volume slider on the application. Max is in control of the iPad; he makes the adjustments while Lily and Nicole watch. He attempts to get the volume to precisely 50% but cannot get it exact. Nicole interjects:

Nicole: Just do 51 [percent] if it makes you feel better. Just let it go. It’s okay.

Max: No, it’s not. (He continues trying to get the slider to 50%).

Nicole: You’re never going to get 50. Just keep it at 51.

Max: Alright.

(They all count down from three, become quiet, and record the data on their sheets of paper).

Nicole: Alright, try it at 25 if you can get it there.

Max: (He begins adjusting the slider to 25 percent). Yes, it’s exact!

Max is keen on getting the volume slider to exact and equal intervals (e.g., 25, 50, etc.) but the precision of the slider did not allow him to always achieve this. Nicole makes sure Max is not taking too long to dial in the slider. When too much time passes, she tells him to keep the slider where it is and move on.

Looking for a Positive Relationship. The students collect data at every 25% volume interval (i.e., 0, 25, 50, 75, and 100). The three of them work together to set the volume, countdown from three, remain quiet for the meters to stabilize, and record the data values. After a couple of minutes of this, they seem confused and start discussing their initial data.

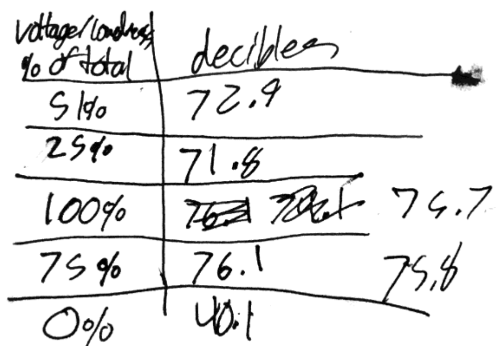

Figure 9. Lily, Max, and Nicole's first round of data.

Max: 75 percent? Alright, 3, 2, 1. (They countdown to record the values from the meters).

Nicole: I think mine's off.

Lily: Really?

Nicole: Yeah, I got 76.1 [decibels] and then we got 74.1 (scribbled out in Figure 9) for the—

Max: Hundred [percent].

Lily: Let's try a hundred again.

Max: 3, 2, 1.

Nicole: I got 75.7.

Lily: I still think something's off with the 75. Run that one again. (They record the data again).

Lily: We should probably organize our data.

The students have just recorded a higher value for 75% (76.1 dB) than for 100% (74.1

dB). They repeat the experiment at 75% again. Lily suggests organizing their data, even though they have been recording their values in a chart format. The conversation shifts off topic but Lily reasserts her idea.

> Lily: I think we should start organizing our data. To find any correlation. Like right now, I feel like if we organize our data we'd have a better clue. Because right now...
>
> Nicole: I think we can't find anything if the data is not accurate and I don't think there's been a constant correlation with the 51 and 52 and it seems like.

Lily believes organizing the data will be helpful for finding a relationship, while Nicole is skeptical about the accuracy of the data. Max asks if having the data in a chart format is organized, and Lily says that she was thinking of organizing the data as a graph instead. The students ask for graph paper and James suggests that they use Excel for graphing their data. They begin entering their data into Excel.

Describing the Non-Linear Relationship Graphically. The students construct a scatterplot graph on the program and Nicole suggests that they collect more data at 20% intervals. They start with 20 percent and Max attempts to get the volume slider exactly at 20. He moves the slider to 19 percent and Lily says that 19 is fine. Max keeps trying and moves the slider to 21 percent, says that it is good enough, and then records the value. Lily asks, “Are we also measuring volts?” Max confirms that he has been entering volts and decibels into Excel.

At this point, Lily suggests that they, “try measuring the background noise.” Nicole adds, “To make it more constant. There's going to be background noise but ... we should measure that before we turn this on as a control so we can subtract that to get a more accurate number for how many decibels the speaker emits.” The students record the noise of the room without the speaker playing a tone. After their second round of data collection, the students begin to discuss and interpret the data.

Nicole: Okay. So, [decibels] stays pretty constant from—

Max: From 41 to 100, it's pretty constant.

Nicole: It could be that that's the max that this particular setup can produce?

Lily: It looks like a radical function. It goes up to a certain point and then it begins to flatten out.

Max: Flatline.

Lily: You guys want to graph?

Max: Okay.

Nicole: I think we should maybe try in the zero to 41% range…

Nicole and Max both notice that the data is almost constant from 41 to 100 percent volume. Lily suggests that it resembles a radical function. Her description of the curve is qualitatively similar to a logarithmic function. Nicole states that they should collect more data below the region of the curve that flattens out (i.e., zero to 41 percent); she suggests collecting at every 5% interval.

Describing the Relationship Algebraically. As Max works on the *voltage*-SPL graph, Lily at first uses her graphing calculator to find a regression between *volume* and SPL.

Lily: I should probably know this, but when you're looking for a regression in a line are you looking for R-squared or R?

Joe: Squared.

Lily: Okay, I'm just trying to find the equation…it's sort of an Algebra II thing. I don't think we learned it in Geometry. (She says this as if to indicate that Max and Nicole may not have learned the same problem-solving strategies).

Lily spends the next couple of minutes calculating several regression equations, using volume as the independent variable.

Nicole: Could you try doing it without the percentages?

Lily: What do you mean without percentages?

Nicole: Just doing decibels to volts instead of ... That may be more accurate.

Lily: Okay. So do you want decibels to equal X and volts to equal Y?

Nicole: Whichever way you think.

Lily: It's going to make a really big difference.

Nicole: Which is why I'm asking you because it's your math.

Lily: Okay, I'm gonna go X for volts…so the volts influence the decibels then? Okay.

Nicole: So volts should be X?

Lily: Yeah, X equals volts. Y equals—

Max: Decibels.

Lily: Yeah decibels.

Nicole states that they should use voltage and decibels. Lily agrees and they decide X should be voltage (volts) and Y should be SPL (decibels). After this, Joe checks in with the students. Lily explains that she made a table of values and used the calculator to look for a regression equation. Joe suggests graphing the points. She takes a minute to do this and proceeds with the discussion. Lily acknowledges that their data does not follow a linear regression because the Y-values (decibels) do not keep increasing after a certain point. While collecting data, Lily did not double check to see if the voltage was increasing past 41% volume and just wrote in the same value for voltage from 41% to 100% volume.

After collecting more data to correct this data collection oversight, Lily generates a second set of regression equations on her calculator. She takes a couple of minutes to write them all down on her paper. When she finishes, she announces to the group.

Lily: This is what I found. According to this [r^2], it says it's a quadratic function…but that doesn't make sense. It almost balances off, it's a radical function...I think it's probably an exponential because exponential functions have an asymptote, which is where the Y values sort of flatten out which is kind of what's happening here.

Lily notes the regression with the highest value of r^2, but then tries to reconcile this with the shape of the graph. She describes the qualitative features of the relationship and uses this information to rule out a quadratic relationship. Lily then suggests that an exponential function is the most appropriate regression equation to model the relationship. In the post-activity interview, Lily described this strategy as “generating a lot of functions that could work.” Additionally, she describes her criteria for selecting the most appropriate equation, “the way I do it is I look for the regression value and the closer the regression value is to 1, the more accurate it is.”

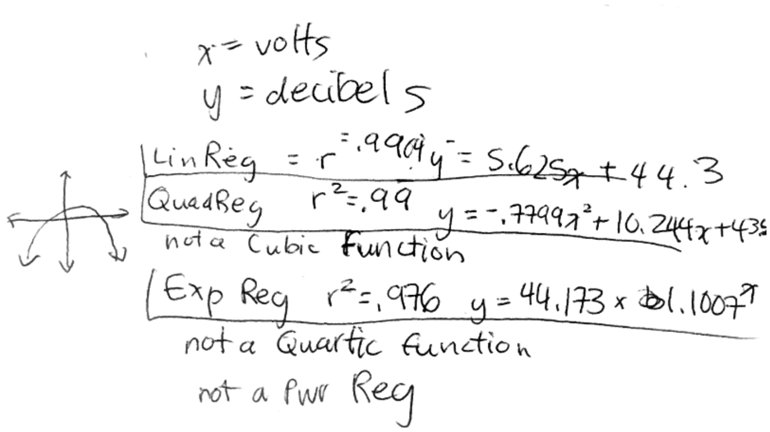

Figure 10. Lily’s second set of regression equations.

Joe assists them to find the actual regression equation in Excel, and the students proceed to plot the logarithmic function over their data. At this point, the activity is concluded.

Cross-case Matrix

The table below highlights the important characteristics of all three cases.

	Case 1: Emily and Melissa	Case 2: Henry and Jonah	Case 3: Lily, Max, and Nicole
Data Collection Strategies	▪ Equally-spaced intervals. ▪ Tried to collect data with increments of voltage to 0.01V. ▪ Repeated SPL measurements for improved accuracy. ▪ Multiple iterations of data collection with increasing number of data points.	▪ Equally-spaced intervals. ▪ Found minimum/maximum points. ▪ Multiple iterations of data collection with increasing number of data points. [1]	▪ Equally-spaced intervals. ▪ Repeated SPL measurements for improved accuracy. ▪ Multiple iterations of data collection with increasing number of data points.
Modeling Strategies	▪ Looked for a "steady rate" ▪ Calculated change in SPL and change in voltage. ▪ Graphed relationship using calculator. ▪ Looked for a "direct relationship". ▪ Ruled out linear relationship. ▪ Considered parabolic relationship. ▪ Ruled out parabolic relationship because "it wouldn't go down". ▪ Calculated regression equation. [2]	▪ Looked for an equation ("there's probably an equation for this…) ▪ Solved for direction variation constant ($k = \frac{y}{x}$). ▪ Graphed relationship via paper and pencil. ▪ Ruled out linear relationship. ▪ Ruled out parabolic relationship, because "it keeps going up until it stops, but it never comes down."	▪ Calculated change in SPL and change in voltage. ▪ Graphed relationship using calculator and Excel. ▪ Generated linear, quadratic, and cubic, quartic, power, and exponential regression equations and r^2 values. ▪ Ruled out all but the exponential function based on r^2 and shape of graph.
Scaffolding Needed	▪ Did not collect upper-range of SPL values. ▪ Did not trust their ability to collect data. ▪ Frustrated with sensitivity of measuring instruments.	▪ Did not collect full range of SPL values. ▪ Graphed Volume vs. SPL instead of SPL vs. Voltage. ▪ Did not properly rescale the X-axis changing from percentage to voltage.	▪ Graphed Volume vs. SPL instead of SPL vs Voltage. ▪ Improperly recorded the voltage data for values above 40% volume.
Final Interpretations	▪ "The curve is just flattening out." ▪ "The change is becoming less drastic between each point."	▪ "Increases less" ▪ "Resembles a square root curve" ▪ "It'll just plateau."	▪ "It says it's a quadratic function…but that doesn't make sense. It almost balances off. It's a radical function...I think it's probably an exponential because exponential functions have an asymptote, which is where the Y values sort of flatten out."

[1] Henry and Jonah (Case 2) collected multiple rounds of data when this was recommended to them.
[2] Emily and Melissa (Case 1) calculated the regression when reminded how.

Discussion

Getting Evenly-Spaced Voltage Intervals.

The students' prior knowledge of linear relationships seemed to influence their data collection strategies. While students collected different amounts of data through iterative processes, they all went about their data collection in a similar way. More specifically, all of them utilized an *equally-spaced* data collection strategy. They attempted to adjust the independent variable using equal-space intervals in order to detect a proportional change in SPL. Whether equally-spacing the values of voltage or volume, students decided on an interval for each round of data collection (e.g., 0.01V or 25% volume). Emily and Melissa (Case 1) explained that they were trying to get evenly-spaced intervals as a way to learning more about the relationship. Their intention was to adjust the voltage by .01 intervals and record the corresponding SPL values. In two of the cases, as students iterated through the data collection process, their intervals would change. Henry and Jonah's (Case 2) interval for their second round of data collection was 20% volume (20, 40, 60), and 2% volume for the next round (2, 4, 6, etc.). Similarly, Lily, Max, and Nicole (Case 3) collected three rounds of data using the intervals 25%, 20%, and 5% respectively.

The evenly-spaced interval strategy was not always easy to implement. The students spent a significant amount of time adjusting the volume of the iPad in order to dial specific voltage values on the voltmeter. In the case of Emily and Melissa (Case 2), it proved to be too difficult to get exact .01 voltage intervals, and they had to settle for approximately evenly-spaced intervals. Max (Case 3) also spent a lot of time struggling to get exact values. Overall, the students attended to the precision of their data by being patient, taking multiple readings, and iterating multiple rounds of data collection.

Looking for and Ruling out a Linear Relationship

In all three cases, their actions during the activity indicated their tendency to look for a linear relationship. Students used prior knowledge of direct variation by looking at corresponding changes in the variables and ruled out a linear relationship.

Looking for a Linear Relationship. Emily (Case 1) indicated her expectation for a linear relationship when she said, “[voltage] should correspond to the change between with the decibels. Is there a change…if I move the voltage up, [SPL] should move up with it at a steady rate?” The students attempted to standardize the change in the voltage to 0.01V, a common approach to finding a linear pattern. Then, they calculated the change in Y over X by organizing their data in a chart, finding the changes between the X- and Y-values, and dividing them. They explained that they were “looking for a direct relationship.” When they failed to find a direct relationship, they doubted their ability to collect data and tried to rationalize a linear relationship was still plausible. After three iterations of data collection, the graph they constructed graph did not represent a line, yet Melissa tried to rationalize that it could be linear, “if the straight line was really steep.” They initially attributed the non-linearity of their model to their data collection procedures rather than the relationship between voltage and SPL.

Similarly, Jonah and Henry (case 2) applied their knowledge of linear relationships as a strategy to the activity. After making preliminary observations, they recognized a relationship between the two variables and indicated that “there’s probably an equation for this.” To them, this meant finding the minimum and maximum data points, and calculating the direction variation constant, *k,* a common strategy taught in algebra courses.

Lily, Max, and Nicole (Case 3) looked for a positive relationship between the variables in the first half of the activity. They calculated the change in SPL and change in voltage to see if a pattern emerged from the data but quickly used Lily’s regression strategy to evaluate both linear and non-linear models. While they did not focus on linearity, Nicole explained that she had been expecting a linear relationship. In the post-activity interview, she said, “I was thinking that it would be a constant rate of change and I was disproven by math and science.”

Ruling out a Linear Relationship. In all three of the cases, the students drew upon their prior knowledge to *rule out* possible models. For Case 1 and Case 2, both groups used their graphs as a way to rule out models and qualitatively model the relationship. When doing this, they had to evaluate their prior knowledge of mathematical concepts and compare that with their graph to make sense. Both groups ruled out the linear relationship once their graph was complete.

Lily (Case 3) was an exception due to her prior coursework in Algebra II. Instead of relying on a graph to rule out linearity, she used a regression strategy taught in Algebra II. She described this below:

> Lily: In Algebra 2, our teacher made us do projects like real-world projects, but she did it by the state's standards so that's why we were taught that if R squared equals 1 it's the correct function, use it.

Lily ruled out a linear relationship when evaluating the various regression equations and r^2values. She picked a cubic regression equation as the first potential model. After correcting some mistakes with her data, she generated another set of regression equations. This time, using both $r^2$and a scatterplot graph of the relationship, she ruled out a cubic function and formed her final interpretation of the relationship.

Describing the Non-Linear Relationship Graphically

Ruling out a Parabolic Relationship. Melissa and Emily (Case 1) considered a parabolic relationship but ruled this out on the basis that the graph "wouldn't go down," as it would if it were truly parabolic. They considered, but ultimately ruled-out a parabolic relationship because "[the graph keeps going up until it stops, but it never comes down." Henry and Jonah (Case 2) ruled out a parabolic relationship from the graph because "it would not come back down." Emily (Case 3) concluded, "A quadratic function…but that doesn't make sense."

Describing the Non-linear Relationship. The students relied mostly on their graphs to make sense and qualitatively describe the relationship. Because they had not studied logarithms in their prior courses, students could not state that it was a logarithmic relationship. Instead, they came up with qualitative descriptions of the nonlinear relationships. Melissa and Emily (Case 1) described the curve of their graph as "flattening out" and the relationship as being "less drastic between each point." Similarly, Henry and Jonah (Case 2) said the relationship "increases less" and that "it'll just plateau." They extend their description further than Melissa and Emily by comparing it to a mathematical function they have learned about; they said the relationship "resembles a square root curve." Finally, Lily (Case 3) in her final evaluation, stated the relationship, "almost balances off. It's a radical function...I think it's probably an exponential because exponential functions have an asymptote, which is where the

Y values sort of flatten out." Lily's description of the relationship is graphically correct, but functionally (exponents) incorrect.

Implementation Difficulties

We identified the three primary phases of the activity in the above sections. However, we also noted difficulties that students had with the implementation of the activity.

Keeping Track of the Variables. Most of the students struggled to keep track of the two salient variables in the activity: sound pressure level and voltage. Henry and Jonah (Case 2) were both familiar with the amplifier from their engineering course and were interested in how the amplifier worked. They began the activity by investigating how the two volume controls (physical and digital) affected the voltage being measured. It wasn't until after we intervened that they switched their attention to the speaker's SPL. During their data collection, they included all three variables (volume, voltage, and SPL) in their data table. After this, they constructed two graphs relating voltage to volume and SPL to volume. They were then reminded that the goal of the activity was to relate voltage with SPL. After the reminder, the students struggled to correctly graph the relationship and made the mistake not rescaling the X-axis as noted in the Case 2 description.

Lily, Max, and Nicole (Case 3) also had issues remembering the variables of interest, SPL and voltage. They first investigated how frequency (pitch) affected the voltage being measured on the amplifier. We restated the purpose of the activity, asked them to keep the frequency on the tone generator constant (440Hz) and use the volume control on the iPad to adjust voltage. The data they collected included all three variables (volume, voltage, and SPL). During their analysis, Lily entered the two data sets for volume and SPL into the graphing calculator, ignoring voltage altogether. Once she shared her initial findings with the group, Nicole pointed her mistake out and asked Lily to include voltage instead of volume in the regression analysis. Unlike Henry and Jonah (Case 2), Lily's scaffolding came from her peer instead of the activity facilitators.

Restricted Range of Data Collection. Students' beliefs about the relationship led them to prematurely model without having collected enough data to represent the relationship. Jonah and Henry initially collected minimum and maximum values of the system. The students drew upon their prior procedural knowledge as a strategy for finding a linear equation. They then moved ahead with modeling the relationship by calculating the direct proportion constant, a common strategy taught in algebra courses. At this point, we suggested they collect more data, which was followed up by collecting four more points at 20, 40, 60, and 80 percent. This still did not yield a rich graphical image of the logarithmic function, which increases most dramatically between 0% and 20% volume. Knowing this, we suggested collecting the third round of measurements below 20% volume. This was a critical step to ensure the students had sufficient data to accurately model the logarithmic relationship with their graph. Henry then explained:

> Henry: The main change happens between zero and 20 [percent volume] like you said. If you just look at 20 through 80 there's basically no change. It looks basically the same in decibels, in voltage there's change, but this, it varies a lot.

Emily and Melissa (Case 1) did not collect across the entire range of possible voltage values before modeling the relationship. Their strategy was to start at 0% and slowly increase the volume. They collected several data values, the calculated change in SPL, and then looked for a linear pattern. By the time they transitioned to graphing and modeling the relationship, they had not collected data from the upper limit of the system (i.e., values close to 100% volume). When they graphically modeled the data, the logarithmic relationship was not fully represented and thus the students struggled to make meaning from their original graph. Once we recommended that they collect SPL values at 100% volume, the logarithmic relationship became more apparent to them.

They expected the relationship to be linear and therefore collected the data needed to calculate a linear equation. When students graphed the relationship with insufficient data, the nonlinear relationship was not fully represented. This may have reinforced students' belief that the relationship is linear and prevented them from exploring alternative interpretations.

