PROJECT-BASED LEARNING IN A HIGH SCHOOL ENGINEERING PROGRAM:

A CASE STUDY

by

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Project-Based Learning in a High School Engineering Program: A Case Study

Thesis directed by Professor Michael Brandemuehl

Generating greater student interest in science, technology, engineering, and mathematics (STEM) has been a major topic of discussion among educators, policymakers, and researchers in recent years, as increasing the number of graduates in these fields is widely considered a necessary step for sustaining the progress of today's society. Fostering this interest must occur before students reach college, and substantial efforts have been made to engage students at K-12 levels in STEM-focused learning. Attempts to involve students in engineering, a vital and growing profession, yet one in which students often have little experience, have frequently emphasized the design and construction of physical products, a practice supported by project-based learning.

This thesis examines the environment of an engineering high school course that employed the project-based model. The course is part of a dedicated curricular program which aims to provide students with positive experiences in engineering-related activities while also preparing them for the rigors of college. A case study was conducted to provide insight into the benefits and drawbacks of the learning model. The study's outcomes are intended to provide guidance to educators participating in the design and/or facilitation of project-based activities, particularly those involved with engineering education.

The research was performed using a qualitative approach. Long-term engagement with course participants was deemed critical to gaining a comprehensive understanding of the interactions and events that transpired on a daily basis. Nine educators involved with the program were interviewed, as were nineteen of the course's thirty-nine students. A wealth of other relevant data – including surveys, field notes, and evaluations of student work – was compiled for analysis as well.

The study findings suggest that experiences in problem solving and teamwork were the central benefits of the course. Limitations existed due to a high focus on hands-on work, which infringed upon the significance of math and science content as well as the utilization of disciplined inquiry. In addition, group

projects failed to hold individuals accountable, leading to assessment challenges. Program-wide, a number of issues hindered the teachers' abilities to institute changes, most notably a commitment to serve students of all abilities.

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INTRODUCTION

Academy purpose

"I think the big key to this is, are you really continually working on breaking the poverty cycle for families that are coming here? Especially the minority population, to be able to open the doors of opportunity for those students to be successful in their lives. And not only change their own life, but change their whole family's life. And that to me is a huge component of why we do what we do."

– Academy administrator

In the fall of 2009, six high school sophomores and forty freshmen were welcomed into a new STEM-focused curricular program, a culmination of nearly two years of research and preparation. The program was initiated as means for rejuvenating the school, a place where students had become apathetic to learning, and which had gained a poor reputation within the community. School administrators understood well that drastic changes were necessary and imminent, particularly due to the opening of another district high school nearby. There was a very real possibility that many of the highest-achieving students would soon take flight, leaving the school in a dire situation. The superintendent called upon the school leaders to stymie the anticipated exodus by creating a program of specialized focus, one that would improve the school's educational standing in the district. One major caveat was included – it was imperative that the program serve the needs of the general student population. This population was diverse; although a large constituent of the students were from middle class families, the majority carried low socioeconomic status.

After school leaders rejecting an initial proposal for implementing an International Baccalaureate program, the acronym 'STEM' emerged. In the words of a school administrator, "So we came upon the idea, and I found on the internet, if you will, STEM. And I go, what's STEM?"

A STEM-focused academy within the high school was considered a natural fit. While fulfilling core curricular requirements, students could concentrate their studies by taking a series of elective courses. This coursework was expected to highlight the engineering field, introducing students to career-oriented pathways and providing context for bolstering students' capabilities in math and science. Access to technology was to serve as an umbrella initiative for the entire school population, a means for developing the skills needed in today's workplace. Students in the academy were provided laptops for a nominal fee, a major incentive since many students had no access to computers at home.

School leaders made a concerted effort to provide an inclusive educational plan, one that did not cater only to the brightest, but also provided opportunities for those who had fallen behind their peers. Noted one administrator, "We didn't just want the top ten percent of kids to come into the academy. We wanted the academy applications to reflect the general population of [the school]."

This unconventional approach was intended to encourage students of all backgrounds and abilities to enroll. By the fall of 2013, four years after its opening, 278 students were enrolled in the academy, representing about one in four students at the school. The school itself, in large part due to the appeal of the academy, had grown to become the largest of several high schools in the district. Importantly, because the foundation of the academy had been set upon a bedrock of inclusiveness in a school with a large minority population, the demographics skewed drastically from those of traditional engineering programs. Thirty-five percent of the academy students were listed as underrepresented minorities, 35% were female, and 23% were from families of low socioeconomic status. While these rates fell short of matching the demographics of the school (58% URM, 48% female, 49% low SES) , compared to those earning engineering degrees across the nation – 13% minority and 18% female[81] – the academy has been an overwhelming success in the promotion of diversity.

As a testament to the value placed upon the STEM education by the school district's administrators, STEM-focused lessons had trickled down from the high school to its feeder middle and elementary schools, where activities on topics such as robotics, forensics, and video game design were facilitated. Students from the partnering college helped develop and deliver engineering activities, both during the school day and as part of after school programs. And summer classes that were originally designed to provide enrichment and literacy support were modified to incorporate more STEM-based lessons.

Beginning as early as preschool, educators within the district aimed to expose students to the design thinking process as well as appropriate levels of STEM content. These curricular modifications, managed by the district's assessment and curriculum department, the district STEM coordinator, and STEM coordinators assigned to each elementary and middle feeder school (positions supported by a Race to the Top grant from the U.S. Department of Education), were put in place in an effort to interest students in engineering and other STEM-related fields, as well as improve upon their abilities to problem solve in authentic situations. By the time the students entered high school, it was hoped that they would feel empowered to succeed in STEM careers, as well as a proclivity to apply the engineering design cycle when approaching complex problems.

To apply to the academy, students were required to compose a short paragraph about their motivations for pursuing a STEM certificate as well as obtain signatures from three of their middle school teachers who were asked to recommend the students based on the students' classroom performance and behavior. (Teachers virtually never refused to sign; even students who had repeatedly performed below average and/or were regularly disciplined for behavior issues were recommended, as teachers commonly viewed these students' participation in the academy as a means to give them a non-traditional opportunity to succeed).

Performance in math was set as the defining threshold for academy enrollment. So long as students were at grade level in math – meaning they had earned at least a C in Algebra I in eighth grade or had achieved an average performance on the state-mandated eighth grade standardized mathematics test – they were accepted. Reflecting the academy's inclusive nature, exceptions were made for those who had not performed well in their math courses, as provisional acceptances were often provided. No limit was placed on the number of available seats for freshmen, as academy leaders were driven to serve all interested students. The number of enrollees thus increased each year.

Table 1 shows the number of students who enrolled as freshman each year of the academy's existence (including the 2014-15 school year), the total number of students enrolled in the academy, and the number who earned a four-year STEM certificate each of the past three years. (These figures do not include the six sophomores who began the program in 2009, as they were unable to earn a certificate. The retention rate is an approximation, taken to be the number of certificate earners relative to the number of freshmen four years prior; some students moved away and some students were later able to join the academy as sophomores and fulfill the certificate requirements.)

Table 1: Academy enrollment and retention figures

School year	*Freshmen*	*Total students*	*Certificate earners*	*Retention rate (approx.)*
2009-10	40	40	N/A	N/A
2010-11	53	91	N/A	N/A
2011-12	65	152	N/A	N/A
2012-13	78	226	31	78%
2013-14	88	278	29	55%
2014-15	127	342	48	74%

Figure 1 below illustrates the general organizational structure of the school district's personnel structure with regards to the STEM initiative at the high school level. This is not to imply that each of these actors solely held the listed roles or that there were only interactions as shown by the arrows; the push for the initiative was often a complex arrangement of grand ideas among the district administrators, while much of the responsibility for creating and implementing the coursework was carried out by the teachers, none of whom had experience in engineering education or problem-based learning prior to joining the academy.

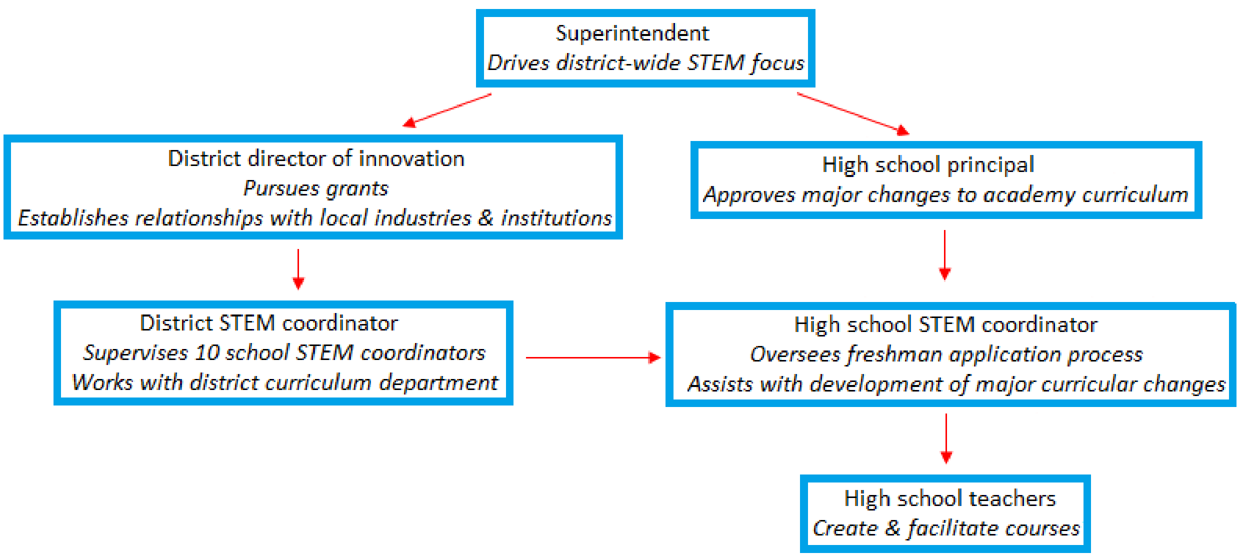


Figure 1: General organizational structure of the high school STEM initiative

Recognition

Since its conception, the academy has garnered support from neighboring post-secondary institutions and companies, those seeking to build strong relationships in anticipation that soon-to-be graduates would apply for enrollment and employment in the coming years. Representatives from a partnering engineering institution, in hopes of better preparing the academy's students for the challenges of college, provided academy leaders with assistance in curricular development. To provide a clearer pathway to the profession, an agreement between the school and college was struck which provided guaranteed acceptance to students able to complete the requirements of the academy, in addition to achieving established minimum grade point averages and college readiness exam scores.

As a testament to the value placed upon the academy by the school district's administrators, engineering-focused lessons have trickled down from the high school to its feeder middle and elementary schools. Students have learned about topics such as robotics, forensics, and video game design before they reach ninth grade. Students from the partnering college have helped develop and facilitate engineering activities, both during the school day and as part of after school programs. And summer classes that were originally designed to provide enrichment and literacy support have incorporated engineering-based lessons.

The academy has been recognized for its approach to engaging students in STEM, drawing regional and national attention from educators and policymakers. Educators from across the region, with intentions of introducing similar programs in their own districts, have sought curricular guidance and implementation strategies. Due to its initial successes, the U.S. Department of Education awarded several million dollars in grant money to provide further support. Academy leaders purchased new equipment, supplied teacher-training, created STEM-focused administrative positions, and established a new technology center.

Educational model

"To help students realize their potential for success in STEM careers by supporting their exploration of STEM-related fields, by encouraging the development of 21st-century skills, and by providing them with a head start in pursuing their post-secondary education."

– Academy mission statement

Original academy plans centered on teaching simplified versions of traditional engineering courses. Faculty from the partnering college recommended otherwise, explaining that highly technical knowledge fell outside the realm of high school, and those who chose to pursue engineering degrees would learn such material in traditional courses at the college level. However, the faculty members did note that while their incoming college freshmen had a solid grasp of math and science concepts, many lacked so-called "soft" skills, particularly in teamwork and communication, which were prized in the engineering world. Rather than focusing on traditional core content, they suggested that the engineering design process be used as a framework for the curriculum. Students would not only have the opportunity to work collaboratively, compelling constant communication with group members, they would be required to present their ideas in both written and oral formats. In addition, the use of hands-on projects would engage students in course projects, forcing them to think critically as they worked through ill-defined problems, and conveying a better picture of the engineering profession. Explained an administrator, "We think that was probably the first thing and the most important thing and even the thing today that we focus more on than anything is really design thinking, getting kids to understand what that process looks like and they're constantly using it no matter what the project is or what the course is, that that's kind of in the back of their mind always."

As this plan was set in motion, it soon became apparent that the four letters of STEM would not share equal standing within the program; engineering was to be the primary subject, with college and workforce preparation becoming a driving force behind the curricular design. Coursework was intended to compel students to "think like engineers" and develop into "problem solvers," as one teacher described. The decision to label the academy under the STEM acronym while favoring just one area convoluted the academy's purpose, an issue that frequently surfaced during the study. For example, an administrator pointed out, "I mean in some ways I almost wish we would've called it the pre-engineering academy, not STEM, because STEM means fifty things to fifty different people, it really does. And truly we're engineering. And our goal was that you're going to do engineering and you're going to learn the science and the tech and the math along the way to be able to do these projects."

The district lacked the budget for purchasing a prepared curriculum, so, after settling on the overarching purpose of the program, two of the school's science teachers (one of whom had earned a degree in mechanical engineering) were tasked with establishing a roadmap for future course development. The teachers sought published high school engineering standards for guidance, but finding little freely available, they began composing their own. Two foundational documents were produced from their efforts, and they were entitled the "Academic Standards" and "Grade Level Expectations."

The Academic Standards established five primary goals, shown in Table 2. The goals centered on preparing students for STEM careers by prioritizing collaboration, relevant content, the engineering design process, and communication. It is noteworthy that even here, at this stage of development and at this level of detail, the academy was still projected as one of *STEM* education rather than *engineering* education, again, a misalignment that generated uncertainty as to the true vision of the program.

