The Dissertation Committee for Pat Ko Certifies that this is the approved version of the following dissertation:

A Long-Term Study of Educational Robotics and Achievement in Math and Science

Committee:

Jill Marshall, Supervisor

H. Taylor Martin

Richard Crawford

Anthony Petrosino

Catherine Riegle-Crumb

A Long-Term Study of Educational Robotics and Achievement in Math and Science

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Pat Ko

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Dedication

For everyone who did not understand, but believed and supported anyway:

for my parents,

for Erin,

for the cats,

and for all the hamsters.

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A Long-Term Study of Educational Robotics and Achievement in Math and Science

Pat Ko, Ph.D.
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Supervisor: Jill Marshall

In recent years, educational robotics has become a popular tool in STEM programs, such as afterschool clubs, and summer camps, as well as classrooms. However, the research on the benefits of robotics have shown mixed results. In addition, many of the studies lack strong controls and focus on short-term effects, while the programs they investigate have few contact hours and do not have a consistent curriculum. This situation indicates that more research is needed.

This work focuses on a public high school in Texas with a year-long robotics class. The first part examines a set of students who enrolled in the robotics class in the 9th or 10th grade, and a comparison group of students who did not enroll in robotics. The robotics and comparison groups were matched on 8th grade standardized math test scores, and demographic factors. Using multiple linear regression and logistic regression, I found that robotics enrollment was not a significant predictor for 11th grade math standardized test scores, or high school enrollment in Physics 1, Physics 2, or Calculus classes.

The second part examines a series of video recordings of student teams in the robotics class working on a capstone project. Using grounded theory, I coded and analyzed recordings of two of the teams, focusing on the math and science discussions between the students and the contexts in which the math and science occur. Three themes emerged from the data. First, students use math/science more frequently to identify and fix problems than in their initial design. Second, students use math/science at a conceptual level and do not perform math calculations. Last, students have a “good enough” attitude and do not prioritize precision. These results may help explain the lack of effect robotics have on math test scores.

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Chapter 1: Introduction

BACKGROUND AND RATIONALE

With over half of the United States' historical economic growth deriving from technological innovation (Bonvillian, 2002), the country has a vested interest in producing more STEM professionals and innovators. To accomplish this, more students need to be encouraged and prepared in STEM fields in K-12 and college. One promising method that has risen to help has been the use of robotics as an educational tool (Nugent, Barker, Grandgenett, & Adamchuk, 2010).

Use of robotics as an educational tool appeared in Seymour Papert's work in the 1980s (Papert, 1993) and underwent rapid acceleration in the 1990s. Since there is no central organization to track educational robotics proliferation, it is difficult to obtain accurate information about the growth of the field. However, FIRST robotics, one of the largest robotics competition organizers, started with 28 teams in 1992, and has increased to 39,000 teams in 2015, representing over 359,000 students (FIRST robotics, 2015a). Since its inception in 1989, over 1 million students have participated in FIRST (Flowers, 2015). In the United States, Myers (2009) estimated that 8% of the 25,000 high schools in the country were involved with FIRST robotics.

Despite its rapid growth, implementing an educational robotics program has several challenges. Monetary cost is one of the major problems. In a typical classroom or after school club, small groups of students work together on a robot, sharing one robotics kit (~$350) and one PC (~$350), yielding a cost of approximately $700 if students work in pairs. For 20 students, a school can expect to purchase $7,000 of equipment. In addition, there is the cost of the teacher and meeting space. Also, robotics competitions typically have registration fees. FIRST robotics charges $5,000-$6,000 per team for one competition, with additional ones costing between $500 and $5,000 depending on location and competition level (regional, district, etc.) (FIRST robotics, 2015b). A five-student team attending a single competition costs at least $1,000 per student. In contrast, the cost of a 3-credit advanced math or science class at a local community college can be $255 per student (Austin Community College, 2016).

Another problem is teacher training and acceptance. As reported by Sullivan and Moriarty (2009), some teachers have a difficult time adapting to the use of robotics. With a steep learning curve, many interviewed teachers were concerned about their own proficiency. Others believed that robotics activities or curricula would be difficult to implement and integrate into regular school periods. While many of these issues are not unique to robotics, they are still barriers to implementation.

Starting a robotics program can be an expensive investment and a challenge to implement. Any organization that wishes to pursue educational robotics needs to ask several questions. First, what are the educational benefits of robotics programs? While the rapid growth of robotics demonstrates a desire for more robotics activities, popularity is not proof of learning (Johnson, 2003). If robotics programs produce favorable outcomes, educational institutions still must address another important question—Do the benefits outweigh the high cost or would the money be better spent on a different program?

Unfortunately, the benefits of robotics programs remain largely undocumented. While there is a substantial amount of published literature about robotics programs, the majority of publications focus on descriptions of implementations of programs (Benitti, 2012), and evidence of learning tends to be anecdotal (Johnson, 2003; Silk & Schunn, 2008). Of the few quantitative studies have been performed, many suffer from small sample sizes, using instruments that may not be reliable or valid, a low number of contact hours, and multiple curricula being used with different groups of subjects (Barker &

Ansorge, 2007; Laughlin, 2013; Nugent, Barker, & Grandgenett, 2008; Wolfgang, Stannard, & Jones, 2003). Some studies used multiple sites, but did not coordinate the curriculum, making it uncertain whether the groups received comparable lessons (Hussain, Lindh, & Shukur, 2006; Lindh & Holgersson, 2007). In addition, most of the studies conducted their evaluation within a few months of the intervention. Thus, they did not measure whether the observed effects persisted or if students quickly returned to their pre-intervention state. Given these issues, it is difficult to conclude whether robotics programs deliver meaningful and lasting benefits for their participants.

What is needed is a longitudinal comparison of a large population of robotics students against a comparison group. The outcome measures should be validated instruments. Students should have an ample number of contact hours and all robotics students should be using the same curriculum.

METHODS AND RESEARCH QUESTIONS

This study is designed to fulfill many of the aforementioned needs. Focusing on a high school with an established robotics program, I will use data from multiple years of robotics students and a comparable matched comparison group. For each student, I will examine math standardized test scores and later enrollment in elective STEM classes. Since standardized test results and class enrollments are routinely recorded by the school district, they are convenient to obtain for large numbers of students. In addition, several prior quantitative studies have used math standardized scores (Laughlin, 2013; Tran & Nathan, 2010a; Wolfgang et al., 2003), so using them here would allow for a comparison of results. Further, these are the outcomes that matter for many if not most school districts.

Summer camps and brief interventions do not deliver many contact hours to the robotics students, so it is possible that some of the students do not derive the full benefit of the program. Likewise, extracurricular clubs do not mandate attendance and engagement; so some students may be "enrolled" but not actively participating. By focusing on school courses, I can filter out the students who skip class and are not engaged by examining the class grades.

By using a school with an established and long-running robotics program, I can obtain a sufficient sample size by including multiple sections of the robotics class over several years. There has been some evidence of robotics increasing interest in STEM subjects (Eguchi, 2016; Iturrizaga, 2000). By comparing STEM course enrollment, I will be able to see if possible heightened interest translates into action and pursuit of that interest. Research has shown enrollment in advanced math and science courses to be correlated with higher math and science achievement (Leow, Marcus, Zannuto, & Boruch, 2004). Standardized math and science tests are professionally designed and typically have published reliability metrics and the validity has been accepted by the state educational administration. As such, by comparing test scores multiple years after the robotics class, I will be able to see whether any gains persist over the long term.

This study includes a quantitative piece (Part 1) and a qualitative piece (Part 2). My research questions for Part 1 and their corresponding null and experimental hypotheses are as follows:

1. *Is there a correlational relationship between enrollment in a high school robotics class and standardized math test scores?*

   H_0: There is no relationship between enrollment in high school robotics and standardized math test score.

μ_0: There is a relationship between enrollment in high school robotics and standardized math test score.

2. *Is there a relationship between enrollment in a high school robotics class and later enrollment in advanced STEM courses?*

   H_0: There is no relationship between enrollment in a high school robotics class and later enrollment in advanced STEM courses.

   μ_0: There is a relationship between enrollment in a high school robotics class and later enrollment in advanced STEM courses.

To help contextualize and triangulate the results of the first two research questions, the second part of this dissertation will be a qualitative study of robotics students. In Spring 2010, students in a robotics class were video recorded for several days over the course of the semester. The class occurred in the same high school studied in the first part of this dissertation. Using the video and written documents produced by the students, I will analyze whether the students were using math and science during the design, construction, and testing of their robotics projects. My research question for Part 2 is as follows:

3. *Are robotics students frequently using math and science in the course of their robotics project, or are there missed opportunities where more math/science use could be encouraged?*

Video recording of the classroom can provide a view into the daily activities of the students and may help explain the reasons for the results of the first two research questions. If the observed students frequently use math and science during the course of their robotics project, the extra practice and reinforcement of the subject matter would lead me to expect improved math test scores and increased enrollment in advanced elective STEM courses. However, if students do not notice or do not choose to use math or science, it would help explain if there are no significant changes in math test scores or enrollments in advanced elective STEM courses.

OVERVIEW OF DOCUMENT

In this chapter, I provided the rationale behind the study, briefly described my methodology, and listed my research questions and hypotheses. I discuss the relevant literature to this dissertation study in Chapter 2. In Chapter 3, I provide more specifics regarding the study methodology. Chapter 4 describes the results of the quantitative and qualitative analyses, while the discussion about these results are in Chapter 5. Chapter 6 summarizes this work, lists limitations, and directions for future research. Appendix A contains the capstone project assignment.

Chapter 2: Literature Review

THEORETICAL FRAMEWORK

In broadest terms, robotics are physical manipulatives, and the use of physical objects as learning tools dates back at least to the 18th century. Johann Heinrich Pestalozzi used stones, plants, and other examples from the natural world to teach forms. Friedrich Fröbel used models of geometric solids to teach shapes and encouraged his students to create their own models and artifacts (Dunn, 2005).

Theoretically, educational robotics is a direct descendant of Seymour Papert's constructionism. A student of Jean Piaget's, Papert's work can be seen not as an alternate view of constructivism, but as an extension of it. Papert acknowledged this foundation when he named his theory by modifying the spelling, and hence limiting the meaning, of "constructivism" (Papert & Harel, 1991). Both theories are rooted in the idea that meaning cannot be directly taught, but rather that students must create their own meaning through personal experience (Ackermann, 2001). "People don't get ideas, they make them" (Resnick, 1996, p. 281).

But where understanding in Piaget's constructivism passes through the concrete to the abstract, Papert focuses attention on the concrete. Indeed, the defining feature of constructionist teaching is the need for the learner to build and create artifacts, whereas constructivist practice may or may not involve the creation or manipulation of physical artifacts. An oversimplification of constructionism reduces the idea to "learning by building". More accurately, "constructionism does not privilege abstract reasoning as the only route to high-level intellectual understanding" (Sullivan & Moriarty, 2009, p. 112).

While the artifacts are often physical models, it is not required. There is room for both the concrete and the abstract.

In addition to a way of learning content, Papert also saw constructionism's potential in the affective domain as a way to pique interest and motivate students to seek out knowledge (Papert & Harel, 1991). Notable was the embrace of technology as a medium for construction and collaboration and its use as a source of inspiration and motivation. The origins of his work with robotics can be seen in his development of the Logo programming language and Turtle geometry for elementary students. Logo enabled students to explore geometric concepts by constructing a program to tell the "turtle" cursor to draw lines and turn through angles to create shapes on the computer screen. His later extension to "physical Turtles"—small, wheeled robots that could be programmed to move around the classroom floor— was an even more concrete expression of the shapes drawn by the virtual Logo Turtle cursor and a physical realization of the commands used to program it. (Papert, 1993)

This work eventually led to a direct collaboration with the LEGO Group to create their next generation of robotics kits, named MINDSTORMS, after one of Papert's books.

Papert saw the potential for constructionism to impact not just instructional methods, but major educational structures as well. He had a vision of constructionist education, specifically, of STEM education, which came to him when he was working at a junior high school and happened upon one of the art classes.

> In this particular art class they were all carving soap, but what each student carved came from wherever fancy is bred and the project was not done and dropped but continued for many weeks. It allowed time to think, to dream, to gaze, to get a new idea and try it and drop it or persist, time to talk, to see other people's work and their reaction to yours — not unlike mathematics as it is for the mathematician, but quite unlike math as it is in junior high school …. An

> ambition was born: I want junior high school math class to be like that. (Papert & Harel, 1991, p. 3)

Here, we can see that his vision was not limited to merely building things, but extended to the whole learning environment. It includes giving students a non-rigid class structure that provides students time and freedom to experiment, work authentically, collaborate, and review each other's work.

There are, however, criticisms of constructionism and constructivism. Studying a programming project with elementary and middle school aged students in a constructivist setting, Bruckman, Edwards, Elliott, and Jensen (2000) found that while some students mastered the material, the majority of students learned little with large amounts of time off task. Other researchers note that while constructivism is a good cognitive model of learning, it has been difficult to translate into useful instructional practices. Gordon (2009) highlights misuses that have led to poor implementations, while Windschitl (1999a, 1999b) discusses inadequate teacher training, and the difficulties in creating a constructivist culture in the classroom. One practice that draws particular criticism is pure discovery learning, where students are left in a low guidance environment where they are supposed to "discover" and construct understanding by themselves. Mayer (2004) states that without sufficient guidance students learn inefficiently and sometimes construct the wrong conceptions. Studying children working in Logo, Kurland and Pea (1985) found that the students created the wrong mental model for recursion. Citing empirical studies and cognition theories, Lehrer (1986) similarly calls for more guided learning.

BACKGROUND

In recent years, robots have been used in education in K-16 education in several ways. The first, which I will call "industrial robotics", is when manufacturing robots are brought into the school and students are taught to operate them as an introduction to the industrial automation environment. In this setting, the students learn to program and operate the machines, but are not designing or creating them. A second, which I will call “educational robotics”, is when students are provided parts and are expected to design and construct the robots out of mechanical and electronic components. Mechanical parts include structural elements and motors, and electronic components include programmable microcontrollers and sensors. Pre-packaged kits, such as LEGO MINDSTORMS or VEX, are included in this second group. The focus of this work is on educational robotics, where students design and create a robot, and not industrial robotics, where students learn to use an existing robot.

There is a belief that educational robotics has a positive effect on students, particularly with respect to STEM education (Barker & Ansorge, 2007). But, despite the popularity of robotics, the research evidence for its merits is somewhat sparse. Benitti's (2012) review of the robotics literature found while there is a substantial literature base on educational robotics, the majority of reports are not critical studies. Of the 197 articles she found that were published between 2000 and 2009, only 5% were quantitative studies (with pre- and post-measures) where robotics was used as an educational tool in K-12 settings. Most published articles on robotics are descriptions of the implementations of robotics programs (e.g. Genalo & Gilchrist, 2006; Lau, McNamara, Rogers, & Portsmore, 2001; McLaughlin, Hardinge, Brown, Jenne, & Stiegler, 2007; Nagchaudhuri & Singh, 2003; Robinson, Fadali, Wang, & Vollstedt, 2004) or ideas for robotics curricula and lessons (e.g. Howell & McGrann, 2003; Lau et al., 2001; Schep & McNulty, 2002). Some merely measured whether the students gained knowledge about using the robotics kits (Barker & Ansorge, 2007; Sullivan, 2008). Despite the large number of articles, few actually try to determine whether robotics students gain knowledge or skills that are transferrable. Of these, there are a variety of skills that are measured, including divergent thinking (Gibbons, 2007) and problem solving ability (Hussain et al., 2006).

PATHWAYS FOR ROBOTICS TO AFFECT MATH AND SCIENCE ACHIEVEMENT

Despite the fact that robotics programs are often considered to be engineering interventions, it is reasonable to believe that such programs can also improve achievement and interest in math and science. Figure 2.1 illustrates potential pathways that I believe can lead from robotics to increased test scores and course enrollment. I labeled the metacognitive pathway with dashed lines because the research literature on this topic is still in its infancy.

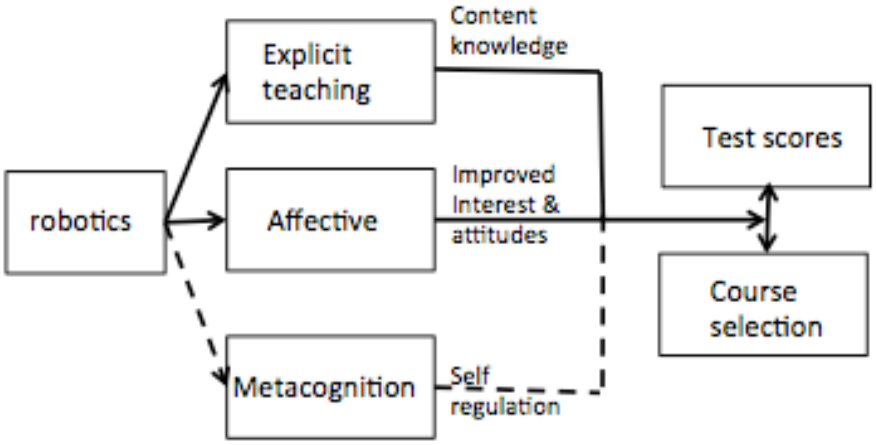


Figure 2.1: Pathways for robotics to lead to improved math/science test scores and course selection.

Explicit teaching

A direct method of teaching math and science to robotics students is to create curriculum and activities to explicitly teach math and science concepts in the context of designing and using the robots. In a middle school summer program, Williams, Ma, Prejean, Ford, and Lai (2007) used robotics to teach Newton's Laws of Motion.

Robinson, Fadali, Wang, and Vollstedt (2004) also taught physics teaching through robotics, but the program was aimed at 8th eighth-grade Limited English Proficient and English as a Second Language students. Meanwhile, Silk and Schunn (2008) studied a program created to teach middle school math concepts.

While ratios, geometry, and physics are common math and science topics for explicit teaching, a wide diversity of subjects have been addressed through robotics, including Geographic Information Systems (Nugent et al., 2010) and evolution (Whittier & Robinson, 2007).

While some projects report significant pre-post learning, (e.g. Williams et al.(2007), not all do. Silk and Schunn (2008) examined a robotics program in which 24 middle school math concepts, such as taking averages, converting between metric and imperial systems of measurement, maintaining accuracy and precision, and calculating percentages, were used by the students in the course of the robotics activities. Anticipating the possibility that they would not measure any significant learning gains, they hypothesized that, by teaching math and science through robotics, the program could be overcontextualizing the math and science concepts. That is, while using concrete examples has been shown to help students learn and apply new material, it can also lead to specializing the knowledge such that students do not abstract and are unable to apply it to other contexts (Bransford, Brown, & Cocking, 2000). Thus, Silk and Schunn (2008) assessed the learning of the middle school students using two sets of questions. One set included published standardized test questions, while the other set was created by the researchers and based on the same topics as the published test questions but rephrased to involve robots. Students performed poorly on both sets of questions, implying that the poor performance was due to something other than overcontextualization. With the large amount of content covered by the robotics project, an analysis of the interaction between the instructor and students indicated that there was little time being spent on any particular topic and no repetition or practice. Thus, they recommended that robotics may be best used to reinforce information that had already been taught and not as a student's initial contact with the material.