Conclusion

In this study, we explored: (1) students' strategies for both collecting data and creating mathematical models, and (2) how they drew upon their prior knowledge and worked through challenges to complete an MEA. Following Lesh et al. (2000), this study utilized this activity as a way to expose student thinking. Middle school students were asked to explore the logarithmic relationship between *SPL* and *voltage* without any prior instruction on logarithms. Consistent with De Bock et al. (2011) and others (De Bock et al., 2003; Ebershbach, 2008; Van Dooren et al., 2007), the use of this MEA revealed students' initial reliance on linearity. These students subsequently re-evaluated their application of prior knowledge of linear and other relationships to make sense of the activity. *Ultimately, with persistence and some occasional scaffolding,* *each of the three groups was able to develop an appropriate graphical non-linear model of their collected data, supplemented by verbal descriptions of their model.*

The issues students faced suggest several conclusions. These students did not have sufficient prior opportunities to work with situations of this type. Their actions and words demonstrated the difficulties they encountered while working with messy real-world data and instrumentation. Moreover, working with a mediating variable (i.e., using volume to adjust voltage) contributed to the complications they faced. Overall, their lack of experience led to issues with keeping relevant variables in mind, collecting enough data across a complete range of possible values, dealing with decimal place values, and scaling axes properly.

Our findings suggest that students should be given opportunities to engage with both linear- and nonlinear-based MEAs. This will facilitate not only students' learning how to determine appropriate ranges and intervals for collecting data, but also expand their knowledge of mathematical functions that are useful in other areas. The range of functions chosen will necessarily depend on the courses taught and mathematical backgrounds of the students, but note that such MEAs can move students beyond traditional expectations. Mathematics teachers could work cooperatively with their science, engineering, and other colleagues to identify situations and phenomena that can be used to develop meaningful MEAs, even some that incorporate several independent variables (e.g., Ampere's Law).

MEAs that involve the collection of data, with measuring instruments, in the context of genuine situations give students experience confronting and resolving realistic measurement issues and, at the same time, allow them to see connections between mathematics and other disciplines. MEA set-ups can be technologically simple or complex, and measurements can be taken with either basic or sophisticated instruments. Of course, a teacher can reduce data collection issues at first by using situations that can be analyzed with simple or rounded data before moving into more complicated situations. For data analysis, graphing calculators can be used, but we also recommend spreadsheets because of additional functionality. But, these tools must be used cautiously and not in rote ways. For example, students should not be led, even unintentionally, to rely solely on a coefficient to evaluate the appropriateness of a model. Technologies can be used to readily generate multiple representations of data to help students construct a model.

Finally, there are several limitations to this study. *First*, our middle school participants had all taken high school level mathematics courses and engineering courses, so they are not representative of middle school students more generally and would be considered by many as outliers. *Second*, the nature of our research was exploratory rather than explanatory. While our results suggest explanations of “what happened,” the work of additional students would need to be analyzed to yield stronger and more detailed findings.

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Manuscript Two

Middle School Students' Computational Thinking in the Context of Physical Computing

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Introduction

Over the past ten years, there has been a steady rise in interest in computational thinking (CT). Policymakers, educators, organizations, and the media have all reported on the importance of CT in a digital world (Barr & Stephenson, 2011). Now recognized as an essential form of literacy for informed citizens in the modern world, CT has garnered the attention of the educational research community (Buckler, Koperski, & Loveland, 2017; Snow, Tate, Rutstein, & Beinkowski, 2017; Szalay & Gray, 2006). Students are exposed to a vast amount of digital information and data in their daily lives and benefit from developing CT skills to interpret and construct meaning from these complex systems of information. Some have even said CT leads to improved cognitive abilities by being able to combine layers of abstraction (Florez, Casallas, Hernandez, Reyes, Restrepo, & Danies, 2017). Given the surge in interest on CT (Google, 2018), attention in the media (Crow, 2014), and educational literature, there is still a lot we do not know about how students come to develop CT.

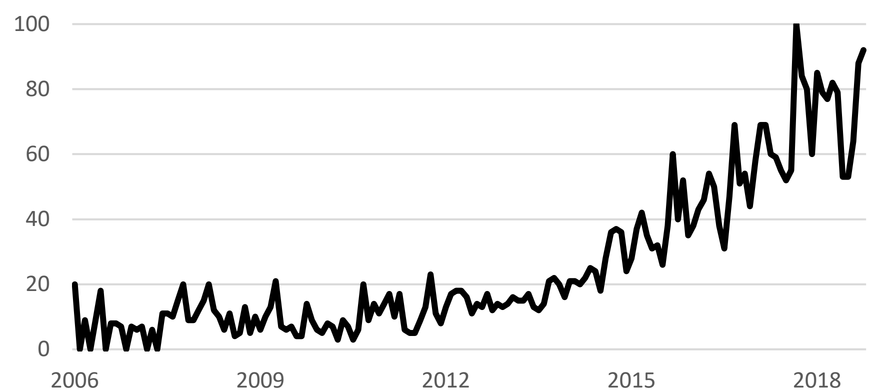

Figure 1. Internet search traffic on *computational thinking* (Google, 2018).

Over a decade ago, Wing (2006) brought attention to the significance of CT and the role it plays in disciplines, including but not limited to computer science (CS). The National Research

Council (NRC) echoed these beliefs by including CT as a part of their framework for science education (NRC, 2012), and as one of eight practices of science and engineering in the Next Generation Science Standards (NGSS Lead States, 2013). A past-president of the National Council of Teachers of Mathematics (NCTM) has acknowledged the role of computational thinking as part of mathematics education (Larson, 2016). In today's digital world, CT will no doubt be important to cultivate among the next generation of scientists, economists, global leaders, and citizens.

What is Computational Thinking?

Since most generally agree developing students' CT is a productive goal, it is essential that these communities (e.g., legislators, educators, and researchers) share the same construct definition. While some have constrained the focus of CT to an exclusive area of computer science (e.g., College Board, 2017), most of the research community have adopted a perspective that CT is not inherently part of computer science and are problem-solving processes applicable to many disciplines (Cuny, Synder, & Wing, 2010; Wing, 2006).

Wing (2006) defined CT as the thought processes involved in solving problems in ways that *can* be carried out by a computer and asserts that this type of thinking exists within other disciplines, such as biology, or in solving everyday problems. Cuny, Snyder, & Wing (2010) later clarified, defining CT as "the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent." One year later, Aho (2011) provided the similar definition of CT as "the thought process involved in formulating problems so their solutions can be represented as computational steps and algorithms" (p. 2). Thus, there appears to be some agreement that CT relates to problem-solving and has specific defining characteristics.

Characteristics of Computational Thinking

While a conceptual definition of CT is generally agreed upon, operationalizing this definition into specific and measurable characteristics is more complicated. CT must be organized into measurable constructs to assess how students develop CT. Most often, researchers do this by specifying *characteristics* associated with CT (e.g., Angeli, Voogt, Fluck, Webb, Cox, Malyn-Smith, & Zagami, 2016; College Board, 2017; Brennan & Resnick, 2012; International Society of Technology in Education [ISTE] & Computer Science Teacher Association [CSTA], 2017). The table below illustrates an example set of CT characteristics published by ISTE and CSTA (2017).

Table 1. Characteristics of CT (ISTE & CSTA, 2017)

Formulating problems in a way that enables us to use a computer and other tools to help solve them.
Logically organizing and analyzing data.
Representing data through abstractions such as models and simulations.
Automating solutions through algorithmic thinking (a series of ordered steps).
Identifying, analyzing, and implementing possible solutions with the goal of achieving the most efficient and effective combination of steps and resources.
Generalizing and transferring this problem-solving process to a wide variety of problems

These characteristics shape the associated learning objectives with CT instruction and thus may assist with the researching of how students develop CT.

Computational Thinking in K-12

Integrating CT in the classroom presents several challenges. Novices often have misconceptions about computer programming which can impact the development of their CT

(Tew, 2010). Students bring these misconceptions into the classroom and this requires teachers to recognize these misconceptions. Unfortunately, many teachers today do not have a background in CT or the necessary content knowledge to be successful in identifying student misconceptions and supporting students' CT. The fact that we know very little about how students' come to develop CT compounds these challenges (Tew, 2010). More recently, researchers have examined different ways to measure and evaluate the development of CT.

Developing a high-quality assessment of CT is critical to integrating it into the K-12 curriculum (Grover & Pea, 2013). Efforts to assess students' CT exist (Fields, Searle, Kafai, & Min, 2012; Han, Koh, Basawapatna, Bennet, & Repenning, 2010; Werner, Denner, Campe, & Kawamoto, 2012), but are still relatively under developed. Tew (2010) points out that most attempts to build assessments use a specific platform or programming language, and thus do not measure whether or not students have developed higher-order skills (i.e., CT) transferable to other contexts. From the prelimary studies on CT in a physical computing, multifaceted CT skills, such as *debugging,* have been shown to be particularly challenging to students (Kafai et al., 2012).

No doubt, developing CT alongside computer programming presents its own set of challenges for teachers and students. Teaching computer programming is complex and requires specific pedagogical strategies (Papert, 1991). Science and mathematics teachers may already teach particular aspects of CT, such as generalizing a formula, but may not be well-prepared these concepts through the use of computer programming. Doing so requires teachers to be comfortable debugging syntax and functional mistakes in students' code. As a result, such CT initiatives exist within the domain of career and technical education (CTE) or engineering education.

Engineering and Physical Computing

Engineering is becoming more prevalent in K-12 schools (Carr, Bennet, & Strobel, 2012), and offers several advantages to developing students' CT. The NRC asserts that computational thinking is an integral part of the engineering design process (2012). Additionally, engineering involves the design and construction of both digital and physical artifacts, and often a combination of the two. Artifacts that are both physical and digital, such as robots, are commonplace today. This domain is sometimes referred to as *physical computing* or mechatronics and is the intersection of mechanical engineering, electrical engineering, and computer science. The construction of such tangible artifacts may afford students with opportunities to learn CT in new ways. The learning theory of *constructionism* suggests that physical computing environments may support and aide in the development of students' CT (Papert, 1991).

Physical Computing

Physical computing is the process of digitizing and computing the physical world around us. For example, a motion sensor that turns on a flood light at home is an instance of physical computing. A device gathers information and data from the physical environment via sensors and communicates this to a computing device (computer or microcontroller). Computing devices interpret digital information and act upon it by controlling some physical device (e.g., lights or motors). A typical example of physical computing in the K-12 setting is educational robotics (e.g., LEGO Mindstorms). However, educational robotics require advanced programming skills and present challenges to the teacher. Simple physical computing activities (e.g., controlling a light) may be more accessible to a broader student and teacher population and offer unique learning opportunities. These more simple instances of physical computing do not appear in the literature. The following chapter will explore the relevant literature and research conducted on computational thinking and physical computing in education.

Literature Review

Computer Science

Computer Science (CS) is one of the more recent branches of science to emerge. It is also the one most shrouded in mystery and misunderstanding. While part of CS is to understand better how computers work, it is also about learning ways in which computers and computing devices can be used to solve complex problems. In the past decade, efforts to include CS into the K-12 curriculum have increased; a recent survey of US principals report that 76% of high schools offer some form of computer science instruction (Gallup, 2016). In 2017, the Virginia Department of Education (VDOE) developed standards for computer science that span grades K through 12. VDOE defines CS as the study of computers and algorithmic processes and cites CT as a necessary skill in learning CS and claims that their standards have CT throughout. I will revisit and expand upon their definition of CT later in this section.

Programming algorithms to solve problems is an essential part of CS. Moreover, developing algorithms through programming code is most frequently associated with CT (Angeli et al., 2016; Basu, Mcelhaney, Grover, Harris, & Biswas, 2018; Chen, Shen, Barth-Cohen, Jiang, Huang, & Eltoukhy, 2017; Cross, Hammer, Zito, & Nourbakhsh, 2016; ISTE & CSTA, 2017).

Programming can be thought of as “formulating problems and solutions using machine recognizable syntax” (Chen et al., 2017, p. 163). Alternatively, computer programming is comparable to the process of writing. Just as with writing, programming involves different languages, formats, contexts, and goals. Programming has syntax structures, semantic definitions, and rules to ensure that a machine can understand the program. Both processes are complex, creative, and have multiple divergent solutions. Some have even empirically explored the relationship between CT and expository writing (Wolz, Stone, Pearson, Pulimwood, & Switzer, 2011).

It is important to note that programming is merely one tool available for developing CT, as will be discussed later in this section. Both mathematics and science educators have begun to explore ways in which to develop students’ CT through these domains. Programming is thus one of many possible means for developing CT and should not be construed as the end goal. It is essential that learning objectives go beyond just learning to code. Crow (2014) emphasizes this point and asserts that CS education is about not training software developers, but instead about promoting the problem-solving associated with CT.

A Historical Perspective of CT

In 1967, a research team of computer scientists developed the programming language, *Logo*, that was intended to assist in the teaching children how to program computers. Chief among this team was Seymour Papert, a protégé of Jean Piaget, and would later go on to receive recognition for developing the learning theory of *constructionism*. Before Wing, Papert discussed the importance of computing and its inevitable influence on the way we think and solve problems. From his perspective, “certain uses of very powerful computational technology and computational ideas can provide children with new possibilities for learning, thinking, and growing emotionally as well as cognitively" (p. 17-18, Papert, 1991). His description of problem-solving in a computational world gets at the same idea that Wing would eventually coin as *computational thinking*.

Papert's work on educational psychology and computer programming would go on to inspire a new generation of CT educators. For instance, one of Papert's doctoral students, Mitch Resnick, founded the Lifelong Kindergarten Group at the MIT Media and developed the Scratch programming language, a visual block-based programming language that inherited many of the same ideas behind Logo. Scratch today is used in more than 150 different countries by over 33 million users (Scratch, 2018), and may be considered one of the most accessible programming languages. Since the term has become popular, Resnick has claimed Scratch to be a platform for developing students' CT and developed a framework for describing the type of learning involved with programming in Scratch (Brennan & Resnick, 2012).

Operationalizing CT in the Classroom

Angeli et al. (2016) propose a simple definition for K-6 teachers seeking to integrate CT into their teaching. They define CT using five characteristics, presented as skills for students to develop. These characteristics are identified and defined in the table below.

Table 2. An operational definition of CT (Angeli et al., 2016)

Abstraction	The skill to decide what information about an entity/object to keep and what to ignore.
Generalization	The skill to formulate a solution in generic terms so that it can be applied to different problems.
Algorithms	The skill to devise a step-by-step set of operations/actions of how to go about solving a problem.

Decomposition	The skill to break a complex problem into smaller parts that are easier to understand and solve.
Debugging	The skill to identify, remove, and fix errors.

These characteristics are then used by the authors to develop a curricular framework composed of standards of learning. For example, *debugging* contains two standards: 1) recognize when instructions do not correspond to actions, and 2) remove and fix errors.

More recently, ISTE and CSTA (2017) jointly published an operationalized definition of CT that uses six characteristics (shown in Table 1), and has been used by some researchers (e.g., Chen et al., 2017). Others, such as the Robotics Institute at Carnegie Mellon University, have used a more simple definition for CT and included only three characteristics: problem-solving, abstraction, and algorithmic thinking (Cross et al., 2016). All of these definitions share characteristics, such as abstraction and algorithmic thinking, and similarly, define terms. These definitions operationalize an otherwise nebulous term and allow researchers to study CT in the classroom.

Researchers have studied computational thinking from several perspectives. Korkmaz, Cakir, & Ozden (2017) developed a *computational thinking scale (CTS)* to assess CT in undergraduate students within STEM majors. A factor analysis conducted on the results of their survey suggested five characteristics to CT: creativity, algorithmic thinking, cooperativity, critical thinking, and problem-solving. The utility of such an instrument is limited when considering a K-12 context since middle school students may not be self-aware of their own CT development and may result in unreliable and inconsistent data.

Chen et al. (2017) evaluated elementary school students' CT using a pre-post instrument developed to aligned with the ISTE and CSTA definition of CT (i.e., Table 1). Instead of a self-report survey, such as the CTS (Korkmaz et al., 2017), their instrument was in the form of a performance assessment that included problems for students to solve in order to demonstrate their CT. Findings suggest that computer programming syntax was a barrier to students' CT, but that the use of physical computing (i.e., robotics) improved students' CT over non-physical computing interventions.

This Study

The dialogue around CT is on-going and should continue to ensure that CT is successfully integrated into K-12. Research has demonstrated that CT exists within digital-exclusive environments such as Scratch and even within cross-cutting domains such as science. However, physical computing offers an alternative but potentially beneficial space to develop students' CT. Moreover, less complicated examples of physical computing (e.g., blinking a light) may offer more accessible to both teachers and students than traditional robotics. These simple and tangible projects align with Papert's theory of constructionism and could provide ways to develop students' CT.

This study reports on findings from an instance of a physical computing unit integrated into an 8th-grade engineering elective course. The purpose was to look at and explore what CT students demonstrate through a physical computing unit and subsequent performance assessment. The goal of which was to better understand how students' CT can be effectively engaged and evaluated through the use of physical computing activities, such as Arduino. As a result, these findings may help better define age-appropriate CT frameworks to assess student growth so that teachers can better support learning, and add to the ongoing conversation around CT in K-12 education.

This work stems from a larger initiative to evaluate how middle school students come to develop CT through the use of physical computing and focuses on a smaller set of questions. The following research questions guided the work of this study. 1) *What computational thinking skills did students demonstrate during a physical computing-based performance assessment? 2) What factors contributed to the differences observed in student performance levels?*

Methods

Before an efficacy study is conducted to compare treatments (i.e., robotics versus basic physical computing), and explorative pilot study is needed to establish how CT can be realized in this environment if it is at all. Therefore, this study was conducted using a posttest only non-experiment design with no control or random assignment of students. Non-experiments are useful when conducting an exploratory case study (Yin, 2018) to better understand the particulars of phenomenon. Because quantiative data alone in this design cannot explain how students demonstrate their CT, a mixed-methods approach was used to collect both quanitative and qualitative data. This study offers insight into understanding CT in the context of physical computing, which represents a depature from interventions that rely on coding alone to develop CT.

Context

This study took place in a small city middle school (Bretton Middle School) in the Mid-Atlantic region of the United States. The school district has a total enrollment (PK-12) of 4,210 with the following demographics: 51% male, 49% female, 41% White, 34% African-American, 12% Hispanic/Latino, and 6% Asian/Pacific Islander/Hawaii. Over the summer of 2018, I worked with the middle school engineering teacher, Mr. Souza, to develop a physical computing unit. The purpose of the unit was to support students' CT with a combination of physical computing artifacts, unplugged activities, and computer programming challenges. The unit was implemented in the fall of 2018, and lasted for approximately nine weeks out of the year. Because aspects of the unit were self-paced, some students finished the activities faster than others and moved onto different projects in the engineering course.

Participants

Teacher. The teacher, Mr. Souza, has been teaching engineering at Bretton Middle School for the past three years. Previously, he had taught middle school mathematics for four years at a public school in New England. His undergraduate degree is in systems engineering, although he indicated having no physical computing experience during his undergraduate education. During his time as an engineering instructor, he has taught several units on physical computing but stated that he had limited success in developing coding among students. During a preliminary interview with Mr. Souza, he cited coding and by extension, CT, as a primary barrier for future engagement and enrollment in engineering electives at the high school level.

Students. There were 87 8th-grade students at Bretton Middle School who completed the physical computing unit as part of an engineering elective course, *Engineering I*. All students enrolled and completed the one-semester elective course, *Foundations of Engineering*, the prior year. *Foundations* is a pre-requisite of enrolling into the *Engineering I* course. *Foundations* cover computer design, digital fabrication concepts, electricity and magnetism, and engineering design. Eight of the students participated in a prior summer engineering academy that included a component on physical computing. The table below shows the complete demographic makeup of the students in *Engineering I*.

Table 3. Engineering I Student Demographics (N = 87)

Gender		*Race/Ethnicity*		*Previous Coding Experience*	
Male	73%	White	49%	Some experience	75%
Female	27%	African American	29%	No experience	25%
		Hispanic/Latino	14%		
		Asian/Pacific Islander	8%		

Surprisingly, 75% of the *Engineering I* students indicated having some prior experience with coding. After sharing this statistic with Mr. Souza, he indicated that students had completed a school-wide “hour of code” project last year and might explain the high percentages. The sample population’s representation of female students (27%) was notably less than the school district’s (49%). The distribution of students across race and ethnicity was more or less consistent with the demographics of the school districts.