Table 2: Summary of the Academic Standards

Standard	*Brief description*
1. STEM career exploration	Awareness of and preparation to pursue careers in STEM
2. Collaboration skills	Ability to work in a team and take responsibility for one's own role
3. STEM skills & knowledge	Ability to apply relevant knowledge and skills to solve a problem
4. Open-ended, hands-on design experience	Ability to define a problem, then develop and evaluate a solution
5. Communication skills	Ability to write a technical report and conduct an oral presentation

These standards mapped well with the three principles of K-12 engineering education put forth by the National Academy of Engineering (NAE) and National Research Council (NRC), shown below in Table 3.[64(p.151-152)]

Table 3: K-12 engineering education principles recommended by the NAE and NRC

Principle	*Additional description*
1. K-12 engineering education should emphasize engineering design	The design process should: a) be highly iterative b) have many possible solutions c) provide a meaningful context for learning scientific, mathematical, and technological concepts d) be a stimulus for systems thinking, modeling, and analysis
2. K-12 engineering education should incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills	These should include the use of the following to support engineering design: a) scientific concepts and inquiry methods b) mathematical concepts and computational methods c) testing and measurement technologies, computational and visualization tools
3. K-12 engineering education should promote engineering habits-of-mind	These include: a) systems thinking b) creativity c) optimism d) collaboration e) communication f) attention to ethical considerations

The academy's standards, completed after the publication of those shown in Table 3, do tend to emphasize the practice of arriving at solutions through a hands-on, experimental approach to problem solving rather than promoting a more professionally-relevant approach as suggested by the NAE and NRC.

For example, "mastery" of STEM skills and knowledge, Standard 3 in the academy, mandates that students "identify, analyze, independently seek, and apply content knowledge necessary to solve a problem" as well as "explain and justify how the content knowledge applies to their solution." The same level of mastery of Standard 4 requires students to design, construct, test, and evaluate a working prototype, then "independently complete an iterative design process to create a final design." There is little to suggest that the students must practice disciplined inquiry or design and apply mathematical models in the development of their products. This oversight of applied math and science would have profound consequences in the academy, as later described in this report.

The academy's Grade Level Expectations were created as a complement to the Academic Standards, providing more specificity of annual milestones in relevant areas, including experimentation, data analysis, fabrication, and computer-aided design (CAD). The standards listed the explicit competencies students were to acquire by the end of each school year. For example, Table 4 displays the expected learning progressions in fabrication and CAD.

Table 4: Grade Level Expectations in fabrication & computer-aided design

Year	*Description*
Freshman	- Can construct a prototype using the provided classroom resources and instructor assistance - Be able to complete detailed drawings with dimensions
Sophomore	- Can construct a prototype using the provided classroom resources - Will use classroom experiences to complete a simple CAD drawing
Junior	- Can construct a prototype using the resources of the Fabrication Laboratory - Be able to incorporate CAD based drawings into class projects on a semi-independent basis
Senior	- Can successfully construct and build a device based on a set of technical drawings - Students have completed technical drawings of their designs using CAD

These milestones were established to provide a clear pathway for the development of students' skill-sets, a significant first step due to the manner in which the academy courses were organized. That is, after their freshman year, students were provided with several course options, a strategy to not only allow students to select topics in which they were interested, but also to provide teachers with opportunities to radically modify the offerings to better suit their own abilities, so long as the standards and expectations were still addressed. An administrator addressed this tactic, saying, "So one of the key things that I think we did well was that we kept the design thinking as the core of each class, and then we standardized what every student would get at each level. And then the topic just changed. So if a teacher left and their passion was doing the aerospace class, and then the next person took over and that wasn't their passion, they could bring in something else. And then that topic could change for students, but they were really getting what they needed at their foundational level."

While students were expected to continuously improve their technical abilities, most notably in fabrication, computer-aided design, performance testing, and data collection, these skills were not mandated pre-requisites. Any student in the school with an interest in a particular course was permitted to enroll in that course, provided he or she had good academic standing. The curriculum could therefore not be considered successive in the traditional sense, as the standards were kept relatively low to allow the coursework to be accessible to all.

Curriculum

Todd: In a traditional classroom where you'd have written homework and written tests, we don't have those in the STEM Academy. How do you feel about that?
Teacher: I feel like it goes along with the intent of the program right now and the idea that we want to make them interested in engineering.

– Academy teacher

Academy students are required to complete coursework as specified in Table 5. Aside from the full-year senior design course, all offerings are one semester, meeting every other day for ninety-one minutes per class. Each school year, four sophomore-level and four junior-level courses are typically offered. In order to earn a STEM certificate, students must graduate with a 3.0 GPA and complete four science courses, one of which must be advanced placement (AP), four math courses, and six STEM courses.

Table 5: Academy courses

Year	*Course title*	*Description*
Freshman	Explorations in STEM	- Taken by all students - Designed to engage students in the engineering design process
Sophomore	Creative Engineering	- Required to take two of the following: Robotics, Sustainable Design, Assistive Technologies, Structural Design, Historical Technologies
Junior	Advanced Engineering	- Required to take two of the following: Robotics, Engineering Science, Biomedical Engineering, Aerospace Design
Senior	Senior Design Capstone	- Taken by all students - Students design and create devices of their choosing

There is no hard cap on the maximum number of students permitted in each section, and depending on the number of offerings and students' schedules and preferences, some classes have included more than thirty students. Teachers have suggested that class sizes of about twenty-four students (to create eight teams of three) are preferred due to the extensive tools and supplies required as well as the relatively small physical space available in the classroom; sections with large numbers of students present much greater facilitation challenges, particularly at the lower grade levels where a lack of direct oversight provides opportunities for less mature students to engage in off-task, even destructive, behavior. These issues were intended to be mitigated by the group-centeredness of the curricula, as all projects are completed in teams, thereby necessitating fewer supplies and allowing students to rely upon and manage one another.

As per the recommendations of the partnering engineering college, courses were based on the project-based learning model, which centered on the development of physical products set within real-world contexts. The intent of the model was to provide opportunities for students to more naturally encounter challenges, thereby motivating them to learn content and develop skills deemed necessary for successful project completion. For example, in the biomedical engineering course, students designed and constructed remote-controlled robots capable of mapping and collecting potentially-cancerous growths (modeling clay) inside a human abdomen (an enclosure line with water-filled rubber tubes). To fulfill the course requirements, students were expected to learn about issues related to laparoscopic surgery and improve upon their prototyping abilities.

Students completed their projects in groups, typically three students per team. According to the Grade Level Expectations, “Students are expected to work and perform within a group setting in STEM courses; most grades and assessments throughout the program will be assigned as a ‘group’ grade.” Since projects can last for several months, and because group work typically accounted for 70% to 80% of a student’s overall grade, the selection of teammates was no trivial matter. Yet there was no academy-wide policy on group formation; for some projects, teachers assigned teammates, but students oftentimes selected their own.

Lectures were kept to a minimum. Teachers did address fundamental concepts related to projects, but courses were designed to allow students to discover new understandings as they worked through activities and extended projects. Teammates were expected to apply their knowledge and use logical reasoning to initiate and optimize their novel designs. In the Sustainable Design course, for example, in which solar water heaters were created from wood, plastic sheeting, rubber tubing, and a variety of other materials, students were to use relevant understandings to test and refine their devices, with a goal of achieving an efficiency benchmark of at least fifteen percent. Teachers also facilitated lessons and activities to help students acquire disciplinary skills, those deemed relevant to the project at hand as well as engineering in general. These tasks, which included the use of spreadsheets, CAD software, and fabrication equipment, were at the discretion of individual teachers, meaning that skill-building was somewhat inconsistent among the courses. Much of this direct instruction took place during the opening weeks of the semester, prior to the introduction of each course's respective project. Once a project was underway, a teacher's role transformed into one more aligned with that of a coach, helping to guide students towards alternative strategies when they struggled; teachers were not expected to provide explicit solutions to encountered challenges.

It is important to point out that the methods by which students addressed presented problems was not always aligned with what could be considered "disciplined inquiry." According to Newmann et al.,[99] disciplined inquiry requires three key attributes: the use of disciplinary content by which students rely upon and demonstrate the use of ideas central to the discipline; a disciplinary process whereby students employ commonly used methods of inquiry, research, and communication; and the need for students to elaborate upon their understandings and conclusions through written communication. Such a process of searching for solutions still allows for creativity, yet in many regards necessitates a systematic approach to problem solving. This process differs radically from that of one which could be described as "guess-and-check" or "tinkering" by which students attempt to find workable solutions primarily through the manipulation of their physical products with little forethought or evaluative analysis. The key differences between these two strategies is that disciplined inquiry strives for *understanding* though a minds-on approach while tinkering aims for *performance* through a hands-on approach.

Notably, though the teachers relied upon a general understanding of engineering design to facilitate the projects, the design process was not explicitly presented to students as a framework for developing their physical products. Teachers did discuss certain facets of the process, such as the need to brainstorm for ideas or implement modifications, but this was on an infrequent basis and thus acted more as an implicit and vague strategy for problem solving. To represent the design process as employed by the students, I assembled the illustration presented in Figure 2, which is based on my experiences within the academy's classrooms. Although these steps are not consistently followed by all students, this representation characterizes typicality among various groups' efforts.

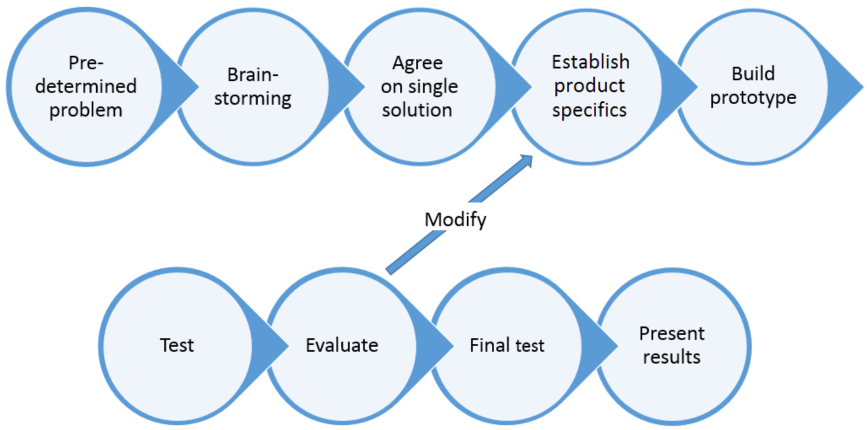


Figure 2: Representation of the engineering design process as practiced within the academy

In accordance with project-based learning, academy leaders decided to forego traditional assignments, choosing instead to make use of more authentic assessments. Homework and written examinations were therefore struck from the course plans, as projects were modeled on the professional engineering workplace, whereby employees (students) are evaluated largely on their abilities to meet deadlines, generate promising prototypes, and discuss their findings in front of an audience.

Case study impetus

The student population of the academy was ever-increasing, a testament to its engaging learning environment. To account for the increase, the number of academy teachers had doubled to four by 2013. During the fall semester of 2013, these teachers met with the high school STEM coordinator over the course of two days to re-examine the program and plan for its future direction. The STEM coordinator, a former teacher within the academy who had recently been promoted to the newly-established position, was a co-writer of the Academic Standards and Grade Level Expectations. In his new position, he was highly involved in the development of a facility elsewhere in the school district that housed a relatively professional technical workshop (with tools such as 3D printers) and accommodated the senior capstone course and classes on computer-aided design and laptop repair. The coordinator had a strong background in the construction industry and had previously taught a plethora of science courses, but he lacked formal training in engineering education. While it was intended that the director would support the teachers in their endeavors, due to his other responsibilities, there was little communication between the coordinator and the academy teachers during the school year, and the teachers were, for all intents and purposes, placed in charge of designing the curricula as best they saw fit.

Discussions about common classroom issues and possible pathways for remediation ensued. The veteran staff members were generally satisfied with the progress made since the academy's infancy, but academic gains were cast in doubt, propagated by a lack of purely objective assessment data coming from academy classrooms. The teachers expressed concerns that a large number of their students lacked basic technical skills, and discussed methods for holding students to higher standards. All believed ample opportunity existed for improvement. Three key issues emerged from the meetings, as outlined below.

Underlying issue #1: Projects could be completed with little demonstration of achievement

To signify the role of product development in the classroom, the assessment structure was designed to favor the construction and presentation of developed physical products. This grading scheme was established under the pretense that a product's performance would naturally align with a similar level of relevant content and skill mastery, as well as students' classroom habits, such as the practice of quality collaboration. When a group of students incorporated appropriate conceptual understandings into their design, made these designs a reality by utilizing the necessary tools, then brought their product to fruition by proper application of the engineering process, it stood to reason that they reached a high level of achievement.

Yet this idealization was flawed. For instance, the Sustainable Design course opened with an introductory project on solar ovens. Concepts related to heat transfer, solar energy, and the greenhouse effect were presented, and students spent the initial weeks of the semester designing and constructing their ovens with the expectation that these new concepts would be incorporated into their designs. While there was clear differentiation among the quality of the teams' work, it was impossible to definitively declare that better-performing ovens were created by students who, for example, understood the material more deeply, possessed superior fabrication skills, or put forth more effort. Consequently, the teachers struggled to assign grades reflective of the students' abilities and contributions.

Underlying issue #2: Teachers were unable to accurately measure individual achievement

As listed in the Academic Standards and Grade Level Expectations, the academy's students were expected to attain proficiency in a variety of areas including computer-aided design, experimentation, and fabrication. However, due to the high value placed on group-centered tasks and authentic assessments, the grading structure was incapable of providing concrete evidence of each individual's level of achievement. Though a team's set of calculations may have demonstrated a high level of understanding, for example, it was impossible to declare that each member of the team had mastered this ability. Noted one teacher, "So it's kind of hard to tell sometimes at the end, because sometimes you see these awesome CAD drawings and it's one person in the group knows what they're doing and the rest of them have no clue. . . . You miss some of that stuff, because of the group aspect, of who really understands or whose skills are you really seeing at that time."