Affective Domain

While many studies consider gains in content knowledge, another common aim is to improve students' affect, e.g. motivation or persistence. In particular, many studies include self-report, pre-post surveys of attitudes toward one or more STEM subjects (e.g. "I think science is fun." (Wendell & Rogers, 2013, p. 538)) and measure students' inclination toward pursuing STEM as a college major or career (e.g. "Working with [STEM] ideas would be an interesting way to earn a living." (Norton & Ginns, 2005, p. 146)). Most papers report an increase in interest and attitudes after robotics projects (Eguchi, 2016; Mitnik, Nussbaum, & Soto, 2008; Nugent et al., 2010; Wendell & Rogers, 2013).

There is a vast amount of literature about how student perception and beliefs affect the choices students make and their achievement in math and science (Singh, Granville, & Dika, 2002). Models, frequently based on goal theory or expectancy-value frameworks, try to capture the complex behavior of students based on internal and external factors (DeBacker & Nelson, 1999). In particular, Eccles's expectancy-value model, a prominent and often used approach, predicts student achievement related choices using a variety of categories of variables, including affective values, such as student interest and attitudes towards the subject, previous achievement, cultural norms, and expectations of success (Wigfield & Eccles, 2000). Singh et al. (2002) found that in eighth-grade students' attitudes and interests towards math and science were correlated with higher math/science grades and standardized test scores.

Interestingly, while working with college-bound students in Germany, Köller, Baumert, & Schnabel (2001) found that at lower grades (i.e., 7th grade), student interest and attitudes toward math did not predict math achievement in 10th grade. However, later in high school, interest and attitudes in 10th grade predicted students' 12th grade math achievement. In addition to a significant direct effect of interest on achievement, there was a significant partial mediation of interest by student selection of the more challenging math courses. The researchers hypothesize that interest and attitudes only become important once students have electives and can choose to enroll in more challenging math courses or take an easier option. According to this model, programs and interventions that enhance a student's attitudes and interest towards math and science in middle school or early high school may not see significant effects until several years have passed and the student is in later high school, when he or she can elect to enroll in advanced coursework.

Metacognition

Broadly defined, metacognition is a person's awareness of his or her own thought processes and the ability to regulate these processes (Goos, Galbraith, & Renshaw, 2002). Studies have shown that metacognition is associated with math and problem solving ability (Lucangeli & Cornoldi, 1997) and course grades (Young & Fry, 2008), and that metacognitive ability can be developed (Bransford et al., 2000). Hypothetically, using robotics has the potential to foster metacognitive development. Students working in small groups (as in robotics teams) can achieve a group metacognition where the members work as peer reviewers of each others' ideas and processes (Goos et al., 2002). However, work on this subject is still in its infancy and studies have predominately focused on pre-school and elementary school children. McWhorter (2009) measured metacognitive changes in a college computer science class that used robotics, but did not see a significant improvement.

Indirect Use and Interactions Between the Pathways

A few robotics programs have shown evidence of improving some math and science skills or student attitudes towards math/science even though those were not major goals for the program. The Robot Diaries, which focuses on storytelling using robots built with craft supplies reports that their students have increased their interest in studying STEM subjects (Nourbakhsh, 2009). Observing teams of middle school students working on a robotics challenge, Sullivan (2008) recorded the scientific skills she saw the students using. Even though the challenge was not science oriented, she was able to code for actions such as observation, hypothesis generation, hypothesis testing, estimation, control of variable, and evaluation of solution. While these are essential skills for science and were learned and practiced in robotics, it is not certain whether they would directly impact math or science standardized test scores. But, if the robotics increases student interest in science or math, it could lead to the more STEM course taking and greater achievement through the affective pathway.

However, there may be a trade-off between these pathways. Comparing a week-long robotics summer camp with 40 contact hours to a one day 3- hour program, Nugent, Barker, Grandgenett, and Adamchuk (2010) noticed that while students in the long program had larger content knowledge gains than the student in the short program, the short program students had more gains in positive attitudes and interest in STEM. The authors hypothesize that the difference was a result of the different focuses and needs of the two curricula. With the extra contact time, the long program was able to use a more cognitively challenging project, while the short program focused on tasks that could be completed within the limited time.

RELEVANT PRIOR STUDIES

This dissertation focuses on math and science achievement. Unfortunately, very few robotics education studies maintain this same focus. I discuss the relevant studies below. While these all have definite strengths, they also have sizable limitations.

The largest study on educational robotics was conducted in Peru when the INFOESCULELA Project expanded use of LEGO robotics kits from 12 primary schools in 1996 to 130 schools by 1998. Using seven pairs of schools matched by social and economic factors, Iturrizaga (2000) conducted a mixed methods study of 2nd, 4th, and 6th grade students over one year, split between experimental schools (robotics) and comparison schools (no robotics). In total, between the experimental and comparison groups, over 500 students participated in the study along with their parents and teachers. Teachers went to robotics training programs on weekends and were provided with robotics instructional material including lessons and projects. Students worked in small groups of 2-4 and worked with robotics for at least 12 hours per month for one school year.

Casting a wide net, students were surveyed and tested in math, technology, Spanish, self-esteem, and hand-eye coordination. The math tests were multiple choice and fill in the blank tests based on the official Ministry of Education program. The Cronbach Alpha reliability was at least 0.79 for all three grades. Iturrizaga reports a significant increase in test scores in each of the three grades, with mean scores of the robotics students 45% to 63% higher than for the comparison students.

This study has some important strengths. It has a large number of subjects split between multiple sets of matched schools. Teachers were trained and there were a large number of contact hours during the year. In addition, the assessment questions were aligned to their standard curriculum and were fairly reliable.

However, considering that the subjects were spread out between 3 grades in 14 schools, 500 subjects yields an average of only 12 students in each grade in each school. It is also unknown how the students were chosen. Furthermore, while the schools were matched, the students were not. Given the relatively low number of students in each grade and school subgroup, controlling for factors such as previous achievement would have been helpful. In addition, one of the weaknesses of this study is that the final assessments were administered shortly after the activities were completed. This method captured immediate short-term effects but provides no indication of whether or not effects persisted in the long-term. According to Köller, Baumert, & Schnabel (2001), changes in interest and attitudes may not improve achievement until students are old enough to choose whether to enroll in STEM electives.

Hussain, Lindh, and Shukur (2006) noted that Peru's education setting and norms are not the same as those of most Western countries. Elementary students in Peru only attend school for half a day instead of a full day, and Peruvian students are less likely to be familiar with technology. Since Iturrizaga's results may not generalize to other locations, they conducted a large-scale study involving over 700 students split between the fifth grade and ninth grade, in multiple schools across central Sweden. Unlike the Iturrizaga study, experimental group teachers were not given robotics lessons and projects, but were told to adjust ordinary school activities to incorporate robotics for approximately eight hours per month. The groups were pretested on math and problem solving and given posttests after 12 months. The math exams were modeled after the

Swedish national math tests for 5th and 9th grades. Using t-tests, the researchers found that for fifth grade students, there were no significant differences in math scores, but there was a significant decrease in problem solving scores for robotics students. For ninth grade students, the researchers found no significant differences.

Using what seems to be the same raw data as Hussain, Lindh, and Shukur (2006), Lindh and Holgersson (2007) divided the students by performance level and reanalyzed the information. They split the fifth-grade students into three groups based on how the students performed on their math tests during their fourth-grade year: low, medium, and high scorers. There was no significant difference between comparison and experimental students who were low scorers or high scorers, but the robotics students who were in the middle on fourth grade math scores had a significant math score gain compared to the comparable non-robotics students.

Even after splitting the subjects between two grades, this pair of studies has a large number of subjects, and the students had a good number of contact hours each month. Also, because entire classes were assigned to either the experimental or comparison group, there was no student self-selection bias. Furthermore, the tests were similar to standardized test questions.

However, there was no guarantee of consistent instruction because the subjects were spread out between schools. Each teacher was charged with designing his or her own robotics curriculum, and thus there was no guarantee of consistent instruction. Also, unlike the fifth-grade students, there was no pattern found with the ninth grade students, which further calls into question the robustness of their findings. As with Iturrizaga (2000), the assessment came soon after the robotics lessons ended and there was no followup in later years to see if there were differences in achievement once the students could choose advanced math/science classes.

Working with an American charter elementary school, Laughlin (2013) investigated whether an afterschool robotics program affected standardized math test scores in fourth- and fifth-grade students. The robotics student participants (23 fourth grade and 23 fifth grade) were matched to a comparison group (76 fourth grade and 87 fifth grade) based on standardized math pre-test score, gender, and gifted designation. While Laughlin found a significant increase in pre to post math scores in the robotics students, the improvement was not significantly different from the comparison group.

This study used reliable standardized tests and there was matching on several important variables. Because there was only one site, it is likely that all of the students had the same curriculum.

Unfortunately, due to small sample sizes, this study had little statistical power. In addition, the setting for the study is a single charter school, calling into question whether the results can be generalized to a national population. As with the previous studies, this work is not longitudinal, so delayed effects are not captured.

Though it did not use a full robotics kit, there may be some lessons available from a long-term study by Wolfgang, Stannard, and Jones (2003). The study spanned 17 years, following students from pre-school until their high school graduation. At the start, 27 pre-school children were graded on a 5-point scale on how well they could use and create with regular LEGO (non-robotic) blocks. A high score indicated that they were insightful and adaptive in their use. There was no significant difference between the higher-scored and the lower-scored children in the third- and fifth-grade tests. However, differences started to appear starting in seventh-grade standardized math tests once the researchers controlled for IQ and gender. As the students aged, the differences between the groups grew statistically stronger. By the end of high school, students' pre-school LEGO scores significantly correlated with their high school math grades, number of honors courses taken, number of advanced math courses taken, and weighted math grade point average.

The main strength of this study is that it is longitudinal and there are many achievement measures. In addition, the researchers controlled for two important variables: IQ and gender.

However, the sample size is very small. By the end of the study, the researchers were only able to track 20 students through the entire period. Furthermore, since the study employed non-robotic LEGO blocks, it is not known whether the addition of the robotic and programming components would have altered the results. Also, since there was no intervention or teaching, it is possible that the LEGO skill differences that were observed are something that cannot be taught.

Project Lead the Way (PLTW) is a series of courses designed to introduce middle school and high school students to engineering. The lessons and other materials are commercially available and have been used in over 1,400 schools across the United States. To participate, schools are required to purchase the materials and PLTW teachers are rigorously trained. Looking at 70 pairs of matched students, Tran and Nathan (2010) used participants' 8th- and 10th-grade standardized math and science test scores as pretests and posttests. Both comparison (no PLTW) and experimental (PLTW) groups increased their scores. However, after controlling for student factors (gender, free/reduced school lunch eligibility, and eighth-grade test scores) and teacher experience (in years) the PLTW students gained less than students who did not participate in the courses.

The strength of this study is that the researchers matched the pairs on several important factors and had an acceptable number of subjects. In addition, because of the PLTW training, all PLTW students likely had similar experiences. This study is also the only one that examined science achievement as well as math.

For our purposes, the main problem with this study is that it is not a robotics class. However, PLTW it is a STEM elective that, like robotics, has projects and improve student interest and attitudes towards science and math. Thus, it may be serve as a surrogate for robotics. It is important to keep in mind that the various PLTW courses are different from each other and from robotics, and thus I cannot rule out that they may have different impacts on math and science affect. However, while the time between pretest and posttest was two years, because the study focused on early high school students, it is unlikely that the students would have been able to take math or science electives within that time; so we would not see any achievement gains due to course selection, as predicted by Köller, Baumert, & Schnabel (2001).

Because of the conflicting results of the above studies, there is no consensus whether or not educational robotics is beneficial to math and science achievement in an industrialized country, such as the United States. All of the major studies on robotics have substantial weaknesses, including low sample size, a different educational setting (Peru vs. Western), inconsistent robotics curricula, absence of controls for student factors, and lack of assessment of long-term effects. What is needed is a study using a large number of robotics students (e.g., Iturrizaga (2000)) who have had a large number of contact hours using a consistent curriculum (Iturrizaga, 2000; Tran & Nathan, 2010a), and the study should follow the students for multiple years into high school (e.g., Wolfgang et al., 2003) and control for multiple confounding factors (Tran & Nathan, 2010a). This study encompasses these features.

Chapter 3: Methodology

This study involves a quantitative piece (Part 1) and a qualitative piece (Part 2). In this chapter, I describe each piece separately.

PART 1: QUANTITATIVE METHODOLOGY

Study Site

The dataset used in this study concerns a single school located in a large city in Texas. In the 2012-2013 school year, which was the last robotics cohort, the school had over 2100 students and was approximately 52% non-Hispanic white, 30% Hispanic, 7% African American, and 6% Asian. 29% of the school was economically disadvantaged, with 7% in special education, and 4% English Language Learners. The school met state accountability standards and the class of 2012 had a 97% graduation rate.

Description of Dataset

The data used by this study is a subset of a larger database which was provided by the school district and consists of standardized test scores, course enrollment, and demographics information for a set of students who have enrolled in robotics at the school and a matched set of comparison students who did not enroll in robotics at the school. The entire dataset consisted of 766 students. All robotics students were enrolled in the robotics course at some point in the academic year range from 2009-2010 to 2012-2013. Since robotics was not restricted to any particular grade level, robotics students could have taken the class any time from 9th through 12th grades.

Unfortunately, many of the subjects in the main database did not fulfill the criteria for this study, and were excluded. The reasons a subject was removed from the study subset were:

1. Missing data – some student records were missing important data points, such as standardized test scores or class enrollment. Because each of the analyses are independent (exit level math test score, each class enrollment), I could have maximized the number of samples available for each analysis by using different subsets of data for the different analyses, e.g. ignore missing class enrollment information for exit level math test score analysis and vice versa. However, using different subsets calls into question whether the analyses are comparable. Therefore, only students with complete records are included in the study subset.
2. Standardized test change – during the time period covered by the database, Texas was in a multi-year transition from the TAKS (Texas Assessment of Knowledge and Skills) standardized testing systems to the STAAR (State of Texas Assessment of Academic Readiness) system (Texas Education Agency, 2017a). Since TAKS test results are not comparable to STAAR scores, in order to simplify the analysis, all students in the study subset use only students with a complete set of TAKS math scores (8th grade and exit level) were included in the data subset used in this study.
3. Grades of robotics enrollment – since the focus of the quantitative study is whether robotics could have a long-term effect on test scores and class enrollment, I only included students who enrolled in robotics during their 9th or 10th grade years and examined exit level math scores (taken in 11th or 12th grade) and math/science electives commonly taken in the 11th and 12th grades.
4. Female students – for some unknown reason, the previous three criteria disproportionately removed female students from the database. Because there were not a significant number of female students who remained in the study

data subset, I chose to remove all the girls in order to focus on the male students and simplify the analysis. Only male students were included in the study subset.

The data includes test scores, course enrollments and demographics for each student. Test scores include students' scaled math TAKS standardized test scores (8th grade and exit level), and the month/year that the tests were administered. The course enrollment data consists of the titles, semester enrolled, and semester grades of every math, science, and technology class that each student enrolled in from 9th grade through 12th grade. The demographic information consists of student ethnicity, gender, economic disadvantaged status, English Language Learner (ELL) status, and special education (SpEd) status.

Variables

Standardized math TAKS test scores (8th grade and exit level). All public school students in Texas take a series of standardized tests over their school career, where the immediate result of each test is a raw score of how many questions the student answered correctly. In the study data subset, all test scores are from the TAKS system. However, because the number and difficulty of test questions changed between test administrations, raw scores from different administrations cannot be directly compared. To solve this problem, charts are provided by the Texas Education Agency to convert raw scores to scaled scores that can be directly compared across test administrations (Texas Education Agency, 2017a).

Typically, students usually take the exit level math TAKS exam in the 11th grade, but occasionally in the 12th grade. In this case, all the students in the study subset took the test between 2012 and 2014. For these test administrations, the Texas Education Agency used a scaling system that had an approximate range of 1200-3300. The minimum standard was set at 2100 points, and commended performance at 2400 (Education Service Center, Region 20, 2009). For exit level tests, I am using the TAKS scaled scores in my analysis as continuous numeric variables.

All the students in the study subset took the 8th grade math TAKS test between 2009 and 2010. During this time, the 8th grade math TAKS test converted from a scaled score with a range of 1200-3300 (similar to the exit level test) to a scale with a 0-1000 range (Education Service Center, Region 20, 2009). In order to compare 2009 and 2010 scores, I used data published by the Texas Education Agency to convert both sets of scores into percentile ranks.

Ethnicity. Student ethnicity was self-reported by the student in the 9th grade and is used as a categorical variable in the analysis. Students had the following options for ethnicity: American Indian or Alaskan Native, Asian, Black non-Hispanic, Hawaiian Native or other Pacific Islander, Hispanic, White non-Hispanic, and Two or More Ethnicities. In order to have groups large enough for valid statistical analysis, several ethnic categories were combined into two main groups:

1. Asian /White, non-Hispanic
2. Hispanic/Black non-Hispanic/Two or More Ethnicities

The categories American Indian or Alaskan Native, and Hawaiian Native or other Pacific Islander did not have any members in the study data subset.

Special Education status. Because students are categorized for special education after they are evaluated for qualification and not upon onset of a qualifying condition, special education status is a lagging indicator. A student may qualify for special education, but not have special education status because he/she has not been evaluated yet. Thus, I treated special education as a dichotomous variable and considered a student as special education if he/she has ever qualified for special education during high school.

Economic disadvantage status. A student's free/reduced lunch status was used as a proxy for their socio-economic status. The school district qualifies families as eligible for free lunch if their income falls below 130% of the federal poverty guidelines, and reduced lunch if it is between 130% and 185%. I did not distinguish between students who receive reduced lunch instead of free lunch. In addition, because, as with special education, lunch status is a lagging indicator, I treated economic disadvantaged status as a dichotomous variable and considered a student as disadvantaged if he/she has ever qualified for free/reduced lunch during high school.

English Language Learner status. In the school district, students judged to be English Language Learners (ELL) are placed in English as a Second Language (ESL) classes and transition out of ELL status upon completion of the program. However, while students who complete ESL programs may be able to communicate in English, they typically do not have the mastery to complete academic work (Lee & Buxton, 2010), thus they continue to be at a linguistic disadvantage. For this reason, I treated ELL as a dichotomous variable and considered a student as an ELL if he/she has ever qualified as an ELL student.

In the complete database, gender was self-reported by the student in the 9th grade. However, as previously noted, because there were not a significant number of female students that fit the criteria for the study subset, I removed all female students in order to focus on the male students. Thus, it is not included as a variable in the analysis.

Matching Criteria

Since students in robotics classes are self-selecting and not randomly assigned, it is possible that robotics students are not representative of the larger school population. Based on discussions with the robotics teacher and classroom observers, it was determined that the robotics classroom may have fewer ethnic minority, female, English Language Learners, and special education students than the rest of the school. Thus, for the dataset, I matched on demographic and achievement factors that I hypothesized may be different.