Physical Computing Unit

This unit was intended to last approximately eight weeks and was scheduled to be the second major unit in the engineering course. However, due to the self-paced structure of the course, the actual time to complete the unit varied by the student but was ultimately capped at 9 weeks. *Arduino* was the chosen platform for this unit as it offers an affordable and simple environment for students. There is also a large community of users and resources available to both students and teachers for Arduino projects. The platform consists of a programmable microcomputer, programming software application, and a text-based programming language. The programmable microcomputer, which can be referred to as the *Arduino board,* gets connected to a computer which has the programming software installed, referred to as the *Arduino Integrated Development Environment (IDE).* The programming language is referred to as the *Arduino programming language* and is used within the IDE to write programs, referred to as *sketches*. The figure below illustrates these major components.

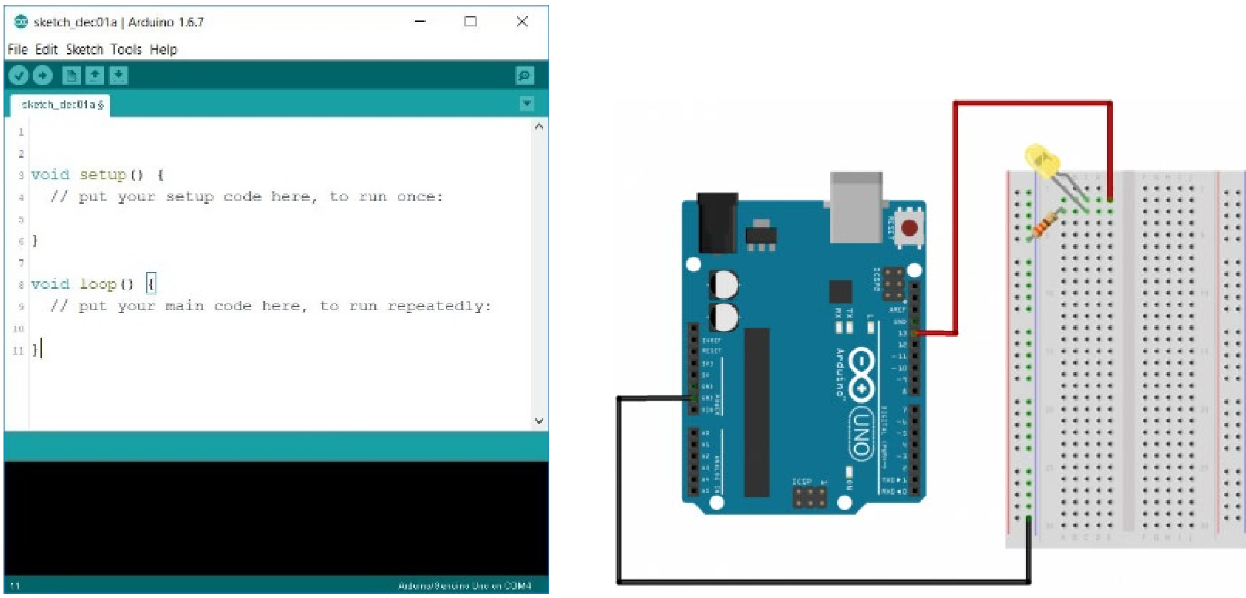

Figure 2. Arduino IDE (left) and board (right) attached to a basic LED circuit.

This unit was the students' first major experience with a computing platform and learning a high-level programming language. Eight assignments were designed to introduce students to algorithms, electronic circuits, computer programming fundamentals (e.g., variables, loops, conditional logic), and physical computing concepts. The self-paced sequence of assignments and instructions was delivered using the school's learning management system, *Canvas.* While students worked independently through the unit, Mr. Souza provided support to students as needed and held students accountable for their own learning. The table below provides a description of the Arduino unit assignments that were developed. After all students completed the assignments in the Arduino unit, Mr. Souza and I administered a performance assessment that was designed to be a summative assessment for the entire Arduino unit.

Table 4. Arduino Unit Overview

Assignment	*Description*	*Concepts Covered*	*CT Characteristic*
1	Students learn how to interpret a basic set of instructions. This unplugged activity familiarized students with interpreting an algorithm without needed to understand the syntax of a particular language.	Interpreting Algorithms	Algorithms
2	This activity introduced the Arduino programming language. Students learn how to print out a text to the computer monitor using the Arduino as a debugging strategy for identifying faulty code.	Arduino Programming Language Debugging (*Serial.println*)	Debugging
3	This activity had students learn how to blink an LED using an Arduino and compare this to blinking an LED using a manual switch. Controlling an LED with the Arduino requiring outputting data to the physical hardware.	Physical Computing Wiring an LED Circuit Blinking an LED (*digitalWrite, delay*)	Generalization
4	Students learn how to read the state of a digital button and control an LED when a button is pressed. Students were introduced to conditional logic using an *if-statement* to turn the LED on when the button was pressed.	Wiring a Button Circuit Reading a Button (*digitalRead*) Conditional Logic (*if-statement*)	Algorithms
5	Students learn how to program more complex control using a momentary digital button to control an LED in a latching way.	Boolean Variables Boolean Logic	Algorithms
6	Students learn how to use loop code structures to control a more complex sequence of LED control patterns.	Iteration/Sequences For Loops	Algorithms
7	Students learn how to develop more complex controls using a button as an input device.	Advanced Algorithms	Algorithms
8	Students learn how to analyze two input devices in parallel and control an LED in more complex ways.	Parallel Processing	Generalization

Data Sources

To answer the research questions and as per the guidance of case study methodology, I collected evidence to support my findings from multiple sources of data. A performance assessment served as the primary data source for my quantitative and qualitative analysis, while observational data was collected to support and explain findings.

Performance Assessment. Mr. Souza and I developed a task to serve as a performance assessment to measure students' mastery of the Arduino unit. We reviewed the unit content and designed the assessment to evaluate students' ability to complete a physical computing project that covered important fundamental concepts in the unit. The task we developed was similar to the assignments from the unit, which focused on reading sensor data (i.e., button), interpreting data from these sensors, and then controlling an actuator (i.e., LED). For a breakdown of all the concepts covered in the performance assessment and the unit, please refer to Table 5.

Performance Assessment Description. Students were asked to wire an LED circuit and button circuit to the Arduino using a new pin configuration. To be successful, students could not copy the work they had done in prior activities and had to be comfortable working with different pins. Next, students' were asked to utilize the button as an input using a new pin to control the LED on a new pin. Students had to implement both *digitalRead()* and *digitalWrite()* appropriately using the new pin configuration. Finally, students had to utilize a Boolean variable into their logic to control the flow of the program as specified. This final task evaluated their ability to construct algorithms with conditional logic. The complete task instructions provided to the students is shown below in Table 5.

Table 5. Performance Assessment Task Instructions

Task 1 Hardware	Wire your Arduino to the following pins: • Button: Pin #4 • LED: Pin #10
Task 2 Software	You have been given some sample code to start with. Do not erase or modify any of the code that has been provided. Write code that will accomplish the following. If the button is pressed one time, the LED will blink according to the following sequence: • ON for ½ second, OFF for 1 second • ON for 3 seconds, OFF for 1 second • ON for 1 second, OFF for 1 second The button CANNOT be held down for the entire blink sequence. It must be a single button push and the entire blink sequence is run. The blink sequence SHOULD repeat forever (it does not need to stop).

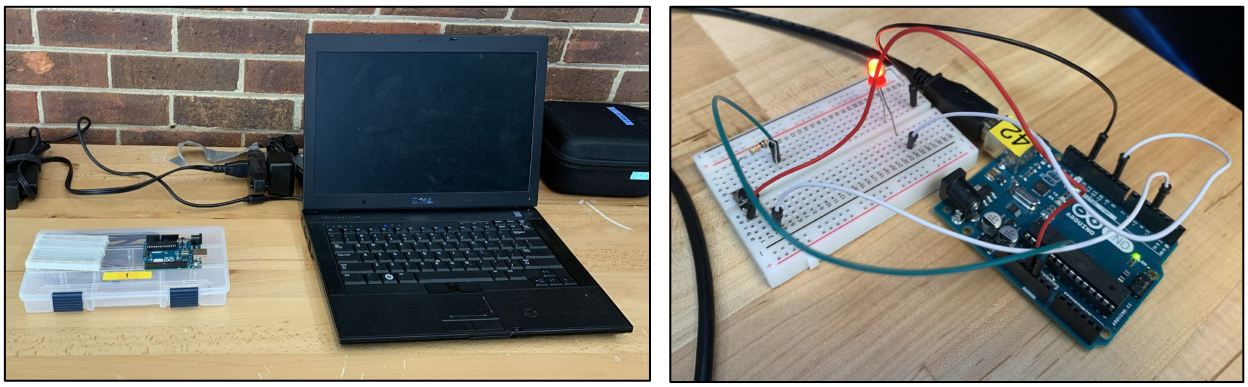

Figure 3. Arduino task setup (left) and sample completed hardware task (right).

Students had access to their Arduino kits, which included the necessary hardware components to complete the circuit and a computer with the Arduino software and template file provided. The template file provided to the students included 1) a Boolean variable *state*, which was required to be utilized in order to achieve a properly functioning algorithm and 2) setup code to establish pin 4 as an input for the button and pin 10 as the output for the LED. The hardware setup and the completed solution are shown above in Figure X, while the software setup and the completed solution is shown below in Figure X.

```
boolean state = false;

void setup() {
  pinMode(4, INPUT);
  pinMode(10, OUTPUT);
}

void loop() {
  // put your main code here, to run repeatedly:


}
```

```
boolean state = false;

void setup() {
  pinMode(4, INPUT);
  pinMode(10, OUTPUT);
}

void loop() {
  // put your main code here, to run repeatedly:
  if (digitalRead(4) == HIGH){
    state = true;
  }
  if (state == true){
    digitalWrite(10, HIGH);
    delay(500);
    digitalWrite(10, LOW);
    delay(1000);
    digitalWrite(10, HIGH);
    delay(3000);
    digitalWrite(10, LOW);
    delay(1000);
    digitalWrite(10, HIGH);
    delay(1000);
    digitalWrite(10, LOW);
    delay(1000);
  }
}
```

Figure 4. Arduino task template (left) and sample completed task code (right).

Table 6. Performance Assessment Concepts

Concept	*Arduino Unit*	*Performance Assessment Task*	*Rubric Dimension*
Wiring an LED Circuit	Assignment 3	Students had to wire a familiar LED circuit to a new Arduino pin.	Hardware: LED Circuit
Wiring a Button Circuit	Assignment 4	Students had to wire a familiar button circuit to a new Arduino pin.	Hardware: Button Circuit
Blinking an LED (*digitalWrite*)	Assignment 3-8	Students had to use the *digitalWrite()* command to correctly blink an LED using a new pin value in the parameter.	Software: LED Control Algorithm
Sequences (*delay)*	Assignment 6-8	Students had to develop a sequence of LED blinks using different rates of delay.	Software: LED Control Algorithm
Reading a Button (*digitalRead*)	Assignment 4-8	Students had to use the *digitalRead()* command to correctly read data from the button using a new pin value in the parameter.	Software: Button Input Control
Conditional Logic (*if-statement*)	Assignment 4-8	Students had to use an *if-statement* correctly to control the flow of the program once the button was pressed.	Software: Button Input Control
Boolean Logic	Assignment 5-8	Students had to use successfully utilize the Boolean variable, *state*, to correctly control the flow of the program once the button was pressed.	Software: Button Boolean Logic
Advanced Algorithms	Assignment 7-8	Students were asked to modify their code to change the behavior of their program.	Software: Control Flow

Performance Assessment Administration and Scoring. The task was administrated after all students had completed the unit on Arduino by Mr. Souza and myself. Students were given the entire block period (approximately 90 minutes) to complete the assessment task and had access to their code notecards as a reference. Mr. Souza and I scored and coded the student's performance on the assessments using an agreed upon rubric developed together (shown in Table 6 below). The rubric was developed into six dimensions (Table 5), based on the important concepts covered throughout the unit and targeted in the assessment. Prior to administering, we discussed how to handle the event where a student could not wire up the hardware correctly, and decided it would be best to offer the solution to the student with the understanding that they would receive a zero for their hardware score and move on to the software task. This was done to provide every student an opportunity to demonstrate proficiency with the software component of the Arduino task.

We piloted the assessment with five students to assess the feasibility of conducting the assessment with the entire class. During the pilot, Mr. Souza and I scored each of the five students separately. We then discussed and agreed upon all five student scores to establish some form of reliability. During each subsequent implementation of the assessment (four total classes), Mr. Souza and I administrated and scored half of the class independently, since the engineering suite is divided into two rooms, we each took a room to ourselves. Finally, after all, four classes had completed the assessment, Mr. Souza and I sat down and went through all the student assessments to confirm and agree upon all scores.

Table 7. Arduino Performance Assessment Scoring Rubric

Dimensions	2	1	0
Hardware			
LED Circuit	Student's LED circuit is correctly wired to the Arduino using a resistor and ground pin.	Student's LED circuit is mostly correct but needed assistance with one component of the circuit (e.g., LED orientation).	Student's LED circuit is not correct or asked for the circuit diagram to be provided.
Button Circuit	Student's button circuit is correctly wired to the Arduino using a resistor, ground pin, and 5V pin.	Student's button circuit is mostly correct but needed assistance with one component of the circuit (e.g., 5V and ground pins are swapped).	Student's button circuit is not correct or asked for the circuit diagram to be provided.
Software			
Button: Input Control Data Interpretation Conditional Logic	Student's code correctly reads the button as an input and interprets the data from the button correctly within the program using a conditional statement.	Student's code has a syntax mistake preventing the program from correctly reading and interpreting the button.	Student's code does not correctly read the button as an input at all. The code is either missing or has multiple syntax and parameter mistakes.
Button: Boolean Logic *Data Interpretation* *Conditional Logic*	Student correctly utilizes the Boolean variable to track the state of the button.	Student attempts to utilize the Boolean variable to track the state of the button but is incorrect.	The student does not attempt to utilize the Boolean variable to track the state of the button.
LED: Control Algorithm *Algorithms*	Student's code correctly sequences the LED as described in the task.	Student's code partially sequences the LED as described in the task. The code may contain syntax errors.	Students' code does not correctly control the LED (e.g., turn ON and OFF).
Program: Control Flow *Algorithms*	Student's control flow code is syntactically correct and is able to both 1) loop the LED control forever after the button is pressed and 2) only once after the button is pressed.	Student's control flow code may have syntax errors and either 1) loop the LED control forever after the button is pressed or 2) only once after the button is pressed, but not both.	Student's control flows logic incorrect and has multiple syntax errors.

Observations. With the guidance of observation protocols, I served as the primary instrument to collect observational data. Over the course of the nine-week unit, I observed approximately 40 hours of classroom time. The *Engineering I* class meets four days per week with one day scheduled as a block (90 minutes) and the other three as a period (45 minutes). My schedule permitted me to attend the same class section of 20 students (e.g., period two) for almost every day of the unit. This allowed me to observe the same students and witness their experiences with the unit and development of CT. During observations, I took notice of how particular events, such as a student debugging an issue with their code, and the particulars of that event (e.g., what was the bug to fix and how long they spent debugging). Observations field notes included the frequency and duration of these particular events, as well as a qualitative description of the student's behavior during these events. Observational field notes were typed up during and after leaving the classroom and additional descriptive and interpretive information was added. These field note write-ups served as the basis for analytical memos.

Data Analysis

In accordance with Yin's (2018) case study methodology, there were several analytical strategies used to answer the research questions. The CT framework described in the previous section provides a theoretical proposition to situate my findings and allows the findings to shed light on the broader empirical research done on CT. Of the five skills described in the framework, only three (Generalization, Algorithmic Thinking, and Debugging) are most pertinent to the Arduino Physical Computing Unit and this study. Quantitative data generated from the performance assessment was analyzed and used to generate initiate results. Qualitative analyses from observational data and student work was then used to explain and unpack these findings.

Quantitative Analyses. Basic descriptive statistics, such as frequency counts and mean averages, were used to analyze the results of the performance assessment and individual dimensions. A principal component analysis was performed through STATA on the six dimensions of the performance assessment to explore the extent to which dimensions on the assessment converged into particular CT characteristics. This allowed for students to be compared using their CT factor scores (e.g., algorithmic thinking) instead of the individual rubric dimensions. Unpaired two-tailed t-tests were used to compare differences in overall performance based on gender (male versus female) and by individual dimensions. To compare the four different class periods, a one-way analysis of variance (ANOVA) was used to determine if any differences existed between students in different classes. This was done due as a proxy for evaluating differences based on other factors since particular classes had higher concentrations of students enrolled in honor classes.

Qualitative Analyses. Students' performance assessment code submissions were analyzed for themes and patterns of behaviors. This included looking at differences between students who scored high and low on the assessment and generating distinguishing characteristics between these performance levels. Codes for common mistakes or behaviors were generated and frequency counts were used to comparing groups and establish findings. Observational field note data was used to triangulate findings from the performance assessment and support the themes and differences found in the performance assessment data.

IRB and Consent

After receiving approval from my university's Institutional Review Board, I received approval from the school district administrator to conduct this study at Bretton Middle School. I had worked with Mr. Souza on prior research and so already had a professional relationship with him. After meeting with him at the beginning of the summer to discuss the scope of my work, he approved and granted me access to his classroom to conduct this study. He assisted and facilitated the consent from student participants. Parents of the students were informed about the study provided their informed consent for their child to participate in the study.

Results

Physical Computing Performance Assessment

Students' performance on the assessment varied based on a number of factors. A perfect score on the assessment meant students demonstrated proficiency in all six dimensions, for a total score of 12. The average student score was 6.6, while the standard deviation was 4.4. Comparing the two task types (i.e., hardware versus software), students were more successful with the hardware task of wiring up circuits than coding the control algorithms. Students' averaged hardware score (M = 1.34) was statistically higher than their averaged software score (M = 0.99); t(86) = 4.88, p < .001.

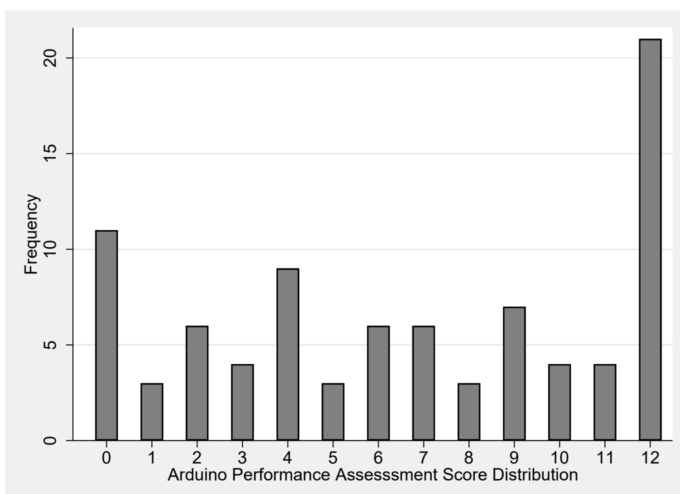

Figure 5. Distribution of Student Scores on Performance Assessment

The large deviation among student performance prompted follow-up analyses on the six dimensions of the performance score and revealed several interesting findings.

Principal Component Analysis

The principal component analysis was done to determine the extent to which the individual dimensions scored on the performance assessment related to higher order concepts of computational thinking. The results of the analysis yielded three distinct components.

Table 8. Principal Components Loadings (promax rotation)

Dimension	*Component 1*	*Component 2*	*Component 3*
Hardware: LED Circuit	0.689		
Hardware: Button Circuit	0.687		
Software: Button Input Control			0.953
Software: Button Boolean Logic		0.550	
Software: LED Control Algorithm		0.338	
Software: Program Control Flow		0.764	

Component One: Electronic Circuit Skills. Students' ability to deal with electronic circuitry was determine by the two circuits that students had to complete in the first task. Students' ability to understand circuits and wire them accordingly was differentiated from their ability to perform software tasks. Students' performance on the two hardware tasks were not statistically different ($M_{LED\ Circuit}$ = 1.38, $M_{Button\ Circuit}$ = 1.31). The total distribution of the hardware component reveals that most students either were able to wire both circuits correctly or neither of the circuits. Students who scored (rubric) a two on their total hardware component partially wired both circuits. That is, no student was able to wire one circuit correctly and not wire the other circuit at least partially.