Underlying issue #3: Unmotivated students persisted in the academy, weakening the environment

According to a veteran teacher, a non-trivial number of students enrolled in the academy "for the wrong reasons." These students' motivations notwithstanding, the real harm caused by some of these individuals was a perceived deterioration of the classroom environment. Some teachers noted that low-achieving students exhibited such poor behavior that classroom discipline became a major issue at times. And, as one teacher mentioned, "middle ground" students could get "sucked in" to the less-than-ideal behavior, further deteriorating the situation. Nonetheless, the teachers time and again brought attention to the purpose of the academy, particularly its emphasis on inclusiveness. Ridding the academy of troublesome students was not their aim; modifying course features to better involve all students was viewed as a preferable pathway.

Case study basics

In light of the concerns put forth by the teachers, it was agreed that a more well-rounded understanding of the project-based learning model would provide valuable bases for taking corrective actions. Conducting an in-depth case study was viewed as a promising first step for improving the learning environment. A proposal was therefore put forth to provide an exhaustive account of a single academy course – with a focus placed on obtaining detailed student input – in an effort to provide sufficient insight for sound curricular decision-making. To further support the study, the teachers themselves as well as key administrators would be asked to participate in the study.

The case study aims to paint a clear picture of a high school engineering course utilizing project-based learning. The findings from this work are not meant to simply support this particular academy; better awareness of the beneficial features and potential pitfalls of the learning model is intended to serve as guidance to outside educators in similar settings. Because there is currently little research upon which to base curricular decisions in high school engineering – demonstrable by the large number of outside teachers and administrators interested in touring the academy – the study provides much-needed support for this evolving educational field.

The immediate research purpose was to identify aspects of the educational model that benefitted student achievement in the course under study as well as the aspects which inhibited learning. In addition, it was necessary to expound upon the challenges faced by the course instructor. In order to provide an in-depth description of this unique environment, a qualitative research approach was taken. Data was collected from a number of sources, including interviews, students' completed work, and surveys, and long-term researcher engagement allowed for a more complete understanding to emerge. Half of the courses' students participated in focus groups, while the cooperating teacher and eight other teachers and administrators involved in the academy were interviewed individually. These contributions, as well as that collected from open-response surveys, was categorized using a coding scheme aimed at quantifying participants' input. By compiling text-based data in this fashion, common perspectives could be more easily identified and communicated. At the same time, salient minority viewpoints were also taken into consideration. Preliminary findings from this analysis were compared against data from other sources in an effort to determine regularities within the course, with special attention paid to potential validity threats.

Course under study

A junior-level course entitled "Advanced Engineering: Engineering Science" formed the basis of this case study. Prior to this course, all students had taken the freshman-level Explorations in STEM course, two Creative Engineering courses, and one Advanced Engineering course. While the topics of these latter courses varied, all students were expected to have gained an understanding of the design process and the basic tools and skills which supported this type of thinking. This included math and science capabilities in data collection, computations, and graphing, as well as experience working in teams, prototyping, and in computer-aided design. The context of the course under study was a call to transport a scientist and her tools across a fragile desert landscape to various research sites, a hovercraft being the most effective vehicle for doing so. Students were exposed to various physics concepts related to forces and flight, and were expected to identify effective hovercraft designs, first by creating several iterations of simple prototypes, then by constructing and optimizing a craft they themselves could ride. Materials included a 4'-by-8' sheet of wood to form the base, a tarpaulin to act as an inflatable "skirt," a leaf blower to provide lift, and a large fan to generate propulsion. Figure 3, drawn by a student of the course, illustrates a basic craft configuration.

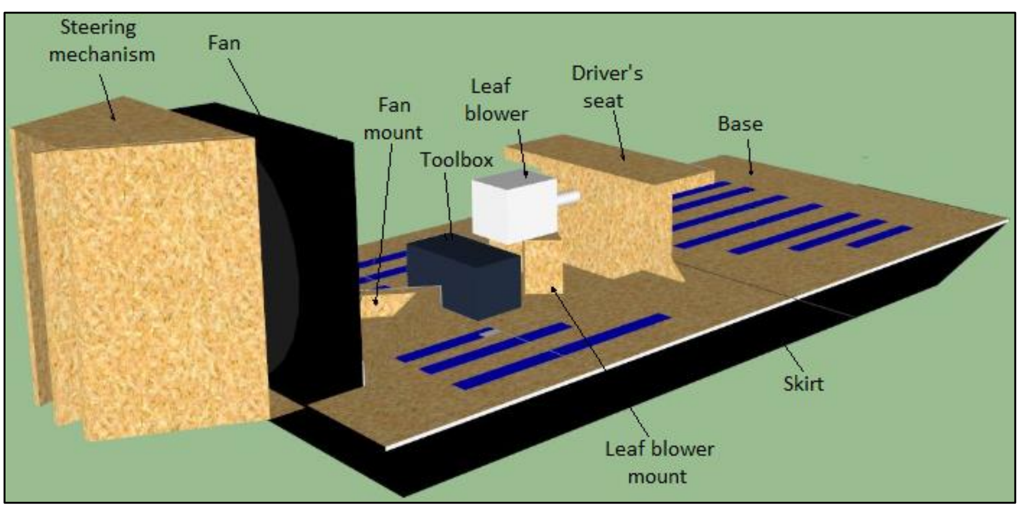


Figure 3: Basic hovercraft configuration

This course was chosen as the study focus because it represented typicality within the academy; it had been offered for several years and followed the general curricular structure of most other offerings, meaning the initial weeks included brief exploratory projects along with a heavier focus on content, followed by an extended project phase. In addition, the teachers voiced a desire to gain an understanding of the academy from the perspectives of students who had studied in the program for a number of years. The course consisted of two sections – one with thirty students and the other with just nine.

The hovercraft course had been taught four times over the previous three years by two different teachers. Lesson plans were created by one of the academy's founding teachers and had been incrementally added to during each successive year. Prior to the course's fifth installment during the spring semester of 2014, the plans were handed over to a third teacher. "Ms. Foster," as the cooperating teacher will be called, was a year and a half into her teaching career, and had just one semester of experience in the academy. She had an impressive background, with bachelor's and master's degrees in physics, and a second master's in education.

Ms. Foster, like all of the academy teachers, had a busy schedule, as she taught two other academy courses as well as physics courses, and served as the leader of the school's robotics club. She had had little time to review the lesson plans and, unfortunately, the hovercraft course's previous teachers were largely unavailable for help. Though the conditions were far from ideal for observing a well-developed course, it was representative of common situations in which inexperienced teachers are tasked with managing an engineering-focused classrooms. The academy leaders did ultimately hope to offer the course curriculum to other school districts interested in implementing engineering programs, and such an offering would surely put course plans into the hands of inexperienced teachers. Observing and working with Ms. Foster thus presented an authentic and worthwhile case.

Ms. Foster and I worked closely over five months to facilitate and modify the lessons and activities in an effort to improve upon the course plans and replicate a realistic engineering project. Because she had not been responsible for designing the original curriculum herself, neither she nor I viewed project successes or failures as reflective of her aptitude as a teacher. Yet when she did create activities or deliver lessons, I was careful to refrain from making any comments that could have been misconstrued as critical since maintaining an open line of communication was vital, and I wanted her to view me as a colleague rather than an outsider passing judgment. Due to this close working relationship, Ms. Foster felt comfortable to offer honest thoughts and feedback, and her frequent input provided a critical viewpoint in the study.

Researcher's role

I had been involved with the school district since the spring of 2013. I assisted with project facilitation and curriculum development at the elementary, middle, and high school levels, though the vast majority of my work took place within the high school academy. My position was sponsored by the National Science Foundation as part of the Graduate STEM Fellows in K-12 Education Program. During the school year, I spent roughly fifteen hours each week at the high school. My role was to assist with the development and facilitation of engineering-based coursework. I also assisted teams and individuals in various areas – for example, calculations, fabrication, and experimentation – as they progressed through the projects, helping to alleviate the stress that can be placed upon a single instructor in a project-based classroom.

My background experience helped me extensively in this endeavor: I hold bachelor's and master's degrees in engineering, had roughly five years of experience in engineering work and research, and through my sponsored position, was exposed to a substantial amount of engineering education curricula. Notably, I was responsible for aligning published K-12 engineering lessons and activities with the Next Generation Science Standards.

It is important to note that fulfilling the roles of researcher and second classroom teacher did have its conflicts. Most notably, due to my perception that the course and academy served primarily to prepare students for engineering college, I somewhat discounted the academy leaders' aim to provide enjoyable classroom experiences related to engineering. I therefore viewed students' lack of abilities in technical areas – including mathematical computation, experimentation and data collection, fabrication, and the application of scientific concepts – as severe shortcomings, and made frequent note of these deficiencies. However, I was also motivated to help teach students these skills, yet when individuals showed disinterest in engaging in such skill-building activities, or when they were satisfied with low quality work, I found this to be unbecoming of purported engineers-in-training. In essence, student actions which did not align with improving their engineering skills and habits were initially viewed with criticism. Methods for dealing with this bias and other validity threats is detailed later in this report.

CHAPTER II

LITERATURE REVIEW

Learning theory

In recent years, there has been a fundamental shift in education.[116] Traditional learning environments – those which stress knowledge acquisition through teacher-to-student information transmission – are slowly being replaced by classrooms which more highly prioritize knowledge application. This shift is in large part due to the demands of the 21st century workplace, an ever-changing job landscape which necessitates higher-order thinking skills.[95] Thus, compelling students to learn by rote memorization is viewed as an outdated educational strategy. Instead, our evolving society values graduates capable of using their understandings in a practical manner, not simply those with deep wells of disconnected facts.[19] Students must be expected to develop sharp critical thinking skills, defined as the ability to reason, make judgments and decisions, and problem solve.[110] Employing this higher-order cognitive process allows for students to hypothesize, examine arguments, weigh evidence, and arrive at defensible conclusions,[122] important abilities in many careers, but particularly valuable in engineering.

In order to prepare students for professional engineering and related fields, schools are turning to active learning methods that stress dynamic student engagement in classroom lessons and activities (as opposed to passive absorption of information). Rather than treating students as empty vessels into which knowledge can be heaped, learning is viewed as an active process of constructing and reconstructing knowledge.[103] Research supportive of active learning points to increased levels of higher-order thinking, long-term information retention, and intrinsic motivation.[41,89] Still, lecturing remains the dominant mode of instruction in the vast majority of engineering and other STEM-based courses.[89]

This is not to trivialize the importance of rote knowledge. Indeed, achieving success in an engineering classroom or workplace requires support by a foundation of factual information.[19] A deep knowledge base helps expert learners flexibly retrieve information with little effort, allowing for them to organize their thoughts, interpret their environments, connect concepts from other disciplines, reason, problem solve, and develop explanations. In other words, by reducing the cognitive load required for factual recall, individuals are capable of expending more energy on higher-order thinking.

This case study draws from the learning theory of constructivism. From a constructivist standpoint, learning is a sense-making activity in which new information is understood relative to how it relates to prior knowledge.[71] Therefore, rather than taking a direct approach to classroom learning by assuming "what they see is what they get," teachers should design lesson plans under the notion "what they think they see is what they get."[125] Considering that all students bring different experiences and understandings into a classroom, learning must be viewed as idiosyncratic, whereby students comprehend new information distinctly different from one another.[69] Thus, in a traditional direct-instruction classroom, where information predominantly flows from instructor to learner, there may exist severe limitations in a teacher's ability to reach all students equally. As such, teachers should not be expected to harness complete control over the educational process, but should instead act more as facilitators, guiding individuals towards learning goals.[3] Students, for their part, should be urged to assume more responsibility for their own learning.

At the same time, learning is less often being viewed as a private activity; social settings are seen as playing a critical role in education.[60] This modification to the constructivist learning theory, aptly named "social constructivism," postulates that individuals construct and share new knowledge during collaborative interactions among peers.[70] The added social aspect further transforms the educational process to one of "what they agree they see is what they get."[125]

In active learning science and engineering classrooms, where activities are often designed to represent professional work, students may be required to conduct experiments, design prototypes, fabricate functional devices, and perform other physical work. These tasks, which involve the creation or manipulation of products to foster understanding through kinesthetic learning, are characterized by "constructionism," another learning theory founded in constructivism, one with an additional hands-on attribute.[90]

The aggregate of the three learning theories described above represents "social constructionism," the learning theory which best embodies the environment of the course under study.

Project-based learning

When people encounter problems, they draw upon their past experiences and apply current understandings to identify solutions. When this process fails, they often recognize that new knowledge is necessary.[42] Many active learning models tap into this desire for knowledge by encouraging educators to design coursework around the context of realistic scenarios. If students are compelled to learn and apply newly attained information in order to solve presented challenges, the material is more likely to be added to their knowledge bases.[137] The same process holds for skill-sets; when skills are required to complete an assignment, they are more likely to be improved. The effectiveness of this educational model can be strengthened by posing problems deemed worthy of investigation (as perceived by students), then highlighting a clear need for knowledge and skill development in order to solve a particular problem.