Because I am interested in math and science achievement, I was concerned about whether the robotics students are starting at the same level as the rest of the school. Thus, I matched on previous math achievement, as measured by their 8th grade math standardized score as well as the demographic factors.

Weaknesses

One of the weaknesses of the data is that in order to protect students from being uniquely identified, the dataset contains only a subset of the total number of robotics and comparison students, which were selected by the school district. This reduces the sample size. In addition, demographic groups that may have only a small number of students may not be represented at all, or may have the critical information masked in the data. Information about the proportions of demographic groups are estimates of the true distributions.

Another limitation is the shift in course requirements during the target time period. During the time period in which the students in the dataset were in high school, the Texas high school graduation requirements changed. The “4x4” raised the math and science course requirements to 4 years of each for the recommended graduation plan, and were in effect for students who started 9th grade between the 2007-2008 school year through the 2013-2014 year. Before this period, students were only required to pass three courses in each math and science. This change may have impacted the enrollment in math and science classes and was accounted for during the analysis by adding an independent variable that describes whether a student was subject to the 4x4 requirement or not.

As previously noted, to simplify the analysis and to maintain consistency between tests, I only used students who took all TAKS tests, had a complete set of records, removed students who took robotics after 10th grade, and removed all female students. The disadvantage is that the sample size available for each analysis is reduced, which in turn reduces the power of the analysis.

Research Questions and Data Analysis Plans

Research Question 1

Is there a relationship between enrollment in a high school robotics class and standardized math test scores?

Data

As previously noted, because I am interested in long term effects, I used only the subset of robotics students who enrolled in robotics during 9th or 10th grades, and their comparison counterparts. To make the Research Question 1 results easier to compare to Research Question 2, I only used the subset of students who also qualified for both questions. The final number of students used in the analysis is N=87.

Dependent Variable

High school students in Texas take their exit level standardized state math test at the end of 11th grade or in 12th grade. Thus, my dependent variable is the students' scaled exit level math standardized test score. I hypothesized that robotics students would have higher test scores than similar students who did not enroll in robotics class in high school.

Main Independent and Control Variables

For categorical variables, effect coding was used so that interactions between them can be studied. The main independent variables are:

- Robotics – this variable describes whether a robotics student was enrolled in the robotics class during either their 9th grade or 10th grade year, or was a comparison student (not in robotics). See Table 3.1 for Robotics year codes.

Table 3.1: Effect coding for Robotics variable.

	Robotics
9th or 10th grade Robotics student	1
Comparison (non-robotics) student	-1

In addition, I added several other predictors as control variables. Most of them have been described above.

- 8th grade standardized math scores expressed as percentile rank
- 9th grade math class – While many students have Algebra I as their 9th grade math class, more advanced students could have Geometry or Algebra II. With a limited amount of time to take math classes in high school, which math class a student takes in 9th grade can be an important factor in whether a student will qualify to take advanced math and science course later in high school. Thus, I included it as an ordinal predictor variable. I effect code this predictor set as the variable Post_Algebra_I. See Table 3.2 for Algebra 1 codes. There were no students in the dataset who were behind schedule and did not have at least Algebra I in the 9th grade.

Table 3.2: Effect coding for Algebra 1 variable.

	Post_Algebra_I
More than Algebra I	1
Algebra I	-1

- Tables 3.3-3.7 contain codes for the following variables: Ethnicity, English Language Learner, Economic Disadvantage, and Special Education. American Indian /Alaskan Native and Hawaiian Native/Pacific Islander are not included in Table 3.4 because there were no students in the study subset who identified in those categories. Simiarly, there is no table for gender since there are only male students in the study data subset.

Table 3.3: Effect coding for Ethnicity variable.

	Asian/White, non-Hispanic
Asian	-1
Black, non-Hispanic	1
Hispanic	1
Two or More Ethnicities	1
White, non-Hispanic	-1

Table 3.4: Effect coding for English Language Learner variable.

	ELL
Student had ELL status in high school	1
Student never had ELL status in high school	-1

Table 3.5: Effect coding for Economic Disadvantage variable.

	EconDis
Student had economically disadvantaged status sometime in high school	1
Student never had economically disadvantaged status in high school	-1

Table 3.6: Effect coding for Special Education variable.

	SpEd
Student qualified for special education sometime in high school	1
Student never qualified for special education in high school	-1

Analysis Plan for Research Question 1

To answer the research question, I used multiple linear regression, which has the general equation:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i + \beta_{i+1} x_1 x_2 + \beta_{i+2} x_2 x_3 + \ldots + \beta_n x_1 \ldots x_i$$

where Y is the dependent variable, x are the independent (predictor) variables and β are the weights. The terms past $\beta_i x_i$ express the interactions between the previous predictor variables.

For the analysis, I created a series of models where I varied the independent variables:

- Model 1: Robotics
- Model 2: Model 1 plus 8th grade math test percentile rank
- Model 3: Model 2 plus 9th grade advanced math class
- Model 4: Model 3 plus ethnicity (Asian/White, non-Hispanic)
- Model 5: Model 3 plus interaction terms for ethnicity (Robotics x Asian /White, non-Hispanic)

Research Question 2

Is there a relationship between enrollment in a high school robotics class and later enrollment in advanced STEM courses?

Data

To answer the research question, I started with the subset of robotics students who enrolled in robotics and who had a complete list of STEM class enrollment through 12th grade, and their comparison counterparts. To make the Research Question 2 results easier to compare to Research Question 1, I only used the subset of students who also qualified for both questions. The final number of students used in the analysis is N=87.

Dependent Variables

The school offers several math and science courses beyond the minimum required. However, because in some of these courses, students do not have an independent outside evaluation of their learning (such as a standardized test), it is possible that these classes are not rigorous. Thus, I focused on classes with an Advanced Placement exam or are in the International Baccalaureate program. Calculus and statistics both have AP exams, but calculus is more commonly required for college STEM majors than statistics. There are several AP science subjects, but physics, particularly mechanics, is directly relevant to robotics. Designing and constructing the hardware for the robot is an exercise in mechanical engineering. The concepts of using motors and generating torque are central to robotics, but are also key topics in physics. In addition, physics is also a common requirement for STEM majors. In addition to AP courses, calculus and a second year of physics are also addressed in International Baccalaureate classes. To be inclusive of both the AP and IB courses, I will refer to these groups as Calculus and Physics 2. Thus, the dependent variables are whether a student enrolls in Calculus class or Physics 2 class, and are dichotomous variables.

This decision aligns with the findings of Sadler, Sonnert, Hazari, and Tai (2014), who found that among advanced high school math and science courses, only calculus, physics and a second year of chemistry predicted student interest in a STEM career. While there was no significant difference between having one or two years of calculus, enrolling in two years of physics was a stronger predictor than just one year. Since the robotics class had no chemistry content, I determined that it was unlikely that students would take a second year of chemistry as a result of their experience in the class, and focused on Physics 2 classes. This is also consistent with Trusty's (2002) work that found that calculus is the most significant predictor of girls majoring in math or science in college, while only physics is a significant predictor for boys. Trusty did not include the number of years of course taking in his study.

Independent Variables

The key independent and control variables for this analysis are the same as for the previous analysis. I controlled for both 8th-grade standardized math test percentile rank, and 9th grade math class, as well as for the demographic factors of ethnicity, economic disadvantaged status (as measured by free/reduced school lunch status), English Language Learner, and Special Education status. The coding was the same as with the previous research question.

Analysis Plan for Research Question 2

To answer the research question, I used logistic regression. Logistic regression has a similar principle to linear regression, but is used with dichotomous dependent variables instead of continuous.

As with the previous research question, I created a series of models where I varied the dependent variables:

- Model 1: Robotics
- Model 2: Model 1 plus 8th grade math test percentile rank
- Model 3: Model 2 plus 9th grade advanced math class
- Model 4: Model 3 plus ethnicity (Asian/White, non-Hispanic)
- Model 5: Model 3 plus interaction terms for ethnicity (Robotics x Asian/White, non-Hispanic)

In addition, I also calculated the odds ratio for the final model, which has the general equation:

$$P_r(Y=1) = \frac{e^{\beta_0+\beta_1 x_1+\beta_2 x_2+\ldots+\beta_i x_i}}{1+e^{\beta_0+\beta_1 x_1+\beta_2 x_2+\ldots+\beta_i x_i}}$$

where x_i are the independent variables and β_i are the weights. The odds ratio describes the odds of a robotics student taking a Calculus (or Physics 2) class compared to the odds of a non-robotics student taking the same class, i.e., for every non-robotics student taking Calculus (or Physics 2), how many robotics students will take the same class?

PART 2: QUALITATIVE METHODOLOGY

Study Site

The site of this study is the same robotics class and high school as in the previous section. The class assumed no previous knowledge of robotics and was a full year course during the 2009-2010 academic year, though all of the data I used here is from the Spring 2010 semester. During this year, the school implemented block scheduling, so the class met for 90 minutes every two days. Every two weeks, the class met on Mondays, Wednesdays, and Fridays, while it met Tuesdays and Thursdays on the weeks in between. There were four sections of the robotics class, but the data was collected only during two of the sections (periods 3 and 5). Combined, there were 51 students in the two periods, and the students were all in the 10th, 11th, or 12th grade.

The teacher for all sections had 10 years of prior high school teaching experience, mostly in science education. He had started the robotics team in 2006, and originated the robotics course in the 2008-2009 school year. In addition, a researcher who was observing and video recording the teams occasionally answered students' questions and prompted teams to explain their thinking. In the transcripts, he is listed as a teaching assistant.

Robotics Assignment

Basic robotics hardware and software were taught in Fall 2009. The bulk of the Spring 2010 semester involved the design and construction of a complex robot system consisting of two robots working together.

The first robot (Rail robot) is a mechanical claw that travels up and down a rail. The claw is programmed to examine a multi-level shelf for plastic balls. If it finds a ball, the robot picks it up, travels down the rail to drop the ball to the second robot, and returns to look for another ball. Figure 3.1 is a picture of a Rail robot on the rail and shelf.

The second robot (Stationary robot, or Stat) catches the ball and detects its color. If the ball is green, it will throw the ball through a particular target. If the ball is black, it will throw the ball through a different target.

Students were assigned to teams, and each team was split into two groups. One group designed and built the Rail robot, and the other group designed and built the Stat robot.

In professional engineering projects, members of a design team may not be located at the same physical location or work in the same time zone. To provide a more authentic experience, the robotics project also required two groups in different sections to work together to complete each robot. In all, four groups formed one team to create one complete robot system. The groups Rail Team 1 Period 3, Rail Team 1 Period 5, Stat Team 1 Period 3, and Stat Team 1 Period 5 worked together to create one Rail robot and one Stat robot pair. Each of the groups was assigned either 4 or 5 students, and each student had a defined role in the team.

Figure 3.1: Rail robot perched on rail and shelf system.

The description of the project given to the students is included in Appendix A.

Description of Qualitative Data

The data collected from the project are videos of one robot system design team (Rail1 P3, Rail1 P5, Stat1 P3 and Stat1 P5). The videos were collected periodically over the semester and document each of the groups designing and constructing their robots. For Rail1 group, there are 21 videos, totaling 9.5 hours. For Stat1 group, there are 7 videos, totaling 6 hours. 10-minute final presentations by each of the groups are included in the videos. These artifacts were originally collected by for use in another study (McKenna, 2014).

Data collection was approved through the University of Texas IRB and data was collected only from students who were properly consented. Older students were able to provide their own consent, and parental consent was obtained for younger students.

Research Question and Data Analysis Plan

Research Question 3:

Are robotics students taking advantage of potential opportunities to utilize math and science in their robotics project, or are there missed opportunities that could have been used?

To answer the question, I used a grounded theory analysis on the videos and Google Docs text produced by the student design teams. Originally described by Glaser and Strauss (Glaser & Strauss, 1967), grounded theory is distinguished from other forms of interpretivist qualitative research by its emphasis on emergence. Glaser and Strauss believed that other qualitative researchers often "over-emphasize rigorous testing of hypotheses, and de-emphasize the discovering of what concepts and hypotheses are relevant for the substantive area being researched." (Glaser & Strauss, 1970, p. 288).

Where other methods start with a theoretical framework through which to interpret the data, grounded theory deliberately avoids it. Instead, the guiding principle is to let the theory “emerge” from the data (Merriam, 2002). By insisting on “grounding” the theory in observed data, the goal is to avoid biasing the researcher into using a framework that may not fit the data.

Grounded theory distills its theory through repeated levels of coding and refinement. The process begins with “open coding” where the data elements in the artifacts are initially examined, identified, categorized, and compared to each other. New codes are created and others modified to fit the evidence.

Because I am interested in how math and science could and are being used by the subjects, my initial list of codes included descriptions of the math and science concepts observed (e.g. measurement, algebra, force, momentum). In addition, I also coded the context of the usage (e.g. describing a problem, fixing problem). Thus, each usage of math and science had multiple codes to capture the situation. While these were the initial codes, I added and modified the list to incorporate potentially useful contextual information as I encountered it. The NVIVO software was used to aid in organizing and coding of the video recordings.

In axial coding, codes and categories are reassembled and modified as the researcher tries to expose the underlying phenomena (Mann, 1993). As these connections between categories become evident, it is important to test these relationships against the data (Corbin & Strauss, 1990). Throughout the entire process, new data can be collected or existing data re-evaluated to support or refute the growing theories. As the concepts coalesce and survive scrutiny, the researcher eliminates the weaker connections to focus on a core category on which to build the theory (Mann, 1993).

The final phase is selective coding, where the non-essential concepts and codes are culled, and essential areas of the core category are expanded upon. At this stage, the literature base is often consulted to see how similar ideas have been developed (Mann, 1993).

To support coding reliability, interrater agreement was determined. Another researcher independently coded a portion (10-20%) of the video and the text data, using the codebook from the open coding stage. The results were judged reliable if the overall agreement between coders was at least 80%.

Below in Figure 3.2 is an excerpt from the final presentation from Stat Team 1 Period 3 with example codes. Underlined sections of the transcript are coded. Math and science concepts that were used or talked about were used as codes. Contextual codes are written in italics and are defined as:

Observation – math/science used to describe a phenomenon, but math/science not necessarily used to do something

Design – math/science used to describe a component of the robot design or how it works.

Problem – math/science used to describe or analyze a problem that they encountered.

Fix – math/science used to describe and solve a problem with the robot.

Transcript	Codes
Our specific strategy is to basically just shoot the balls into the specific goal and we do this we have a funnel that collects the balls. The rail robot drops them off at the funnel and they just through the motion of gravity and one wheel that spins to help transport them move to the shooter that is a couple of wheels that ball goes through and are spun by motors and goes off a Lexan ramp and just fires to the goal from there.	Gravity *observation* Angular->linear *design* Motor, inclined plane *design*
And the functional requirements are that it has to the balls have to transport from the funnel to the shooter. And that was a difficulty in our original building design and we had to compromise design because we didn't have a way for the balls to once they fell down from the funnel to the shooter, so that's important and we had to figure out a way to do that. And we also need a powerful enough motor to be able to spin the wheels enough so that they can launch the balls and the balls will actually be able to like have enough momentum to travel into the goal.	Gravity *observation* Angular->linear *design* *fix* Kinematics *fix*
And basically. I kinda gave already a description of the design overview. But so basically our robot was kinda like a box sort of thing which was where the balls went into and on top is the funnel that they were dropped off into and then from they from there coming out of the box was an up sloped ramp with the wheels near the box that the balls went	Inclined plane *design*

Figure 3.2: Sample transcripts with codes

Transcript	Codes
through to shoot them up. And we went through a lot of original construction designs. Originally we wanted to have a rotating base so that we could turn the robot and have it shoot to various goals but that idea was swapped with an idea to have a sorter hooked up to a light sensor and have two shooters going on opposite ends, but then that was too complicated so we simplified it to one shooter that shot both the balls and regardless of like. It would only go to one goal. So it wasn't as like efficient like as some of these other ideas were but it was more simple and doable so that was how it turned out.	
The shooter it…, we had already talked about it but, uses two motors and a series of 4 gears on each side to give each side a little more power. The motor and gears are on the bottom of the piece of Lexan and the wheels are on the top so Gears on the bottom so it doesn't get caught … the ball doesn't get caught on the gears	force *problem fix*
And the funnel is a piece of posterboard then folded and taped into the shape of a funnel and is the maximum catchability cause the balls won't bounce out cause of the slope.	elastic collision, kinematics angle of bounce *problem fix*

Figure 3.2 (continued)

Transcript	Codes
The ramp to the shooter... the ramp is two pieces of metal that are bent into an incline that goes down into the shooter .	incline plane *design*
It also has a wheel that sits in between each piece of metal to help propel the balls into the shooter to get them there.	angular->linear *design*
This wheel is powered by a motor and a gear system. There's one motor and 2 gears to help the balls get up the slight incline before the shooter	angular->linear *design*
All right, so as we were building our robot we ran into a few problems. The first, as --- mentioned, was the competing ideas of either a rotating base or just two different shooters that get fed balls by a sorter. And the problem with these two shooters was that on the base that we constructed there wasn't enough room for both shooters to fit and overall it was just overall too complicated so we kind of scrapped that idea and went to one shooter. The second problem was the sorter. The sorter was pretty much .. if you can like a imagine a chicken rotisserie thing. It's a rod with prongs that like spin and knock the balls either left or right depending on whatever the light sensor read and that was to fix the initial like … if you've got a green ball you don't want to shoot it to the yellow goal or whatever. So that's what the two	

Figure 3.2 (continued)

Transcript	Codes
shooters were doing but the problem with the sorter was it would knock it down but the ball would lose all of its speed that it had from being dropped and it wouldn’t be able to get up the shooter and get launched out by the wheels. And the second .. uh third problem was balls	Velocity *problem* Momentum *problem*
were bouncing out of the frame of the robot . And the robot is basically a square with like a box on top of it made of like tubes and when balls would go down the sorter originally, they would ..	elastic collision *problem*
some of them would bounce out to the left or right and we fixed that by putting	elastic collision *problem*
rubber bands on.	elastic spring *fix*
Our tough challenges. The biggest one was to make a rotating base stable and the double shooter design that was intense and the balance robot was also hard because there was a lot of moving	force balance *problem*
parts that needed to be stable at the same time. And the sorter was probably a huge part because it had to deal with the light sensor, the rotisserie thing and communicating with other groups was probably the main problem. It’s just really hard.	force balance *problem*

Figure 3.2: (continued)

Chapter 4: Results

QUANTITATIVE RESULTS

Dataset Descriptives

As mentioned in the previous chapter, this study used a subset of the complete dataset of robotics and comparison students provided by the school district. The students in the subset have no missing data, took only TAKS exams, and all robotics students were enrolled in the class in either the 9th or 10th grades. The final number of samples is N=87.

Table 4.1 displays the numbers and proportions of the demographic variables in the study data subset. Students were considered Special Education students or an English Language Learner if they had ever been in one of those categories during their high school career. Students were categorized as Economically Disadvantaged if they had ever qualified for free or reduced price school lunch during their high school years.

Table 4.1: Frequencies of demographic variables.