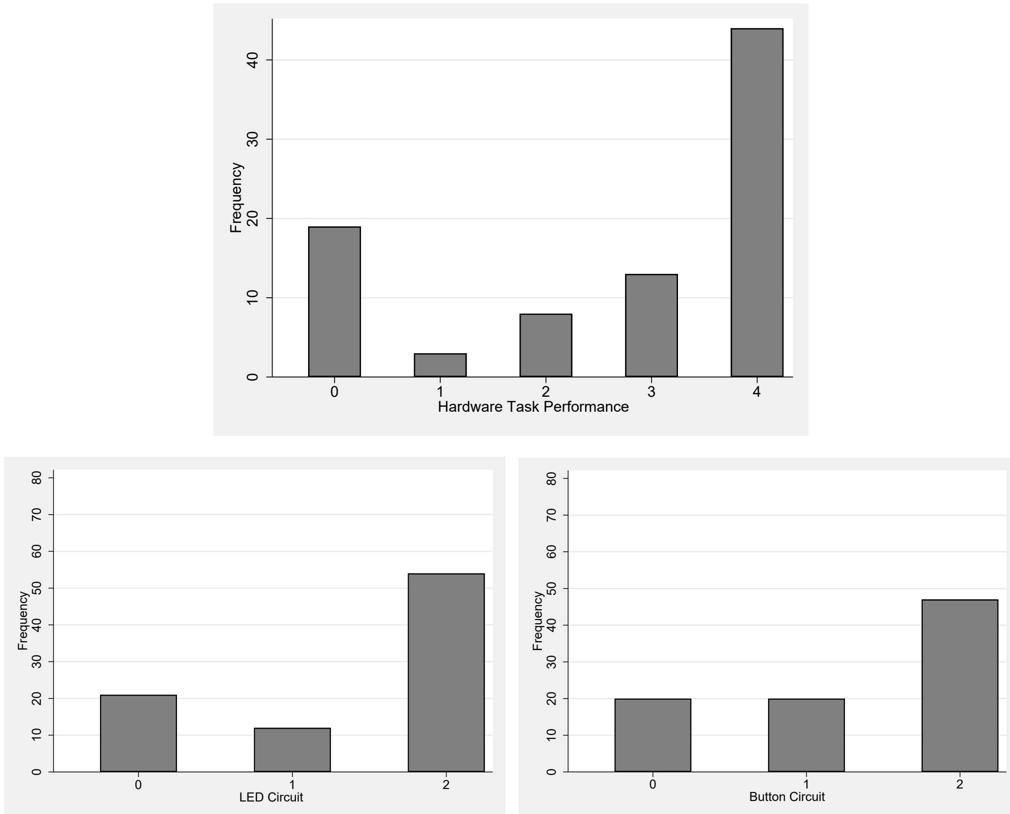

Figure 6. Rubric Score Distribution of Hardware Component by Individual Dimensions

Component Two: Algorithmic Thinking. The second component of the performance task can be described as algorithmic thinking. This component was based on loadings of three dimensions from the software task: students' use of the Boolean variable in conjunction with the button (*Button Boolean Logic)*, students' ability to control the LED with the correct sequence of delays (*LED Control Algorithm)*, and students' ability to construct a complex algorithm with conditional logic control flow (*Program Control Flow)*. Students' ability to deal with more complex algorithms that involved conditional logic (*Button Boolean Logic* and *Program Control Flow)* weighed stronger onto students' overall algorithmic thinking factor score than their ability to sequence a basic control algorithms (e.g., LED control). Students with high factor scores on this component were able to develop complex algorithms with conditional statements and Boolean logic. The distribution of factor scores reveals a bi-modal pattern that tells us there are a lot of students at both extremes of algorithmic thinking.

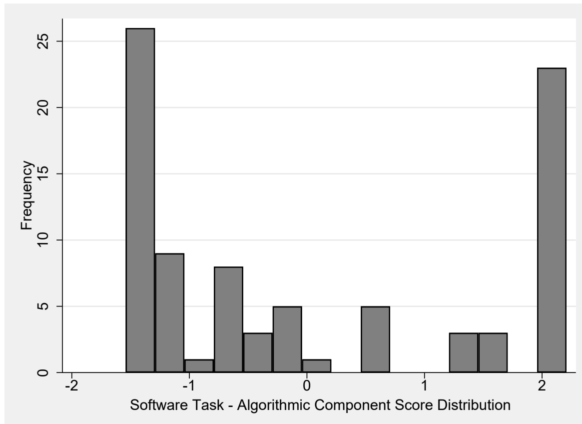

Figure 7. Factor Score Distribution of Algorithmic Thinking Component

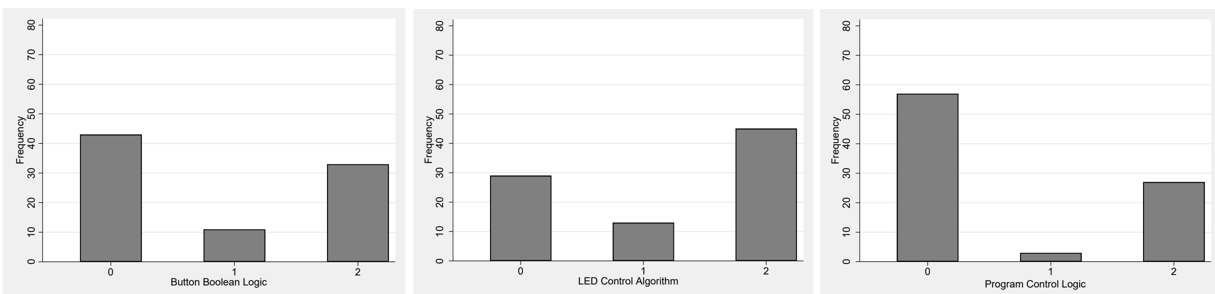

Figure 8. Individual Dimension of Algorithmic Thinking Distribution of Rubric Scores.

Component Three: Generalization. The third component of the performance assessment can be described as students' ability to reuse or generalize the *digitalRead()* function in a new context. This component is solely composed of the *LED Button Input Control* dimension of the software task. Students who scored a two on this component understood the role of the hardware button and the *digitalRead()* function and successfully utilized this using a different pin configuration. Dealing with physical computing, such as reading and utilizing the input from a button, plays an important role on its own and was distinct from the other two components (hardware and algorithmic thinking). Students who scored a one attempted to reuse the *digitalRead()* function in their program but did not use the correct parameter values and were unsuccessful. Students who scored a zero did not attempt to reuse *digitalRead().*

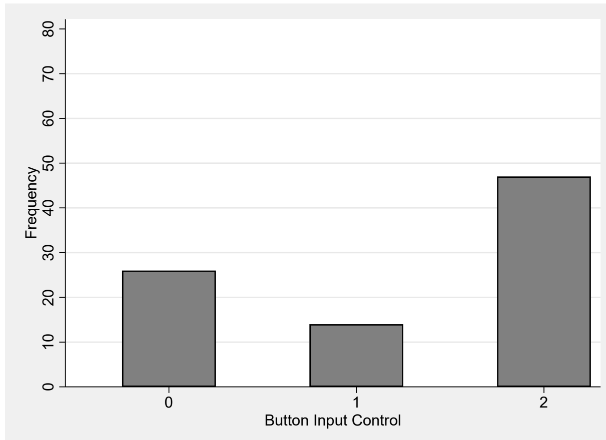

Figure 9. Score Distribution of Physical Computing Data Component

Patterns of CT Behavior

To investigate the qualitative differences among student performance, students' final code submission was analyzed for patterns of behavior. Based on the results of the software task in the performance assessment, students typical fell into one of three categories: high, medium, and low performers. Analysis of students' code revealed commons patterns between these three groups and validated categorizing students into three levels of computational thinking.

Table 9. Student CT Performance Levels

	Software Rubric Score	*Frequency*	*Percentage*
High CT	6 – 8	33	38%
Medium CT	3 – 5	18	21%
Low CT	0 – 2	36	41%

High Computational Thinking. A total of 33 students (38%) were categorized as having high CT skills based on their performance. These students all demonstrated a level of understanding and proficiency with the Arduino programming language and produced programs that had similar qualities. Described below are the *four* qualities that best describe high CT students' performance on the physical computing task.

1. Program Functionality: Complete. High CT students were able to demonstrate that the program works as expected by demonstrating the physical computing components (i.e., pushing the button and blinking the LED). Their code does not contain any Arduino-related syntax mistakes, such as a missing semi-colon or a misplaced bracket, which were dealt with through the process of debugging. Their code demonstrated a level of mastery and fluency with the Arduino programming language by reusing functions, such as *digitalRead()* and *digitalWrite(),* to control an LED with a button without mistakes.

The example below in Figure 10 provides a high CT student example, who scored perfectly on all six dimensions of the performance assessment.

```
int buttonpin = 4 ;
int ledpin = 10;
unsigned int x = 500;
boolean state = false;

void setup() {
  pinMode(4, INPUT);
  pinMode(10, OUTPUT);
  Serial.begin(9600);
  digitalWrite(buttonpin, LOW);
}

void loop() {
  // put your main code here, to run repeatedly:
  Serial.println(digitalRead(buttonpin));
  if (digitalRead(buttonpin) == HIGH) {
    state = true;
  }

  if (state == true) {
    Serial.println(x);
    digitalWrite(ledpin, HIGH);
    delay(x);
    digitalWrite(ledpin, LOW);
    delay(1000);
    x += 2500;
    Serial.println(x);
    digitalWrite(ledpin, HIGH);
    delay(x);
    digitalWrite(ledpin, LOW);
    delay(1000);
    x -= 2000;
    Serial.println(x);
    digitalWrite(ledpin, HIGH);
    delay(x);
    digitalWrite(ledpin, LOW);
    delay(1000);
  }
  x -= 500;
}
```

Figure 10. Student example of a fully-functional program.

2. Programming Features: Use of Variables. High CT students created variables and used them appropriately within the program. Incorprating variables demonstrates both a conceptual understanding of how variables work and also good programming habits that assist in interpreting the program and making it more efficient. The example shown above in Figure 10 illustrates how variables, such as *ledpin* can be used to make a program more readable. The rubric used to score students' performance did not include a dimension for the use of variables and therefore students' overall scores were affected by this program feature.

3. Algorithmic Thinking: Complex. High CT students would often construct complex algorithms that included control structure (e.g., while loop) or writing a sequence of operations to modify the delay time algorithmically. In Figure 10, the student develops a sequence of operations to modify a variable *(x)* to represent the changing delay time throughout the program. This complex algorithm modifies the variable *x* such that the delay times followed the specified delay times (500, 3000, 1000). This type of algorithm was a departure from the expected solution, which students would merely enter the actual delay time into each *delay()* parameter and not develop an algorithm for modifying the delay time.

***4. Flow of Control: No Issues*.** One of the distinguishing characteristics of students with high CT was their ability to integrate Boolean logic into their program in order to control the flow of their program. High CT students' code changed the state of the Boolean variable, *state,* from *false* to *true* after the button was pressed and then run the LED control algorithm if the *state* was true. Controlling the flow of the program with Boolean logic turned out to be a challenge for medium and low CT students and is described in more detail later in this section.

Medium Computational Thinking. A total of 18 students (21%) were categorized as having medium CT skills. While this group of students was the least common, they all still demonstrated similar patterns of mistakes on their programs. Described below are the *four* qualities that best describe medium CT students' performance on the physical computing task.

1. Program Functionality: Partial. Medium CT students were able to demonstrate some functional aspects of a program, such as the correct blinking LED sequence, but the program was not functioning up to the specifications. Their code may have had issues related to syntax or the flow of control. Figure 11 provides an example of a medium CT student, who received a rubric score of six (out of 12). The code provided is syntactically correct and can blink the LED in the proper sequence when the button is pressed. However, the lack of a Boolean prevents the program from functioning as specified in the task instructions.

```
boolean state = false;
int button = 4;
int led = 10;
void setup() {
  pinMode(4, INPUT);
  pinMode(10, OUTPUT);
  Serial.begin(9600);

}

void loop() {
  // put your main code here, to run repeatedly:
Serial.println(digitalRead(button));

  if (digitalRead(button) == HIGH) {
    digitalWrite(10, HIGH);
    delay(500);
    digitalWrite(10, LOW);
    delay(1000);
    digitalWrite(10, HIGH);
    delay(3000);
    digitalWrite(10, LOW);
    delay(1000);
    digitalWrite(10, HIGH);
    delay(1000);
    digitalWrite(10, LOW);
    delay(1000);
  }
```

Figure 11. Student Example of a Semi-functional Program

2. Programming Features: Lacking. Medium CT students' programs lacked many aspects of good programming. Students may have attempted to utilize aspects, such as variables, but failed to incorporate them throughout the program. In the example shown above, the student declared a variable, *led*, but did not incorporate this into the *digitalWrite()* function as other high CT might have done. Students were not scored any differently for not incorporating variables into their programs.

3. Algorithmic Thinking: Predictable. Medium CT students' algorithms were done so in a predictable pattern. For instance, the delay times were manually entered with every instance of the delay() function instead of a more creative solution using variables. The example provided above in Figure 11 demonstrates a predictable algorithm for sequencing the LED. Medium CT students' predictable algorithms were not scored any differently than more sophisticated algorithms from high CT students. However, these qualitative differences are worth noting.

4. Flow of Control: Functional Issues. Medium CT students were not able to utilize the Boolean variable, *state*, into their programs, and was the primary reason their programs were not functioning up to specification. In Figure 11 (above), the student did not attempt to incorporate any Boolean logic to control the program, while the student who submitted the code shown in Figure X (below) tried to include the Boolean variable, *state*, but did so incorrectly. Students referenced the variable *state* in a conditional statement but forgot to update the variable to *true* when the button was pressed — not being able to control the flow of the program via Boolean logic distinguished medium CT students from high CT students.

Generalization: Functional Issues*.* Students' failure to correctly utilize the *digitalRead()* function in Arduino was common among medium CT students. This dimension required students to reference the *digitalRead()* function within their program and input the correct pin number as the parameter of the function. For example, if the button is wired to the Arduino's pin four, then the function should be written, *digitalRead(4)*. Medium CT students often used the incorrect parameter value borrowed from previous Arduino assignments and failed to understand the role of the parameter value concerning the hardware configuration. In almost all cases, students used pin number two, which was the pin number used throughout the unit assignments. This mistake was the difference between a two and one on the Button Input Control dimension of the performance assessment task.

```
void setup() {
  pinMode(4, INPUT);
  pinMode(10, OUTPUT);
  Serial.begin(9600);
}


void loop() {
  // put your main code here, to run repeatedly:

    if(digitalRead(2) == 1)
    if(state == false);
    digitalWrite(10, HIGH);
    delay(500);
    digitalWrite(10, LOW);
    delay(1000);
```

Figure 12. Functional issue with *digitalRead():* Incorrect parameter value.

Low Computational Thinkers. A total of 36 students (41%) were categorized as having low CT skills. These students, who composed the largest percentage, all struggled with similar issues. Described below are the *five* qualities that best describe low CT students' performance on the physical computing task.

1. Program Functionality: None. Low CT students were unable to construct a functional program in nearly all aspects. If the student received partial credit on a dimension, it was typically for controlling the LED (i.e., turning it ON and OFF) but not sequencing it correctly. The figure below is an example of a low CT student who submitted a non-functional program. This program did not function correctly in any way according to the specifications of the task and contained numerous mistakes.

```
boolean state = false;

void setup() {
  pinMode(4, INPUT);
  pinMode(10, OUTPUT);
  Serial.begin(9600);
}


void loop() {
  // put your main code here, to run repeatedly:
 {
digitalWrite (4,INPUT);
delay (500) ;
digitalWrite (4,OUTPUT);
delay (1000);
if (digitalRead (10) == 1);
}

}
```

Figure 13. Example of low CT student code with no functional aspects.

2. Programming Aspects: Poor. Low CT students' programs lacked any aspects of good programming. Low CT students would often submit incomplete or sometimes no code for their program that contained syntax and functional errors.

3. Flow of Control: Missing. Similar to medium CT students, low CT students failed to include any Boolean logic to control the flow of their program. The example shown below illustrates a low CT student who was able to write the control algorithm for the LED sequence but omitted all aspects of the control logic and the Boolean variable, *state*.

```
void loop() {
  digitalWrite(LED, HIGH);
  delay(500);
  digitalWrite(LED, LOW);
  delay(1000);
  digitalWrite(LED, HIGH);
  delay(3000);
  digitalWrite(LED, LOW);
  delay(1000);
  digitalWrite(LED, HIGH);
  delay(1000);
  digitalWrite(LED, LOW);
}
```

Figure 14. Example of low CT student with Boolean logic omitted.

4. Generalization: Missing. Low CT students failed to reuse the *digitalRead()* and did not appreciate the importance of reading the button as a controlling factor within the program. While medium CT students had functional issues (not using the right parameter value), low CT students omitted the *digitalRead()* function altogether.

```
void loop() {
  // put your main code here, to run repeatedly:



  if (state = true);
  digitalWrite(8, HIGH);
  delay(500);
  digitalWrite(8,LOW);
  delay(1000);
  digitalWrite(8, HIGH);
  delay(3000);
  digitalWrite(8,LOW);
  delay(1000);
  digitalWrite(8, HIGH);
  delay(1000);
  digitalWrite(8,LOW);
  delay(1000);

}
```

Figure 15. A student example of omitting the digitalRead() function.

5. Debugging: Syntax Issues. An additional characteristic was noted for Low CT students who struggled to use the correct syntax for an *if-statement* in Arduino. This issue was evident in both students' code from the performance assessment, as well as observations throughout the unit. The low CT student code from Figure 14 illustrates two syntax issues: 1) missing brackets to encapsulate *if-statement* logic and 2) using a semi-colon with an *if-statement*. The examples below illustrate the proper and improper use of an *if-statement* within the Arduino performance assessment. In the example on the left, each if-statement contains 1) a conditional statement, 2) code to execute if the condition is true, and 3) no semi-colons. Not using semi-colons with if-statements was a special rule that students had to remember for Arduino syntax, since most lines of code end using a semi-colon, students had to remember this special rule with if-statements.

```
void loop() {
  // put your main code here, to run repeatedly:
  if (digitalRead(5) == 1) {
    state = true;
  }
  if (state == true) {
    digitalWrite(8, HIGH);
    delay(500);
    digitalWrite(8, LOW);
    delay(1000);
    digitalWrite(8, HIGH);
    delay(3000);
    digitalWrite(8, LOW);
    delay(1000);
    digitalWrite(8, HIGH);
    delay(1000);
    digitalWrite(8, LOW);
    delay(1000);
    state = false;
  }
```

```
void loop() 
  // put your main code here, to run repeatedly:
 {
digitalWrite (4,INPUT);
delay (500) ;
digitalWrite (4,OUTPUT);
delay (1000);
if (digitalRead (10) == 1);
}

}
```

Figure 16. Example of correct use of brackets (left) and incorrect (right).

This mistake does not necessarily illustrate a conceptual misunderstanding but highlights the interaction between programming languages' syntax rules and computational thinking. In the student program shown above in Figure 16, it may be that the student understood the conditional relationship between the if-statement and the LED control code below but the proper syntax to build this correctly became a barrier to doing this.

Differences between Groups

Gender. Gender was found to be a factor related to students' performance on the assessment. In general, female students performed better on the assessment (M_{female} = 8.04) than male students (M_{male} = 6.10). This difference was statistically significant; t(87) = 1.74, *p* = .057, and had a medium effect size (Cohen's *d* = 0.41).