Engineering courses at the K-12 level often forego traditional lecture-based methods in favor of hands-on, discovery methods, with project-based learning commonly serving as the model. The incorporation of product design differentiates project-based learning from other active learning models; this provides a tangible means to gain experience with the engineering design process. The purpose of hands-on projects is to engage students in constructive investigations that emphasize decision making, prototyping, and discovery, leading to greater knowledge construction.[127] Students are expected to apply acquired knowledge and skills and work collaboratively with classmates. Their completed products are intended to demonstrate achievement, whereby the degree of success correlates with product performance.[24]

Project-based learning prioritizes authenticity.[127] Students are presented with complex, ill-structured problems, offering multiple solution pathways for the successful design and creation of physical products, much like could be expected in an engineering firm. Coursework is, to a degree, student-driven. Teachers largely serve as facilitators, offering guidance as students conduct their own investigations to identify valid solutions to posed problems, a practice that is common in just-in-time learning. Authentic achievement requires that students attain new understandings and skills in the context of professionally-relevant activities.[99] By honing their abilities through guided practice in the creation of original ideas and physical products, students are expected to construct knowledge in relation to their previous understandings. To map professional work, student findings should be expressed through elaborate forms of communication, including technical reports, presentations, and demonstrations. Outside audiences commonly evaluate student projects, helping to support the connections between students' work and the professional world.[124]

Studies on project-based methods have shown several benefits. A review of the literature by Thomas concluded that the learning model employed at the K-12 level led to improved student motivation and self-reliance.[127] This was reiterated by Bender, who noted that the key advantage to project-based learning was enhanced student interest, which thereby led to increased engagement and achievement.[9] Much of the research has been conducted not within engineering-specific coursework, but in classrooms that aimed to engage students in a number of skill-building activities such as writing, mathematics, and research, with a central authentic project acting as the motivating factor. For example, a study in a fifth grade social studies course led Gültekin to conclude that project-based learning "develops a variety of abilities"[53(p.553)] by encouraging students to cooperate with peers as they learn within an enjoyable setting. Similar findings were put forth from a study of third, fifth, and tenth grade students.[7]

Project-based methods have been shown to improve students' engineering and investigative skills as well. For instance, a study of a sixth grade classroom on the application of project-based methods focused on teaching geometry through architecture and design led to increases on summative geometry tests.[6] A study conducted within an urban middle school found that science students educated with project-based methods fared better on standardized tests than their traditionally-educated peers.[48] A longitudinal study conducted Boaler within two high school mathematics classrooms revealed that students engaging in project-based methods were more apt to view math as a subject which required exploration and thought; these students performed better on a standardized test.[16] And a study of fourteen elementary schools using project-based methods found critical thinking and cooperation to be the most advantageous aspects of the model.[130]

Numerous engineering colleges are now relying on such methods to drive first-year courses as well as comprehensive curricula.[25,45,85,113] For instance, a first-year mechanical engineering course that took a non-traditional, project-based approach was seen to foster students' abilities in problem solving, information retrieval, laboratory skills, and teamwork.[44] Another study in a first-year industrial management and engineering course found project-based methods to improve teamwork, communication, and motivation.

Other research has highlighted the model as an effective method for differentiated instruction, affording opportunities for students to learn and work at their own paces, which is particularly beneficial for lower-achieving students.[9] Because the model employs a team-oriented classroom structure, students in project-based classrooms have demonstrated improved teamwork and communication skills.[94] Perhaps most prominent of noted benefits is an increase in student motivation, attributed to a more natural learning environment that values contextual and inductive learning, generating life-long learning skills.[9,107,127]

Best practices cited within the relevant literature suggest that, first of all, because project-based classrooms lack the instructor-directedness found in most traditional classrooms, it is vital that students have a clear understanding of the expectations of each of their projects as well the manner in which they will be held individually responsible.[96] Although high schoolers often express a desire to work without direct supervision,[102] they are generally incapable of solving complex problems on their own, and it is therefore necessary for teachers to scaffold their inquiries by building on their previous understandings and present problems that are relevant to their personal experiences.[118] For this reason, it is important that teachers take a formative approach to assessment, since students require assistance with the learning process.[23]

Although there is wide evidence that both teachers and students who have taught and learned in project-based classrooms find the model engaging, the true benefits are not well defined. Project-based learning could very well be perceived as more beneficial than traditional methods simply due to its novelty or because the activities are fun.[127] In other words, exposure to a presumed innovative learning model, particularly one unschool-like in which students show a higher level of engagement, may lead participants – including educational researchers who assess such classrooms by observation – to overestimate its benefits.

Additional research is needed to ascertain what is truly being learned in engineering design courses that utilize project-based learning. It is important to more clearly identify the specific mechanisms that contribute to the productiveness and unproductiveness of this model. Doing so will allow the model to be utilized more widely and with more confidence.

How People Learn framework

The How People Learn framework, illustrated below in Figure 4, represents the structure of a well-planned educational environment.[19,125]

The conceptual framework is constructed of four distinct yet overlapping classroom ideals:

1. Knowledge-centered – focused on deep understanding of content and disciplinary processes
2. Learner-centered – focused on the knowledge, skills, attitudes, and needs of students
3. Assessment-centered – focused on revision through formative and summative evaluations along with frequent instructor feedback
4. Community-centered – the three ideals above are supported by an environment of learners with a shared vision, connected to the larger community outside of the classroom.

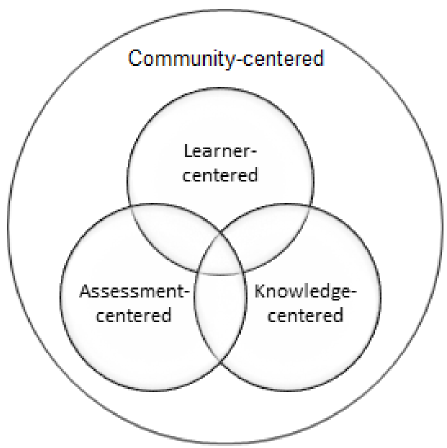


Figure 4: The How People Learn framework

This framework helps define and support the key attributes of this study, as outlined in the following sections.

Knowledge-centered

A knowledge-centered classroom emphasizes sense-making of disciplinary content, as opposed to rote memorization. Students are encouraged to reflect upon their own understandings of material and ask questions of themselves and their instructors when new information clashes with any preconceptions they may have. In order to develop deep understandings, students must be given the opportunity to investigate and discover knowledge on their own. For this reason, many teachers hesitate to employ active learning methods since self-discovery of knowledge necessitates a greater allotment of class time, meaning that the quantity of content must be reduced.[118] This presents an issue, as teachers commonly feel obliged to cover all required subject matter, regardless of how deeply students may learn the material.[9] Classroom practices which attempt to emphasize quality over quantity are thus often perceived as ineffective educational models since content reduction may prevent complete coverage of a subject's required standards. This situation can be exacerbated by school district administrators who refuse to allow implementation of innovative curricula, insisting that a particular teaching method first be supported by a proof of concept to confirm that any non-standard approach will lead to high standardized test scores.[116]

Project-based learning has much in common with problem-based learning, a more well-established active model with a longer history and broader application.[123] Problem-based learning has been shown to provide educational benefits, but some studies claim that it simply breaks even with traditional teaching methods or that its effectiveness is unreliable.[50,58,69,123] In other cases, researchers contend that a teacher's experience, content knowledge, and pedagogical training – not the curriculum – matters most, asserting that while some teachers using problem-based methods have outperformed those using traditional methods, the reverse has also been found to be true.[109] The effectiveness of the model thus arguably depends on a number of factors.

Problem-based learning prioritizes knowledge acquisition and application, but does not feature product creation. While it may seem logical to utilize this model in engineering courses, engineering educators often view problem-based methods as inauthentic.[94] In fields such as medicine, from which problem-based learning originally grew, posed scenarios typically have one correct answer (e.g., the diagnosis), and students are expected to arrive at this answer in a fairly straightforward manner. Engineering design problems, on the other hand, commonly possess numerous successful pathways. Under such conditions, students must be afforded autonomy to explore and discover potential solutions with little instructor interference, thereby fostering creativity and critical thinking. In addition, by extending project timelines over several weeks or even months, students are provided the opportunity to gain experience in prototyping, task delegation, and time and resource management, all of which are considered relevant skills in the engineering profession.[103]

Project-based engineering curricula are expected to provide contexts for the application of math and science, a significant benefit considering that many students view these two core subjects as professionally irrelevant early in their educational careers.[132] The inclusion of math and science should be rigorous and developmentally appropriate, representative of professional practice. Unfortunately, this does not always transpire. For example, math included in K-12 engineering curricula commonly involves very basic procedures such as taking measurements and presenting data, while little attention is paid to solving for unknowns or using mathematical models.[129] Furthermore, while strong curricula in STEM fields should have a concentrated focus to provide students the opportunity to master key topics, design-based courses often require students to apply a broad spectrum of knowledge.[28,114] Yet with semi-autonomous teams generally working independently of one another on potentially dissimilar products (depending on their creativity), ensuring that students confront and construct the "right" knowledge (that which has been established as significant in a course) can be daunting.[103] Thus, there is risk in heavily relying on project-based methods in fields with hierarchical knowledge structures – including math, physics, and engineering – whereby topics must be learned sequentially.[94,103] Accordingly, it has been noted that students in these classrooms may have a less rigorous understanding of subject fundamentals, with recommendations that the model not be utilized as a comprehensive instructional method.[94,103] Rather, some view direct instruction as a necessary means to ensure students learn the appropriate material, but such measures can diminish an environment's authenticity and learner-centeredness.

Some engineering colleges address this issue by employing a mixed-mode approach whereby first- and second-year courses are generally lecture-based to provide disciplinary fundamentals, followed by coursework that is more student-driven and design-based.[117] The drawback, as noted by Randy Atkins, the director of the National Academy of Engineering's Grand Challenges for Engineering project, is that it takes "too long to get to the real-world stuff, the fun stuff."[79] Students find design work interesting, and delaying this aspect of engineering in deference to knowledge- and skill-building by traditional methods fails to take full advantage of the field's potential to engage students. Some teachers feel that jumping into the design process leads to more efficient learning, as illustrated in a comment by Ziyad Duron, chair of engineering at

Harvey Mudd College: "The earlier we expose them to project-based learning, the earlier we break down their barriers, their fears over hardware and software, and the cleaner their learning experience is."[79]

In addition, people typically learn inductively, meaning that knowledge is first acquired in specific contexts, then generalized to broader scales.[40] A traditional "basics first" approach, however, is deductive, moving from generalities (principles and theories) to specifics (application). Design-based activities not only provide opportunities to learn inductively, they allow students to gain experience with the engineering design process during their entire academic careers, offering better perceptions of professional fields.

A common complaint about hands-on activities in the learning model is that they are often not "minds-on."[118] That is, the focus of activities may become the manipulation of objects rather than the development of skills and understandings, an issue that can be perpetuated by teachers who routinely describe the tasks to be completed rather than the material to be learned. Misalignment between hands-on projects and content represents a fundamental challenge facing educators. Because physical products are central to the curriculum in project-based learning, content and projects should not exist in isolation. Instead, course plans should "be crafted in order to make a connection between activities and the underlying conceptual knowledge that one might hope to foster."[6(p.274)]

Learner-centered

In a learner-centered environment, students take a more active role in the educational process. As opposed to a traditional teacher-directed classroom, students are expected to determine and pursue the knowledge required to solve questions themselves; a purely learner-centered environment is one without standards, rules, or rote practice and memorization, where learning unfolds naturally.[108] Opponents of this progressive ideal, skeptical that students discover knowledge when left to their own devices, argue that classrooms should be orderly and disciplined.

To ensure students are engaged in coursework, it is critical they have a clear understanding of the expected learning goals (defined as the knowledge, skills, and habits learners are expected to possess after gaining experience in a course). This necessitates that teachers understand and communicate these goals clearly, a practice supported by psychologist Carol Dweck, who commented, "With learning goals, students don't have to feel that they're already good at something in order to hang in and keep trying. After all, their goal is to learn, not to prove they're smart."[36(p.122)] If learning goals are not well understood, students may doubt their own abilities and lose interest.[80] In engineering, learning goals can be categorized into four broad areas: 1) factual knowledge, 2) conceptual understanding, 3) skills, and 4) habits-of-mind.[38] These areas are detailed below.

A foundation of factual knowledge, regarded as lower-order thinking, is necessary to support effective cognitive processing in the other realms. Such knowledge must be "usable" such that the information is connected to and organized around key disciplinary content.[19] Without a solid knowledge base, students lack the ability to justify higher-order conceptual understandings, vital for generating novel solutions to complex problems.

Skills can be separated into procedural and communicative domains. Procedural skills are necessary for disciplinary tasks such as experimentation and data collection, prototype construction, and computer-aided design. Communication skills are required for verbal presentations and written work, including essays and technical reports.

Habits-of-mind include critical thinking, creativity, and collaboration. In addition, affect – or the positive feelings one associates with a given topic – is considered an important habit-of-mind because it helps engage students in coursework, and is purported to lead to life-long learning).[29,64] These habits are often regarded as "universal" since they are valuable in nearly every line of work.

Inquiry

By compelling students to investigate meaningful yet ill-defined problems, create and test physical prototypes, and make evaluations in an iterative cycle, project-based learning maps well with many authentic features of engineering.[103] This process of inquiry is most effective when students are given an opportunity to explore at their own pace with their own preconceptions.[75] During exploration, students should be encouraged to work analytically and expound upon their observations through written reflections, providing a means for instructors to examine their understandings and offer feedback, thereby allowing new ideas to be more readily embedded within students' preconceptions.[99] Once new knowledge is constructed in such a manner, students should be able to apply it in existing and novel situations. This rather lengthy learning process is viewed by progressive teachers as a more effective alternative to traditional lecture-based learning, and was supported by developmental psychologist Jean Piaget, who noted that "each time one prematurely teaches a child something he could have discovered for himself, that child is kept from inventing it and consequently from understanding it completely."[104(p.715)]

Self-regulation

Self-regulation describes the manner in which students are able to monitor and control their own thinking, motivation, and behavior during the learning process.[100,135] A degree of self-regulation is a necessity for students to optimize the educational benefits of any learner-centered classroom. With high levels of self-regulation, students are able to plan, set goals, and take on responsibility for their own learning, leading to more persistence, resourcefulness, and confidence. Fostering self-regulated learners requires explicit attention paid to meta-cognitive strategies, those which emphasize reflection upon one's own thinking.[116] Students who practice self-regulation better reflect the behavior of professionals since they make deliberate decisions to improve their work and consciously take ownership for their results. Without these behaviors, students may remain dependent upon others for direction and judgment.[56]

Expert learners with high self-regulatory capabilities are typically well-suited to project-based learning. Conversely, inexperienced learners who lack self-monitoring skills often experience difficulties since they are expected to initiate inquiry, conduct investigations, manage time, and use technology productively.[127] Teachers should explicitly discuss and model self-regulation strategies – that is, helping students learn how to learn – since from a constructivist point of view regarding science instruction, "Unless hands-on science is embedded in a structure of questioning, reflecting, and re-questioning, probably very little will be learned."[12(p.46)] Thus, the overall effectiveness of project-based methods may ultimately depend upon a teacher's ability to develop students' self-regulatory skills.[19,118]

Problem solving

Employing the engineering design process is fraught with failure, but learning to fail productively is a cornerstone of the process. While failure may generate frustration, students who encounter situations which present new information that conflicts with their previous knowledge are better able to recognize and revise their misconceptions. Committing errors is thus viewed as a necessary step in the reconstruction of knowledge.[58,59] The engineering design process, with its emphasis on iterative optimization, promotes such error-making, as it allows for new information to become more ingrained, increasing the potential for deeper comprehension. If these understandings are then applied in a practical manner, critical thinking can be promoted as well.