	Robotics (n=53)	Comparison (n=34)
Race/Ethnicity		
American Indian/ Alaskan Native	0 (0.00%)	0 (0.00%)
Asian	2 (3.77%)	0 (0.00%)
Black, non-Hispanic	0 (0.00%)	1 (2.94%)
Hawaiian Native/Pacific Islander	0 (0.00%)	0 (0.00%)
Hispanic	14 (26.42%)	11 (32.35%)
Two or More Ethnicities	1 (1.89%)	2 (5.88%)
White non-Hispanic	36 (67.92%)	20 (58.82%)
Economic Disadvantaged	8 (15.09%)	8 (23.53%)
English Language Learner	4 (7.55%)	2 (5.88%)
Special Education	9 (16.98%)	5 (14.71%)

Due to small numbers of some race/ethnicity groups, I combined the Two or More Ethnicities and the Black, non-Hispanic students with the Hispanic students, and I combined the Asian students with the White, non-Hispanic students. While Asian students are often combined with other minority students, there are several reasons why I am grouping them with the White students. First, while African-American and Hispanic students are underrepresented in STEM disciplines compared to percentage of the population, Asians are typically overrepresented. Thus, the division is a separation between overrepresented groups versus underrepresented instead of any individual race or ethnicity.

The means and frequencies of the predictor variables used in the statistical analysis in this study are displayed in Table 4.2. For continuous variables (i.e. 8th grade math test percentile rank), the table lists the means and standard deviations of the overall data, robotics group, and comparison group. For categorical variables (9th grade advanced class, and White or Asian, non-Hispanic), the table lists the percentages in each group. In addition, the distributions of the predictors over the robotics and comparison groups were conducted and are included. A t-test was used for the continuous variable while $\chi 2$ was used for categorical variables. Because the set of robotics students may not match the general population of the school, I had requested that the set of students included in the dataset would be approximately matched with respect to race/ethnicity and 8th grade math test achievement. The results in Table 4.2 show that there are no significant differences at the 0.05 level between the distributions of any of the predictor variables over the subset of data used in the study.

Table 4.2 : Descriptive statistics for predictor variables for the comparison and robotics groups.

	Overall (N=87)	Robotics (n=53)	Comparison (n=34)	Test statistic (df=93)	p
8^{th} grade math test percentile rank	70.30 (25.89)	72.33 (25.52)	67.13 (26.51)	t = -0.91	0.364
9^{th} grade advanced math class	34 (39.08%)	24 (45.28%)	10 (29.41%)	χ^{2} =2.19	0.139
White or Asian, non-Hispanic	59 (67.82%)	39 (73.58%)	20 (58.82%)	χ^{2} =2.07	0.150

*p<0.05

Table 4.3 displays the intercorrelations between the predictor variables. Overall, the correlations are weak to moderate between the predictors, with the strongest being between 8th grade percentile score and 9th grade advanced class at 0.50.

The means and frequencies for the dependent variables, and the distribution of robotics and comparison students are detailed in Table 4.4. While there is no significant difference between groups for Physics 1 enrollment, a significantly larger percentage of robotics students take Calculus and Physics 2.

Table 4.3: Intercorrelations for predictor variables.

	1	2	3	4	5
1 Robotics	1.00				
2 8^{th} grade percentile score	0.01	1.00			
3 9^{th} grade advanced class	0.16	0.50	1.00		
4 Asian/White, non-Hispanic	0.15	0.30	0.20	1.00	
5 Robotics x Asian/White, non-His	0.32	0.14	0.11	0.15	1.00

Table 4.4: Descriptive statistics for dependent variables for the comparison and robotics groups.

	Robotics (n=53)	Comparison (n=34)	Test statistic χ^2	p
Physics 1	49 (92.54%)	29 (85.29%)	1.14	0.285
Calculus	22 (41.51%)	7 (20.59%)	4.08	0.043*
Physics 2	19 (35.84%)	4 (11.76%)	6.18	0.013*

$^*p<0.05$

Regression Results

Tables 4.5-4.8 display the results of the linear and logistic regressions performed. For each analysis, the models used are:

Model 1: Robotics

Model 2: Model 1 + 8th grade math test percentile

Model 3: Model 2 + 9th grade advanced math class

Model 4: Model 3 + Asian/White, non-Hispanic

Model 5: Model 4 + Robotics x (Asian/White, non-Hispanic)

Exit Level Test Scores

To analyze the exit level math test scaled scores, I performed a 2-tailed multiple linear regression on the data using an $\propto=0.05$ significance level. A separate regression calculation was performed for each model, applying the predictors specified above. Table 4.5 displays all of the regression results.

In Model 1, the only predictor is whether the student was enrolled in robotics, and it did not prove to be significant. The addition of 8th grade math test percentile rank in Model 2 created a marked increase in the accuracy of the modeling equation, causing the R^2 value to jump from 0.03 to 0.54. Unsurprisingly, the new predictor is significant at the

$p<0.001$ level. Although Model 3 adds another highly significant predictor, there is only a small increase in the R^2 value to 0.60, indicating that 9th grade advanced math class only accounts for a small part of the variance. Through all of the models, only 8th grade math test percentile rank and 9th grade advanced math class were significant predictors.

Model 4 adds the race/ethnicity predictor of non-Hispanic White or Asian students, and Model 5 introduces the interaction of Robotics and non-Hispanic White or Asian. It is interesting to note that while the main effect of race/ethnicity has a positive coefficient, indicating that non-Hispanic White and Asian students are predicted to have higher 11th grade math scores, the interaction term is negative, suggesting that underrepresented minority students in robotics may receive a math score boost over their non-Hispanic White classmates and Asian classmates. However, since neither predictor is significant, these effects are far from certain. Though with a significance level of the 0.107 for the interaction term, it is possible that a larger dataset could push this term to significance.

For each TAKS administration, there is a mapping from the raw score (number of questions answered correctly) to a scaled score. However, the mapping is non-linear. The difference between answering 21 questions correctly and 22 questions correctly increases the scaled score by 2 points. However, the difference between answering 56 questions correctly and 57 questions correctly increases the scaled score by 101 points. The increase in scaled score for an extra correct question ranges from 2 points to 173 points. The largest score increases happen at the extreme ends of the scale. For students in the middle 68% (one standard deviation from the mean), the average scale score gain for each question is approximately 13.7 points. Typically, the exit level math TAKS test has between 58 and 60 questions. Using this approximation of 13.7 for each question, in Models 1-4, robotics students scored 2.6, 1.5, 1.1, and 1.1 additional questions correctly respectively. Since Model 5 adds the interaction term, race/ethnicity must also be taken into account. Asian/White, non-Hispanic students who take robotics scored 4.16 points less than their comparison group counterparts. Meanwhile, Hispanic/Black, non-Hispanic/Two or More Ethnicity students scored 50.14 points more, which I estimate to be 3.7 additional questions correct.

Physics 1

In this work, I define Physics 1 as the first high school class dedicated solely to physics. Unlike later physics classes, knowledge of calculus is not a requirement.

Since enrollment in a class is a binary variable, logistic regression was used for the following set of calculations instead of multiple regression. A separate logistic regression calculation was performed for each of the five models. Table 4.6 shows the results of the analysis. As before, $\propto=0.05$ was used as the significance level.

Focusing on the odds ratios, for Models 1-5, robotics students are 1.45, 1.39, 1.36, 1.37, and 1.33 times more likely to enroll in Physics 1 than comparison group students, respectively.

However, robotics failed to be a significant predictor of Physics 1 enrollment in any of the models. Since Table 4.3 shows that the great majority of both robotics and comparison students enroll in the class, this is not a surprising result. Physics 1 seems to draw from a wide cross section of students. In fact, 8th grade math test percentile was the only significant predictor in any of the models.

There is one outside factor that may have affected the data surrounding Physics 1. During this time period, students in Texas were subject to the “4x4” science and math graduation requirement, where the recommended public high school graduation plan required students to pass four science and four math courses, which was an increase from the previous requirements. During the years the “4x4” was in effect, there is likely to have been a boost in science and math elective course enrollments, including Physics 1, among students who would have otherwise enrolled in other electives, potentially reducing the effect that robotics may have had in promoting physics.

Calculus

In the study school, calculus was taught in multiple courses. In addition to the AP AB Calculus and the AP BC Calculus classes, the International Baccalaureate (IB) Mathematics Higher Level, covers a number of topics including calculus. Students in all of these classes were grouped together as Calculus students.

The results of the logistic regression on the five models are shown in Table 4.7. In the first model, robotics was the only predictor variable and was significant at the $p<0.05$ level. However, as I progressed through the models and more predictors were added, the significant variables shifted. In Model 2, 8th grade math test percentile rank became highly significant ($p<0.001$), and robotics became non-significant. In Model 3, the results shift again. Now, whether students were enrolled in an advanced math class in 9th grade is highly significant ($p<0.001$), and both robotics and 8th grade math test percentile become insignificant.

This result remained stable in Model 4, with 9th grade advanced math class as the only significant predictor.

The fact that enrollment in an advanced math class in the 9th grade is a highly significant predictor is not surprising. The typical math sequence consists of year-long courses in Algebra 1, Geometry, Algebra II, Pre-Calculus, and then Calculus. If a student is enrolled in Algebra 1 in 9th grade, and takes one math course each year, then he/she will only reach Pre-Calculus by the end of four years. While it is possible to enroll in two math courses in a year and reach Calculus, it is a rare occurrence. Nearly all Calculus students passed Algebra 1 before the 9th grade.

While robotics was not significant past the first model, it remained much closer to significance than the other predictors other than 9th grade advanced math class. It is quite possible that a modestly larger dataset would cause the p-value to cross the threshold.

Based on the odds ratios, for Models 1-5, robotics students are 1.65, 1.63, 1.86, 1.87, and 2.11 times more likely to enroll in one of the Calculus courses than comparison group students, respectively.

Physics 2

Like Calculus, students at the school had several options for a second physics class: AP Physics B, and AP Physics C classes, and IB Physics 2. While I have grouped all the students enrolled in these courses together as Physics 2 students, it is important to note that some of the courses, such as AP Physics C, are calculus based and require it as a co-requisite course, while others, such as AP Physics B, do not use calculus.

Table 8 displays the logistic regression results of Physics 2 enrollment. In Model 1, robotics is established as a significant predictor of enrollment at the 0.05 level, and in Model 2, robotics becomes less significant while 8th grade math percentile rank immediately becomes highly significant ($p<0.01$). In Model 3, 9th grade advanced math class becomes highly significant ($p<0.001$) and 8th grade math test percentile becomes insignificant. It is not surprising that the predictors are following the same pattern as calculus enrollment since many of the Physics 2 courses are calculus-based. Typically, students in Physics 2 are enrolled in a calculus class in the same year.

However, unlike the results for calculus, robotics remains significant through Model 3. But even in Model 4, robotics is close to the threshold. It is possible that a larger sample size would maintain the significance of robotics.

According to the odds ratios, for Models 1-5, robotics students are 2.05, 2.06, 2.13, 2.03, and 1.85 times more likely to enroll in one of the Physics 2 courses than comparison group students, respectively.

Table 4.5: Multiple regression predicting exit level math TAKS scaled scores for robotics and comparison group students. N=87.

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Robotics					
coefficient	35.30	20.08	14.81	14.78	22.99
SE	22.68	15.52	15.07	15.28	15.84
t	1.56	1.29	0.98	0.97	1.45
8th grade math test percentile rank					
coefficient		5.86***	4.97***	4.97***	5.06***
SE		0.59	0.65	0.68	0.67
t		9.96	7.62	7.35	7.56
9th grade advanced math class					
coefficient			47.78**	47.77**	47.80**
SE			17.34	17.46	17.26
t			2.75	2.74	2.77
Asian/White, non-Hispanic					
coefficient				0.26	2.53
SE				16.55	16.41
t				0.02	0.15
Robotics x Asian/White, non-Hispanic					
coefficient					-27.15
SE					15.80
t					-1.72
Constant					
coefficient	2473.45	2064.78	2138.93	2139.02	2135.82
SE	22.68	43.86	50.08	50.69	52.14
F statistic	F(1,85)	F(2,84)	F(3,83)	F(4,82)	F(5,81)
	2.42	52.17	40.04	29.67	24.89
R^2	0.03	0.55	0.59	0.59	0.61

*p<0.05, **p<0.01, ***p<0.001

Table 4.6: Logistic regression analyses predicting enrollment in a Physics 1 class for robotics and comparison group students. N=87.

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Robotics					
B	0.37	0.33	0.31	0.32	0.29
SE	0.36	0.38	0.38	0.38	0.39
Odds Ratio	1.45	1.39	1.36	1.37	1.33
95% CI of Odds Ratio	[0.72, 2.92]	[0.66, 2.92]	[0.65, 2.88]	[0.65, 2.91]	[0.62, 2.84]
8th grade math test percentile rank					
B		0.04**	0.03*	0.03*	0.03*
SE		0.01	0.02	0.02	0.02
Odds Ratio		1.04	1.03	1.04	1.03
95% CI of Odds Ratio		[1.01, 1.07]	[1.00, 1.07]	[1.00, 1.07]	[1.00,1.07]
9th grade advanced math class					
B			0.32	0.33	0.33
SE			0.61	0.61	0.61
Odds Ratio			1.37	1.39	1.40
95% CI of Odds Ratio			[0.41, 4.56]	[0.42, 4.61]	[0.42, 4.63]
Asian/White, non-Hispanic					
B				-0.11	-0.09
SE				0.41	0.41
Odds Ratio				0.90	0.91
95% CI of Odds Ratio				[0.40, 1.99]	[0.41, 2.04]
Robotics x Asian/White, non-Hispanic					
B					0.21
SE					0.39
Odds Ratio					1.23
95% CI of Odds Ratio					[0.58, 2.63]
Constant					
B	2.13***	-0.11	0.30	0.26	0.30
SE	0.36	0.77	1.09	1.10	1.10
Odds Ratio	8.43	0.90	1.35	1.30	1.35
95% CI of Odds Ratio	[4.20, 16.91]	[0.20, 4.06]	[0.16, 11.49]	[1.51, 11.24]	[0.16, 11.63]

*p<0.05, **p<0.01, ***p<0.001

Table 4.7: Logistic regression analyses predicting enrollment in a Calculus class for robotics and comparison group students. N=87.

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Robotics					
B	0.50*	0.49	0.62	0.63	0.74
SE	0.25	0.28	0.44	0.44	0.53
Odds Ratio	1.65	1.63	1.86	1.87	2.11
95% CI of Odds Ratio	[1.01, 2.72]	[0.93, 2.85]	[0.79, 4.40]	[0.79, 4.47]	[0.75, 5.90]
8th grade math test percentile rank					
B		0.06***	0.02	0.02	0.02
SE		0.02	0.03	0.03	0.03
Odds Ratio		1.06	1.02	1.02	1.02
95% CI of Odds Ratio		[1.03, 1.10]	[0.97, 1.07]	[0.97, 1.07]	[0.97, 1.07]
9th grade advanced math class					
B			2.62***	2.63***	2.65***
SE			0.60	0.61	0.62
Odds Ratio			13.84	13.92	14.15
95% CI of Odds Ratio			[4.24, 45.24]	[4.22, 45.86]	[4.20,47.73]
Asian/White, non-Hispanic					
B				-0.05	-0.05
SE				0.50	0.52
Odds Ratio				0.95	0.95
95% CI of Odds Ratio				[0.36, 2.55]	[0.35, 2.58]
Robotics x Asian/White, non-Hispanic					
B					-0.23
SE					0.52
Odds Ratio					0.80
95% CI of Odds Ratio					[0.29, 2.21]
Constant					
B	-0.85**	-5.61***	-2.56	-2.56	-2.71
SE	0.25	1.52	2.09	2.09	2.12
Odds Ratio	0.42	0.004	0.08	0.08	0.07
95% CI of Odds Ratio	[0.26, 0.71]	[0.00, 0.07]	[0.00, 4.65]	[0.00, 4.66]	[0.00, 4.27]

*p<0.05, **p<0.01, ***p<0.001

Table 4.8: Logistic regression analyses predicting enrollment in a Physics 2 class for robotics and comparison group students. N=87.

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Robotics					
B	0.72*	0.72*	0.75*	0.71	0.61
SE	0.30	0.33	0.38	0.38	0.44
Odds Ratio	2.05	2.06	2.13	2.03	1.85
95% CI of Odds Ratio	[1.13, 3.71]	[1.09, 3.89]	[1.02, 4.45]	[0.96, 4.29]	[0.78, 4.38]
8th grade math test percentile rank					
B		0.06**	0.03	0.03	0.03
SE		0.02	0.02	0.02	0.02
Odds Ratio		1.06	1.03	1.02	1.03
95% CI of Odds Ratio		[1.02, 1.11]	[0.98, 1.08]	[0.98, 1.08]	[0.98, 1.08]
9th grade advanced math class					
B			1.62***	1.63***	1.65***
SE			0.43	0.44	0.44
Odds Ratio			5.04	5.13	5.21
95% CI of Odds Ratio			[2.15,11.81]	[2.17,12.10]	[2.18,12.42]
Asian/White, non-Hispanic					
B				0.51	0.45
SE				0.42	0.44
Odds Ratio				1.66	1.58
95% CI of Odds Ratio				[0.72, 3.82]	[0.67, 3.70]
Robotics x Asian/White, non-Hispanic					
B					0.18
SE					0.44
Odds Ratio					1.20
95% CI of Odds Ratio					[0.51, 2.84]
Constant					
B	-1.30***	-6.15***	-3.93	-3.97*	-3.86
SE	0.30	1.77	2.01	2.02	2.03
Odds Ratio	0.27	0.00	0.02	0.02	0.02
95% CI of Odds Ratio	[0.15, 0.49]	[0.00, 0.07]	[0.00, 1.02]	[0.00, 0.99]	[0.00, 1.14]

*p<0.05, **p<0.01, ***p<0.001

QUALITATIVE RESULTS

The qualitative analysis is based on video recordings of a robotics class as they work on a capstone project, and focuses on two student teams, one rail robot team and one stat robot team. While the recordings were spread out throughout the duration of the project, not all class meetings were recorded. In total, there were 10 hours and 47 minutes of the rail robot team and 8 hours and 27 minutes of the stat team. For each of the students who appear in the recordings, the proper consents/assents were collected.

To answer the question of what math and science learning opportunities could have occurred in the class, I must first answer what math and science usage actually occurred. In order to characterize the possible learning, the following questions must be asked:

1. What math and science topics and skills were being used by students in the class?
2. How were the topics used? Were students calculating formulas or were they applying them at a conceptual level?
3. In what context were the students using math and science?

Transcription and Coding

The first step of the analysis was to transcribe the relevant information from the videos. Not every spoken word was transcribed, but only the speech that was relevant to the teams' work on the project. In addition, where the speech was ambiguous or it referred to something visual, I added contextual information in brackets to aid comprehension of the situation. Two examples of this are listed below:

R: We're going to have like a thing [makes roof shape with hands] like this.

> N: It’s going to move like this [bends arm at the elbow and swings forearm] … like that and have a grabbing hand.

Some of the video includes interactions between team members and either the teacher/teaching assistant or other students in the class. Relevant discussions about the project that include math or science were also included.

In the first phase of the analysis, open coding, using the transcripts, I created codes centered around the above questions: what math/science topics were being discussed or used, how were the topics used, and context of the usage. Table 4.9 shows the codes used along with examples from the transcripts.