Table 10. CT Performance Assessment Results by Gender

	Male (N=62)	*Female (N=25)*	*Total (N=87)*	*p-value (two-tailed)*
Hardware				
LED: Circuit	1.21	1.80	1.38	.003
Button: Circuit	1.15	1.72	1.31	.003
Hardware Average	***1.18***	***1.76***	***1.34***	***.002***
Software				
Button: Input Control	1.13	1.52	1.24	*.063*
Button: Boolean Logic	0.87	0.92	0.89	.826
LED: Control Algorithm	1.02	1.52	1.16	*.021*
Program: Control Flow	0.71	0.52	0.66	.390
Software Average	***0.93***	***1.12***	***0.99***	***.311***
Total Scores	**6.10**	**8.04**	**6.66**	**.057**

Follow-up analysis tests indicated several individual items that differentiated male and female students. First, female students scored better on both hardware tasks ($M_{female\text{-}hardware}$ = 1.76) than male students ($M_{male\text{-}hardware}$ = 1.18); t(85) = 3.19, *p* = .002. Female students did not outperform male students on the software task overall but were more successful on two of the dimensions. First, female students were able to code the input control for the button ($M_{female\text{-}button}$ = 1.52) more so than male students ($M_{male\text{-}button}$ = 1.13); t(85) = 1.88, *p* = .063. Second, female students were more successful at coding the control algorithm for the LED ($M_{female\text{-}led}$ = 1.52) than male students ($M_{male\text{-}led}$ = 1.02); t(85) = 2.53, *p* = .013. The other two software dimensions were not statistically different between groups.

Class Periods. Comparison between the groups of four different classes revealed significant differences in performance on the assessment; F(86) = 7.41, *p* < .001. Follow-up comparison confirmed that students from period five performed worse than all three of the other groups. The distribution of scores by class period is shown below in Table 11.

Table 11. CT Performance Assessment Results by Class Period

	Period 2 (N=19)	*Period 4 (N=23)*	*Period 5 (N=24)*	*Period 7 (N=21)*	*Total (N=87)*
Hardware					
LED: Circuit	1.80	1.43	0.96	1.43	1.38
Button: Circuit	1.68	1.30	0.88	1.48	1.31
Hardware Average	**1.74**	**1.37**	**0.92**	**1.45**	**1.34**
Software					
Button: Input Control	1.53	1.57	0.58	1.38	1.24
Button: Boolean Logic	1.32	1.00	0.33	1.00	0.89
LED: Control Algorithm	1.47	1.13	0.79	1.43	1.18
Program: Control Flow	1.00	0.83	0.04	1.01	0.66
Software Average	**1.33**	**1.13**	**0.44**	**1.17**	**0.99**
Total	**8.79**	**7.26**	**3.58**	**7.57**	**6.66**

To explain this discrepancy in performance between class periods, Mr. Souza provided me with the distribution of math enrollment; students in each class were either enrolled into Pre-Algebra, Algebra I, or Geometry. The highest performing class, Period 2, had the largest percentage of students enrolled into Geometry (71%). The lowest performing class, Period 5, had the smallest percentage of students enrolled in Geometry (17%), and instead, had the highest percentage of students enrolled into Algebra I (62%).

Table 12. Distribution of Math Enrollment by Class Period

	Period 2	*Period 4*	*Period 5*	*Period 7*
Pre-Algebra	4 (16%)	5 (21%)	5 (21%)	4 (19%)
Algebra I	3 (13%)	12 (50%)	15 (62%)	11 (52%)
Geometry	17 (71%)	7 (29%)	4 (17%)	6 (29%)

Individual Dimensions. A comparison of the individual software dimensions revealed two particularly challenging ideas for students. Most medium and low CT students struggled to incorporate the Boolean variable to track the state of the button ($M_{Boolean}$ = 0.89) and were least successful in properly controlling the logic of the program ($M_{ProgramControl}$ = 0.66), both of which are related to a program's *flow of control.* Designing and writing control logic to enter and exit code structures (e.g., exiting the blink sequence loop after one iteration) was the most challenging component of the software task and performance assessment overall. Students were most successful in programming the input control for the button ($M_{Button\ Input}$ = 1.24) and programming the algorithm to blink the LED in a specific sequence ($M_{LED\ Algorithm}$ = 1.16).

Discussion

The goal of this research was to contribute to the on-going conversation and help better define CT in the context of K-12 education, and more specifically, physical computing. Results of this study suggest that most students engaged in physical computing activities, such as Arduino programming, demonstrated either high or low CT skills. Many students were successful in completing the performance assessment with a near-perfect score in the provided time. However, many students were also unsuccessful at demonstrating any level of proficiency with Arduino. Thus, there was a consistent pattern of students who got it and students who did not.

Students' Computational Thinking Skills

Electronic Circuitry. Although not necessarily a CT skill, most students were able to deal with the electronic circuitry to some degree. All students had access to reference materials, such as schematics and wiring diagrams. Those students who could interpret these diagrams correctly and understood that there was a need for connecting the circuits to new pins on the Arduino were successful. This task evaluated their ability to interpret circuit diagrams and apply them to a slightly different context (i.e., different pins on the Arduino), and was easy for students who interpreted the diagrams successfully. Students who made mistakes made minor wiring mistakes such as flipping the LED orientation and were able to partially wire both circuits. Based on observations, students who scored a zero for these two hardware dimensions, appeared confused, and had no clue where to begin or what to do.

Algorithmic Thinking. Algorithmic thinking (AT) is the process of automating solutions through a series of ordered steps (sequencing) and conditional logic (flow of control), an essential characteristic of CT (Angeli et al., 2017; CSTA & ISTE, 2017). Students' ability to correctly control and sequence the LED demonstrated the sequencing skill of AT. Students' ability to utilize the Boolean logic to control the flow of the program demonstrated the flow of control skill of AT. Flow of control proved to be one of the most differentiating skills between high, medium, and low CT students.

Quantitative and qualitative analysis of the data suggest that students demonstrating a high level of CT and high AT factor scores, were successful in dealing with Boolean conditional logic and therefore controlling the flow of the program. This was the most consistent factor found to be different between high CT students and lower level students. Flow of control through conditional logic is an important aspect of CT (Brennan & Resnick, 2012), and has been shown to be a difficult concept for students to grasp (Bers, Flannery, Kazakoff, & Sullivan, 2014; Ebrahimi, 1994). Du Boulay (1986) notes that programming novices often fail to appreciate a program's flow of control and some students, "hope that the system will of itself jump around and ignore sections of code which are not wanted under some circumstances" (p. 68). Students holding this perspective may have not considered or appreciated the role of such Boolean variables and operators in their program, and thus omitted or misused them. In fact, Boolean operators used within *if* statements, such as the ones contain within high CT student programs, have consistently been found to be the most challenging concepts across programming languages (Ebrahimi, 1994). According to Angeli et al. (2017), controlling through the flow of a program and determining which actions are executed is a critical skill for constructing algorithms and thus, plays an important role in CT.

Moreover, the results suggest a strong relationship between mathematics level (i.e., geometry, algebra, pre-algebra) and their CT level. Students currently enrolled in geometry, who have completed a year of algebra, appear to be the most successful with Arduino programming. These students' familiarity with variables from their algebra coursework may have been more comfortable dealing Boolean *variables* in Arduino, which differentiated student performance the most. Hence, students in lower mathematical levels may need additional supports to be successful in such a unit.

Generalization. Generalization is the ability to "remix and reuse resources that were previously created" (p. 51, Angeli et al., 2017), and was entirely demonstrated by students' ability to utilize the button as an input to the program. Students had previously used the *digitalRead()* function before and were able to use their prior code developed from prior labs. The performance assessment asked students to reuse familiar code in a new context (i.e., using a different pin configuration) and evaluated their ability to generalize process of utilizing the button as an input to their program. Generalization in the context of physical computing introduces challenges to students. Common mistakes indicate that students did not understand the relationship between the hardware (button wired to a specific Arduino pin) and the *digitalRead()* function. Students may have viewed *digitalRead(2)* is a universal command to read all information from the any button connected to the Arduino. Dealing with the hardware introduces another layer of complexity that students need to appreciate when wiring physical computing code.

Debugging. Based on the results of the CT post-assessment, low students struggled to identify and correct for mistakes in Arduino. This is not surprising, given prior research points to debugging as being a complicated process for students (Kafai et al., 2014). Du Boulay (1986) describes debugging as part of the, *pragmatics of programming*, which includes the skills to develop, test, and debug a program using the available tools, and is known to be an area of difficulty for programming. Based on observations, the lack of syntax errors in students with high CT suggests that they took advantage of Arduino's debugging tools to filter out simple mistakes, such as misplaced bracket or semi-colon. Students who demonstrated a lower level of CT would frequently have syntax mistakes that could have been easily identified and corrected through debugging.

Moreover, the complexity of physical computing is such that both the hardware and software functionality are intertwined and debugging is not always just finding a syntax mistake in the code (Kafai et al., 2012). This finding aligns with prior research on debugging and agrees with the notion that debugging plays an essential role in computational thinking (Angeli et al., 2017) within the context of physical computing.

Gender. One unexpected positive outcome from the results was the achievement level among female students. Contrary to prior research suggesting female students underperform their male counterparts with robotics (Nourbakash et al., 2005), most female students engaged in this physical computing unit did not struggle with the software programming and in fact were more likely to be successful on the performance assessment. Given the historical underrepresentation of females in STEM fields, especially computer programming, the implications of computing projects that are accessible to female students are worth mentioning. While the scope of the data collection did not allow for me to make assertions regarding *how* girls interacted with the Arduino unit and assessment, future work should be done to investigate how factors such as peer influence relate to female students' performance on computational thinking projects and assessments.

Theoretical Implications. CT frameworks, such as the one employed in this study (i.e., Angeli et al., 2017), are limited to computer science or *software-exclusive* environments. As a result, these frameworks do not capture the nuances of CT when situated in the context of physical computing or *hardware-software* environments. For instance, *debugging* as a CT skill was demonstrated by students throughout the physical computing unit and assessment. However, debugging Arduino issues required two different skills: identifying and correcting hardware circuitry problems and identifying and correcting software code problems, both of which may require their own set of scaffolds from the instructor. Further, debugging physical computing software code introduced unique challenges to students that may differ from *software-exclusive* coding environments. For instance, low CT students struggled to reuse the *digitalRead()* Arduino command with the appropriate input parameter value, which corresponds to how the hardware circuitry is configured. Thus, a CT framework in the context of physical computing may benefit with additional characteristics describing the skills associated with hardware versus software.

Recommendations for Practice

Given the bi-modal nature of performance on the Arduino task, students' who demonstrate patterns of low CT behavior require scaffolding related to both their mathematical understanding and familiarity with the Arduino programming language. Several studies suggest introducing block-style programming, where text-based syntax is not a concern for students and teachers, may provide the necessary algorithmic thinking skills without the burden of learning the text-based syntax programming language (Grover & Basu, 2017). Students prior-to or concurrent with a physical computing unit may benefit from having the opportunity to program using a block-based programming language, before jumping straight into the text-based programming language. Scaffolding students with block-style programming may also support debugging syntax and functional issues seen throughout the performance assessment.

Arduino as a computing platform for teachers and students has several advantages over other proprietary systems, such as *LEGO Mindstorms*. It is currently the most affordable microcomputer platform on the market and has the flexibility to work with any hardware, not just a robotics kit. These features make the Arduino platform attractive as an entry-level computing platform to schools. However, educators should be aware of the learning curve associated with Arduino's text-based programming language and consider front loading an Arduino project with block-based programming to aide students in programming concepts.

Limitations & Future Work

There were several limitations to this study. This study was meant to be an exploratory in nature, and thus generalizations cannot be made outside the context of this case. Other possible confounding factors may have been overlooked throughout the analysis of the data. The CT post-assessment was completed by only 28% and thus establishing the construct validity of this instrument is limited by this. Also, students enrolled in the Arduino unit were self-selected into the course and thus may have an inherent bias towards programming and computer science. While the results of the performance seem promising, future work should be done to revise and improve the overall implementation and scoring rubric to further load onto more CT characteristics.

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Manuscript Three

Supporting Students' Engineering Design Process through Design Briefs and Journals

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Abstract

This study explores teaching strategies used throughout an engineering design summer academy that provided a unique approach to scaffolding students' design thinking and engineering skills. Rising 9^{th}-grade students completed complex design challenges involving mechanical engineering, electrical engineering, and computer science (i.e., mechatronics). The use of *design briefs* was the primary instructional strategy used throughout the academy to guide students through the design process. This study unpacks the ways that students' engineering design was supported by a teacher in order to develop students' design thinking skills. The findings indicate that students in this particular context, receiving this particular support, can thrive as designers, engineers, and makers.

Introduction

Many view science, technology, engineering, and mathematics (STEM) education as a critical part in developing skills required for a workforce and economy in the 21st century (National Research Council [NRC], 2011; President's Council of Advisors on Science and Technology [PCAST], 2012). Until recently, engineering has not received the same level of attention in K-12 education as the other STEM subjects (National Academy of Engineering [NAE], 2010; NRC, 2009). Organizations, such as the NRC and NAE, have called for STEM education reform, advocating that K-12 schools should incorporate an engineering curriculum (NAE, 2010; NRC, 2009, 2012). The NRC has developed a framework for K-12 engineering that aligns most state's standards for engineering. A fundamental component of the NRC's engineering standards and many other states' standards are engineering design (Carr, Bennet, & Strobel, 2012), the iterative process of designing and testing solutions to a problem (Guzey, Tank, Wang, & Roehrig, 2014; NAE, 2010).

More recently, engineering design has been explored as a pedagogical approach to support students' learning of science and mathematics (Guzey, Harwell, Moreno, Peralta, & Moore, 2017; Guzey, Moore, Harwell, & Moreno, 2016; Mehalik, Doppelt, & Schunn, 2008; Riskowski, Todd, Wee, Dark, & Harbor, 2008; Schnittka & Bell, 2011; Sandy, Christensen, Knezek, Kjellstrom, & Bredder, 2016). As a rationale, Purzer, Strobel, and Cardella (2014) claim four benefits to integrating engineering into K-12 education. First, engineering provides a real-world context to connect student learning among the STEM subjects. Second, it gives a natural environment for students to develop their problem-solving skills. Third, it promotes the development of communication and collaboration skills. Fourth, it provides a motivating and engaging setting that improves students' attitude toward STEM careers.

However, engineering design itself, as a learning objective, has been less explored and hence, the development of engineering design skills at the K-12 level is not well understood. Furthermore, teachers are not well prepared to support students through this complex process. As more states incorporate engineering into their standards (Moore, Tank, Glancy, & Kersten, 2015), teachers implementing engineering will be faced with new challenges (Brophy, Klein, Portsmore, & Rogers, 2008; Lesseig, Nelson, Seidel, & Slavit, 2016). Preparing teachers to implement engineering design pedagogical strategies requires learning unfamiliar content and poses complex teaching situations.

This paper reports on the findings from research conducted on a particular case of engineering design. The study took place during a two-week Engineering Design Academy in the summer of 2018, in which approximately 20 middle school students were invited to participate and complete intensive engineering design challenges. Students' engagement with the engineering design process was supported through the use of unique pedagogical strategies. Students were given a level of autonomy and accountability through the use of design brief meetings. The purpose of this research is to provide more insight as to how teachers can successfully engage students in engineering design. The goal is to better understand how students can be supported in order to develop engineering design skills, which according to the NGSS is an important aspect to K-12 science education (NGSS Lead States, 2013).

Literature Review

Engineering

Engineering is the process of designing solutions to complex problems within our society in a systematic and purposeful method (Katehi, Pearson, & Feder, 2009). Engineering design is purposeful in that it addresses some problem or need, and systematic in that there is an iterative and methodological process (i.e., not done through trial-and-error). Engineering design is also done under constraints, which range from naturally-occurring (e.g., laws of physics) and human-constructed (e.g., resources such as money and time). Engineering is divided into areas of expertise depending on the context of the problem. Each field of engineering relies on the application of one or more disciplines of science. For example, chemical engineers must be knowledgeable of concepts within the field of chemistry. In addition to science, engineers utilize mathematics and technology to design systems. Thus, engineering is a profession that requires the application of knowledge from multiple domains and is an authentic way to provide interdisciplinary education.

Engineering Education in K-12 Schools

When the topic of engineering comes up in education, it is usually done so in the context of science, mathematics, and technology; the so-called STEM subjects. Advocates for engineering education often cite the critical role these subjects will be to the U.S.'s future success in competing in a global economy and solving complex issues in society (Katehi, Feder, & Pearson, 2009; PCAST, 2010). Below is an overview of each discipline.

Table 1. An overview of the STEM subjects.

	Definition	*Topics*
Science	Study of the natural world	Biology, Chemistry, Physics, Geology, Astronomy

Technology	Study of the human-constructed world	Nature of Technology, Technology and Society, Technological Abilities (ITEEA, 2007)
Engineering	Study of the design process	Systems, Constraints, Trade-offs, Optimization (Katei, Feder, & Pearson, 2009)
Mathematics	Study of quantity, shape, chance	Arithmetic, Algebra, Geometry, Calculus, Statistics

Mathematics and science are the most well-established subjects of the four. Over the past 30 years, national and state standards have been developed, implemented, and assessed in both subjects. By comparison, both engineering and technology have received less attention from educators in the classroom. Purzer, Strobel, and Cardella (2014) explain that the "Committee of Ten" in 1892 recommended science and mathematics as part of the standardized curriculum, while technology and engineering were left out. They suggest that back in the late-1800s, technologies were mostly used in agriculture and would be learned by children while working at home on the farm. However, the past 100 years of development in technology through engineering and innovation have warranted educators to reconsider the role of engineering and technology in education.

In 2000, technology and engineering education received a significant boost in recognition due to the efforts of the *International Technology and Engineering Education Association (ITEEA).* They published the first comprehensive set of K-12 standards for technology education, which included engineering design as one of the four content areas (ITEEA, 2007). Since then, several more efforts have been done to better understand K-12 engineering education. In 2001, the Massachusetts Department of Education (MDOE) implemented the first state-wide technology and engineering standards (MDOE, 2009). The *National Research Council* (NRC) and *National Academy for Engineering* (NAE) conducted an exhaustive report on the state of K-12 engineering education (Katehi, Feder, & Pearson, 2009). Finally, the *Next Generation Science Standards* (NGSS, 2013*)* were published using a framework released by the NRC (2012) that incorporated engineering design as a core concept and pedagogical strategy for learning science concepts. To support these efforts, organizations, such as the *National Center for Technological Literacy* (NCTL) have developed curriculum materials and professional development opportunities for pre-service and in-service teachers to learn about integrating engineering into their instruction.

The research community within K-12 engineering education has investigated a variety of questions. Student outcomes, namely achievement in mathematics and science, is the most prominent area of interest. Another area of interest for research is the potential for the use of engineering education to help address the well-documented performance gap concerning gender and historically underserved populations in the STEM subjects (Katehi, Pearson, & Feder, 2009). Other student outcomes that research has looked at include student interest in pursuing careers within STEM fields, students' knowledge and understanding of engineering as a field and process (i.e., types of engineering fields, engineering design process), students' technological and engineering literacy (NAEP, 2014), and student identity **(CITE).**

The increasing prevalence of engineering represents a significant shift in the landscape from the original report on K-12 engineering education put out by the NRC and NAE (Katehi, Pearson, & Feder, 2009). Their report found limited evidence of the efficacy of using engineering design as a pedagogical strategy for teaching mathematics and science, but remained optimistic and suggested the need for more rigorous and generalizable studies. Similarly, Tran and Nathan (2010) found mixed results regarding the efficacy of integrating engineering design for improving student achievement in the STEM subjects. Since these initial reports, more recent studies have continued to demonstrate the potential learning outcomes of K-12 engineering education. However, the efficacy of engineering has been primarily measured by how well it develops students' science and mathematics knowledge. There is a lack of emphasis on supporting and developing students' engineering design skills.

Engineering Design

The Next Generation Science Standards (NGSS Lead States, 2013) defines engineering design as a systematic practice for solving problems. There are three significant components of engineering design that everyone should learn: 1) defining a problem, 2) developing and testing possible solutions, and 3) optimizing solutions. Mathematics and science knowledge are required to generate and evaluate solutions and are, therefore, a critical component of the engineering design process. More specifically, NGSS specifies engineering design standards for different grade bands, shown below in Table 2.