Because it is iterative, engineering design is often likened to a process of trial-and-error. But students who employ this tactic only truly learn if they work through the process mindfully. Mindful behavior can be defined as an ability to investigate relevant situational cues and underlying meanings, to gather new information and generate alternative strategies, to evaluate outcomes, and to construct new ideas based on connections drawn from evidence.[5] Without mindfulness, students fail to problem solve in a manner befitting engineers-in-training, whereby critical thinking plays a large role in the design process. This point was illustrated by pediatrician and educational researcher Mel Levine, who wrote, "Effective problem solving is a systematic, logical, well-paced, and planned step-by-step process. It is the direct opposite of doing the first thing that comes to mind. Instead it represents excellent judgment, well-founded decision making, and the use of logical thought processes."[76(p.197)] Consequently, students who attempt to solve problems without mindful behavior fail to develop knowledge as intended by the project-based model.

Guidance

The end goal of a learner-centered classroom is to foster students' abilities to conduct "full inquiry," characterized as the practice of investigating, designing, implementing, and evaluating one's own work in the same manner as professionals.[97] Achieving full inquiry in the classroom, however, should in fact not be expected, particularly at the high school level, since students lack the knowledge bases, procedural skills, and motivation of professional engineers.[62,69] Rather than mirroring professional work, students should be expected to practice "adaptive inquiry."[39]

Adaptive inquiry describes the relationship between the knowledge and abilities a student brings into the classroom and a teacher's capacity to flexibly shape lessons and activities in response to the student's needs. An instructor's guidance must be tailored to each individual's cognitive level and background experience to supplement inquiry with supportive measures (e.g., demonstrating how to conduct an experiment) in an effort to generate an adaptation of an authentic situation. If students are not provided adequate guidance in specific components of the inquiry process, they may flounder in a state of "unguided discovery" during which they may expend excessive amounts of time exploring unproductive ideas.[106] That is, their inquiries go off track as they pursue ideas peripheral to the driving questions, resulting in frequent false starts and inefficient learning.[15,69] Under these circumstances, students' misconceptions may metastasize into more misconceptions, and any confusion may soon thereafter be followed by frustration.

Learner-centered classrooms require teachers who practice "formative" instruction.[14] In this teaching mode, teachers focus their attention on students' thought processes and serve as "actuators" who provide suitable correction to their progress.[13] Rather than answering questions directly, teachers facilitate the learning process by posing open-ended or leading questions designed to make students' thinking visible.[58] Conversely, teachers who choose to identify all essential information or offer guidance before students have been given a chance to generate their own ideas do not compel students to learn and problem solve on their own.

Because class-wide direct instruction is kept to a minimum in active learning environments, teachers commonly have a greater number of interactions with individuals, opportunities in which to provide immediate verbal feedback. This feedback is often given in the form of indirect guidance (e.g., hints and references) during "moments of contingency," points during in the learning process when instruction can change direction in light of new evidence of student achievement.[14,51] While this manner of teaching keeps students more actively engaged, instruction becomes much less predictable, a feature of the learning model to which many teachers are averse.

While students with minimal disciplinary understandings or experience in practices of inquiry require more guidance, those with severely limited knowledge bases or deficiencies in self-regulation may not be best served by an inquiry approach to learning.[52] These lower-achieving students are often unable to deal with the authenticity of complex, authentic situations, even when abundant guidance is provided. If students are forced into realistic situation for which they are unprepared, cognitive overload may consequently result, negatively affecting their learning capabilities. In these situations, direct instruction is favored over inquiry.

Motivation

In active learning, a key influence on students' motivation is their perceived value of classroom lessons and activities, the extent by which tasks are seen as useful, worthwhile, and relevant.[80,122,135] Schoolwork that lacks relevance – or is perceived as lacking relevance – is commonly met with disinterest. For instance, material that simply adds to a student's breadth of knowledge, without a direct connection to professional work, is often regarded as superfluous. Furthermore, students may also expect that content be delivered and learned in an enjoyable manner. In engineering and other STEM fields, where there are often attempts to pique students' interest by emphasizing the "fun" side of related professions, active learning methods can straddle the line between engagement and entertainment.

It is true that traditional teaching methods, with their emphasis on rote, passive learning, often fail to capture the full attention of students. In science, for example, students tend to dislike excessive note taking, learning from textbooks, memorizing facts, and conducting procedural labs.[80] Such tasks can lead students to view the subject as boring, and many would prefer to engage in more practical work.[38] Although relenting to pressures to create fun environments is likely to increase classroom engagement, this engagement does not guarantee knowledge acquisition or skill development.[19] The truth is that mastery of knowledge and skills is not necessarily fun, and often requires disciplined, hard work.[105] Students of all abilities need to be challenged if they are expected to develop new understandings and skills.[122] Indeed, a common reason students view science as boring is because there is a perceived lack of challenge.[80] Achievement in project-based classrooms has been shown to improve as a result of implementing a "culture of quality" that stresses student revision, multiple checkpoints, frequent constructive feedback, and high expectations.[10] At the same time, it must be recognized that coursework viewed as overly difficult commonly leads to a decrease in retention. Teachers must therefore find the threshold of developmentally-appropriate lessons and activities.

The manner in which teachers present classroom tasks can have a major influence on students' motivations towards learning.[56] It is vital that teachers clearly communicate the learning goals, then emphasize and reward content and skill mastery to help orient students towards these goals. In project-based environments, it is particularly important to distinguish between the product and the learning goals, specifically, what students are to learn by creating the product.[11,118] If students' motivations to create a successful product overshadow their desires to learn, they is greater potential that they will view their individual achievements as a reflection of their own abilities, opening the potential for reinforcing a "fixed" view of learning.[100] Under this mindset, learners perceive their innate abilities as more important than the effort they put forward, leading to ego-involvement and a propensity to frequently compare their work to others'. As a consequence, they are more likely to give up in the face of failure, believing that they have little control over their achievements, and they may attempt to protect their self-esteem by attributing any shortcomings to external factors. In contrast, students with more "malleable" views see failures as challenges that are to be overcome, resulting in an increase in effort.

If learning is perceived as a source of satisfaction in and of itself, creativity and higher-order thinking are likely to improve.[105] Educators should therefore focus on improving students' intrinsic motivations by designing engaging projects. Still, the expectation that each student will become intrinsically motivated by awe-inspiring lessons and activities is not reasonable, and the use of extrinsic motivation – that is, using external rewards such as grades to drive learning – must oftentimes be included within course plans. Overuse of external rewards, however, can lead students to view learning as a means to an end, again orienting them towards performance goals and, consequently, shallow learning. A balance between intrinsic and extrinsic motivation is thus regarded as necessary. This strategy is supported by educational researcher Suzanne Hidi, who wrote, "A combination of intrinsic rewards inherent in interesting activities and external rewards, particularly those that provide performance feedback, may be required to maintain individuals' engagement across complex and often difficult – perhaps painful – periods of learning."[57(p.159)]

For many students, assessments provide the primary form of motivation, dominating their study habits.[49] Consequently, assessments are the most commonly used tool for increasing extrinsic motivation, and have been called the most important factor to enhance or destroy students' desires to learn.[56] As written by educational researchers Garrison and Anderson, "Successful learners most often rely on assessment deadlines and activities to both pace and direct their learning efforts. Effective teachers use assessment activities strategically to motivate learners to engage successfully in productive learning activities."[46(p.95)] Yet this view is not universal among educational researchers.[11] Those opposed to this strategy recommend that grades not be used as motivation or punishment, the rationale being that lowering students' grades does not compel them to work harder, since many students are likely to continue to underperform or will simply give up after receiving poor scores.

In truth, the effect of extrinsic motivation can depend upon the particular task at hand.[105] These tasks can be divided into two categories: "algorithmic" tasks follow a set of established instructions down a single pathway to a single conclusion, which "heuristic" tasks often necessitate deeper investigation and experimentation, and offer students opportunities to devise a myriad of novel solutions. The use of external, contingent rewards (i.e., grades) can indeed help narrow a student's focus, aiding in task completion when there is a clear solution path. But this comes at a cost – extrinsically-motivated students are less efficient in using available information to solve novel problems, are more illogical in their problem-solving strategies, and tend to choose easier tasks. And though they may work harder and produce more activity, their work is often lower quality and less creative. In other words, external rewards can be effective for algorithmic tasks, but they may diminish students' abilities to think critically and creatively. This resultant behavior is attributed to the idea that external rewards require students to forfeit some autonomy – and therefore some potential intrinsic motivation – since they are being driven to towards task completion. These motivational effects can have a profound impact in project-based learning environments in which critical thinking is the hallmark of expected outcomes. And, significantly, 70% of job growth in the U.S. is expected to be in heuristic-type fields.[61] Preparing future professionals for such careers is thus essential to the nation's economic well-being, and the importance of higher-order thinking, rather than product performance, should be stressed in the classroom. Unfortunately, many schools are moving in the wrong direction, emphasizing routine work when most jobs will be non-routine, and choosing to offer performance rewards such as pizza, electronics, and even money.

It is therefore critical to bear in mind the achievement goal orientation theory.[35] According to this theory, a student's motivation is influenced by the way he or she thinks about what must be accomplished. The types of orientation are listed below:

1. Mastery orientation – students are focused on the learning process
2. Performance approach orientation – students are focused on competition and high grades
3. Performance avoidance orientation – students are focused on avoiding mistakes
4. Work avoidance orientation – students attempt to minimize their efforts by searching for simple problem-solving strategies

Steering students towards mastery orientation should clearly be the goal in any classroom, but cognizance of this theory is particularly critical in learner-centered classrooms where students are afforded the opportunity to work with little oversight, and where the performance of physical products may naturally present a competitive atmosphere.

Assessment-centered

According to the How People Learn framework, an assessment-centered classroom requires frequent opportunities for students make their thinking visible. This aligns well with formative instruction by which teachers conduct frequent informal checks of student understanding through observations, one-on-one conversations, whole class discussions, and short writing assignments.[58,138] These tasks represent formative assessments, relatively brief evaluations which occur during the learning process, which are used to guide students toward the learning goals. Through formative assessments, students' understandings and misconceptions can be more easily identified, providing opportunities to draw comparisons and connections between their current and expected knowledge.[31] These comparisons afford teachers the ability to not only provide more accurate guidance, but also to identify weaknesses within their own instructional methods as well. The significance of this assessment process is illustrated in a statement by psychologist David Ausubel, who said, "The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly."[4(p.163)] The crux of formative assessment therefore lies upon a teacher's ability to design effective classroom activities that elicit evidence of learning, a potentially challenging task in a project-based learning environment.[127]

Since students often avoid content on which they will not be tested, some educators believe that in order to capture their interest, every classroom action and task must be assessed.[49] Yet this enormously time-consuming approach is quite impractical, and can easily lead to a mindset of, "How can we measure this?"[108] This psychometric question often shapes class assessments, and therefore the direction of a course. In an engineering design course, this approach may lead to an emphasis on product performance. Instead, questions such as, "Is this worth measuring?", "What do students really need to know?", and, "And can we measure that knowledge?" should be asked.

Authentic assessment

Possessing abilities to think critically and creatively, collaborate with others, and communicate ideas is vitally important for an engineer. Indeed, graduates with excellent interpersonal skills, for example, are often more highly sought after than those with superior technical skills.[34,41] But measuring these soft skills with confidence can be arduous or borderline impossible, particularly by employing traditional assessment techniques. To better match instruction with value-laden skills, there is a growing consensus – from educators, researchers, and policymakers – to utilize alternative forms of assessment.[33] Educational researchers are pushing for widespread use of authentic assessments, those which require "students to use the same competencies, or combinations of knowledge, skills, and attitudes, that they need to apply in the criterion situation in real life."[52(p.69)] In an authentic science classroom, for example, where achievement is viewed as the ability to think and act like a professional scientist, authentic assessments are designed to allow teachers to capture the complexities of the thinking inherent in science.[55] In engineering design classrooms, as well as project-based classrooms in general, authentic assessments place more emphasis on evaluating students in action during inquiry and product design.[33] This approach maps well with engineering education, since the steps students take to arrive at a solution are typically considered more important than the solution itself.[30]

According to a framework put forth by Gulikers et al., the authenticity of assessments can be measured by five dimensions.[52] First, the classroom task must confront students with activities commonly carried out in the professional workplace. It is important to give students ownership over assigned tasks, affording opportunities for them to expand upon their abilities to create, evaluate, and modify their work with little outside assistance.

Second, the social context of a project depends upon the situation being modeled. For example, if the actual social situation is collaborative, the assessment should also be collaborative. Third, a project's physical context should fairly resemble a professional project in terms of its available time and resources. While it is impossible to match a professional workplace in this regard, it is important for students to partake in extended projects and have access to supplies and tools for prototyping and performance testing.