The topic codes were simply the science or math subject that the students were referencing in their discussion. Often, the correct code was easily determined because the students would use the appropriate terminology or the reference would be clear (e.g. “it would have enough momentum”, “it was pretty heavy”), but sometimes, the appropriate code would have to be ascertained from the discussion (e.g. “motors to be able to spin the wheels enough so that they can launch the balls”). Some of the codes overlap or are more specific versions of other codes (e.g. gravity and force, pneumatic and pressure). This reflects the fact that there is different terminology for subcategories of concepts, i.e. gravity is a type of force. Also, sometimes student discussions are clear and specific about concepts and sometimes they are vague or the speak more generally. In each case, I used the most specific codes which fit the context. Where necessary, multiple codes were applied to some statements.

Table 4.9: Codes used in qualitative analysis

Category	Code	Example
Math/Science Topic	Force	… so it won't go that way and that way and won't fly out.
	Speed	… we wanted it to be fast
	Weight	… so it was pretty heavy …
	Force balance	We put more weight on this side so that it would be even, like equally balanced
	Diameter, radius	The PVC looks like 3 inches inner diameter
	Measurement	… and from that, we measure about 1.63 inches away.
	friction	Like put a wheel sideways or something so the rubber would keep it from sliding
	2D geometry	How they have like a triangle with a rectangle and another triangle coming down
	Revolve	… the top base spins …
	Material strength	Is that too much weight for like the top piece?
	Elastic collision	…some of them would bounce out to the left or right and we fixed that by putting rubber bands on.
	Pressure	It has to be really tight.
	Momentum	…the balls will actually be able to like have enough momentum to travel into the goal
	Inclined place	… coming out of the box was an up sloped ramp …
	Angular->linear	…powerful enough motors to be able to spin the wheels enough so that they can launch the balls …
	Pneumatic	Pneumatic so that we could make a door for the funnel that would control which ball would come through
	3D geometry	I want them to be concentric, but I want them on a different plane.
	Gravity	…have something come down right here so the ball doesn't fall?
	Angles	Well, it just seems more complicated than suckering two flat pieces together at a 45 degree angle.
	Torque	And so it was twisting off the rail…
	Stability	Four has more points of contact, so it's more sturdy.

Table 4.9 (continued)

Category	Code	Example
Math/Science Topic	Spatial	So do you think we can keep this size, but flip the motors here
	Power	… so the more weight it has, the more power it has to do …
	Material rigidity	“Isn’t this supposed to bend?”
	Parallel	How do you make this, like, parallel …
Context	Explain	For all the times the small one turns, it will take 12 times for this to turn to actually turn the big one once
	Observation	This base is so sturdy.
	Description	The motors are going to mount, like right here
	Design	We were going to use gears for the arm, right?
	Problem	These gears don’t turn when the axle turns
	Fix	Wouldn’t it be like really heavy? No, it can be like really thin metal.
	Teacher initiated	You should say “center of gravity”.
Usage	Conceptual	If it doesn’t bounce, all we have to do is add more metal.
	Calculation	What fraction is a .93333?

Two codes were used to describe the students’ usage of math and science material: calculation and conceptual. The first one was applied if the students used or computed a formula or performed some other mathematical calculation. The students could have used a calculator or a computer as well as performed it by hand. On the other hand, the conceptual code was applied if the students talked about a math or science idea but did not perform a calculation.

To help capture context, I used a series of codes to describe the project activity that the teams were engaged in when they discussed the math or science.

- Explanation – explaining a math/science concept to someone else
- Observation – using a math/science concept or terminology when making an observation about the project or a robot

- Description – using math/science when describing their robot to others
- Design – using math/science when discussing design decisions or choices with team members or teacher/teaching assistant
- Problem – using math/science in reference to a problem in their design
- Fix – using math/science concepts when referring to a possible method to solve a problem

In addition, I used the code "Teacher initiated" to indicate the occasions when the teacher or teacher's assistant introduced new math or science ideas and terminology to the students.

In the second phase of the analysis, axial coding, the previous codes were refined. The Texas Essential Knowledge and Skills (TEKS) specify the required curriculum for Texas public schools (Texas Education Agency, 2017b). Two codes were added to reflect whether the topics used by students are covered in the high school math or science TEKS. The courses I included were the required math classes (Algebra I, Geometry, and Algebra II) and Physics.

In the final phase, selective coding, codes were finalized and the main themes were identified and explored. Lesser themes were discarded.

Main Themes

From the transcribed videos of the rail and stat team, three main patterns were identified concerning the students' math and science learning and usage.

Theme #1: Math and science concepts were invoked/applied more often during problem solving than design.

Figure 4.1 displays a chart of the proportion of each contextual code that was encountered in the transcripts. The majority of math and science students were engaging in was in either the context of talking about a problem with the robot or in an attempt to fix the problem. Students talking about the design of the robot accounted for less than one fifth of the math and science discussion. This result was somewhat counterintuitive since I coded as "design" several activities that a high potential for math and science content. These include expectations of how the robot would operate, design trade-offs, and discussing the pros and cons of alternative design ideas.

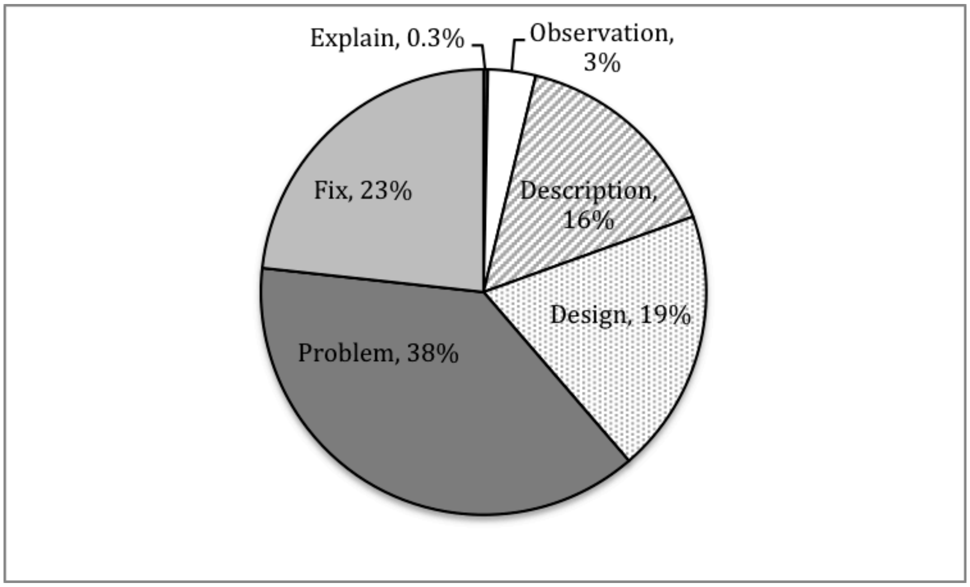


Figure 4.1: Relative proportions of context codes

The following are three examples of typical statements and exchanges about design.

> R: Maybe the funnel doesn't start right here. Maybe it's just like a slightly [gesturing a shallow ramp] thing

> R: So, an arm is going to attach. Like the shoulder. How is the shoulder and arm going to, is it going to be on the inside?
>
> N: Well, no cause the way she did it the motor is attached to the house then. Like that [gesturing with pieces] . So it is attached like that.

> R: I don't know. Maybe the middle would be a better position.
>
> N: We want to do the middle. That way when we have the second motor here. Like mounted to the bottom, right?
>
> P: This is going to be attached to the side of the house, no?
>
> N: This is going to be attached to the top of the house.

In the first example, R is making a design suggestion, which uses an inclined plane. Here, the student has brought in a physics concept to help accomplish their goal.

In the second, the students discuss details of how to attach the robot arm and how it fits within the constraints of the existing design, and in the third example, they are optimizing the placement of a part. In the first two cases, while the students are engaging in design activities, neither of the issues they are working around involves math or science concepts.

In contrast, below are five typical statements and exchanges between students who are confronting a problem with their design and need to fix it.

N: The gears are instead of like meshing; they’re leaning into each other [makes leaning gesture with hands], so they’re brushing [makes rubbing motion]

N: I see what you are doing. What I’m thinking is I’m going to make this massive cube and do that Hole Wizard thing where it’s like

R: But wait. Wouldn’t that be the opposite of a funnel? Like a funnel mold?

N: let’s see if it fits … we’ll just attach it like that. Really we could just use it. Screw it down. That doesn’t necessarily need to be attached, you know.

R: But then it would be less stable, you know.

N: That’s true.

P: See it’s going to slip [grabbing ball with claw]. It has to be really tight …

M: I’m just trying to think of a way to keep it from sliding and I thought if you did that [points at part held by S] and then mounted a wheel on it or something.

O: Yeah, case then the rubber would

S: It would rotate

M: That’s cool. Like put a wheel sideways of something so the rubber would keep it from sliding.

In the first example, N is trying to communicate the problem with their gearing system. Not only is she discussing details of the function of the gears, but she is touching on the idea of friction between the teeth of the unaligned gears.

In the second case, the students are using the Solidworks modeling tool and have run into a problem attempting to create a model of a funnel. Here, N is proposing a 3D geometric solution where instead of adding one 3D shape to another, she takes a cube and subtracts a cone shape using the Solidworks Hole Wizard tool. R points out an error in N's geometric thinking.

In the third example, R notices that N's idea has a problem in that the design is less stable than the alternative. Here, stability can be thought of in terms of a force balance and stability is the tolerance for imbalance between the forces.

With example four, P notices that the claw mechanism does not have enough friction to keep the ball from falling (gravity), and then solving the problem by increasing by increasing friction through increasing the pressure the claw exerts on the ball.

In the last case, M is discussing the problem that he noticed because there is not enough friction between two surfaces, and proposed a solution using a repurposed wheel with tire because rubber has a higher coefficient of friction. S points out a problem with M's plan because the tire will rotate when a force is applied. M offers an additional fix by altering the alignment of the tire to be sideways (perpendicular) to the direction of the force to minimize rolling.

These sample problem and fix statements demonstrate that these students are comfortable thinking and communicating math and physics concepts to each other, and therefore math and physics should not be a barrier when conducting design activities.

However, it is still more common for the students in this study to use math and science when solving problems than it is when creating the initial design.

While this class did not use a formalized design cycle, it is important to note that discussing problems and fixes are necessary parts of the design process. In fact, in a survey of popular design cycles used in education and industry, though they are sometimes listed under different names, addressing problems and finding fixes are integral in each one (Guerra, Allen, Crawford, & Farmer, 2012). Many of these cycles have project phases dedicated to the redesign or optimization of an original design. Each redesign/optimization either implicitly or explicitly includes another round of problem and fix steps.

Theme #2: Most of the mathematics content in the videos can be placed into two categories: geometry and measurement.

While some of the robot design and construction utilized angles and shapes, most of the geometry was utilized when the students created mathematical modeling using the Solidworks CAD software. Much of the geometry was based in the simple two-dimensional shapes of rectangles and circles, and finding the diameters. However, largely due to the CAD component, students also needed to create three dimensional shapes from either the extrusion of 2D shapes or by combining simpler 2D and 3D shapes similar to Constructive Solid Geometry (CSG) in computer graphics.

> N: I don’t know how to make a circle on the same, on a different plane. Like I want them to be concentric, but I want them on a different plane.
>
> R: Oh, I gotcha.
>
> N: Cause I want to make this funnel. I decided that since the this is a Boss/Base, I could just [makes a stretching motion], and it works.

In this example, N was attempting to create a model of a conical funnel (a truncated cone) by using the Solidworks Boss/Base tool to extrude a smaller circle into a larger circle.

> M: You know like grocery carts? How they have like a triangle with a rectangle and another triangle coming down and the wheel comes up inside of it?

Here, M was attempting to describe the shape of caster and wheel using simpler geometric figures.

Predictably, all of the science content was related to physics. Given that it is a robotics class, it would have been surprising to see chemistry, biology, or earth science directly used by the students. With the robotics kits abstracting away most of the electrical details of the control and motors, all of the codes created concern mechanics and kinematics. While much of the communication involved ideas from the first-year physics course, such as force, force balancing, inclined planes, and momentum, a substantial amount of discussion centered around more advanced concepts, such as gears and material strength. In the following example, N is explaining the system that they are using to slow down the movement of their robot.

> N: This will make the small one turn. For all the times the small one turns, it will take 12 times for this to turn to actually turn the big one once … and it will go slower …

While it can be expected that some new math and science concepts were taught to students in the course of the robotics class, it is surprising how often those new concepts were used. Forty-two percent of the student discussions used science and math concepts not taught in the high school math or physics TEKS. In fact, several of the most commonly used codes (e.g. gearing, material strength) were not TEKS subjects.

Theme #3: "Good enough" vs. precision in design.

One surprising pattern that emerged from the analysis of codes is that all of the calculations performed by the students were in relation to measurement.

> R: It will be right there. It starts. [measuring and drawing] and then 3.16 inches … So this is 3 and a half, 3 and three quarters. What's an eighth?
>
> N: I want to say it's like [using calculator]

This means that all of the physics used by the students was done at a conceptual level without computing any formulas. However, without working through formulas, it can be difficult to predict the effects of design decisions. While a conceptual understanding of mechanics can allow one to identify the forces at play in a situation, it does not allow one to tell if the forces are balanced or if a system is underdesigned or overdesigned. Imbalances and underdesign can lead to a system failure. Overdesign may not always lead to failure, but may be unnecessarily costly and limit options. Without accurate predictions, successful completion of a design proceeds through either trial and error, or through leveraging the experience and knowledge of an authority. The following was taken from the oral presentation each team made at the conclusion of the project. A classmate in the audience asked the team a question.

> Classmate: So when y'all were making the robot, … did it get harder and harder to keep it balanced on the rail? Like did that ever become a really big problem?
>
> R: Actually, we thought it would be a really big problem, but it really wasn't.
>
> N: Yeah, also because we had a lot of motors and servos, we had to have several motor controllers so that it sort of luckily worked out the extra motor controllers counteracted the weight of the arm.
>
> R: Yeah, but like who knows what would happen if we programmed it.... we don't know if would fall off or anything.

Indeed, it seems that the teacher was encouraging an experimental approach to comprehending and fixing some design problems instead of promoting a more scientific understanding and characterization of the issues. In the following example, it seems that the teacher is rushing the team to immediately make a physical model instead of a more a scientific method of encouraging the team to think of hypotheses of how the system works before using a physical model to verify their ideas.

> T: You guys kind of played around with the angles, different options [holds wheels against rail at angle]. Um, I do know a group, yesterday, was kind of messing around with that and theirs was too wide and the thing was just moving around all over the place. … But I think if you make a prototype, even though it seems like we are close to running out of time, if you make a prototype, you are going to understand the situation much better.

The lack of formulas and thoughtful prediction seem to be part of a larger culture where precision and exactness is not a priority. Throughout the class, it seems as there was a “good enough” attitude where instead of optimizing a design, the primary goal was to simply achieve a minimum level of functionality. This is demonstrated in the next two examples.

N: OK, let's just make it longer and see what happens. Cause we can always cut it off but we can't

R: Should we make this a nice whole number, like 18.

N: Let's do it. ... totally random number ... OK, uh. What happens when we don't smart dimension everything. OK. This needs to be smart dimensioned.

R: So do you just want to keep just 9 inches? That's a pretty solid number...

N: Yeah

R: We need to draw in our 6 blah blah [sic] inches. And from that, we measure about 1.63 inches away.

…

N: Yeah, why do we need to do 1.63 inches away from …?

…

N: ... have a little bit more room for safety's sake. [holds pieces against old roof] We don't necessarily want all this content right up there. You know like . It'll be nice if there was a buffer. Is buffer a preferred word for it?

R: I think so. It works. So we're going to ... down six and a half inches.

In the last example, despite having calculated an exact measurement, the students deliberately veer away from it by an arbitrary amount to provide an extra margin for error. In the next example, the teaching assistant (TA) is helping a student with a Solidworks problem.

TA: That is a good question... the gears will mate to one another?

A: Yeah

TA: But these won't?

A: Yeah. I could do that, but ...

TA: But they're not mated?... Did you select both parts to mate?... Huh, I wonder if it doesn't believe it's a gear. That's kind of weird. Maybe there's an artifact.... Do you need it to? It looks like it's not quite there.

A: Or I could just leave it like that.

TA: You could. It's just a drawing. I doesn't have to be mechanically right. And since you're on a deadline, that might be it.

Chapter 5: Discussion

RESEARCH QUESTION 1: STANDARDIZED MATH SCORE ACHIEVEMENT

A number of previous studies have found significant increases in math achievement after a robotics intervention. Iturrizaga (2000) worked with elementary school children in a dozen schools across Peru. Working in Sweden, Hussain et al. (2006) separated students into math test performance bands and found that there were math gains for students in the middle bands, but not for the high or low performing students. The only researchers who completed a longitudinal study, Wolfgang et al. (2003) found significant standardized math score benefits for students who were more adept at LEGO construction, with the gains becoming more significant as the students progressed in school. The adept students also tended to enroll in more elective math classes, which may have further affected their test scores. However, it must be noted that their sample size was very small (n=19), and they were using non-robotics LEGO.

On the other hand, Laughlin (2013) failed to find significant results for math score achievement among the 4th and 5th grade students she studied. Meanwhile, Tran and Nathan (2010) discovered a significant negative impact on math scores for a large sample of PLTW students.

Most studies of robotics and math achievement are concerned with the immediate, short-term effects of robotics. However, like Wolfgang et al. (2003) and Tran and Nathan (2010), my goal was to examine the effect on math achievement over the period of years. In this study, I examined whether enrollment in robotics class in the 9th and 10th grade was associated with standardized math score achievement in the 11th grade.

The results of the regression analyses states that robotics class was not a significant predictor of math achievement in any of the models. Of the input variables, only 8th grade math score percentile and 9th grade advanced math course were of significance. This result agrees with the findings of Laughlin (2013). Unlike Tran and Nathan (2010), I did not find a negative effect. Unfortunately, because the number of samples is small, I was unable to separate the results into performance bands like Lindh and Holgersson (2007) to see whether middle performing students had different results than either top or bottom performing students.

This answer is consistent with what I observed in the video recordings of the class. There was little discussion of math concepts and no calculations outside of measurement. Of the concepts that were discussed, a few were geometry topics, such as circumference, but most were not subjects covered in the standard high school math curriculum. Based on the qualitative data, I would not have expected to see any impact of robotics on math test scores.

In later the models, overrepresented/underrepresented race/ethnicity was added to the list of predictors. Interestingly, in Model 5, the interaction effect of robotics and White or Asian (non-Hispanic) points in the opposite direction than the main effect. While I cannot draw definitive conclusions since neither result is significant, the model gives non-Hispanic White students and Asian students a small gain (5.79 points) while the interaction effect subtracts a much larger amount (-24.62) from the same group. The p-value of the interaction effect is also much closer to significance than the main effect (0.107 vs. 0.714). With a larger sample size, it is possible that the interaction effect could cross the $p<0.05$ threshold. Given the emphasis on helping underrepresented minority students enter STEM fields, the possibility that robotics could offer an outsized gain to those students is worth further study.