Table 2. NGSS Engineering Design Standards

	Grades 3-5	*Grades 6-8*
Define	Identify situations that people want to change as problems that can be solved through engineering	Attend to the precision of criteria and constraints and considerations likely to limit possible solutions
Develop	Convey possible solutions through visual or physical representations	Combine parts of different solutions to create new solutions
Optimize	Compare solutions, test them, and evaluate each	Use systematic processes to iteratively test and refine a solution

Engineering design projects can draw upon multiple subjects within and across various domains. For example, one published engineering design project included topics from life science (ecosystems), physical science (heat transfer), and algebra, and data analysis (Guzey et al., 2017). Only recently, researchers also have begun to measure engineering learning objectives such as engineering design thinking (Mentzer, Becker, & Sutton, 2015) and engineering content knowledge (e.g., design, modeling, constraints, and systems). While some work on this has been done, we still do not well understand the teaching strategies, circumstances, and conditions in which students' develop and are supported through the engineering design process.

Engineering Design Pedagogy

Engineering design pedagogy represents nonlinear learning paths and complex problems with multiple and unpredictable solutions. It requires teachers to value failure as a learning opportunity (Sengupta-Irving & Mercado, 2017) and make difficult judgments to determine how much scaffolding to provide students through the design process. Engineering design-based pedagogy represents a paradigm shift for most school teachers, and preparing them to integrate engineering into their teaching has had mixed results (Guzey et al., 2017). In fact, pedagogy remains one of the primary barriers to integrating engineering design challenges into the classroom.

Crismond and Adams (2012) advance a framework to better understand how teachers can support students' design processes. Their *Informed Design Learning and Teaching Matrix* helps teachers identify design behaviors associated with beginner and informed levels of design and apply appropriate instructional strategies to support the engineering design process. This framework will be used to guide the data analysis process and is shown in the table below.

Table 3. The Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012).

Design Strategies	*Beginning Designer Patterns*	*Informed Designer Patterns*
Understand the Challenge	Treat design task as a well-defined, straightforward problem that they prematurely attempt to solve.	Delay making design decisions in order to explore, comprehend and frame the problem better.

Build Knowledge	Skip doing research and instead pose or build solutions immediately.	Do investigations and research to learn about the problem, how the system works, relevant cases, and prior solutions.
Generate Ideas	Work with few or just one idea, which they can get fixated or stuck on, and may not want to change or discard.	Practice idea fluency in order to work with lots of ideas by doing divergent thinking, brainstorming, etc.
Represent Ideas	Propose superficial ideas that do not support deep inquiry of a system, and that would not work if built.	Use multiple representations to explore and investigate design ideas and support deeper inquiry into how system works.
Weigh Options & Make Decisions	Make design decisions without weighing all options, or attend only to pros of favored ideas, and cons of lesser approaches.	Use words and graphics to display and weigh both benefits and tradeoffs of all ideas before picking a design.
Conduct Experiments	Do few or no tests on prototypes, or run confounded tests by changing multiple variables in a single experiment.	Conduct valid experiments to learn about materials, key design variables and the system work.
Troubleshoot	Use an unfocused, nonanalytical way to view prototypes during testing and troubleshooting of ideas.	Focus attention on problematic areas and subsystems when troubleshooting devices and proposing ways to fix them.
Revise/Iterate	Design in haphazard ways where little learning gets done, or do design steps once in linear order.	Do design in a managed way, where ideas are improved iteratively via feedback, and strategies are used multiple times as needed, in any order.
Reflect on Process	Do tacit designing with little self-monitoring while working or reflecting on the process and product when done.	Practice reflective thinking by keeping tabs on design strategies and thinking while working and after finished.

This matrix provides a useful framework to study the behaviors of novice designers and has not been utilized to look at engineering design at the middle school level. Middle school is a time when students may first be exposed to design projects and are likely to exhibit beginner design patterns of behavior. Furthermore, middle school students may require unique scaffolds throughout the design process that do not apply to novice designers at the collegiate levels. This study expands on the work of Crismond and Adams (2012) by applying their framework to the context of a middle school engineering design in order to better understand how teachers can support students at this level throughout the design process.

Research Questions

The following research questions guided the research:

1. Teaching Behaviors and Strategies
    a. *What pedagogical strategies did the facilitators of the design challenge employ when encountering students exhibiting beginner design behaviors?*
    b. *How did these pedagogical strategies support and scaffold students' design process?*
2. Student Behavior
    a. *What were the student design behaviors observed in this particular case of a middle school engineering design challenge?*

Methods

Research Design

This study employed a case study design (Yin, 2018) in order to understand better how middle school students' exhibit beginner designer behavior and what strategies teachers employ to support informed design. Case study designs are appropriate when pedagogical strategies, such as supporting the design process, are not well understood. Moreover, this research methodology allows the research to go deep into the particulars of a case and relate these findings in with the literature. The unit of analysis for this study is a student group project, the *Transportation Device* group, and is described in a subsequent section. The scope of this paper has been narrowed to focus on one specific group that responded to particular teaching strategies. This smaller case is part of a larger study that looks at these behaviors from a holistic perspective.

Context

Site. This study took place in a small city middle school (Bretton Middle School) in the Mid-Atlantic region of the United States. The school district has a total enrollment (PK-12) of 4,210 with the following demographics: 51% male, 49% female, 41% White, 34% African-American, 12% Hispanic/Latino, and 6% Asian/Pacific Islander/Hawaii. The two-week academy occurred at the beginning of the summer school break in 2018. The academy was a collaboration between the city school district and the nearby University and had been run for the past three years. However, this was the first year that the current engineering design challenge format was implemented.

Engineering Design Academy. Students were grouped into teams of three and assigned to a specific design challenge project. There were a total of four group design challenges: 1) *Transportation Device*, 2) *Electromagnetic Launching System*, 3) *Telephone*, and 4) *Rotary Motor*. Each group was given a slideshow deck via Google Docs that provided students with the goal of the design challenge, some helpful background information, and criteria for a successful design project. At the start of the academy, students were briefed by the facilitators to explain the format of the academy. In general, most days began with a *design brief* scheduled among all the four student groups and was the only structured time the students had. Beforehand or afterward, students worked together in their groups independently on their design challenge. They had access to a digital fabrication lab which included computers with CAD software, a laser cutter, and multiple 3D printers. Finally, students were expected to document their design experience through online journals, setup using *SeeSaw*.

Participants

Students. Twelve rising 9th-grade and eight rising 8th-grade students were invited to participate in the engineering design academy. These students self-selected to apply for the program and interviewed with Mr. Souza, the middle school engineering teacher. Rising 8^{th}-grade students had previously completed *Foundations of Engineering,* an introductory course that covers computer design, digital fabrication concepts, electricity and magnetism, and introduction to engineering design. Rising 9th-grade students had previous completed *Engineering I,* a follow-up course that covers more advanced engineering design projects. The students in the *Transportation Device* group became the focus of this study and included Ivy, Jamar, and Oliver. These rising 9th-graders represent a unique case to study that describes the engineering design process.

Facilitators. Four adult facilitators participated in the Academy: 1) Mr. Souza, the middle school engineering teacher, 2) Dr. Sandy, the school district's STEM coordinator, 3) Mr. Koffman, a professional engineer, and 4) Mr. Rutter, the author of this paper. Mr. Souza, Dr. Sandy, and I had all worked together for the past three years running different iterations of the Engineering Design Academy. Because the students had previously taken *Foundations of Engineering,* Mr. Souza had already developed a relationship with the students participating in the Academy and was considered the lead facilitator among the group. Mr. Koffman was a recent graduate from the University's aerospace engineering program and had no formal classroom teaching experience.

Transportation Device Design Challenge

For the *Transportation Device* team, the design challenge was to build off a prior project in the *Engineering I* class, where students built a basic linear motor (shown below in Figure 1). The students were to construct a device that could travel a given distance using the linear motor to power it. In their prior coursework, the students had learned how a linear motor works but had not ever used it to create rotational motion.

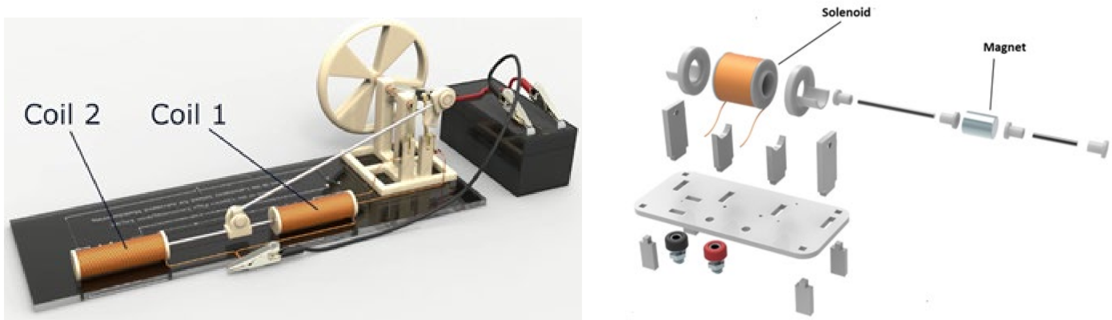


Figure 1. Background materials provided to the linear motor transportation team.

In addition to background information, students were given specific non-negotiables and negotiables that served as criteria for a successful design. Students were able to negotiate with the facilitators with certain criteria, such as the steering system, and omit them from their final design. Shown below in Table 4 is the list of criteria given to the students.

Table 4. Linear Motor Transportation Machine Design Challenge

Non-negotiables	*Negotiables*
Be powered with a linear motor	Have an onboard motor, control mechanism, and power system
Travel a distance of 5 meters	Move forward, backward, and turn left and right
Be controlled using an Arduino microcontroller	Be powered with a battery

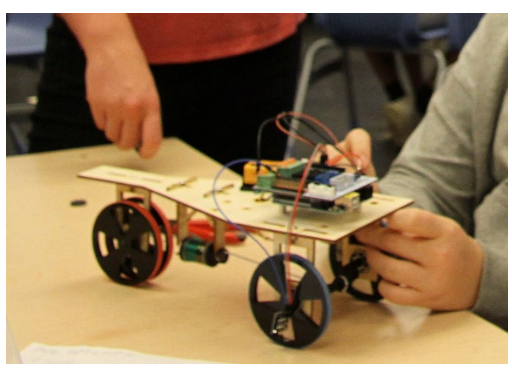


Figure 2. The Linear Motor Transportation Team's Final Design

Schedule. Students were given eight full days (six hours) to complete their final designs, with an additional day used for presenting to the general public at a museum. At the end of the first week, students were expected to have completed their first design prototype and present it to a panel of experts, referred to as a *red team*. This was students' first major milestone and opportunity to receive feedback on their designs from people outside of the facilitators. The full academy schedule is shown below in Table 5.

Table 5. Summer Engineering Academy Schedule

		Week 1		
	Tuesday	*Wednesday*	*Thursday*	*Friday*
Morning Session	Design Briefs	Design Briefs	Design Briefs	Design Briefs
Afternoon Session	Group Share-out	Group Share-out	Group Share-out	Working Prototype Demos with "Red Team"
		Week 2		
	Monday	*Tuesday*	*Wednesday*	*Thursday*
Morning Session	Design Briefs	Design Briefs	Design Briefs	No Design Briefs
Afternoon Session	Group Share-out	Group Share-out	Group Share-out	Final Working Demos Completed

Data Sources

Case study methodology calls for multiple sources of data to be collected and used to generate findings (Yin, 2018). For this study, participant observations, design brief meeting transcripts, and online design journals were collected as data and used in the analysis. Each of these sources are described below.

Design Brief Meetings. The facilitators conducted group discussions, referred to as *design briefs,* with each team for approximately 30 minutes each day. The students were expected to lead these meetings with questions they had for the facilitators, updates on their design progress, and concerns they had about their project. For the facilitators, these meetings were the primary opportunity for employing pedagogical strategies to support the students' design process. Students' online journals were reviewed prior to the meetings, and used by the facilitators to devise questions related to the students' design progress. Concerns about the student's design behaviors (e.g., not conducting valid experiments) were raised and addressed as needed. From a research perspective, the facilitators employed their strategies during design brief meetings, and thus, served as an essential data source. This was a time when the facilitators reacted to beginner design behavior with subsequent pedagogical strategies. The questioning and discussion largely shaped the findings.

Online Design Journals. Engineering requires breaking down complex problems into smaller, simpler tasks. It also involves reflecting on what has and has not worked out. In order to capture this perspective on students' design thinking, we used a student journaling platform, *SeeSaw,* to provide students with opportunities to document and reflect on their team's progress throughout the academy. Students were encouraged to make regular posts (at least one per day) on their progress and any milestones. Facilitators would review the SeeSaw posts and comment directly on their online journals. The entire journals were collected in the form of a PDF and analyzed for patterns of design behaviors. This also provided evidence for how students responded to facilitator feedback during the design brief. The facilitators also used these online design journals to interact with students, which served as additional evidence for pedagogical strategies used in the Academy.

Observations. Because of the access granted to me as an active participant of the engineering academy, I was able to observe and participate all eight days of the academy from 9:00 am to 3:00 pm, for a total of 64 hours. This level of participation provided me with both a holistic perspective on the academy and the specific details of students' engineering design process. Observational field notes were documented via a word processor on a laptop and audio recordings of specific interactions. Methodological documentation of observations were done in the form of field note write-ups at the end of each day.

Data Analysis

The observational field notes, design journal entrees, and transcripts of design brief meeting were integrated to create a complete case description of the participants' experience with the design challenge. Analyzing the complete datum allowed coding all facets of the students' design behavior and the facilitators' pedagogical strategy. Preliminary analysis coded behavior as either *student design* or *pedagogical strategy.* Subsequent coding utilized the dimensions from the *Informed Design Teaching and Learning Matrix* (Crismond & Adams, 2012) for categorizing student and facilitator behaviors. For instance, the primary codes used in the analysis included *understanding the challenge, conducting experiments, making decisions, troubleshooting, and revising and iterating.* Using this as a conceptual framework allows the results to be situated back into the broader empirical research of how teachers can scaffold students' engineering design process. Qualitative analysis strategies such as pattern-matching and theme generation were used to analyze these second-tier codes and construct the findings (Yin, 2018). The three data sources provide an extent of triangulation to ensure that findings are credible and trustworthy.

IRB & Consent

After receiving approval from my university's Institutional Review Board, I received approval from the school district administrator to conduct this study at Bretton Middle School. I had worked with Mr. Souza on prior research and already had a professional relationship with him. We met before the Academy to discuss the scope of my work, upon which he approved and granted me access to serve as both a participant and researcher. He assisted and facilitated the consent from student participants. Parents of the students were informed about the study provided their informed consent for their child to participate in the study. Participation and acceptance into the Academy were not contingent upon consent and was granted after students had been selected for the Academy.

Researchers' Role

Due to the collaborative nature my relationship with the facilitators, I identify my role in this research as an active observer-participant. Throughout the two-week academy, I engaged with students as a facilitator and developed personal relationships. This provided me with a unique level of access to the students and additional insight into their behaviors. As the researcher of this study, I acknowledge the subjectivities that shape the final research. Therefore, it is vital to disclose potential biases that I bring to the study and discuss how this could affect how data is collected and analyzed. My background is in electrical & computer systems engineering, running informal educational programs (e.g., after-school activities), and serving as a digital fabrication consultant. This experience may affect how student and facilitators' behaviors are observed and analyzed.

Results

The facilitators implemented various strategies throughout the Academy to scaffold students successfully through the design challenge. To explain the evolution of the students' design process, the results are organized by day and discussed in the order in which they occurred during the Academy. The pedagogical strategies utilized by the facilitators are described within these daily results and are accompanied by excerpts compiled together from the observations, design briefs, and online design journals.

Day One

During Day One, the students were primarily focused on understanding the challenge through functional descriptions, representations, and prototypes. The design brief focused the students on the more tangible goal of prototyping a one-wheel spinning device first, and then adding a second wheel once one-wheel was working properly. By the end of the day, the students had not quite got their prototype working.

Asking for Design Concepts. The facilitators utilized initial design briefs to support students' understanding of the challenge by asking them to explain their design concepts. Thus, students had the opportunity to demonstrate patterns of informed designers by framing the challenge in terms of its criteria and providing a functional description of their design concept. Misunderstandings of the challenge were clarified through the use of follow-up questions by the facilitators. In the following excerpt from the case description, the students provide the facilitators with a functional description and representation of their proposed design.

> Jamar begins the meeting by discussing the group's initial design concept. He explains that they will construct a *linear motor with a solenoid* and use the back-and-forth motion to propel the device forward.
>
> Ivy jumps in to explain further, "Basically we need the solenoid to move so that the wheels actually rotate completely and we need to figure out a way the solenoid moves to stay in the general area but still move."
>
> Oliver adds, "If it's fixed right there (pointing to their design sketch) because this metal piece is gonna be angled then it's just not gonna work, so we have to have it so that it can tilt like that so that…We're also working on a steering system that we could do after, right now we want to

focus on just making it move forwards or backwards. If that does work then we'll probably add the steering system probably with a servo so we'll have some type of servo in the front"

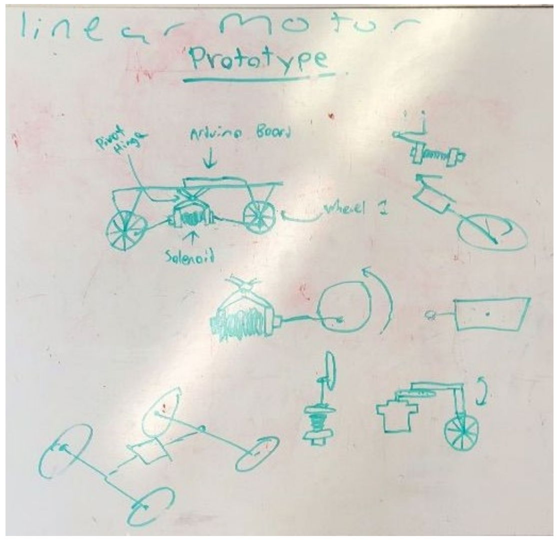


Figure 3. Students' Representational Sketch of the Transportation Device

Asking for Explanations. Students' representation of their early ideas helped the facilitators review and clarify their designs. Students represented their initial ideas through quick sketches on a whiteboard, shown above in Figure 3. Their representational sketch explained some aspects as to how the solenoid motor will convert the linear motion into rotational motion, the first significant milestone to accomplish in their design. However, the facilitators felt as though the students' sketches lacked depth and contained conflicting ideas that the students did not discuss in their functional description. This prompted the facilitators to ask clarifying questions.

> Mr. Rutter – In that design, is there one magnet and one solenoid controlling two wheels? *He is pointing to the representational sketch on the whiteboard.*
>
> The students think about it and agree that one solenoid will control two wheels. Mr. Souza, observing that their drawing shows a design concept with solenoid and four wheels, pushes back and asks the students to clarify how they would expand their device to four wheels.
>
> Ivy – Yeah, 'cause if it's on one side it won't turn 'cause the power won't push it, well depending on how the wheels are put in it could turn.

> The students agree that it is better to have solenoids on both sides. It had appeared they originally planned for one solenoid, but decided to include two solenoids for four wheels during the design brief.

In this excerpt, *the facilitator's clarifying questions led the students to think things over and make a design decision*: one solenoid powering a front and back wheel. Following this, Mr. Souza recommended quickly prototyping and focusing on a smaller tangible task, two strategies that are discussed in a later section. Ultimately, the students decided to prototype a one-wheel spinning device as their next step and design decision.

In addition to design briefs, students' online design journals provided the facilitators with opportunities to communicate with the students and support their design process. When students posted an ambiguous post entry in their journal, the facilitators asked clarifying questions. In the following excerpt from the case description, Ivy posts an image of their prototype of the linear-to-rotational crank device with a brief caption of what happened.

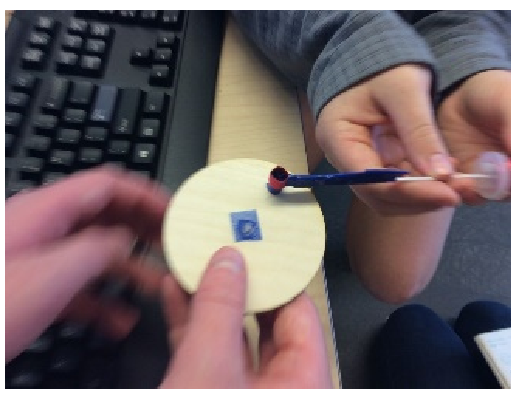


Figure 4. Ivy, "Our first prototype – it didn't work!"