Fourth, authentic assessments should lead to outcomes representative of a particular field. In the case of project-based engineering coursework, it is important that students not only create physical products, but also engage in communication representative of engineers. This included four different communication styles: interpersonal (via teamwork), verbal (via presentations), visual (via graphs and charts), and written (via logs and reports).

Lastly, since workforce employees know the standards to which they are held, it is imperative that students know the same. Unlike traditional assessments, where the questions are typically unknown beforehand, authentic assessments are based on situations established well in advance. It is therefore important for instructors to explicitly communicate the standards by which students will be graded.

Challenges

The facilitation of efficient learning through the project-based model comes with several challenges, the most glaring being related to the physical context. The design and fabrication of working devices is highlighted by the model, but it may not be possible to conduct authentic product assessments because the tools and supplies may be far beyond the reach of a school.[27] And, importantly, it is necessary for engineering instructors to evaluate students' technical and soft skills in real time, yet finding sufficient opportunities to observe each individual as they proceed though the design process can be demanding, if not completely impractical. As noted by Chappuis et al., "[H]ow many performance assessments would you have to create, administer, and score to cover all the knowledge you want students to acquire?"[27(p.96)] These types of assessments are thus often better suited for formative applications.

From a teacher's standpoint, the ideal assessment has curricular value, so well embedded in the curriculum that it is nearly indistinguishable from instruction itself.[33,116] Yet in order for such assessments to prove worthwhile, there must be sufficient "disclosure" of learning.[31] That is, the evidence which demonstrates student understanding and non-understanding. Since many classroom tasks do not reveal detailed information about students' thought processes, authentic assessments may exhibit issues with "fidelity," defined as the capability of teachers to accurately interpret the evidence that students disclose about their understandings. The accuracy of these interpretations can be heavily influenced by teachers' own expectations, leading to inconsistent scores from teacher to teacher.

Disclosure and fidelity can limit the credibility of authentic assessments (as well as impair a teacher's decision about the provision of guidance), and these limitations are commonly attributed to subjectivity. It is argued, however, that when rubrics are properly designed and utilized, authentic assessment strategies are far less subjective and more accurate than perceived.[111] Unfortunately, there is a common belief – especially among parents and lawmakers – that authentic assessments are simply too subjective to be of real use, presenting a major obstacle in the implementation of such measures. Teachers should therefore consider assessing students by traditional means (e.g., multiple choice and short answer questions) to support evaluation of comprehension and reasoning, areas in which authentic methods commonly fall short.[27,52]

Community-centered

In the How People Learn framework, fostering a community-centered classroom provides a foundation for supporting knowledge-, learner-, and assessment-centeredness. Relating classwork to the outside world is a key point of emphasis as this connects students to the larger community, adding to the authenticity of their studies. And significantly, the framework emphasizes the importance of developing a community of learners who work closely together towards common goals.

Yet due to the autonomy provided teams of students in project-based classrooms, instructors often struggle to balance the active engagement of students in the learning environment and the chaos that can easily emerge.[96] Because students must manage their own time and materials, collaborate with teammates as they see fit, and make their own decisions – in effect, take responsibility for organizing their own work – project-based learning is typically less-structured than other active learning methods.[112] As a result, learning environments may appear unorganized, off-task, and out of control. In high school classrooms, where students with vastly different maturity levels, language abilities, and capabilities work together, project-based lessons can test a single instructor's ability to involve all (or most) students in productive activities without sacrificing content or losing control of the class.[41,120]

If students perceive that an environment impedes their efforts to learn, their aspirations can suffer.[87] It is exceptionally important that instructors take measured steps to provide a supportive atmosphere in STEM fields since students commonly fail to remain engaged in course material. Notably, the reason for this discontent is typically not due to overly challenging subject matter or disinterest in content, but more often caused by poor-quality environments.[119] The culture of a classroom, as well as the school's, has an incredibly profound influence on learning.[98]

Group work

An ability to work within groups is considered one of today's major workforce skills.[136] Since most professional engineering is completed in cooperative groups, this ability is highly sought after by professional engineering firms.[41] In fact, in a 2013 survey conducted by Express Employment, 69% of employers viewed interpersonal skills as more important than technical skills.[101] The Accreditation Board for Engineering and Technology (ABET) has recognized the importance of collaboration, mandating that student outcomes of accredited post-secondary engineering institutions include "an ability to function on multidisciplinary teams" and "an ability to communicate effectively."[1]

Students who work within well-functioning teams tend to learn more and at a deeper level as compared to those in lecture-based courses.[33,42] They develop better critical thinking skills and interpersonal skills, and they commonly create work that exceeds the quality of that produced by individuals working in isolation.[34] (Quality teammates are defined as those with skills in leadership, decision making, conflict management, and an ability to guide others and build trust within a team.[119,136]) In addition, collaborative work improves students' motivation, self-confidence, and dispositions towards the subject matter. These findings carry great significance; studies of college students, for example, have determined that a failure to establish a social network and an inability to become academically involved in class are two major reasons students drop out of programs.[119] In STEM fields, where isolation and alienation are two of the best predictors of failure, it is essential to foster a sense of community.

Collaborative settings provide opportunities for co-construction of knowledge, the process by which students jointly discover solutions and build understandings through an active give and take of ideas.[70] However, it is common for students to divide tasks, an effective means for completing coursework, but one which undercuts the intent of group assignments. In order to foster teamwork skills such as communication, leadership, conflict resolution, and project management, a project cannot be divided and worked on individually.[42] There must be positive interdependence whereby students rely on each other to attain success. This includes goal interdependence (a shared vision of the project), role interdependence (fulfilling assigned roles), and reward interdependence (a shared grade).[119] Effective collaboration requires more than participation; students must exchange ideas to support one another. It is also necessary to point out that individual accountability is still vital in a group-based setting.[42]

In project-based courses, where design is a social process and learning takes place under the influence of others, coursework attempts to merge diverse skills and personalities in hopes that teammates will work towards common goals.[73] Yet group assignments are inherently problematic. Students who are not truly invested in a course or who lack maturity commonly take advantage of their teammates by "hitchhiking" – they shirk team responsibilities and instead take a "free ride."[65] At the other end of the spectrum, students who feel a need to control situations or often come to dominate their groups.[73] These individuals assume more responsibility than is appropriate and do not allow teammates to fully participate, oftentimes because they do not trust their teammates' capabilities.

Ensuring individual accountability is most effectively accomplished by utilizing appropriate assessment strategies. If grades do not reflect individual efforts, students cannot be held accountable, hard-working students resent others, and teachers appear to permit laziness and irresponsibility.[65] But it is challenging to identify the specific contributions individual students have contributed in a group project.[140] Of the commonly employed assessment strategies in group-based settings, all possess drawbacks. These include self-assessments (over-inflated grades), peer assessments (heavily influenced by social relationships with classmates), situational judgment tests whereby students are questioned about various scenarios (objectivity is difficult), behaviorally-anchored teacher-rating scales (i.e., participation points; logistical difficulties), and team interviews (prohibitively time-consuming).[84,86,136] Further compounding the individual evaluation process is the daunting prospect of measuring individuals' collaborative skills.[121]

Nonetheless, measuring each student's achievement of the learning goals by utilizing individual assessments is critical because students typically view overall group grades as unfair.[65] This policy, suggested even if the authentic context of a situation calls for a collaborative setting, extends beyond engineering and project-based learning. In study of a nursing program that used problem-based methods, for example, individual testing was stressed although most nursing activities are collaborative. Said one program instructor, "[A]ssessing in groups is a soft spot, we just don't know how to assess students together, because at the end we want to be sure that every individual student is competent."[52(p.82)]

Peer evaluation tools have shown promise, as several meta-analyses of peer evaluations have determined that inter-rater reliability among teammates correlates well with outside evaluators' assessments.[82] In an effort to identify the best items from a large pool of available peer-assessment instruments, the Comprehensive Assessment of Team Member Effectiveness (CATME) was developed by analyzing 392 initial items. The number of items was reduced to 87 to evaluate 29 types of team member contributions, all falling into five total categories: 1) contributing to the team's work, 2) interacting with teammates, 3) keeping the team on track, 4) expecting quality, and 5) having relevant knowledge, skills, and abilities.[83] This instrument was designed to be used within any team-based setting, though it is predominantly used at the post-secondary level.

Engineering education significance

Investment in STEM fields has merit. Over the course of the 20th century, more than half of the growth in per capita income in the U.S. can be attributed to advances in science and technology.[38] Likewise, the work conducted by scientists and engineers disproportionately creates jobs for others, although these professionals comprise just four percent of the nation's workforce. Unfortunately, while the number of American jobs requiring math or science knowledge has increased – from 12.8 million in 2000 to 16.8 million in 2013 – student interest in these fields has remained relatively flat.[32]

There has been some upward movement, measured by the actual number of undergraduate and graduate degrees awarded in STEM fields, but most reports assert that the demand for workers with these degrees exceeds the supply.[2,98] This disparity is likely to increase, as sixteen of the twenty occupations with the largest projected growth in this next decade are STEM-related.[74] Unfortunately, as of 2010, only about one hundred STEM-focused K-12 schools existed, serving less than one in one thousand students.[38] To meet the rising demand, the President's Council of Advisors on Science and Technology recommended establishing one thousand more such schools by the end of the decade.

College enrollment numbers have shown promising signs, since 28% of all college students pursuing bachelor's degrees in the U.S. are in STEM fields, a relatively high figure.[133] But half of those students drop out or change majors. Due to a notably poor retention rate in engineering and a particularly low representation of females and minorities, many engineering colleges are seeking to change their environments, giving more attention to the structure, content, and delivery in classrooms.[43]

Yet fostering student interest in engineering does not fall squarely upon post-secondary institutions. More must be done at the K-12 level. Many students decide early on in their careers that STEM fields are boring, too difficult, or unwelcoming.[38] Efforts to improve these environments have largely emphasized improving math and science courses.[64] Focus on these subjects is largely due to poor student achievement (e.g., less than one-third of eighth graders are proficient in math and science) and large achievement and interest gaps (i.e., white and Asian-American males generally demonstrate higher abilities and interest levels than African Americans, Hispanics, Native Americans, and females).[38]

More school district have been adding technology components to their curricula, but a relatively small number have added engineering courses, causing the "E" to be called the missing letter in STEM. Engineering has received little attention from policymakers at the K-12 level, noted by the lack of nationally-mandated K-12 engineering standards and the limited number of states which have integrated the discipline into their own standards.[115] But the environment is changing. Engineering was included in the Next Generation Science Standards, and an increasing number of schools are adopting nationally-recognized engineering curricula such as Project Lead The Way (PLTW) and EPICS (Engineering Projects in Community Service) High. Research on these and similar engineering focused programs has been promising. An analysis of thirty studies on PLTW, for example, concluded that the program supports student achievement in math and science, and has a positive influence on students' interest in engineering.[126] The EPICS High model, which focuses on making connections between engineering and helping people, provides a better opportunity to draw in a greater number of students and a more diverse population.[128]

While these programs have shown great promise for engaging students in engineering work, many conclusions of the curricula are drawn from self-reported attitudinal surveys; more research is needed to better solidify the true benefits and limitations of each, particularly in regards to increasing students' math and science abilities, as not all study results have been ideal. For example, research comparing schools using the two curricular programs found that students successfully developed problem-solving abilities and worked collaboratively, yet mathematical thinking was underutilized as a design tool, a finding that was likewise discovered in similar studies.[66,67,68] And in a study of 176 high school students involved in PLTW, for instance, students performed only marginally better in math, and no significant relationship was found between the program and science achievement.[130]

Likewise, little research exists which describes how experiences in engineering differ from those in math and science, particularly how learning is assessed and how programs are evaluated.[21] As noted in a report by the National Research Council, "It is challenging to identify the schools and programs that are the most successful in the STEM disciplines because success is defined in many ways and can occur in many different types of schools and settings, with many different populations of students."[98(p.8)] It is therefore important to gain a clearer understanding of the type of learning that is occurring in high school engineering classrooms.

CHAPTER III

CASE STUDY DETAILS

Research questions

Based on the increasing enrollment numbers and the interest generated within and around the community, the academy demonstrated remarkable promise, and there were aspirations by some within the school district to someday offer the curriculum as a national model for STEM education. Project-based learning, highly regarded by administrators as a method for better involving students in coursework, was a seen as natural fit within the academy, and its use was expanded into the middle and elementary grade levels as part of the district's STEM-focused initiative. At the high school as well, teachers within the science department were tasked with developing their own project-based lessons.

However, as evident in the literature, studies have noted issues within the model, particularly in facilitation and assessment, areas similar to those expressed by the academy teachers. The presented case study therefore intended to identify strengths and weaknesses of the model, specific to the manner in which it was utilized within the course under study. This research was guided by the following questions:

In a high school engineering classroom wherein project-based learning served as the educational model . . .

1. What were the perceived and potential benefits?
2. What obstacles prevented expected achievement?
3. What tensions were generated?

To bound the study, benefits were outlined as those connected to the goals of the academy, put forth by the administrators and teachers, and those of the hovercraft course, noted by Ms. Foster. To better delineate these items, general engineering learning goals were referenced as well, particularly those provided by the President's Council of Advisors on Science and Technology as well as by the National Academy of Engineering and National Research Council.[38,64]

The goals of the academy were to:

1. Provide students with positive experiences related to engineering

2. Offer an accessible learning environment for students of wide-ranging abilities
3. Prepare students for engineering college and the workforce, particularly through improving their understandings, skills, and habits-of-mind

This preparation is further defined by the course learning goals, which were for the students to learn and develop their:

a. Science content knowledge
b. Science investigation skills, specifically drawing conclusions from data and applying them to the project
c. Math skills, including abilities to carry out data analyses
d. Building skills
e. Teamwork skills, including both task delegation and working with others
f. Creativity

Achievement was noted in these areas when demonstrated by through assignments, during discussions one-on-one, team, and class-wide discussions, and by behavior representative of professional engineers. For instance, students who articulated design decisions based on established concepts, who conducted controlled experiments to gather meaningful data, and who brainstormed with teammates were noted as attaining success. Less emphasis was placed upon the performance of a finished product.