The answer to the research question of whether there is a relationship between participation in a robotics class and later standardized math scores is that, according to this analysis, there is not, and I fail to reject the null hypothesis.

RESEARCH QUESTION 2: STEM COURSE ENROLLMENT

This study also investigated whether there was a correlation between high school robotics class and future enrollment in high school STEM courses, specifically, Physics 1, Physics 2, and Calculus. Physics 1 was defined as an introductory course devoted to physics curriculum. All second courses in physics, both calculus and non-calculus based, were included in our definition of Physics 2. These include all AP Physics courses and the IB Physics 2 course. For Calculus, I chose to include all AP Calculus classes, as well as the IB Mathematics Higher Level course, which contains a substantial amount of calculus in its curriculum.

This study focused on these courses because Sadler et al. (2014) found an association between high school physics, calculus, and 2nd year chemistry enrollment and interest in a STEM career. Due to the low amount of chemistry, I judged that it was unlikely that robotics class would have a significant effect on advanced chemistry enrollment and concentrated on the physics and calculus courses.

While many of the previous studies are concerned with math test performance, only Wolfgang et al. (2003) addresses the matter of future course selection. They found that the pre-school students who performed better on LEGO construction skills tended to enroll in more advanced math courses in high school than the lower performing students. However, as previously mentioned, the Wolfgang et al. (2003) study used very few subjects and used non-robotics LEGO.

Since the robotics class does not focus on explicitly teaching math and physics skills, the pathway to affecting performance and enrollment is likely to be through the affective domain by increasing student motivation and interest in those subjects. In the video recorded sessions, there was little evidence that students use many of the mathematics concepts in the standard high school curriculum or perform any calculations in the capstone project beyond measurement. However, there are ample amounts of physics concepts being discussed between the students in the groups and with the instructors. The topics discussed ranged from Physics 1 subjects (e.g. projectile motion) to Physics 2 ideas (e.g. torque) and some that are outside the scope of the ordinary curriculum (e.g. material strength and gearing). Based on the proportion of physics talk to math talk, it would be reasonable to expect that the effect would be a greater on students' interest in physics than in math. It is not obvious whether a greater emphasis on computation would increase interest in either subject.

Physics 1 was a very popular class and was enrolled in by the majority of both robotics and comparison group students. Thus, it is not surprising that robotics was not a good predictor. In fact, the only significant predictor at the $p<0.05$ level is 8th grade math test score percentile. Both overrepresented and underrepresented race/ethnic groups enrolled in the class and the interaction between race/ethnicity and robotics was not significant either.

As previously mentioned, a major confounding factor in this calculation is that all of the students in our final dataset were subject to the "4x4" requirement, which likely increased levels of enrollment in science electives, including Physics 1. It is probable that this effect is obscuring whether Physics 1 enrollment was impacted by robotics. While it is easy to search the records of pre-4x4 years to estimate the increase in Physics 1 students due to the requirement, without knowing which of the students were in robotics, I would not still not be able to answer whether robotics has an effect on enrollment in the class.

While Physics 1 enrollment is interesting, the results of the Calculus and Physics 2 enrollment analyses are more important for several reasons. First, Wolfgang et al. (2003) found more significant differences as the subjects grew older. Also, while Sadler et al. (2014) found an association between enrollment in high school physics and interest in a STEM career, the effect is stronger for students who enroll in Physics 2 than students who just take Physics 1. Finally, both Calculus and Physics 2 are beyond what is required by the state high school graduation plan. Unlike Physics 1, there should be little impact due to the 4x4 requirement.

The results for Calculus and Physics 2 are quite similar. This is not surprising since many of the Physics 2 classes require calculus, and the Physics 2 students in the final dataset usually enrolled in a calculus class in the same year. In both cases, robotics starts as a significant predictor in the first model, but as more predictors are added, the significance fades. Ultimately, the only significant predictor is 9th grade advanced math class. However, while the p-value of robotics erodes, it is never far from the threshold limit. In Model 4 of the Calculus analysis, which is the most complex model which uses only main effects, the p-value is still 0.084. In Physics 2, robotics stays significant through Model 3, and only rises to 0.063 in Model 4. With the increased power of a larger dataset, it is quite possible for robotics to stay significant predictor.

The earlier observation that there was greater amount of physics talk in the classroom than math talk, led to the prediction that there would be a greater impact of robotics on physics enrollment than on math enrollment. While robotics was not significant for either subject, it is consistent with that expectation that Physics 2 is closer to significance than Calculus.

Based on the analysis of the results from the final dataset, the answer to the research question of whether there is a relationship between robotics enrollment in subsequent STEM classes is that there is no significant effect at the $p<0.05$ level, and I fail to reject the null hypothesis. However, repeating the analysis with a larger dataset with more statistical power may yield positive results.

RESEARCH QUESTION 3: MATH AND SCIENCE MISSED OPPORTUNITIES

Emergent themes

Theme #1: Math and science concepts were invoked/applied more often during problem solving than design.

It is not surprising that students talk about math and science concepts more often when discussing problems and fixes than when doing their design. Other studies have also seen this phenomenon (Berland & Busch, 2012). The larger question is why this occurs.

There are three possible explanations. First. it is possible that this is a "false" effect due to measurement issues. Since not every class meeting was recorded, it is possible that the design discussions which were not captured had heavy amounts of math and science talk instead of the amount that was observed on the videos. Similarly, the other students in the class may have been heavily discussing math and science and the chosen student groups that were recorded were not representative. The inability to review all of the discussions and interactions of every student in the class is a limitation of the study.

Another theory is that students could be thinking about math and science concepts while designing, but are not openly discussing it with their teammates as frequently as they do when they encounter problems and try to fix them. Because the recordings only capture the spontaneous interactions between the students and between the students and teachers in the classroom, silent thinking would not have been evident. Had the students been asked to do a “think aloud” or prompted them to talk about their design approach, there might have been more recorded incidents of math and science usage. Comparing groups of novice design students in high school, and expert professional designers, Crismond (2001) observed that while the experts often made spontaneous connections between their design and the underlying science and math concepts, the novices rarely did so. This suggests that the robotics students, like the novices, are likely not making many math and science connections and that “silent math/science thinking” is probably not the cause of the difference.

The final hypothesis is that problem identification and fixing are more conducive environments to use math and science than design. This could be due to the nature of engineering design versus science. Whereas design is typically concerned with creating multiple solutions and evaluating the trade-offs between them, science tries to find one cohesive theory to explain the observed event (Committee on Integrated STEM Education, 2014). When an unexpected problem occurs in a project, the first task is to examine the error to discover an explanation of why it is happening. Since a goal of science is to explain natural phenomena by developing theories to explain all known evidence (Berland & Busch, 2012), this problem solving situation is more consistent with the processes of science than the processes of the design phase of a project. Crismond's (2001) work may also support this theory. Since experts are good at noticing math and science connections, they may be able to identify potential problems earlier in the project and avoid errors before they occur. Novices are not able to foresee possible difficulties, and so they only realize that there is an error after construction when it manifests as a problem to fix. It may be that both novices and experts could have similar discussions about math and science, but experts discuss them earlier in the design cycle.

Theme #2: Most of the mathematics content in the videos can be placed into two categories: geometry and measurement.

Nearly all of the mathematics used in the robotics class fell under the categories of geometry or measurement. Having a limited range of math is a common occurrence in pre-college engineering. Prevost, Nathan, Stein, Tran, and Phelps (2009) noticed the same pattern while investigating the Introduction to Engineering Design course from the PLTW curriculum. While surveying a range of K-12 engineering courses, Welty, Katehi, Pearson, and Feder (2008) found that nearly all the math used by students was related to measurement, and gathering, organizing, and presenting data, and that there was very little consideration of using formulas to solve for unknowns.

This pattern can be thought of as a downstream result of two other pedagogical decisions. In design classes, students best learned the material that had immediate use to them (Edelson, 2001). Similarly, Berland and Steingut (2016) found that students made a greater effort to learn math and science if they expected that the material would help them complete their engineering project. Indeed, as a general instructional design principle for STEM-design classes, Berland (2013) advised that all science and math introduced to the class should be immediately applicable to the student design project. While the beginning PLTW classes used little math, one of the later courses focused on digital logic. Once that class started, students were introduced to binary number systems and Boolean logic (Prevost, Nathan, Atwood, & Phelps, 2011). However, creating a "good enough" classroom environment where students do few calculations makes it difficult to incorporate many fields of math authentically. Algebra, trigonometry, and calculus all make heavy use of equation solving. It seems that including more high school math content into engineering courses requires a classroom environment that demands precision calculations.

At the same time, a high percentage of the math and science topics discussed, such as 3D shape extrusion and gearing, were beyond the scope of the school curriculum. This highlights the mismatch between the math and physics curriculum sequences and the needs of engineering. As long as there is no focus on computation, robotics does not need algebra or trigonometry. However, adding more geometry, particularly related to 3D solids, rotations, translation, and extrusion, would deepen the connection to drafting and the CAD tools. While many different physics (mainly mechanics) topics were discussed by the students, the topics did not adhere to the high school sequence. Some of the topics are covered in the regular physics class (e.g. projectile motion) and AP Physics (e.g. torque). But other areas, such as gearing, come from outside the high school curricula. Unfortunately, as it stands, the science and math used by the robotics course is out of alignment with the standard math and science curriculum.

Theme #3: "Good enough" vs. precision in design.

Regardless of the actual goals and philosophy of a classroom, when working with real physical materials, a certain amount of "good enough" is necessary. Where abstracted math and physics problems specify frictionless surfaces, perfectly elastic collisions, and exact sizes, realized projects must tolerate non-negligible lower order effects, assumption violations, and inexact parts.

Having a "good enough" attitude in the classroom is not necessarily a problem, but can be viewed as a difference in values between science and engineering. Schauble, Klopfer and Raghavan (1991) claim that the goal of science is to understand the relations among causes and effects, and when running experiments, all feasible combinations of input variables are systematically tested. Meanwhile, the goal of engineering is to make a desired outcome occur, and variables are tested only until the desired outcome is achieved. Similarly, Berland and Busch (2012) posit that in science, the goal is to create theories that explain observed phenomenon, but in engineering, the priority is creating working practical solutions. For engineers, accurate and complete explanations are not as important as fulfilling requirements, obeying constraints, and avoiding failure (Berland & Busch, 2012). Furthermore, in their observation of student groups working on an engineering project, Berland and Busch (2012) found that the students ignored the science goals and only paid attention to the engineering goals. Instead of engaging in deep learning about the science, students used a minimum amount of science needed to complete their design.

One clue why this attitude is both pervasive and accepted in the engineering classroom is be exhibited when the teaching assistant says, “It’s just a drawing. It doesn’t have to be mechanically right. And since you’re on a deadline, that might be it.” In the videos, there are multiple instances of the teacher reminding the students that there are pressing deadlines, and that they need to have a finished robot by the due date. The students may have had difficulty managing their time, possibly due to inexperience with the design process or due to procrastination, or because the instructor did not allow an adequate amount of time for each phase of the project. In any case, it is clear that both teams were under a pressing time constraint to deliver a working robot. In his work on adaptive expertise, Hatano specifies that one of the criteria necessary to develop a deep understanding is a lack of “urgent external needs” so sufficient amount of time and effort can be spent on comprehension (Hatano, Ericsson, & Hoffman, 2002). In reviewing the research, the National Research Council has found that to increase student interest, it is important to not only provide enough time for students to complete their tasks, but also allow them time to initiate and work on some self-directed tasks too. Furthermore, students need to feel competent at what they are working on (Committee on Integrated STEM Education, 2014). If time is short and students are only rewarded for a working project, it is rational for them to prioritize advancing the project forward by investing only the minimum amount of time on exploration and understanding. While they may complete the assignment, they may not feel accomplished. This could be seen as a symptom that the teacher and students have different priorities; the teacher wants to students to learn the material and develop interest in it, while for the students, it may be more important to get a high grade. It is possible that the amount of time allocated to complete a project is inadequate for the students to learn the science deeply and explore the underlying concepts.

Fittingly, even if the student who was having difficulty mating the two parts in Solidworks were able to complete the action, it still would not have been “mechanically right”. The TA is correct when he states that it is just a drawing. Solidworks does not model the physics of the mechanical parts acting upon each other. It is not kinematically driven, but rather it merely plays an animation of the pieces moving. “Good enough” applies to the software too.

Improving the math/science content

Berland and McKenna (2012) divide challenge-based engineering classes into three categories. Problem classes concentrate on providing large complex problems which students solve by applying the STEM content in the lessons. Of the three categories, problem classes tend to be the most math/science focused (Valtorta & Berland, 2015). On the other hand, design-based classes emphasize engineering practices and habits of mind by trying to provide students a chance to engage in work of the sort done by design engineers. While math and science concepts may be used, it is not the primary goal of the course and the connections between the design and math/science may not be made explicit. Often, the design challenges can be accomplished without a thorough understanding of the underlying math/science principles. The last type, labeled STEM-design classes, attempts to better integrate math and science into the engineering design environment. Design projects are formulated so that they cannot be successfully completed without understanding and applying the intended math/science content. Berland and McKenna (2012) note that with few exceptions, STEM-design is typically found not in standalone classes, but implemented as projects within science classrooms.

By this classification system, the robotics class that was studied in this work is an example of a design-based course. Its primary purpose was to introduce students to engineering, not to advance math and science knowledge and skills. However, with some modifications, it could convey much more math/science content and be closer to a STEM-design class.

To adapt the robotics class for math/science learning, there are two frameworks that are useful. First, the class can be examined at the scale of daily activities and individual interactions. Explicit integration is defined as any time an instructor or the curriculum material specifically point out a math/science principle, law, or formula and how it is used to understand an engineering concept or to perform an engineering task. In contrast, implicitly embedded concepts or skills occur when the math/science is part of a tool, representation, or procedure used for engineering, but is not specifically pointed out by the instructor or curriculum material. One example is a CAD program which is used to create a mathematical model of a physical object. If the teacher points out that the software uses a combination of linear algebra and trigonometry to display rotations and translations of the object on the screen, the math integration is explicit. If the instructor does not specifically alert the students to the underlying mathematics used by the CAD program, then the math content is implicitly embedded

Prevost et al. (2009) assert that students learn math/science better in engineering classes if the connections between the math/science content and the engineering are made explicit. While expert designers often make spontaneous connections to math and science concepts while novice designers rarely do. Making connections across disciplines can be particularly difficult for students, since the ideas and tactics that students have developed to make connections within each field may no longer apply (Committee on Integrated STEM Education, 2014). However, through scaffolding, novices could be helped to make the necessary leaps (Crismond, 2001).

To illustrate how existing material can be improved, Prevost et al. (2009) took samples of curriculum materials and added episodes of explicit integration. Similarly, in this section, I will do two things. First, I will create some curriculum materials that explicitly connect aspects of the design project to the underlying physics and math. Second, I will examine several teacher-student interactions from the robotics class and suggest ways the teacher could have increased the explicit integration of math and science into the engineering discussion.

In their review of K-12 engineering programs, Welty et al. (2008) noted that few programs had students engaged in modeling. Of the models that were created, they tended to be just graphical or physical representation of student design ideas. What would be more useful, they said, would be mathematical models which the students could use as a data source to make inferences about their design ideas. In addition to the modeling problem, when students tried to improve their designs, they typically just brainstormed ideas without first performing an analysis of their work. Having appropriate models can aid students in analysis and make iterative improvements more informed and with less trial and error.

Here, the robotics project can be improved by introducing mathematical models of common problems encountered by student teams. Figures 5.1 and 5.2 are physics problems based on the rail robot and stat robot projects. As previously discussed, students are more likely to learn and expend more effort in learning if the content is directly relevant to helping them complete their project (Berland & Busch, 2012; Berland & Steingut, 2016). Thus, each of these problems comprises a physics-based design problem that the team needs to solve to ensure robot functionality. For the Rail robot, the problem involves making a counterweight to balance out the torque generated by the robot arm. For the Stat robot, the problem involves calculating the launch angle to throw the ball in order to hit the target. For each, the physics concepts are sufficiently self-contained that even students who have not had physics can be helped to complete the assignment. The result of the problem will provide a starting point for students to use in their design.

Your ball launcher throws the ball in a parabolic arc and it follows a simple law of projectile motion:

$$\text{Distance} = \frac{v^2 \sin(2\vartheta)}{g}$$

where v is the initial velocity of the ball and θ is the launch angle

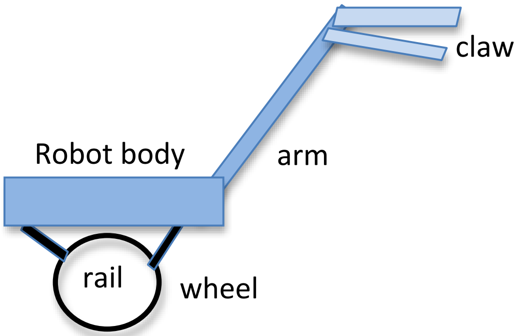
Now that you have a working ball launcher, use the above equation to calculate:

1. The initial velocity of the ball
2. The theoretic maximum distance that your launcher can throw a ball
3. The launch angle you would need to hit a target 2 meters away

In addition, draw a force diagram of the ball at the moment of launch, and a force diagram of the ball in midflight.

Figure 5.1: Physics problem for Stat robot teams

Your rail robot design probably looks something like the diagram below, with the main robot perched on top of the rail and an arm/claw assembly extending out from it.



Unfortunately, this design suffers from one major problem. The weight and position of arm and claw unbalances your robot and creates a torque (a rotational force). What do you think will happen to your robot because of this balance problem?

A simple fix is to attach a boom and counterweight on the other side to balance out the torque from the arm and claw.

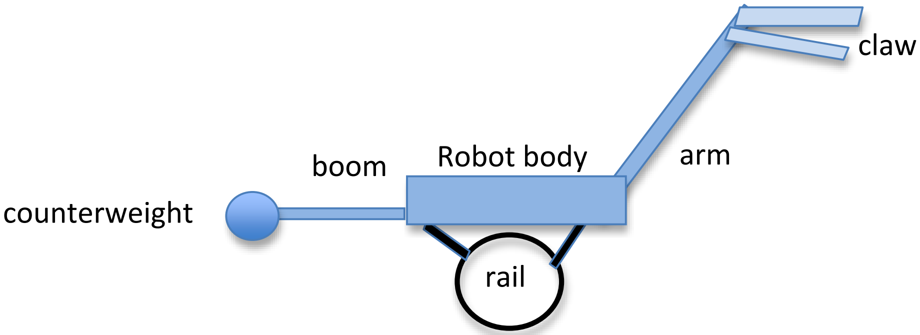


Figure 5.2: Physics problem for Rail robot teams

To make the following questions easier, you can make the following simplifying assumptions:

a. the origin for your coordinate system is the center of the rail
b. the weight of the boom is negligible
c. the entire weight of the arm is located at the midpoint of the arm
d. the entire weight of the claw is located at the midpoint of the claw

1. Draw a force diagram for your robot, labeling the torque from the arm, the claw, and the counterweight.

2. To make this first calculation simpler, assume that you will be able to make the counterweight 100% of the weight of your arm and claw assembly. Calculate the length of the boom that you will need to balance your robot on the rail. Use the weight and dimensions of the assembly that you built. The formula to calculate the torque due to an object is:

   Torque = $rF\sin\theta$

   where F is force, r is (in this case) the distance from the origin to the center of the object,
   θ is the angle between F and r, and torque is the rotatonal force from the object.