> Dr. Sandy comments on their post – Prototype of what?
>
> Oliver replies back – It is our prototype of our basic linear motor that we are trying to make. You can see the main wheel and the crank piece, and then the push rod that is connected to the crank piece…Also, you can kind of see the solenoid but it is a bit out of the picture

> Later, the students post another entry in their design journal, updating the facilitators with their progress and intentions for tomorrow.
>
> Jamar – By our design brief meeting tomorrow, we will have one wheel working on our prototype, and by the end of the day, we hope to start 3D printing parts for the final.
>
> Dr. Sandy – I have no idea what this goal statement means. It's important to write in a way that facilitators and team members who are not present can still understand.
>
> Jamar – Our prototype is us trying to move a wheel around using a linear motor, we are 3d Printing parts for it, and we hope to be done by the end of today.

In this excerpt, Dr. Sandy utilized the online design journal to ask the team to clarify their understanding of the challenge and reflect on their design. Jamar struggled to describe their next prototype in terms of its functionality clearly. However, through the use of clarifying questions, Jamar and the rest of the group were able to more fully describe the challenge and identify the next task in the design process. In summary, the facilitators elicited functional descriptions and representations and asked clarifying questions to scaffold the design process. As a result, the students revised their design concept to prototype a one-wheel spinning device and worked on getting this working by the end of the day.

Day Two

By Day Two, the students had prototyped a one-wheel device powered but were unable to get it spinning reliably. The facilitators felt as though the students were designing haphazardly by not utilizing their function drawings nor conducting valid experiments to inform their design. Prior to the design brief meeting, the facilitators strategized how to handle these behaviors best.

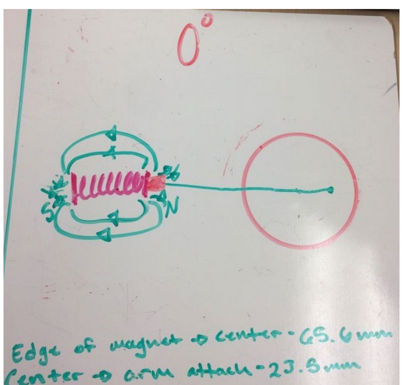
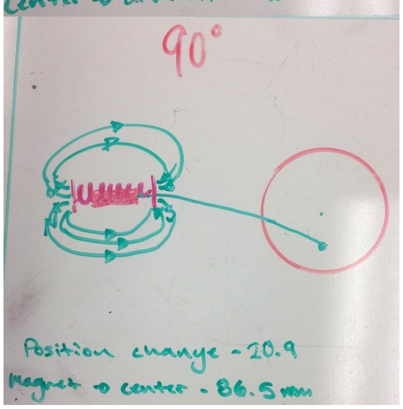
Asking for Deeper Inquiry. Conducting valid experiments to understand better the design of the device was something not observed in the students' design behavior. The students' prototype of a spinning wheel was not informed from any theory or experiments. The facilitators utilized the design brief meeting as an opportunity to emphasize the importance of conducting valid experiments and making informed design choices. The following excerpt from the case description is an example of the facilitators asking the students to conduct experiments in order to inform their design.

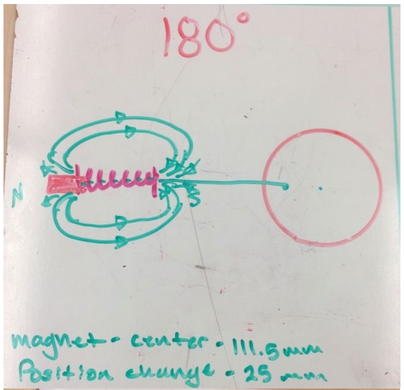
> At the start of the meeting, the students demonstrated their current prototype. During the demonstration, the wheel did not spin in a smooth or consistent manner and fell apart within seconds of testing.
>
> Dr. Sandy appears unimpressed by the students' prototype and after a moment, he states, "I want a drawing of your solenoid and your magnet. I want you to include the entire range of motion that your magnet is doing within the solenoid, and I want it to include rudimentary; that means simple, magnetic field lines, and polarity."
>
> The facilitators suggest that the functional drawing include all major events in the rotational motion (i.e., every 90-degrees) with measurements (position of the solenoid and distance between armature and wheel).
>
> Dr. Sandy launches into a brief lecture, "Now, yesterday you posted a drawing of a design idea that you had, that I didn't understand. So, just keep in mind that your goal is to move something, right? It's a transportation device. So, all of my future questions are going to surround, 'why are you doing this?', in the context of trying to move something. Your goal at this design brief was to get your wheel to rotate around once. Right? And I think you did that. I mean, it was one of those times it did come off and it wobbled all around. It was very inconsistent. It jerked, right? Kind of like it had set positions that it was moving to."
>
> Mr. Souza jumps in and states that all groups have been lacking in theory, so he is pushing everyone towards understanding and describing the theoretical model of their device. He concludes by asking them to document their testing in a quantitative way with video evidence of their working prototype. Finally, he emphasized that their theoretical functional diagrams should be labeled, detailed, and finished before lunch.

The facilitators provided two scaffolds for informed design. First, the facilitators not only re-emphasized representing the design through a functional drawing but also explained how these drawings could be more useful when more detail is included. The students are asked to draw a more detailed drawing of the solenoid, magnet, armature, and wheel. The drawing will represent the underlying theory to assist with *troubleshooting* and *making design decisions*. Second, the students are asked to conduct more structured and systematic tests with their device. These strategies led to a noticeable improvement in the students' design process, discussed in the following section.

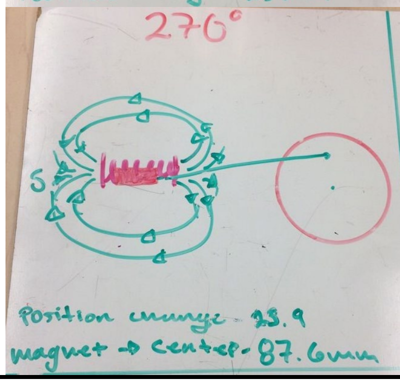
Student's subsequent representations. After the intervention from the facilitators in the morning, the students sketched a theoretical model of the linear-to-rotational motion device. Shown below in Table 6 are the four major events that occur every 90-degrees of rotation.

Table 6. Students' Theoretical Drawings for Functional Device Model

	This is a picture of our linear motor at 0 degrees. The distance from the center to the front edge of the magnet is 65.6 mm and the distance between where the arm attaches and the center is 23.5 mm. This measurement will stay the same for every degree interval.
	The second interval we did was 90 degrees. From the center to the front edge of the magnet is 86.5, and the magnet position change was 20.9 mm.



The 3rd interval was 180 degrees. From the center to edge of magnet was 111.5, and the magnet position change was 25.



The last interval was 270. The measurements were not exact, but because it is the same as the 90 degrees, it should have very similar measurements. From center to the front edge of magnet was 87.6, while the position change of the magnet was 23.9.

This representation of the device provides more specific and detailed information about the position of the magnet about the spinning wheel. The students also have included how far the magnet moves (displacement) during each 90-degree phase of the motion. This distance is a vital component to the success of the device that the students had not yet appreciated.

Students' subsequent experimentation. With their theoretical model complete, the students revised their prototype and proceeded to experiment with their next prototype. This prototype addressed some of the concerns raised by the facilitators, such as constraining all the component to a fixed base.

Figure 5. Students' revised prototype.

The students attached their device to an external power supply that drives the motor back and forth at a fixed rate (one back and forth motion per second = 1Hz) and a fixed voltage. The students perform five experiments and document the outcome for each one as a video on their design journals. Their best outcome was documented in their fourth experiment.

Table 7. Students' conducting experiments on their prototype.

	Voltage	*Rate*	*Outcome*
Experiment 1	5V	1HZ	Failed – Solenoid was too strong and broke the device.
Experiment 2	1V	1HZ	Failed – Solenoid was too weak and did not turn the wheel.
Experiment 3	2V	1HZ	Failed – Solenoid was too weak and did not turn the wheel.
Experiment 4	4V	5HZ	Success – Solenoid was able to turn the wheel.
Experiment 5	4V	5-8HZ	Success – Solenoid turns the wheel over a range of rates.

Their experiment was done systematically. For the first three trials, the students kept the rate of the solenoid fixed at 1Hz and adjusted the voltage. Once they found that 4V was powerful enough to turn the wheel, but not so powerful as to break the device, they varied the rate. The students commented that 5Hz appears to work best, and the device does not work well at lower frequencies. Their experiment demonstrated informed design behavior and assisted in the development of their next iteration.

Day Three

By Day Three, the students had hit the first significant problem with their design. The students failed to use the solenoid's back and forth motion to turn two wheels connected on either end of the linear motor. When the facilitators did not observe any progress being made with the students' troubleshooting, they intervened with the student's design process in a significant way.

Assisting Students out of Problematic Designs. During the Academy, students faced a spectrum of issues, with some more serious and concerning to the facilitators than others.

When students were faced with a more challenging issue, the facilitators intervened with the troubleshooting and often provided informed design choices from prior experiences. The following excerpt from the case description provides an example of the facilitators intervening in this way. Having successfully prototyped the solenoid turning one wheel during day two, the students now faced an impasse with getting two wheels to turn together synchronously. Shown below is a screenshot from an uploaded video of a failed attempt at getting this device to work.

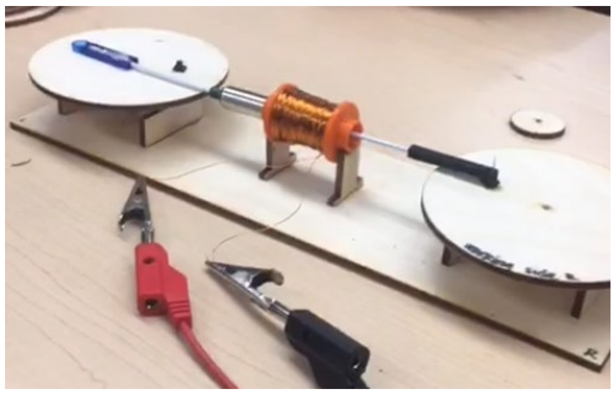


Figure 6. Student’s two-wheel solenoid device.

> Today’s design brief begins with Jamar updating the facilitators. He notes cautiously that they hope to “get two wheels working by tomorrow, probably.”
>
> The facilitators had expected the students to already have their working two-wheel device by this point and are concerned with the students’ timeline. They decide to put the meeting on hold and step out into the hall to have a *sidebar* meeting without the students present. During this meeting, the facilitators decide that the students’ current strategy with driving two-wheels will be extremely difficult to troubleshoot and get working reliably. They decide to reframe the challenge and make a design decision for the students regarding the axle design. They would like the students to design two independent axles with the solenoid turning one axle, instead of the students’ original design choice of having one solenoid on either side of the device driving a front and back wheel. The facilitators return to the students and update them on their decision.
>
> Mr. Rutter – So when we talked together as a group and I think given our timeline, we would like to update our non-negotiables so that we only have one solenoid driving one axle of the vehicle for the transportation mechanism. Does that make sense?
>
> Jamar – So we only need one side? How would that make it a car though?
>
> Mr. Rutter – It'll still be a car. A car has four wheels, and those wheels are connected to an axle.

A two-wheel drive car has the back axle driven by one motor. It has one power system. And in your case, that's a solenoid. And so that power system is turning one axle.

There is some confusion among the students about what the facilitators are asking of them, which leads to some questioning from the students. The facilitators explain to ensure that the students understand the reframed design challenge. The students seem slightly concerned that they have invested a lot of work into something that they now have to change, but the facilitators emphasize that the background knowledge that they have developed in prior experiments will be applicable to this new design.

Intervening with the students' design choices was a complex decision that the facilitators had to make. However, once the students understood what the facilitators were asking for, they were able to make a digital representation of the new design by the end of the day and get it prototyped and tested by the end of day four. Additionally, the students were introduced to *relays*, a device that was unfamiliar to the students but provided a solution to develop their electronic motor control. They were able to incorporate this device into their updated design by the end of the day as well.

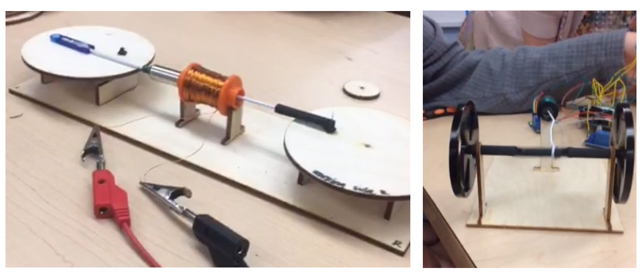


Figure 7. Students' original design concept (left) and redesign using an axle (right).

Day Four

During the morning session of Day Four, the students attempted their device's wheels spinning in the air. Their design now had two wheels attached by an axle which turned via the linear motor, and a third unpowered wheel at the front of the device. However, when the facilitators arrived at the design brief, the students were troubleshooting their axle in a way that concerned the facilitators. This initiated a guided exercise to develop some critical background knowledge, described below.

Questioning and Guiding Design Solutions. When students exhibited novice design behavior during their iterations, the facilitators took measures to scaffold their design process into a more informed way. Poorly informed design decisions were documented through the design journals, which facilitators had access to and routinely checked. When facilitators observed questionable design decisions documented in their journals, these issues were brought up and discussed during design briefs. The following excerpt from the case description demonstrates this teaching strategy to develop important background knowledge.

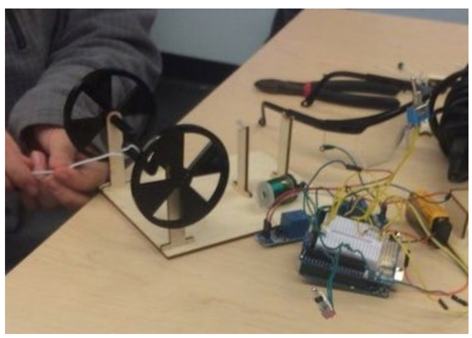


Figure 8. "This is our attempt at a working axle and wheel. The larger axle doesn't work because the iron rod isn't long enough."

> At the start of the meeting, the students display their latest prototype of the transportation device in front of them. The device now resembles some type of car and has two laser-cut wheels attached to a 3D printed axle. The axle has a kink in it where the solenoid motor's armature connects and cranks the axle in a rotational motion. This new iteration reflects the updated design criteria that the facilitators requested during yesterday's design brief. Dr. Sandy does not seem satisfied with the students' explanation why the prototype was not working and begins asking questions.
>
> Dr. Sandy – What is this distance? *He points to the kink in the crank axle*. Why did you choose the distance of the crank axle? What is it based off of? *He is referring to the distance between the wheel's axle (center point) and the location of the crank-shaft armature, and important distance that has implications on their design. He is making sure they understand the relationship between this distance and their design.*

Ivy – We figured that this was too far away, and this is like, less than an inch, so we thought that it would rotate too much and be too big, so we made it smaller so it wouldn't rotate as much because it's going to make a cylinder shape.

Dr. Sandy – What is it based on? Why did you make this design decision?

Jamar – Because they told me to make it smaller.

Dr. Sandy – There is a direct relationship to this distance here (crank axle offset), and your magnet displacement. Do you know what displacement means? *The students shake their heads to say no.* It's a fancy word that just means how far it moves. Displace. How far it's displaced from one position to the next. So this, if it is not the same or in relation to the displacement to your magnet, will not work. *He is turning the wheel as he explains the relationship between the crank and the magnet's displacement.* The distance from this to this has to be an exact number. I want you to look for a relation between this and the total displacement of your magnet. So, measure how far your magnet moves from here to here, and get the relation.

Based on the theoretical drawings from the previous day, the students are aware of the ideal range of motion for the magnet to travel. However, they did not understand that the crank axle directly controls how far the magnet travels back and forth. Thus, there is a direct relationship between these two measurements and should be incorporated into the design. The facilitators walk them through this process until they figure it out.

Mr. Souza – Alright, so let's summarize, what did we just learn?

Jamar – Magnet displacement.

Mr. Souza – That's a two-word phrase. *He says it in a way as if he is expecting more than just a two-word phrase explanation from the students.*

Ivy – Magnet displacement represents the diameter.

Mr. Souza – Diameter of the...?

Ivy – Circle, I think? *The students take a moment to think about it and write it out on a whiteboard, "magnet displacement represents the diameter of the wheel".*

Dr. Sandy – Is it really diameter of the wheel? Because this is a wheel, right? And this is not the same diameter as the wheel.

Oliver – It's the diameter of where the crank or whatever you call it sticks out…or where it's like, connected on the wheel.

Dr. Sandy – Yes. It happens to be a circle because it's a weird chain sliding through rotary motion, which is a circle. Does that make sense? *The students nod in agreement.* That's going to help you maximize the efficiency between your solenoid and your crank. That means at the point where the magnet is pulling on your crank and pushing on your crank, it's going to be at the perfect place to maximize that power.

Mr. Souza – Alright, so that's a good discovery. So, we'll build a new axle, given that relationship.

Based on the students' initial attempt at building a crank axle for the device. The students were not incorporating theory in a well-managed way. The facilitators used today's design brief to make sure the students were making well-informed decisions that were based on the theoretical model that the students had previously developed. When the students incorporated this new information into their design, they were able to get their device's wheels spinning reliably in the air. At the end of the fourth day, which was the end of the first week, the students posted a video of them successfully turning the axle and wheels using the solenoid and Arduino with relays. In a reflection at the end of the week, Oliver reports out:

> "At the end of the first day, we didn't even have a working prototype. Now, we have 2 wheels that we can make spin fairly fast and consistently with one solenoid. We had a lot of issues making the first prototype, like length and timing. So, we spent a lot of time troubleshooting and fixing things to make everything run smoothly…we still need to cut out the main body of the car, mount everything on it, and create the steering system and the 2 other wheels."

Day Five

At the start of the new week, the students decided to add ball bearings to reduce friction between the wheel-mounts and axle. The decision to use ball bearings was primarily influenced by the facilitators introducing them to the ball bearings as the students were unfamiliar with such a device. However, by the time of the design brief, the students had failed to properly mount the ball bearings.

Assisting Students to the Next Task. Students exhibited beginner designer behaviors when troubleshooting the design of the mechanical components of the device. For example, when faced with construction concepts, such as tolerances, students did not approach this is any systematic way. For instance, by Day Five, the students had begun to assemble their final vehicle and were incorporating ball bearings into their wheels and axle. In order to do this, the students needed to laser cut a hole that is the exact dimension of the diameter of the ball bearing.

Figure 9. Students' design for the friction fit ball bearing stand.

Jamar – We figured out how to kind of get it working with the ball bearing, except we need to put something in between the ball bearing and the crank, because it's not the same size. And we could try to print a new crank but…we tried to put a little bit of hot glue.

Ivy – It's like getting the ball bearing stuck.

Mr. Souza – So, it seems like your focus right now is getting the tolerance right between the ball bearing and the axle. What other questions do you have?

Oliver – Well, I was wondering about... we might not use this for another like day or two, but I was wondering about the motion sensors. So, with the motion sensor, would it only like turn if there is something moving in front of it?

Mr. Rutter – Yeah. The sensor that I gave you is like a passive motion. So, it's like, yeah. I think what you need is like a sonar type.

Mr. Souza – We have tons of them at our school. Okay, yeah. I'd say let's get the thing moving before we even start thinking about it (motion sensor).

Oliver – We are probably not using it for a while though.

Mr. Souza – Yeah. Alright. So, we need to get that axle and ball bearing tightened so that we can get some... have you been able to get some at least decent testing?

Oliver – Oh yeah. We got it moving pretty fast, but then we tried to secure it more but it got messed up, so.

Mr. Souza – Okay. So, let's say you do get that tolerance right. You've got both ball bearings on both sides. You've got some pretty good spin. What comes next?

Oliver – Well, then we'll flip it up so it's the two wheels on the bottom and see if we can move at like a pretty decent speed and then we'll go from there.

Mr. Souza – Another thing that you could potentially do is print a couple of different sizes, not redesign the whole thing. Just design maybe three different diameter barrels that are half inch tall and then see which one of those fits the best and then once you know which one is printed... which one that you printed is the best, then you go and redesign this. We'll print it over the lunch break and it will be ready when you get back. Typically, when you test for tolerance, you design a couple of different ones and see which one fits best. And if you just do a half inch tall, that way it fits through the bearing and you can see, it's a quicker print time.