"Tensions" were defined as conflicting perspectives put forth by study participants which strained curricular decision making, complicated classroom facilitation, or otherwise inhibited the teachers' abilities to promote student engagement and learning. Conflicts included those among the teachers themselves, among the students themselves, and between the students and academy leaders.

Research methodology

To best provide insight into the academy, it was necessary capture subtle classroom dynamics and interactions, thereby allowing a specific course to be characterized as it was experienced by the students. To accomplish this task, a qualitative study was deemed appropriate, as the broad goal of such research is to seek better awareness of social or human problems, observed in their natural settings, so that a more complete understanding of a situation is possible.[77]

The study utilized an inductive approach. That is, it was conducted without a driving priori hypothesis to permit unexpected phenomena to emerge. A major benefit of this strategy is flexibility; modifications to the research design could be implemented in light of new evidence during the data collection process and as a result of preliminary analyses. By investigating the motivations and perceptions of the educational model from the viewpoints of not only the students, but from the course instructor, her colleagues, and key program administrators, areas of commonality and conflict could be drawn out. It was, however, important to have a metric of success for the research. Because the original idea for the case study was born out a need for making justifiable improvements to the academy, it was necessary for the academy teachers and administrators to find the research outcomes to be agreeable. If the findings were recognized to be in alignment with their own experiences in the program, then it could reasonably be established that the data analysis was suited well to the study. But rather than simply approve of the findings, it was essential for the academy leaders to find them worthwhile and insightful. The most pragmatic method for establishing success in this regard was to see if they took the research into account when they made modifications to the curriculum (they did).

The study is best described as an ethnographic case study, where ethnography can be described as, "[P]articipating overtly in people's daily lives for an extended period of time, watching what happens, listening to what is said, asking questions-in fact, collecting whatever data are available to throw light on the issues that are the focus of the research."[54(p.1)] This methodology was chosen for its capacity to investigate the classroom environment in-depth and within its true context, in other words, to "grasp the native's point of view"[26] and produce situated descriptions of the events as they transpired in "an attempt at capturing the essence of what the phenomenon means to the participant."[134(p.6)]

The study can also be classified as a "descriptive" case study, defined as "one that is focused and detailed, in which propositions and questions about a phenomenon are carefully scrutinized and articulated at the outset."[93(p.288)] This articulation helps define the boundaries of the case study, the main goal of which is to assess a specific phenomenon in detail and depth, "to penetrate the essential understandings of the case and offer up for scrutiny a case for informing theory development, in addition to potentially providing a valuable addition to the case study databank for future researchers."[93(p.289)]

Importantly, the conditions of the case were unique to the academy, and a major strength of the methodology is the ability to illuminate a particular topic by examining it with an insider's view. Five key course features defined the uniqueness of the course: 1) lesson and activity plans were exclusive to the academy, 2) the academy was very inclusive, resulting in a large variance in student ability levels, 3) no homework or tests were delivered in lieu of authentic assessments, 4) the course was extremely hands-on and about half of the semester was spent in a non-traditional setting, and 5) the teacher was inexperienced in project-based methods, in engineering, and in general. Assessing project-based learning under these conditions provided a valuable evaluation of the model.

To provide greater detail of the context, it was imperative to focus upon a limited group of participants. The sample size was relatively small – a total of forty-eight participants, with concentrated focus placed on a select few – allowing for detailed input to be gathered. Most advantageously, formal and informal inquiries, or "interventions," into deeper meanings could be made when prominent issues arose, investigated through repeated interactions with the participants, and supported with direct observations.

A quantitative approach was rejected for several reasons. First of all, the general intent of the study was to expand upon the knowledge of student learning and interaction in a unique environment, and capturing the intricacies of human behavior based on predictions and randomized controls is not always possible.[72] Indeed, a case study is fitting for situations with excessive numbers of variables and data sources to consider.[139] Second, gaining meaningful awareness of the manner in which the learning model was being utilized necessitated that participants be allowed to freely offer input, and evaluating preconceived theories through fixed interventions would have limited the possibility for unexpected ideas to emerge. Third, key contributions to studies with similar goals are often made by individuals who represent extreme cases, and compiling strictly quantitative results in an effort to conduct a statistical analysis would have potentially buried the voices of underrepresented groups.[137] Ultimately, it was critical to focus upon a small number of participants so that the setting and interactions could be examined in greater detail, the end goal being to richly describe the situation in such a way that the full meaning of the context and perceptions of its participants are readily apparent.

The theoretical perspective of the study was based on interpretivism, specifically social constructionism. This perspective argues that there are multiple subjective realities, resulting in variability among the understandings of shared experiences since learners possess different backgrounds and motivations. The research aim was to understand these perceptions and determine key commonly shared and opposing viewpoints, providing a more comprehensive understanding of the course under study and the role it served within the academy as a whole.

Findings were generated after compiling and analyzing predominantly text-based data from a host of sources. To better manage elaborated forms of direct communication from the study participants, it was necessary to break comments down into smaller pieces, allowing for them to be categorized and quantified. Though such analyses, commonalities among various viewpoints became more apparent. These commonalities could then be weighed against other data, with a goal of substantiating emergent findings through multiple sources.

Data sources

To best gain an evaluate student achievement and the value of the learning model as perceived by those involved, a well-rounded data collection approach was undertaken, including direct participant input in the form of interviews and focus groups, informal discussions, surveys, and course assignments, in addition to indirect input by means of classroom observations. The data served to answer the research questions by addressing the contextual conditions and idiosyncrasies within the setting, taking into account participants' self-reported input as well as that which was demonstrated by their work and behavior. The substantial number of data sources provided opportunities to produce situated descriptions of events as they were experienced by various participants. Data was collected from January to June 2014, summarized in Table 6 and described in the following sections.

Table 6: Data sources

Data	*Source*	*Specifics*	*Purpose*
Cooperating teacher disc's	Classroom teacher	Informal discussions, before and after classes	To gain an understanding of the teacher's perspective during the study
Teacher interviews	STEM teachers (4) & long-term sub	One-on-one, semi-structured	To gain perspectives of those involved on a daily basis & probe for elaboration
Administrator interviews	HS & district administrators (4)	One-on-one, semi-structured	To gain perspectives of those involved in big picture & probe for elaboration
Focus groups	Students (19)	Six groups of 2 to 5 students each, semi-structured	To gain perspectives from a range of student types & probe for elaboration
Records	Students (26)	Socioeconomic status, STEM & overall GPAs, ethnicity	To aid in the creation of individual student profiles
Assignments	Students (39)	Products, worksheets, warm-ups, logs, essays, presentations	To evaluate learning goals, interest, comprehension & collaboration
Grades	Students (39)	25 total assessments (e.g., logs, presentations)	To evaluate course rigor & manners in which students were assessed, to identify challenging areas for students
Formative assessments	Students (39)	Two quizzes, not included in grades	To evaluate comprehension of content
Likert-type survey	Students (37)	Taken at end of course, 7 questions – scaled 1 to 5	To collect a class-wide quantitative sample on various topics
Open-response survey	Students (37)	Taken at end of course, 12 questions – open-ended	To allow all students to provide individual perspectives & suggestions
Observations	Researcher	Recorded after each day's classes	To monitor engagement, collaboration, instruction, behavior & use of class time

Cooperating teacher discussions

During the initial weeks of the semester, the cooperating teacher and I had planned to meet formally every two to three weeks to discuss prominent issues that arose in class. I hoped to gather her thoughts on topics such as the course curriculum, ideas for improvement, the classroom environment, her interactions with students, and the quality of student work. As it turned out, it was more practical and informative to engage in less formal discussions immediately before and after each class since her ideas were fresh and she appeared more willing to share her opinions when a specific agenda was not pre-established. Over time as our working relationship grew, she became even more forthcoming and often approached me to seek advice on challenges she encountered in the classroom as well as to obtain feedback on curricular modifications she was contemplating. These frequent and open interactions helped establish the teacher's intentions as well as her views of the learning model as it played out in the course. She also offered her perceptions of the students' efforts and understandings.

Teacher interviews

The academy teachers were highly educated and brought extensive experience into the program. They were interviewed individually, with each interview lasting sixty to ninety minutes. The interview questions focused on learning goals and student achievement, the importance of math and science in projects, assessment, and the learning environment, particularly its group-centeredness. The interviews were intentionally left semi-structured, a common practice in qualitative studies,[77] to allow discussions to deviate into unrecognized areas of significance, and to permit more in-depth questioning when noteworthy points were raised. A key drawback of such an approach is that the extent of comparability among participants' responses diminishes the more that different topics emerge and are addressed. An effort was therefore made to retain relative consistency among the line of questioning. The cooperating teacher's interview, which took place after the semester had ended, focused more explicitly on the course under study.

In addition to interviewing the four academy teachers, a long-term substitute who served in the academy for several months also participated in the study. She had formerly taught at a nearby high school where she had developed her own engineering-focused microcomputer course. Before entering education, she had worked as a professional engineer for five years. Her input was highly valued because she was the only participant with engineering education experience outside of the academy. Table 7 lists the profile of each teacher.

Table 7: Teacher profiles

Teacher	*Department*	*Earned degrees*	*Years in teaching*	*Years at school*	*Years in academy*	*Comments*
"Ms. Foster"	Physics	Bachelor's: physics Master's: physics & education	2	1	1	Cooperating teacher
A	Physics	Bachelor's: mechanical engineering & education	10	10	5	Founding teacher
B	Physics	Bachelor's: biomedical engineering; Master's: biology	9	4	4	Taught course under study
C	Math	Bachelor's & Master's: chemical engineering	7	2	1	Professional engineer 2 yrs.
Long-term substitute	Physics	Bachelor's: physics & mechanical engineering	~25	0	0	Professional engineer 5 yrs.

Administrator interviews

Four school district administrators also agreed to participate in the study. These administrators were invited due to their strong ties with the academy, three of them having been highly involved with its foundation. The backgrounds and experiences of each are listed in Table 8.

Like the teacher interviews, the format was semi-structured. Interview questions focused on the purpose of the academy as well as its broader learning goals, the original aims of the curriculum, particularly the inclusion of math and science, and assessment. Since the administrators generally dealt with the big picture of the program, their responses generally lacked the details that were provided by the teachers, and discussions were quite briefer (lasting fifteen to forty minutes). Nonetheless, they provided a much-needed perspective to better establish the foundational details of the academy as well as its long-term goals.

Table 8: Administrator profiles

Current position	*Background*	*Involvement during foundation*
District director of innovation	Physical education teacher & business experience	Principal, hired to transform school by creating specialty program
High school principal	Math teacher	Assistant principal, tasked with researching & creating STEM program
High school STEM coordinator	Science teacher, experience in construction industry	Teacher, tasked with creating course curricula, taught course under study 3 times
District STEM coordinator	Science teacher, led international student climate research campaign	None

Focus groups

Common among most qualitative studies, it was important generate enough variation among the data sources – in this case, the students – to prevent particular areas of input from being ignored. The focus group interviews were thus formed purposively, organized according to students' genders and demonstrated abilities and motivations. The intent was to include students with distinct backgrounds and perceptions of the course who were representative of the class as a whole (and to a large degree, the entire academy). Six total groups were formed, ranging from two to five students each.

Additionally, it was imperative to avoid any uneasiness or judgment – real or imagined – among interviewees, as such feelings would have diminished the potential for candid responses (e.g., a low-achieving student may not have been willing to admit any misunderstandings if a high-achieving student was present). An attempt was therefore made to establish a relaxed setting in which students would feel comfortable to share honest feedback (and because one-on-one student interviews were not permitted). By placing students with like-minded classmates, the focus group interviews oftentimes better resembled discussions, in that students elaborated on individual topics amongst themselves with little interviewer interference, thereby providing more insight as they conversed. Though conformity by groupthink was a concern, the non-threatening atmosphere appeared to mitigate this outcome since individuals often raised conflicting viewpoints, willingly bringing their own experiences into the fold. Nineteen total students participated, their genders and ethnicities as compared to the entire class shown in Table 9.

Table 9: Focus group gender & ethnicity makeup

Category	*Focus groups*	*Class*
Total	19	39
Total females	7 (37%)	12 (31%)
White females	3 (16%)	6 (15%)
Hispanic females	2 (11%)	4 (10%)
Asian females	2 (11%)	2 (5%)
Total males	12 (63%)	27 (69%)
White males	11 (58%)	19 (49%)
Hispanic males	1 (5%)	7 (18%)
Asian males	0 (0%)	1(3%)

Teams during the course itself were also taken into consideration. Teammates who demonstrated quality collaboration were placed together in focus groups so that their specific team dynamics could be openly discussed. Teammates with conflicting ideals were separated, providing a better opportunity for them to describe the challenges they encountered. Three focus groups were comprised entirely of teammates. These teams operated vastly differently, with one demonstrating an ability to problem solve together, one putting forth effort but lacking in key competencies, and the other completely failing to try. Two of these teams were selected for concentrated observation towards the beginning of the course due to their vastly different classroom actions and interactions, and an individual from each team was selected for in-depth investigation, detailed later in this report.

However, not all voices were fairly represented. Three introverted females who participated little in class discussions, seldom requested guidance, and lacked confidence during times of decision making, declined to participate. Similarly, two minority males who had agreed to be interviewed failed to return consent forms. More detailed input from these students was therefore lacking. Conversely, students with whom I had established closer relationships were over-represented. This was not by accident; these students were more apt to provide constructive criticism of the academy and course, and openly discussed content areas they did not understand. Unfortunately, three of the nineteen students did appear slightly insincere, as their responses seemed slightly rehearsed, likely meant to downplay their own lack of effort or understanding. But these response types accounted for just a small fraction of their total input. Ultimately, a diverse mixture of student perspectives were provided. Focus group details are shown in Table 10.