3. Suppose that your robot is too heavy and you need to lighten the load. Suppose your counterweight can only be 25% of the weight of your arm and claw assembly. How can you generate the same amount of torque using the lighter counterweight? Use the equation to get a specific answer.

Figure 5.2 (continued)

In addition to curricular materials, the connection between the design projects and physics and math content can be emphasized and made explicit when the teacher talks to the student teams. Here, I will provide several excerpts of teachable moments from the video transcripts and suggest ways the teacher could have made more explicit connections.

In the first example, the teacher was describing a problem encountered by another team involving an unbalanced robot falling off the rail.

> Teacher: Um, I do know a group, yesterday, was kind of messing around with that and their's was too wide and the thing was just moving around all over the place.
>
> R: So they were like this high?
>
> Teacher: Yeah. It was actually kind of like this. [holds wheels through roof cutouts perched high on the rail] And so it was twisting off the rail and it was kind of going like this. [wheels twisting off rail] But if is further out, it is going to hold on better. [holds wheels wider on rail].

The teacher described the problem as “twisting off the rail” and immediately offered a possible solution, widening the wheelbase on the robot to add stability. However, he never described the reason for the twisting problem or why his proposed solution should work. Instead, the teacher could have asked the student to draw a cross-section diagram of the robot perched on the rail and overlay it with a force diagram. This would have led to a discussion about the center of mass of the robot, why it needs to be roughly on top of the centerline of the rail, and what would happen if it is not. Then, the conversation could be steered towards how to improve the stability of the robot and whether it would be better to have a narrower or wider wheelbase.

Then, the teacher could introduce the concept of torque, and how it is calculated. To emphasize the point that torque increases with distance from the center, he can ask the students how the forces change when the robot arm is extended to pick up a ball. This would spur the design question of how to compensate for the torque from the arm. If the team is stuck on ideas, the teacher can direct them by saying that the rail robot is essentially a building crane and asking them to find pictures of other cranes and see if they can figure out how they handle the issue. Along with this discussion, the teacher could give the team members the modeling problem in Figure 5.2 to provide them the chance to perform the calculation.

In the next example, P is having difficulty making the metal claw on the rail robot grab and hold on to a ball without it sliding away.

> P: See, it's going to slip. [grabbing ball with claw] It has to be really tight .. and then it's just going to roll… it kept slipping. I'm trying to find something
>
> TA: Some grip tape. Have you seen it?
>
> P: No, I haven't seen it.
>
> TA: Put tape on one side
>
> P: Really? That would be so nice.

While P understands that pressure can reduce the ball from slipping out of the claw, she does not understand what other factors she can also use to craft a solution. Instead of offering a quick fix for the problem, the teaching assistant could have asked her to use the Internet to look up the formula for friction. From the formula, he could have pointed out the meaning of the variables and asked what factors she could adjust to increase the friction of the claw on the ball, which would lead her to look at the coefficient of friction. From there, they could have discussed what it means to have a high coefficient of friction and look up what common materials have high coefficients. Eventually, P could figure out that she could put rubber bands or some other ‘grippier’ material on the claw to solve her problem.

> N: Also, some people are saying that maybe the Lexan would be enough power to support our whole robot cause all the weight that's going to be on the robot and all the motors and all the balls that are going to be in there and like if we make our funnel or basket or whatever we are making out of metal then that's going to weigh more. We don't know.
>
> R: I don't think we'd make the basket out of metal. That's doesn't sound ...
>
> N: I just want to make sure. Would Lexan be strong enough?
>
> Teacher: I think so. We can .... If let's say, it wasn't or we get concerned ... we can do something like… angle supports to it or whatever that will hold up to it.

Here, when N says, “would be enough power”, the context strongly suggests that the intended meaning is “have enough strength”. Since the amount of weight that a sheet of Lexan can support is a complex problem that depends on many factors, including the thickness of the Lexan, the distribution of the weight, and the structural supports holding the Lexan, the students would not be able to perform a simple calculation to answer their question. In this case, the teacher could have helped the students explore the question and their options.

The students seem to have a fuzzy idea about the weights in the problem. First, he could have asked the students to estimate the weight of the robot with a metal funnel/basket and compare that to the weight of the robot with a non-metal funnel/basket. Since the robot is not completely built, they can use the parts that they intend to use to calculate a number. While the computation of the weight of parts is not in itself a complex mathematical task, it quantifies the problem and allows the students to calculate the proportional change in weight between metal and non-metal parts. If the robot is much heavier than the funnel/basket, the proportional change may be smaller than expected, which could cause the students to decide that the metal/non-metal problem is not as important as they had thought. If the proportional change is larger than expected, it could steer their design in a different direction.

In addition, the teacher could have brought up another potential issue. Depending on the placement of the funnel/basket and its weight, the funnel/basket could create a torque that may require the team to recalculate and adjust the counterweight. This could lead to a discussion about how to design the funnel/basket to help balance the forces on the robot and shift the center of mass.

The common thread through these three cases has been that the teacher and teaching assistant have been quick to offer workable engineering solutions. To increase the science and math learning, the teacher could have guided the students to analyze the problem and introduced concepts and vocabulary (e.g. torque) to help them design more robust solutions.

At a larger scale, the class can be analyzed at the lesson and course level. Based on the available literature, Berland (2013) provides 6 instructional design principles for creating STEM-design classes with well integrated content. Figure 5.3 shows the 6 principles. The last principle requires detailed knowledge of the limitations of the school and school district. Redesigning the entire course and situating it within the needs of the school community, is beyond the scope of this work, However, I argue that this framework is still useful to review the qualities of the capstone project.

Expanding on the first principle, Berland adds the four criteria in Figure 5.4. The first criterion calls for an open-ended project that permits multiple possible implementations. While there are several constraints and requirements of the capstone project (in Appendix A), implementation details are still left to the teams. The two teams in the videos made numerous design decisions over the course of their project and different teams had different solutions to the problems. In the transcription of the Stat team's final presentation presented and coded at the end of Chapter 3, the team members discuss some of the design decisions that they made to arrive at their solution.

1. Contextualize all student work within STEM-design challenges.
2. Specify specific course and unit learning goals.
3. Employ a standardized engineering design process as an instructional framework.
4. Engage students in sensible forms of engineering practices from day one.
5. Ensure that all science and math concepts, and technology tools employed are necessary for students' successful completion of the STEM-design projects.
6. Attend to the constraints of the high school and school district systems.

Figure 5.3: Six principles of STEM-design (Berland, 2013)

The second criterion speaks to the scope of the course and its ability to survey the breadth of engineering. While exposing students to multiple engineering disciplines is useful, it may be best done at the course level instead of within a single project.

The National Research Council has also noted that using "real world" problems is a strategy to increase student interest (Committee on Integrated STEM Education, 2014). However, as written, the rail and stationary robots do not address any societal needs. This is perhaps the most obvious failure of the capstone project with respect to this framework. The project problem is entirely artificial and has no purpose or relevance outside of the classroom. While none of the videos showed that the ad hoc nature of the project was demotivating, it is unknown whether a more socially conscious challenge would have yielded better results.

1. The challenge must have multiple plausible solutions so as to create opportunities for students to solve the problems creatively rather than to execute their teacher's plan.
2. The challenge will require students to consider the problem from multiple engineering disciplines and, throughout the course, different challenges will emphasize different disciplines. This will ensure that students experience the interdisciplinary nature of engineering and will introduce students to a range of possible foci for their professional trajectory.
3. The challenge must address a societal need as this has been shown to attract individuals from populations that are typically underrepresented in engineering.
4. The challenge will directly draw upon math and or science concepts such that students have an opportunity to apply domain specific knowledge to their engineering design work.

Figure 5.4: Criteria for contextualizing student work (Berland, 2013)

In regard to the 4th criterion, using the physics problems which I added in the previous section, student teams would be able to use the results of their newly acquired knowledge to drive design decisions. Rail teams will be able to create a counterweight and Stat robot students will be able to predict how to angle their shooter to target the goals.

The intent of the second instructional design principle is to specify learning goals so that the goals can be used to drive the creation of the projects. Unfortunately, it is unknown whether there were specific written learning goals used to create either the capstone project or the course. In its absence, I have created a sample list of learning goals for the project that includes the new physics activities (Figure 5.5). In addition to the new science and math material, the learning goals also include learning new engineering content (working with Lexan), practice with skills and processes, and skills for the final presentation.

1. New physics concepts (Rail Teams: torque, Stat Teams: projectile motion)
    a. Understand basic concept and terminology
    b. Apply concepts and formulas through practice (activity)
    c. Apply to project design
        i. Create force diagram with relevant forces
        ii. Apply formulas correctly
        iii. Use result to guide design specifics
            1. Rail team: length of boom, weight of counterweight
            2. Stat team: angle of launch
        iv. Get feedback from implementation and revise
2. New materials
    a. Design and construction with Lexan
3. More familiarity with existing engineering and group skills through practice
    a. 3D CAD modeling
    b. Physical Construction of robot parts
    c. Programming
    d. Staying on schedule
        i. Assessing progress
        ii. Checking on team members and helping out
    e. Problem diagnosing and fixing
4. Presentation skills
    a. Organize ideas in logical order
    b. Explain clearly how design functions
    c. Assembling list of problems and solutions
    d. Speaking clearly and confidently
    e. Making clear, readable PowerPoint slides

Figure 5.5: Sample learning goals for capstone project with new activities

The purpose of employing an engineering design process (EDP) is to introduce a structure to guide students. Having it as a stable base for every project enables students to focus on the specifics of the assignment with clear, consistent expectations (Berland, 2013). Unfortunately, the robotics class did not teach a standardized engineering design process as part of the curriculum.

By "sensible" engineering practices, Berland (2013) notes that at times, attempts to follow a particular process can become empty of meaning if it is not directly useful to the students. It is not desirable for students to follow the instructions solely to satisfy the assignment without understanding the purpose of the task. This principle is a parsimony rule, to omit steps that are not useful. In the videos, all of the tasks the students performed advanced the design and implementation of the project and there were no complaints of performing "busy work". However, it may have been more useful to the teams if instead of simply using their CAD drawings as a diagram for their construction plans, to use them in a design review with the teacher or present them to the class.

The fifth principle can be thought of in two ways. First, did the instructor attempt to teach math or science concepts that were not used to design and implement the engineering project? Since the class was intended as an engineering class, and not as a vehicle to teach science and math concepts, there was no extraneous math/science content taught in the course of the capstone project. For this evaluation of the project, a more applicable interpretation of the principle is whether teaching more math/science would have made the student design projects more successful. In other words, what is the optimum amount of math/science to teach for this set of capstone projects? As I showed earlier, each of the two project problems would have been good entry points to introduce various physics concepts: torque and friction for the rail robot, and projectile motion for the stationary robot. Since students in the class span grade levels from freshmen to seniors, they will have different amounts of math and science in their backgrounds. Some students will have studied geometry and physics, while others will have not. Thus, it is not possible to precisely target the content for each student’s knowledge level. However, using the concepts and materials I created may allow the students to better understand some important design decisions they will need to make. While some design ideas may require additional math and science knowledge to implement, the concepts in the materials cover key content needed for the project.

Berland's (2013) instructional design principles were written as a guide the creation of new STEM-design courses, but I have repurposed them to analyze an existing project. With the exception of social consciousness, using a formal design process, and possibly written learning goals, the robotics capstone project with the proposed content additions generally follows her ideas about good STEM-design principles. Unfortunately, without details about the rest of the curriculum, I cannot speak to whether the entire course also follows these design ideals.

Comparing practicing engineers to robotics students

A number of researchers have investigated how practicing engineers use math and science in the workplace, and found that the relationship is complex and somewhat contradictory. Kent and Noss (2002) interviewed civil and structural engineers at a large firm in the UK, while Gainsburg (2006, 2007) shadowed both junior and senior engineers at two structural engineering firms in the US as they worked through multiple projects. Given that the primary job of structural engineers is to analyze the sturdiness of building plans and guarantee their safety across a wide range of conditions, Kent and Noss (2002) expected large amounts of math and physics being used in rich varieties by the engineers daily, but to their surprise, there was very little calculation. "Once you've left university you don't use the maths you learnt there, 'squared' or 'cubed' is the most complex thing you do." (Kent & Noss, 2002, p. 1) Much of the difference is because while complex mathematical modeling of the physics of structures is still a core task of these firms, the actual modeling and calculation is no longer performed by the majority of engineers. Detailed modeling is assigned to either junior engineers fresh from college or to mathematical modeling specialists, or building codes are consulted for answers (Kent & Noss, 2002).

> There is a whole lot of maths in what we do that we don't need to think about really, because other people have done it for us ... certainly been set up so that we can avoid doing the complicated maths 95% of the time. (Kent & Noss, 2002, p. 1)

Meanwhile, Gainsburg (2007) found that solving equations is actually one of the easiest engineering tasks, as analysis software can automatically perform all the calculations in minutes, or answers can be looked up in building codebooks. With the difficult math offloaded, the remaining math that the engineers performed was relatively simple. The bulk of the math that she witnessed represented concepts taught at the 9th grade level and below. Even these calculations typically were not performed by hand, but entered and executed by a spreadsheet.

While the previous studies were conducted with civil and structural engineers, anecdotal evidence suggests that engineers in other disciplines also encounter very little advanced math or calculation in their everyday practice (Pearson, 1991).

One factor that complicates engineers' use of math/science is the constraints that the design is subject to. While Gainsburg (2007) notes that constraints make engineering possible, by steering the design in particular directions, limitations in cost, safety regulations, and the materials available help dictate what designs are possible, what kinds of analyses need to be performed, and which analyses are not worthwhile. In particular, she singles out for particular influence, and situations in which the engineers decide to accept the results of rough analyses because they could not afford the time to run more accurate calculations. "But in buildings you approximate hugely because you have to get it done in a day, and there's nothing wrong with that, part of the art of structural design is learning how to approximate." (Kent & Noss, 2002, p. 2)

The general relationship that the observed engineers have towards mathematics (and the science that it models) has been described as "skeptical reverence", a balance between accepting the usefulness and necessity of mathematics, and understanding its limitations (Gainsburg, 2007, 2012). Having detailed mathematical models and analysis software is a requirement for structural engineering. Designs must be justified through mathematics. However, engineers need to understand potential problems with the software and analysis methods. One engineer actually cautioned against over-reliance on mathematical methods because it could obscure one’s understanding of the behavior of structures. Models may use extremely idealized conditions, such as assuming that some materials are perfectly rigid or infinitely flexible, in order to encompass the widest range of possibilities, and Gainsburg’s engineers recognized that neither pole represented realistic results and worked to create a better model. One engineer noted that the analysis software his firm was using causes spurious results when the elements are too small, and therefore it was important to review the modeling results for answers that looked unusual (Kent & Noss, 2002). Having too little or too much deference to the math and physics can compromise the project's safety or its budget (Gainsburg, 2012).

Furthermore, while computer-based mathematical modeling makes the analyses possible, it does not necessarily generate ideas. Design must precede analysis. Thus, math and science, while necessary, are not sufficient. The typical project starts with a design produced not by analysis, but by an architect. Then the engineers run appropriate analyses, propose solutions, and then rerun the analyses. The nature of the work is iteration that continues until an acceptable solution is found that satisfies the constraints, including safety and cost (Gainsburg, 2007).

One of Gainsburg's interviewees has a particular relationship with the technological tools. While he states that he is in favor of using more mathematical analysis in the work, he also admits, "I use all the classical methods to figure out what the answer ought to be, and then I use that to figure out exactly how I'm going to arrange my model." (Gainsburg, 2007, p. 499). Here, mathematical modeling is a post hoc justification of the decisions he has already deemed acceptable through more traditional non-computer-based analyses.

Through the research, it is clear that some math and science related skills are used more than others, particularly since all calculations are handled by computers. Though repeatedly, through their interviews, the engineers speak of the need to understand geometry, (Kent & Noss, 2002).

> Geometry is enormously important. For example, its relation to structural behavior: the bending moment in a beam being a significant shape --- it's a parabola, and not just any old parabola, but one that represents the structural behaviour. ... Or, in a complex three-dimensional tent, there's the equilibrium of forces in three dimensions. (Kent & Noss, 2002, p. 4)

However, the skill most valued by the engineers interviewed is what the subjects frequently call "engineering judgement". While other researchers have attempted to define it roughly as making design or analysis decisions based on past experience

(Graham, Wescott, & Kluck, 2001), Gainsburg (2007) was able to code the situations in which it was used in her data. Of these, there were three categories that particularly applied to mathematics and science.

First, judgement is used where complex problems need to be simplified in order to be analyzed. Indeed, with the complex math mainly performed by computers, simplification is arguably one of the most difficult remaining tasks performed by the engineers (Gainsburg, 2007).

Secondly, not all calculations need to be calculated at the highest precision. Since the models may be based on assumptions and simplifications, the inaccuracies from the inputs limit the amount of precision that can be calculated. "You can get lost in doing a too-detailed job for your method ... If you use a method you have a lot of confidence in, you can go to a lot of decimal places …" (Gainsburg, 2007, p. 488) Other reasons may be less technical. In an example mentioned above from Kent and Noss (2002), the time pressure from deadlines required the engineers to decide whether a quicker, but less accurate approximation was sufficient for their purposes.

Lastly, at times, calculations and estimates done by the engineers sometimes came into conflict with other sources. In these cases, a decision needed to be made on which set of numbers to use. In one instance, when considering the properties of a material, a senior engineer deferred to the specifications provided by a vendor. In another, the engineer decided that the building code was not sufficiently safe and ordered extra reinforcement. Making these decisions requires knowledge of both one's own estimate process and an idea of the process used to create the other estimate and weighing the two while taking into account the tolerance for error and the needs of the project.

In a similar vein, it is not the ability to perform complex calculations on the geometry that is prized, but the engineer's "qualitative" understanding of structures.

> Qualitative understanding is based on sets of rules that are very clearly based on the mathematics of how forces and elements are interacting between each other. You have to draw the structural diagrams, and you're looking for clues, and some of those clues come from the maths you've done. (Kent & Noss, 2002, p. 5)

Kent and Noss (2002) call it an intuition that is developed through experience and is sometimes used synonymously with "structural feel". Their description of it implies that it is a conceptual understanding of the physics that is honed to give approximate quantitative solutions.

To recapitulate, I identified three main themes from analyzing the robotics class video recordings:

1. Students are using math and science more in problem identification and fixing and less in design.
2. Students are not calculating formulas. Most of the math used is either geometry or measurement.
3. Students have a “good enough” attitude instead of calculating with precision.

These traits, particularly the last two, make it difficult to cover many math and science topics in the classroom. But following the instructional design guidelines from the research (Berland, 2013; Prevost et al., 2009), I made some suggestions on how to increase the amount of discussion and calculation. In particular, I created physics problems that are relevant to their design projects. But enacting these changes may create a different conundrum, reduced “authenticity”. Practicing structural engineers seem to exhibit much of the same three traits as the robotics students.