In this example, Mr. Souza provides several supporting strategies for the students. First, he draws attention to the current problem and encourages them to address this before moving on to other tasks. When Oliver begins asking about the motion sensor device, Mr. Souza acknowledges the question but re-directs the conversation to the issue at hand. Next, he offers advice on how to systematically test and evaluate press-fit construction tolerances on the 3D printer. He suggests trying three different diameters for the bearing barrel and picks the one that fits the best. Finally, he provides a time-saving tip for the 3D printer to encourage rapid prototyping. The students would go on to complete the press-fit ball bearing for the wheels and axle by the end of day five.

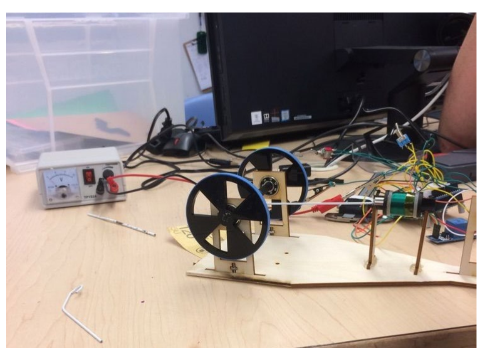


Figure 10. Students' transportation device prototype with ball bearings installed for the wheels.

Day Six

Day Six represented a significant change in the students' solution to motor control. By the end of the previous day, the students were having issues with the relay wiring and complained that their batteries were getting hot. Because the students had limited knowledge of the possible solutions for controlling the motor, the facilitators had planned to suggest some solutions and introduce unfamiliar devices along the way.

Guiding Solutions Through New Knowledge. Unlike the other intervention with the students' design process that was in response to unanticipated student behavior, some intervention was planned ahead of time. The final design reflects solutions that the facilitators suggested and introduced throughout the Academy. For example, the final design of the transportation device incorporated a *magnetic sensor* and an *h-bridge* shield for the Arduino, shown in Figure 11. The students did not simply seek out these components or ask the facilitators if they could use them. Instead, the facilitators sought out opportune moments to suggest solutions as a possibility to the students. Sometimes these solutions included;;;;;;;;;;;;; devices that were unfamiliar to the students. To explain this teaching strategy, consider the evolution of the students' electronic control design for the vehicle shown below in Table 8.

Table 8. Evolution of the Students' Electronic Control

	Day 2	Day 4	Day 6
Solution	*PASCO Function Generator*	*Arduino with Relays*	*Arduino with H-Bridge*
Pros	Out of the box familiar device used to drive the solenoid at specified voltage and frequency.	Relays provide portable (9V battery) high-power control to the solenoid.	H-bridge does not require external components of wiring to power solenoid.
Cons	A large device that is not portable and plugs into the	External components that require additional wiring,	Unfamiliar technology that required assistance from facilitators.

wall. Not as practical as a final design solution.	prone to making wiring errors.

In the following excerpt from the case description, Mr. Rutter and Mr. Kaufman introduce and explain the h-bridge shield to the students.

> Mr. Rutter – So, this is a *h-bridge*, it adds functionality to your Arduino, and it just plugs right in. An h-bridge is a digital relay. With a normal relay, you hear the clicking sound? *The students all nod and confirm, "yes".* If you were to open that up, there's actually like a mechanical switch. An h-bridge takes advantage of transistors to do the exact same thing, but it does it without any moving parts. Relays are really great and they're still used in certain applications, but a lot of people now use h-bridges. I think that's probably why we're recommending using something like this, because it might be easier for controlling purposes and it will cut down on the amount of wire that you have.
>
> Oliver – Would this be like, more helpful than the [relays] we already have?
>
> Mr. Kaufman – It's basically these [*pointing to the relays]*, like, contained.
>
> Oliver – So if one of these can make it go back and forth ... okay.
> Mr. Kaufman – I should also add, you don't have to use the Hyperduino shield.
>
> Jamar – We don't have to?
>
> Mr. Rutter – You don't have to.
>
> Jamar – Is it more helpful?
>
> Mr. Rutter – I think it might help. It's also going to reduce the weight, which I think it's an important... I think there's trade-offs that you have to consider. The advantage to continuing the relay is that you have already figured out how to get them to work. The disadvantage is that it's more wires, more parts, and more weight. Right?

The facilitators introduced a new technology, an *h-bridge*, and explained the tradeoffs for incorporating it into their design to replace the relays. The students took some time to discuss these tradeoffs and ultimately decided to integrate the h-bridge into their design a better solution for the electronic motor control. The facilitators utilized this teaching strategy to offer a new solution with more benefits but were careful to provide the students with space and autonomy to make the design decision for themselves. The students' final post for the day showcases the new design solution integrated into their device, shown below in Figure 11.

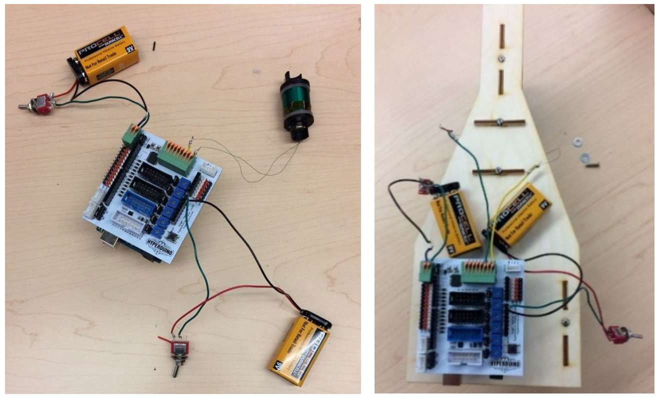


Figure 11. Ivy, "We are now using a HyperDuino [h-bridge] in place of the relays. This is our configuration with the HyperDuino. It is a lot simpler that what we had before, which was a mass of wires and a couple of relays."

Day Seven

During Day Seven, the students were met with another substantial impasse. After successfully integrating the new electronic motor control solution into their design, the students were finally ready for their first test of the vehicle on the ground. Up until now, the students had only been testing with the wheels spinning in the air, with the vehicle upside down. When they tested the device on the ground, it only moved a few inches. Realizing that this would be a challenging issue, the facilitators assisted the students with troubleshooting.

Assisting Students out of a "Dead End." When students' were faced with a problem outside of their conceptual knowledge, the facilitators assisted in identifying the problem and a potential solution for the students. The problem was related to the change in the wheel's rotational velocity when introduced to the friction from the ground. The students' electronic control and *timing* for the solenoid had been calibrated in the air, without any substantial friction, and did not work once the car was on the ground. This assisted troubleshooting allowed the students to overcome a complex problem that would have required background knowledge in physics. Moreover, once the problem was identified, the facilitators offered a solution to the students using a *magnetic sensor* to determine the wheel's rotational velocity and electronic timing for the solenoid.

In the following example, the problem described above is identified by Dr. Sandy. After explaining this to the students, he offers a potential solution to overcome this problem.

> Dr. Sandy begins the meeting by discussing the issue of having the magnet move back and forth at a different rate of the rotation of the wheel. The wheel is changing its rotational velocity, but the timing of the solenoid power is set as a constant. Therefore, if the solenoid does not receive power at the right time, the magnet will not be in the correct position, and thus, the solenoid will not propel the magnet properly. He tells them about a *magnetic sensor* which would detect the presence of a magnet to the Arduino. He explains that they could use this so that they could trigger when the polarity (i.e., power) is sent to the solenoid based on the position of the wheel.
>
> Mr. Kaufman jumps in to clarify that the ideal way to deal with their issue is to make an adaptive control system for the device. This requires using a magnetic sensor and the Arduino to determine the optimal time to power the solenoid. He stresses that they will need to figure out where to position the magnet so that when the coil is powered, it is propelled efficiently.
>
> Dr. Sandy draws three solenoids and a magnet next to each coil. This drawing is intended to illustrate when the ideal time to change the polarity of the solenoid based on the position of the permanent magnet. He asks them, "When do you flip the polarity of the coil?" Ideally, this occurs when the magnet is in the center of the solenoid or when it is halfway outside of the coil. This is the range of motion that the crank-axle displaces the magnet and therefore the solenoid's polarity should be flipped at either extreme of this displacement.

The facilitators assisted with the troubleshooting process by identifying and explaining the issue related to the timing of the solenoid. This strategy focused the students' troubleshooting to just getting the magnetic sensor to work with their current design, a topic that they had prior knowledge with input sensors and Arduino. By the end of the day, the students got the sensors installed and working, but would not get the entire system working until the final day.

Figure 12. Jamar, "Testing with the magnetic sensor…the new code for the Arduino with the hall effect sensor. Both of the magnetic sensors working but when they turn on the magnet only vibrates instead of pulling and pushing, it could have something to do with the code."

Day Eight

On the final day of the Academy, the students were able to successfully incorporate the magnetic sensors into their design so that they have a dynamic motor control that adjusted to the speed of the wheels. They posted a video of the device running on the ground for approximately five meters. The video shows them going out into the hall and letting the car run on its own for approximately 15 seconds. The students report out excitedly, "this is the best and farthest it has gone."

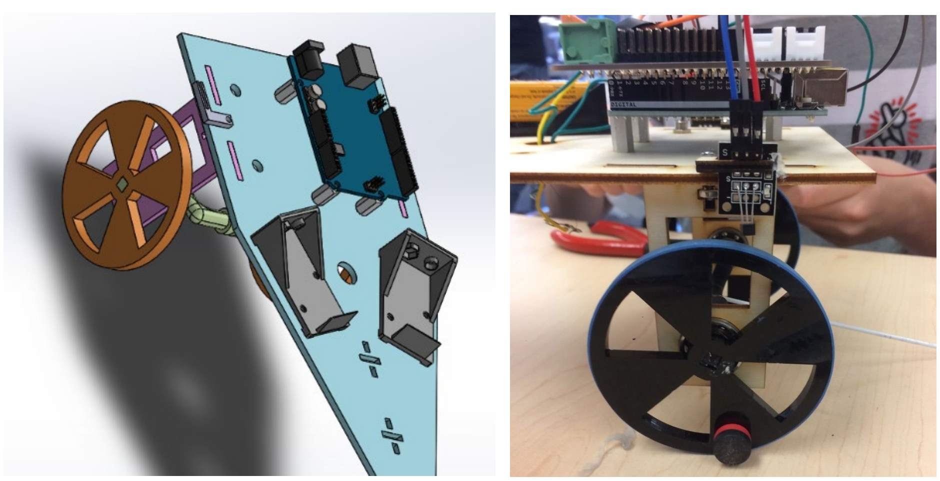


Figure 13. Final Design Journal Post

Discussion

Throughout the Academy, the facilitators employed a variety of pedagogical strategies that supported the students' design process. These strategies served as scaffolds for supporting students as informed designers and assisted the students in overcoming complex engineering design problems. Ultimately, the students were able to develop a working solution for the transportation device. The table shown below illustrates and organizes the pedagogical strategies employed throughout the academy along with the resultant informed design behavior observed by the students. While other design behavior dimensions occurred, the ones discussed below are the most salient behaviors in this case.

Table 10. Overview of Resulting Pedagogical Strategies

	Pedagogical Strategies	*Resultant Informed Design Behavior*
ELLICITING REPRESENTATION & SOLUTIONS	**Asking for Design Concepts** Method: Planned Student-led Presentations	Understand the Challenge: Students presented early design concepts. Represent Ideas: Students sketched simple functional diagrams. Generate Ideas: Students brainstormed one solenoid powering four wheels.
	Asking for Explanations Method: Unplanned Questioning	Weigh Options & Make Decisions: Students decided to have two solenoids, one on either side with a front and back wheel connected to the solenoid. Represent Ideas: Students explained their design prototype in more detail.
	Asking for Deeper Inquiry Method: Unplanned Guided Instruction	Represent Ideas: Students improved functional models to include more theory. Revise/iterate: Students redesigned motor armature to connect and turn the wheel. Conduct Experiments: Students investigated and discovered how to power the solenoid in order to turn the wheel.
	Questioning and Guiding Design Solutions Method: Questioning and Guided Instruction	Represent Ideas: Students expanded their representation by adding the relationship between the axle-crank, wheel, and magnet displacement to their model. Revise/Iterate: Students next design revision incorporated this new understanding of the relationship by adjusting the axle-crank length.

ASSISTED TROUBLESHOOTING	**Assisting Students Out of Problematic Designs** Method: Unplanned Intervention	Troubleshoot: Students adopted the axle design as a solution to fixing the issue of spinning two wheels with one solenoid. Revise/Iterate: Students incorporated facilitator feedback into the next design revision.
	Assisting Students to the Next Task Method: Unplanned Guided Instruction	Troubleshoot: Students incorporated ball bearings into their design as a solution to solving axle friction issues. Revise/Iterate: Students utilized a systematic method for testing and revising the laser cut joints for friction fitting the axle bearings.
	Assisting Students Out of a "Dead End" Method: Unplanned Intervention	Troubleshoot: Students adopted the magnetic sensor into their design and focused their attention on the solenoid timing issue. Revise/Iterate: Students successfully incorporated dynamic motor control to provide appropriately timed power.
GUIDING SOLUTIONS	**Guiding Solutions Through New Knowledge** Method: Planned Instruction	Build Knowledge: Students expanded their knowledge of electronic components (e.g., relays and h-bridges) that control motors. Revise/Iterate: Students incorporated relays at first to control the motor and then revised to replace the relays and wires with an h-bridge. Weigh Options & Make Decisions: Students considered trade-offs between relay and h-bridge and make an informed decision.

Eliciting Students' Representation and Solutions

The first pedagogical theme of strategies, *eliciting student representations and solutions,* encouraged students to think more deeply and carefully about the design process. In response to these strategies, students progressively engaged more in detailed drawing and modeling to represent their ideas and inform the next revision of their design. Each subsequent strategy led to a more complex and sophisticated model and prototype. These strategies allowed students to understand better how the system worked, which had implications related to other design behaviors (e.g., troubleshooting and revising/iterating). As a result, students exhibited patterns of informed design across several dimensions of the *Informed Design Matrix* (Crismond & Adams, 2012).

Asking for Design Concepts was a planned strategy to begin the design challenge; this elicited beginner design patterns, such as surface ideas that would not work if built. In response to students' superficial ideas, facilitators employed other strategies, such as *Asking for Explanations* and *Asking for Deeper Inquiry* to encourage informed design behavior. *Asking for Deeper Inquiry* led to students conducting valid experiments and adding another layer of complexity to their design representation (i.e., the four 90-degree rotation points of the system). Finally, *Questioning and Guiding Design Solutions* was employed as a response to students' exhibiting patterns of beginner design behavior. When the facilitators noticed students designing the crank without using any prior knowledge from their system models (drawings), they provide instruction that ultimately led to the students revising their crank-axle and prototyped a working solution.

Assisted Troubleshooting

The second pedagogical theme of strategies, *assisted troubleshooting*, intervened with students' design process when problematic design behaviors occurred. These strategies were employed when students exhibited particular patterns of beginner design behavior: 1) making premature commitments (Cross, 2000) and working with just one idea (Crismond & Adams, 2012), 2) using an unfocused or haphazard troubleshooting approach, and 3) reaching a "dead end" with their design and asking for assistance. Strategies to address these behaviors ranged in their level of intervention with the students' design process, but ultimately led students to shift towards exhibiting patterns of informed designers through diagnostic troubleshooting (Crismond & Adams, 2012).

Assisting Students out of Problematic Designs was a major unplanned intervention the facilitators employed as a result of observing the students pursuing a difficult design concept without reflecting on or weighing any tradeoffs. When students failed to consider any other options for turning two wheels with the solenoid, the facilitators intervened by guiding students away from this design concept. *Assisting Students to the Next Task* was an unplanned minor intervention that encouraged focused diagnostic behavior when troubleshooting. When students appeared unfocused in their troubleshooting, such as trying to solve two problems at once, facilitators refocused their priorities and shifted the attention onto the most immediate problem. Finally, *Assisting Students Out of a "Dead End"* was a major unplanned intervention employed when the students faced a substantial barrier without the means or knowledge to address it. Facilitators decided to introduce new and useful knowledge to the students (e.g., magnetic sensor) and describe how it could be used to address the issue. This focused students on their troubleshooting and ultimately led to a functional transportation device design solution.

Guiding Solutions

The third and final pedagogical theme was *guiding solutions.* This strategy had significant consequences on the students' final design solution and was a strategy planned ahead of time by the facilitators. Because students did not have prior knowledge of relays and h-bridges, the facilitators had agreed to introduce these as possible solutions to the students gradually throughout the Academy. After students learned about these devices, they incorporated it into their next design revision. In the case of h-bridge, the facilitators provided students with an opportunity to weigh options and make decisions in a way that exhibited patterns of design behavior (Crismond & Adams, 2012). In the end, they decided to go through the trouble of learning and integrating a new component (h-bridge) in order to reduce the complexity of the relay wiring.

Theoretical and Practical Implications

The idea of using *design briefs* as a teaching strategy for the informed design was suggested by Crismond and Adams (2012) to ensure students understood the challenge or problem statement at the *start* of the design. However, based on these results, *design briefs* – checking in with students on their design concepts and ideas – could be used *throughout* the design process and not just at the beginning. Especially when dealing with younger students with little to no experience with the design process, students' behavior can change from informed to a beginner at any moment throughout the design process. That is, teachers should not take for granted that a *one-time* intervention or strategy at the beginning of the design challenge will sustain a beginner-to-informed transition, as middle school students can quickly become discouraged or flustered by the challenges along the way and resort to beginner behaviors.

The results of this study illustrate that individual strategies do not address specific design behaviors on their own. That is, the dimensions of students' design behaviors are often interconnected and may respond to pedagogical strategies in unity. Moreover, one strategy on its own may not fully address students' beginner design behavior, and instead may require a collection of strategies to support multiple design behaviors. While Crismond and Adams (2012) provide independent strategies that address particular dimensional behaviors, I suggest that teachers and researchers take a more holistic view of such strategies. The dimensions of design are intertwined and too complex for independent remedies. Instead, *themes* of student design patterns of behaviors, such as the ones observed and described in this paper, may be more applicable for younger students (i.e., middle school or elementary). Utilizing one pedagogical approach to address multiple beginner design behaviors may also make implementing design pedagogy more accessible to teachers that are themselves novice to the design process.

Supporting the design process requires teachers to evaluate a variety of student design behaviors and make judgments about how much to intervene. In the case described in this paper, a variety of interventions were used and thus impacted students' final design. In particular, students struggling in the early phases of the design process – representing ideas, understanding the challenge, conducting experiments – may benefit from *eliciting strategies*. However, teachers should be cautious of students fixating on one design, especially if that design seems problematic in the long-run, and intervene accordingly. Students pursuing uninformed design ideas may lead to the need for more troubleshooting, and thus more assistance from the teacher. Ultimately, the teacher will need to routinely monitor student design behavior across these dimensions to ensure that students have the means to produce a successful solution.

Finally, the results of this study suggest that preparing teachers for integrating engineering design into the classroom may not require learning specific engineering pedagogical knowledge from the ground up. Pedagogical strategies utilized by the facilitators in this study correspond with similar pedagogical strategies found in science and mathematics classroom. For instance, eliciting students' ideas and asking for representations are common strategies that teachers may already be familiar with. Framing engineering design pedagogical in terms of shared pedagogical knowledge from mathematics and science education may make integrating engineering design less intimidating to teachers with no engineering background.

Conclusions

In summary, this study has described several important engineering design pedagogical strategies in action. The students from this case responded positively to such strategies and transitioned in several dimension from beginner to informed designers to complete a challenging design project. Recommendations for practice should be taken with caution due to the limitations of this study. The case described in this paper provide insight into only one student group and would require additional student groups and cases to make findings more transferable.

Furthermore, the context and conditions of the Engineering Design Academy are in some ways unique and may not transfer to the context of a K-12 engineering classroom with limited time allotted. A follow-up study is needed to determine the extent to which these pedagogical strategies are possible within a formal classroom context. Finally, more work should be done to include other cases in order to make strategies more general to the design process and not this particular project (e.g., transportation device).

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