1. While math and physics are crucial for structural modeling and analysis, they do not help generate new ideas, and thus, are not always useful during the design phase. Instead, they are more beneficial for verifying whether a design idea is sound and to guide modifications.
2. Due to computer technology and job specialization, engineers no longer need to manually compute formulas and can operate at a more conceptual level. Nowadays, having a qualitative understanding is more important than the ability to crunch numbers. Freed from performing calculations, the important math knowledge is geometry and measurement.
3. Despite the ability of computers to perform detailed modeling, engineers frequently make judgement calls to perform analyses at a reduced level of precision. Time constraints and software bugs are some of the reasons that the decisions are necessary. The engineers are able to use the "good enough" results, even though they are potentially less accurate.

The number of parallels between the students' relationship to math and science and that of practicing engineers is an unexpected benefit of the robotics class. Should the robotics students continue on in engineering, they will already be well acquainted with some of the practices and attitudes towards math and science. Making changes to the robotics class to increase the math/science content will make it closer to being a STEM-design class. However, it may also change the engineering environment and shift the relationship to be less similar to an actual workplace, overemphasizing the role of math/science in the day-to-day practice of engineering. Since the goals of K-12 engineering education include exposing students to engineering practices and the design environment, there is a trade-off to be considered. Curricular gains need to be weighed against the cost of a less accurate portrayal of the profession.

There are, however, several caveats to this comparison. First, none of the studies involved, including my own, claim to have a representative sample of either all structural engineers or all robotics students. Secondly, all of the studies on practicing engineers are of structural engineers. Other types of engineers, such as electrical or chemical, may exhibit different traits.

Chapter 6: Conclusion

SUMMARY

The past two decades has seen a tremendous rise in the use of robotics in education. However, there has not been a corresponding rise in research on the effects of robotics on students, particularly persistent effects over multiple years. Much of the available literature lacks treatment consistency, often focuses on short-term measures of performance, and disagrees on results.

This study focused on a high school that has created a full year academic class on robotics. From the school district, I obtained data on some of the students in the robotics class and a matched set of comparison students. The data included demographic information, 8th and 11th grade standardized math test scores, and STEM course enrollment. The students were matched on factors including race/ethnicity, and 8th grade standardized math test score. In addition, I obtained video recordings of robotics students working on their capstone project from the same period of time covered by the quantitative data.

The first research question asked whether there was an association between taking a robotics class and later standardized math test scores. Using a series of models that added predictors, I found that there was no significant relationship between 9th and 10th grade robotics class and 11th grade standardized math test scores. The only significant predictors were 8th grade math score (measured as a percentile) and enrollment in an advanced math class in 9th grade. This result is consistent with the qualitative evidence. In the video recordings, students had few discussions of math topics, and the math they used had little overlap with the standard math curriculum. Furthermore, outside of measurement, there was no calculation of formulas, so students did not receive any practice in solving equations.

While race and ethnicity did not prove to be significant in any of the models, the p-value of the interaction between race/ethnicity and robotics suggested that robotics classes could affect underrepresented minorities differently than White and Asian students. Though not conclusive with this study, it may warrant further examination with a larger sample.

The second research question asked whether future enrollment in STEM courses could be associated with robotics class. Focusing on Physics 1, Physics 2, and Calculus, I found that while there was a significant relationship to 9th or 10th grade robotics class in the simple models, adding other predictors caused the relationship to robotics to fade out of the threshold of $p<0.05$. Ultimately, only 8th grade math scores were significant for Physics 1, and 9th grade advanced math class enrollment was significant for Calculus and Physics 2. However, although it did not cross the threshold for significance in the most complex models, for Calculus and Physics 2, robotics remained close to it, particularly for Physics 2. It is quite possible that with a larger dataset, robotics would be significant predictor. With the heavy amount of physics discussion evident in the video recordings compared to the uncommon math talk, the result that robotics is closer to significance with Physics 2 than Calculus was expected.

The third research asked whether there were opportunities to teach math and science that were missed in the robotics class. To answer this question, I first needed to find out what and how the students were using math and science in the classroom. Using a grounded theory approach, I coded video recording of two student teams working on the robotics capstone project. After analyzing the results, three themes emerged. First, students used math and science more often when they encountered problems and needed to fix their design than they did performing the design work. Second, the students did not perform any calculations or solve any formulas in the course of their project. The math was limited to measurement and some geometry concepts. Last, in the classroom environment, there was a pervasive attitude of “good enough”. While practical matters can never be ignored, the concern is that there is too much focus on completing tasks and not enough on understanding the underlying science principles for an effect on math/science achievement to be expected.

With these themes in mind, I found the terminology described in Berland and McKenna (2012) to be a useful framework in which to think about how to increase science and math learning in the robotics class. Following the instructional design guidelines from Berland (2013), I made suggestions and created sample materials to help convert the robotics class capstone project from an engineering project into a STEM-design project, which increases science and math content with the goal of understanding the principles.

While the robotics class project may have done a better job of conveying a deep comprehension of the underlying math and physics, I found that it was quite successful in a different way. Looking at studies of the attitudes and day-to-day tasks of practicing structural engineers, I found that the robotics students operated very similarly to the real engineers. The three themes emerging from the video analysis correspond to descriptions from interviews with engineering and observations of the workplace. While adding additional science and math learning to robotics is a clear benefit, it may come at the price of being a less authentic engineering environment. Ultimately, there is a value judgement that needs to be made on whether it is more important to use robotics as a vehicle to teach science and math or to teach engineering principles.

LIMITATIONS

The most serious limitation of this work is that it draws all of the data from one school. There have been only two instructors for the class, and the curriculum was designed by the main teacher. The results computed in this study are not readily generalizable to other contexts. Other schools using other curriculums could have different results.

In addition, the school is in a relatively affluent neighborhood in the district. The graduation rate and mean standardized test scores are higher than the state average, and the percentage of English Language Learners and students who qualify for free and reduced school lunch is lower than average. As seen in Table 4.2, for the final dataset, the mean 8th grade standardized math test score is over the 66th percentile for the comparison group, and the 72nd percentile for the robotics students. Also, it has the resources to offer multiple math and science elective courses, such as Astronomy and Aquatic Science, unlike many smaller or lower performing high schools.

As previously mentioned, due to inconsistencies and omissions in the dataset, the number of subjects was drastically reduced. This has severely limited the statistical power of the analyses and prevented me from further analysis of subgroups, such as the performance bands used by Lindh and Holgersson (2007).

In addition, since the reductions disproportionately affected some groups, such as women and minorities. The final dataset may not fairly represent the actual demographics of the robotics classes. Due to small numbers, women were excluded from the final statistical analyses entirely. While I included underrepresented minorities as predictors in the statistical models, the sample sizes are not large enough for definitive conclusions. Whether robotics has a different effect on math achievement and STEM class enrollment among women and minorities is still an open question.

One question that hangs over the entire set of analyses is the issue of interest. Popular models state that student performance on tests and enrollment in math and science classes are dependent on the student's interest in the subject (Wigfield & Eccles, 2000). Since this study uses historical data, no direct measure of students' interest in STEM subjects prior to robotics class was available. However, because 8th grade math achievement on standardized tests correlate with 8th grade interest in math and science (Singh et al., 2002), I was able to use the test scores as an indirect measure for STEM interest prior to robotics class. However, it is possible that for this dataset, 8th grade math score is not a good predictor, and the effect of interest is not sufficiently controlled for in the analyses.

As previously mentioned, the students in this study were all subject to the "4x4" rule, in which the recommended high school graduation plan increased the math and science requirements from 3 years each to 4 years and stipulated which subjects must be taken for three of the four years (Biology, Chemistry, Physics). Most likely, the rule spurred an increase in enrollment in math and science courses, such as Physics 1, compared to previous years, and may be masking some of the effect of the robotics class. However, it may be possible to estimate the magnitude of the 4x4 effect. The High School Longitudinal Survey of 2009 (HSLS:09) is a national survey of over 23,000 9th grade students with follow-up surveys in 2012, 2013, and 2016 (National Center for Education Statistics, 2009). Since the project collected high school transcripts, one could compare the number of calculus and physics courses taken by students in Texas (with the 4x4) to students in other states who do not have a similar requirement. Furthermore, in the first follow-up survey, students were asked whether they were taking math and/or science courses and the reason they were enrolled in the class (National Center for Education Statistics, 2012). From this question, one can estimate how many students are only taking a math/science class because of graduation requirements. Geographic information is however, not included in the publically available version of the data, and must requested under restricted use (National Center for Education Statistics, n.d.).

Unlike quantitative studies, which attempt to collect large volumes of data and avoid overly focusing on any one group, qualitative studies need to purposefully choose and focus on the subjects who are able to provide the most useful data (Creswell, 2015). For the qualitative section of this study, I chose to focus on one student group from each of the two projects (Rail and Stat). The Rail team, which consisted of students I, K, N, P and R, was chosen because they were the team with the most discussion between team members and the highest quality of discussion. This team had more group discussions and tended to talk through design problems, which better exposed their thinking processes than teams which partitioned problems between group members and had members work individually. While the majority of the robotics class was male, and almost 90% of the quantitative data is male students, four out of five members of the Rail team are female. Although all members of the Stat team are male, there is a higher percentage of women in the qualitative data than there are in the robotics class. While women are not in the quantitative data, they are overrepresented in the qualitative.

It may not be coincidental that the most communicative team consisted of mostly girls. Interviewing teachers working with elementary school students in single sex robotics programs, Voyles, Fossum, and Haller (2008) noticed that the teams that were composed of girls tended to work more cooperatively. More often, teams of all boys needed to be reminded to share and cooperate with their teammates. The girls also asked questions and otherwise communicated with the teachers much more often than the boys did. If it is the case that it is more difficult to collect quality data from majority male teams, then it may be necessary, as I did in this study, to rely on majority girl teams and assume that boys are having a similar experience.

Also, video recordings were only available for selected class periods. Considering that the robotics class met for an entire academic year, only a small number of the classes were captured. Less than 11 hours were recorded for Rail Team 1, and less than 9 hours for Stat Team 1. It is possible that the available hours were not representative of the actual behavior of the students.

FUTURE RESEARCH

While this study adds to the literature on educational robotics, there are many possible directions for future work in the field. Certainly, studies of other schools using other robotics curriculums would increase the generalizability of the conclusions from this work. Studying schools with different demographic characteristics, particularly with more minority, English Language Learner, and low SES students, can expand our understanding of the benefits of robotics.

The relatively low number of samples hampered many of the statistical results. In several of the analyses, predictors were not quite significant. A larger set of student data would provide more statistical power to provide more clarity to some of the results. In addition, it could enable the analysis on the demographic factors that were eliminated (gender, economic disadvantage, special education, English Language Learner), recombined (race/ethnicity). It could also permit analysis by performance band as used by Hussain, Lindh, and Shukur (2006).

Instead of using historical and already collected data, a forward-looking version of this study can solve one of the main limitations by surveying students at the start of a robotics class (and a comparison group) about their interest level in STEM subjects. As the years go by, students can be resurveyed to find if their interest remains consistent and whether robotics influenced their course choices and other educational decisions.

This work is centered on a high school robotics class. However, robotics has been used with students from elementary school through undergraduates. There are interesting questions to be asked with both younger and with older students.

I posited that robotics may influence enrollment in STEM classes through the affective domain by increasing student motivation and interest. While the analysis showed that robotics was not a significant predictor, the p-value was close enough to the significance limit that it is possible that repeating the study using a larger dataset could push robotics over the threshold. Instead, the main predictor of both Calculus and Physics 2 enrollment was whether the student was in an advanced math class in the 9th grade. Köller et al. (2001) theorized that interest in math does not become a factor in math performance until the student is able to act on their interest by enrolling in more challenging or elective math courses. Since Texas allows students to opt into advanced math in middle school, student interest in math may be a factor earlier. Perhaps introducing robotics in elementary or middle school could increase student interest and provide the motivation to take the advanced 9th grade math course, thus increasing students' opportunities to enroll in Calculus and Physics 2 later in high school.

One of the findings is that robotics students performed few calculations. A possible reason for this is that the students may not have taken physics yet, or are not yet comfortable enough with the material to use it in the robotics context. It would be interesting to see if more experienced students, such as engineering undergraduates, use more calculations or whether they stay at a conceptual level. If they use more computation, it could be a sign that robotics curriculum is more useful to more experienced students.

Although I was able to obtain enrollment records for Physics 1, Physics 2, and Calculus classes, I was not able to access reliable data on how the students performed in the courses. It is plausible that their robotics experiences could have increased their learning, particularly given the amount of physics concepts the students were exposed to. While class grades are a measure, the analysis would need to account for the differences between teachers. A more reliable measure would be to compare standardized test scores, such as the AP exams.

Test scores and course enrollment are only a few of the metrics that robotics may impact. It would also be useful to compare robotics students against a comparison group on high school graduation rates, rates of college attendance, and how many majored in STEM subjects.

This study focused on an academic class conducted by a school because it provided several research advantages, including a large number of contact hours and access to school and district data. However, many students do not learn and interact with robotics in a class setting, but instead through after school clubs, summer camps, and other extracurricular activities. While these less formal settings are more difficult to study, the fact that students are participating in them makes it important to perform rigorous research into the experiences students are receiving and measure what they are learning, as well as long-term affective and metacognitive outcomes.

Hussain et al. (2006) and Lindh and Holgersson (2007) both showed some positive gains working with robotics embedded in a math class. Berland and McKenna (2012) would likely categorize this context as a STEM-design class instead of the engineering class of this study. More in-depth examination of embedded robotics could yield more positive math test results than what I found in this context.

One instructional design principle that was advocated by Berland (2013) is making design projects address social issues in order to motivate students. The capstone projects in the observed class did not follow that ideal and created contrived artificial problems to solve. A redesigned project may be worth further study to see if the changes produce more student engagement and positive impacts.

Appendix A: Robotics Capstone Project Description

2010 Robotics Challenge

Setup

As part of a major installation of a city art project, you are asked to design two components of a robotic Goldberg machine. Your components will combine with others to form a large robotic art installation.

Robots

1) Pickup and Dropoff: This robot must move along a 3” diameter tubular rail that is approximately 7 feet long. This robot must also collect 4” diameter balls which rest on a shelf just below and to one side of the tubular rail. These balls will rest 6” apart as measured from the center of one ball to the center of the next (6” on center). Additionally, a third row of balls will sit in the middle of the shelf. These balls will be placed at varying heights. Each ball must be delivered to a launcher robot positioned on the ground about 5’ below the tubular rail. The position of the launcher robot is fixed.
2) Catch and Fire: This robot rests on the ground and receives balls dropped from the Pickup and Dropoff robot. Catch and Fire must then shoot the balls through a specified target zone, black balls to the black target and green balls to the green target.

Game Specifics

- You will be able to control your robots manually at first, but by a specified date (TBA), each robot must operate autonomously.
- You may use additional materials to build your robot.
- Points:
    - (1 pt.) Ball picked from shelf and dropped
    - (2 pts.) Ball picked from shelf and dropped into Catch and Fire robot
    - (1 pt.) Ball launched through target
    - (2 pts.) Ball launched through target of correct color
- Pick-up and Drop-off
    - Pieces of tape along the tubular rail will coincide with the center of the balls on the shelf.
    - Balls must be dropped *without stopping the robot.*
    - Robot can be designed to fit completely around the 3” diameter tubular rail, if desired. Game apparatus will be disassembled to accommodate this.
- Catch and Fire
    - Robot rests on the ground, and its position is fixed.

        - Robot must fit within a box measuring X x Y x Z.

Teams

You will work in a team of 4-5 students designing one of the two types of robots. Your team will need to coordinate its efforts with other teams in your class as alliance members during game play. Cooperative strategies, alignment of designs and communication between robots may all be things for your team to think about and discuss.

Team Roles

Each team will have four member roles with specific duties to perform. In the case of a 5 member team, duties will need to be shared. At different times throughout the project, each role will assume the role of team leader. For example, during the design phase, the CAD Manager will be incharge.

Team Member Role	Responsibilities
Build Manager	o Understand and describe the current build of the robot: ▪ how strategy and design fit together ▪ specific mechanical features ▪ principles of physics supporting the design[1] o Maintain a parts inventory o Maintain a photographic record of the build process o Help insure team productivity
Automation Manager	o Understand and describe the current program version: ▪ how the program fits with strategy and design ▪ specific programmatic features ▪ how the program works with the physics behind the design o Insure that robot brain is programmed correctly and that the robot is behaving predictably o Maintain program versions o Help insure team productivity
CAD Manager	o Understand and describe the current robot drawing: ▪ how robot is represented in CAD ▪ workings of sub-assemblies and how they fit together ▪ accuracy of representation ▪ Can someone not on your team build the robot from the drawings? ▪ Show how your robot relates to other robots and

	the game apparatus. o Maintain drawing versions. o Help insure team productivity.
Project Manager	o Understand and describe the overall picture of the project: ▪ How do the robot, program, drawing, strategy fit together? ▪ Report on coordination efforts between teams. ▪ Describe set-backs and accomplishments during the life of the project. o Maintain project folder and flash drive. o daily accounts of who did what and for how long o Find answers to questions through other teams, outside resources and Mr. Sperry. o Help insure team productivity.

About Member Responsibilities

Although different members are responsible for different things, these responsibilities are not exclusive. Each of you should understand something about the robot, strategy, drawings, program, coordination with other teams and the overall progress. It's *your team*, and you have to help make it successful. Some days the Project Manager may have do some programming, or the Build Manager may have to attend to the project folder. Help each other out as best you can.

Daily Routine

Each work day will be split between meeting time and work time.

1. Collect project binder and flash drive.
2. Review previous days' work.
3. Examine and discuss what you cooperating team has done or suggested.
4. Make a plan for today.
5. Work on that plan.
6. Review and make notes on today's efforts.
7. Store latest electronic file versions on flash drive.
8. Communicate with cooperating teams.
9. Return project binder and flash drive.

Assignments

Ongoing
  A. Project notebooks
  B. On-line discussions
Initial Design Phase
  A. Design proposal (in exchange for metal)

        a. Items to include in the proposal
            i. Description of strategy
            ii. CAD drawings of the robot including isometric and other views
            iii. Mathematics and physics based predictions of the robot's performance. Ex. a mathematical explanation of why you expect the launcher to hit the target. This shall include equations and graphs.
            iv. Projection of the number of manhours dedicated to each portion of the project: design, build, test, redesign, etc.

Testing and Design Iteration Phase

- A. Submit request for test document to another team for testing
    - i. Things to include
        1. Specific requests for the components you want to be tested
        2. Basic description of what the robot *should* do
        3. *Do not include* specific performance information
        4. Operational instructions
- B. Test report submitted back to design team
    - i. Things to include
        1. Detailed description of the object under test. A third party should be able to determine which robot was tested based solely upon the description.
        2. Detailed description of the test method, apparatus, and procedure.
        3. Test results including synopsis, data tables and graphs.

Engineer's habits of thinking

calculation-based thinking (computational thinking)
designs are model driven
first solution as best vs elegance

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