Table 10: Focus group details

# Students	*Gender*	*Ethnicity*	*Engagement in content*	*Engagement in building*	*Collaboration*
3	Male	White	Low, disruptive	High	Low
3	Female	2 URM, 1 W	Moderately high	Low	Moderate
5	Male	White	High	High	2 High, 3 Low
3 (team)	Female	1 URM, 2 W	Moderate	Moderate	High
3 (team)	Male	White	High	High	High
2 (team)	1F/1M	URM	Low	Moderate	Low

Focus group questions focused on motivations and expectations, group work and the classroom environment, guidance, the importance of math and science, and assessment. Again, interviews remained semi-structured; students were encouraged to speak about areas not explicitly addressed by the line of questioning. When they presented noteworthy input, they were asked to go into more detail. These interviews were conducted without interruption in a private setting, but because they needed to take place during students' lunch time, they were occasionally compelled to give concise responses and could not fully elaborate upon some of their ideas. Interviews lasted 25 to 50 minutes, dependent upon the number of interviewees.

Student records

Records were released from the school district's office of assessment, curriculum, and instruction for the twenty-six students who returned signed consent forms. The requested information included students' overall GPAs, GPAs earned in the academy, ethnicities, and enrollment in the district's free and reduced lunch program, used to identify their socioeconomic statuses. These records were released after the course had ended so as not to influence evaluation of students' behavior and completed work. The records were used to develop in-depth profiles of individuals selected for concentrated investigation.

Assignments, formative assessments, and grades

Each assignment delivered by the cooperating teacher was reviewed to evaluate the explicit and implicit learning goals of the course, as well as the course rigor. Challenging topics and common misconceptions were noted, allowing for better identification of deficiencies within the curriculum. The quality by which each team's physical products performed was monitored, with attention paid to the verbal reasoning with which they supported their designs. Likewise, teams' presentations were noted for the justifications used to back their decision-making.

Students' written assignments were also reviewed to evaluate their levels of comprehension. Students' notebooks included their responses to daily warm-up questions and end-of-class logs, which provided awareness of individuals' math abilities, their project intentions, their claimed accomplishments, and their general interest in the course. Students were also encouraged to write about their struggles or any in-team conflicts, offering another layer of insight. Written group assignments were shared online among teammates and allowed each team member to work simultaneously on the same document. Saved in Google Drive, the documents featured a "revision history" which displayed each team member's individual contributions, providing a unique look into engagement and collaboration.

Two computer-based formative assessments were delivered during the semester, one of which was given in a pre-test/post-test format. While the assessments did not factor into the gradebook, the results did provide a more objective measure of students' abilities, particularly in regards to math achievement and comprehension of basic content discussed during class.

Upon completion of the course, graded assignments were categorized and weighed according to the number of possible points for each type. A total of twenty-five grades were assigned during the semester, with the average final grade being 87%, good enough for a B+. The average grade per category and the weight each carried in the course are shown in Table 11.

It is important to note that completion grades predominantly consisted of those assigned to notebooks. Though these grades do not indicate comprehension, they do indicate the relative proportion of students who chose to complete the basic tasks of the course. Essays could have also been included in this category, but were kept separate, as they too were largely evaluated on completion.

Table 11: Categorized course assignments and associated grades

Category	*Points*	*Weight*	*Avg. score*
Individual	155	30%	85%
Group	370	70%	88%
Individual work:	*Points*	*Weight*	*Avg. score*
Completion	70	13%	88%
Brief essay	35	7%	89%
Participation	30	6%	83%
Worksheet	20	4%	73%
Group work:	*Points*	*Weight*	*Avg. score*
Presentation	166	32%	87%
Device performance	100	19%	93%
Craftsmanship	46.5	9%	88%
Task summary	45	9%	84%
Worksheet	12.5	2%	88%

Likert-type & open-response surveys

At the end of the course, thirty-seven students completed a seven-question Likert-type survey which addressed topics such as assessment, rigor, guidance, the classroom environment, and problem solving. The survey allowed for a simple, straightforward collection of easily quantifiable data from nearly the entire student participant population and helped capture viewpoints that were not easily observable. Yet a major drawback of this data source was a lack of depth, notably an inability to identify the reasoning behind the students' responses. For instance, a student selected "strongly agree" for the statement "I'm glad I joined the STEM Academy." While a positive response on the surface, during a focus group interview, this student clarified that she was in fact dissatisfied with her experiences in the program, but continued to pursue a STEM certificate solely because she wanted to enhance her college applications.

An open-response survey was also distributed to the students, with questions focusing on learning goals, acquired skills, recommendations for improvements, group work, and affect towards engineering. This survey offered a chance for all students to provide input, and many took advantage of the opportunity by responding with detailed opinions on each topic. This data source thus provided a great deal more depth than the Likert-type surveys.

Observations

Detailed field notes were recorded immediately following each day's classes. These observations focused specifically on the teacher's communication of learning goals, presented content, student behavior and engagement in tasks, teacher-student and student-student interactions, and comprehension demonstrated by individuals. In addition to these subjective observations, the manner in which time was allocated during the course was recorded.

To minimize any distraction that these observations may have caused to the teacher or students, brief notes were jotted down during class time and elaborated upon afterwards. Insightful ideas put forth by participants were immediately recorded verbatim. The students were made aware of the study at the beginning of the semester and seemed indifferent to my actions. The cooperating teacher also believed the research had little to no impact on the environment, and stated that the students appeared oblivious to it.

My role as an insider allowed me to probe for student understandings, particularly during phases of group work when ample freedom was provided for problem solving, designing, and fabricating. During these times, I made a point to interact with all teams and gauge their progress. I also took advantage of my position to systematically pose questions to all individuals. These informal interventions aimed to address their comprehension of specific content as well as group dynamics

By the time students began working on the main course project, when individual behaviors and abilities had been fairly well established, eight students were selected for more focused observations. Individuals were tracked in order to highlight specific progressions through the course from vastly different viewpoints. Of the original eight, four students were profiled in-depth. These four individuals provided a well-rounded perception of the course and academy from widely-varying perspectives, each possessing unique abilities and motivations.

The observations served to provide a first-hand account of the setting's events. Although explicit comments from study participants helped support these accounts, recorded notes were nonetheless naturally-biased. Observations therefore did not serve as a primary source in the analysis of collected data, as these notes lacked credibility on their own. Still, this information helped substantiate data from other sources and provided a richer context for the environment.

Data analysis

The entirety of the data was analyzed following the conclusion of the semester. The primary goal of the data analysis was to identify commonalities which addressed the research questions, with those substantiated by multiple sources and various participants given more weight. Of particular interest was the evaluation of students' perceptions of the course under study and the academy as a whole related to topics such as the learning environment, collaborative work, and understandings of math and science. The various perceptions which emerged were then compared amongst each other as well as against those of the cooperating teacher, her colleagues, and the administrators. Inconsistent perspectives were denoted as potential areas of miscommunication and conflict among the participants. The analysis was largely completed using the qualitative research analysis software NVivo as well as Microsoft Excel, both of which aided greatly with the compilation and organization of the data.

The study did not only aim to determine the general consensus, but to also give a voice to individuals, a major benefit of qualitative studies. Select accounts from discussions and interviews were included as a means to give a better vision of the participants' experiences. To illustrate common viewpoints, quotes deemed representative of a specific group of participants were highlighted. At the same time, salient points from those in disagreement with the majority were noted, helping to ensure that unique opinions were brought forth.

Because the vast majority of the collected data was text-based, it was necessary to systematically draw out "repeatable regularities."[63] This most significantly applied to interviews and focus groups (which were audio recorded and transcribed) as well as open-response surveys. The data from these sources was categorized and "quantitized" utilizing a coding scheme (tags used for assigning units of meaning to "chunks" of information).[18,92] Codes allowed a large amount of text to be compiled into analytical units for more straightforward identification of main themes across various perspectives, serving to determine the ideas that were repeatedly shared by participants, and pointing to regularities within the setting.

Initially, participant responses were assigned "descriptive" codes whereby interpretation of underlying meanings was minimal or unnecessary.[92] So-called "interpretive" codes, those which require participants' meanings to be deciphered, were largely avoided for the sake of objectivity. In the case of misunderstood comments or behaviors, intentions were made to probe further for clarification. In some qualitative studies, it is strategic to begin with a start list of codes before observational work commences; such a priori list can be based on previous literature, research questions, hypotheses, or problem areas. However, generating a start list may influence the means by which data is collected and analyzed, as this cause a researcher to focus on specific items and ignore others, which may detrimental effects in descriptive case studies. On the other hand, beginning with no coding list better allows themes to emerge without researcher influence, but a completely inductive approach may present challenges to bounding the situation and providing a focus. An alternative general coding scheme, as suggested by Bogdan and Biklen,[17] falls between a priori approach and a strictly inductive approach. This general scheme is not content specific, but provides a structure from which relevant codes can be generated. A brief outline of this coding scheme is presented below:

1. Settings and context – a description of the surroundings for usability in a larger context
2. Definition of the situation – how people understand a setting or topics
3. Perspectives – how people think about a setting
4. Ways of thinking about people and objects – how people think about each other and objects in a setting
5. Process – a sequence of events
6. Activities – behavior that occurs on a regular basis
7. Events – specific activities, particular infrequent activities
8. Strategies – people's methods for accomplishing things
9. Relationships and social structure – cliques, coalitions, friendships, and enemies
10. Methods – pros and cons of the research process

After this first-level coding was completed, commonalities were identified when possible, helping to summarize the data into a more manageable number of categories. Responses were subsequently lumped together into "pattern" codes, or categories used to link together similar ideas, according to the positions taken by the participants. As an example, statements provided during student focus group sessions were placed into fourteen categories, including "Recommendations," "Guidance," and "Problem solving." Table 12 lists the emergent categories from the interviews.

Table 12: Emergent categories from participant interviews

Student focus groups	*Teacher interviews*	*Administrator interviews*
Reason	Purpose of academy	Purpose of academy
Expectations	Learning goals	Expectations
Recommendations for academy	Curricular design	Learning goals & Strengths
Recommendations for course	Understanding	Achievements
Learned in academy	Collaboration	Challenges
Best of academy	Participation	Assessment & Accountability
Learned in course	Individual accountability	Math & Science
Best of course	Math & Science	
Math & Science	Peer-assessments	
Problem solving	Interactions	
Guidance	Environment	
Grades	Strengths	
Group work	Project completion	
Environment		

Within each of these categories, more detailed themes emerged as well. For example, within the student category "Best parts of course," the following themes were recorded as being credited to more than one participant: *Building, Product is large scale, Riding craft, Applying M&S, It was simply fun, Learning while building, Freedom, Futuristic.* By placing participant responses into categories and themes, it was more feasible to compare general beliefs among participants.

Depending on their complexity and length, statements made by participants may have been assigned one or multiple codes. In response to the question, "Is the academy what you expected?" for instance, part of a student's response included the statement, "I thought it was going to be like science, technology, engineering, and math, not just engineering." This statement fit into the "Expectations" category and was accounted for once in the theme *More STM* (expected more science, technology, and/or math) and once in the theme *Not just E* (expected more than just engineering).

Although the main idea of comments assigned to the same theme carried the identical quantitative weight, the context and richness of each item was often vastly different. For example, the following comments were made by students in response to the question, "How do you feel about working in groups?"

"I like it more than I like working by myself."

> "I really enjoy working in a group because I kind of tend to fall into a one-track way of thinking, whereas these two ideas I've come up with, they're going to be the best and they're going to work. And it always helps to have other people sending out ideas like that's dumb, that's silly, you can't do

> that. Or even to have someone else who can maybe suggest something that I can work off of and create my own idea off of."

> "I love it, yeah. I don't know, I like working with other people and I like the fact that, I mean you can always come to a consensus with someone, and it just works. Like I've never had anything that has completely failed because there was always two other people or three other people to kind of help pull you along if you are falling a bit behind. And vice versa."

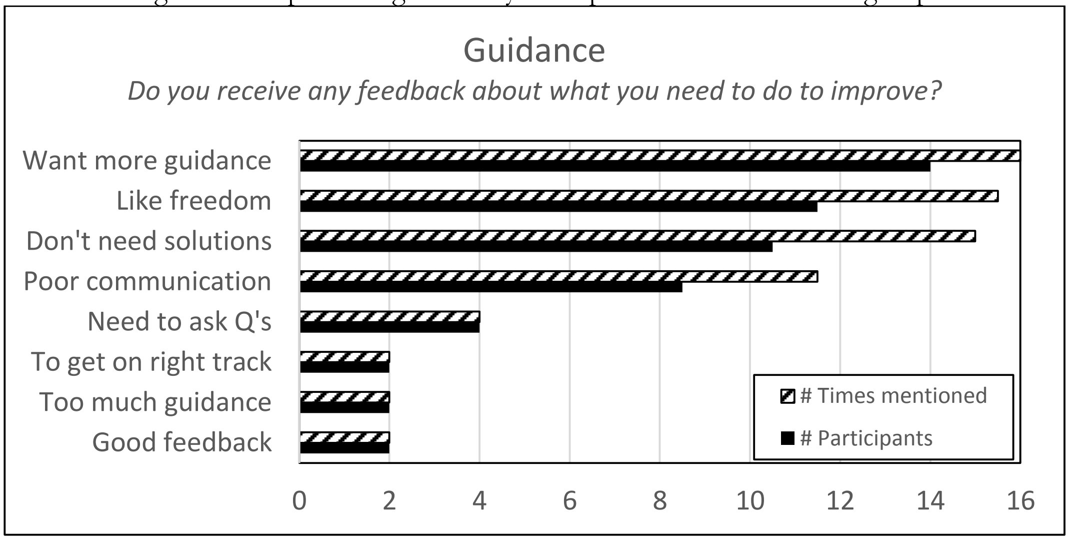
> "I like it. I could not do these things by myself."

While all of the responses were coded with the tag *Enjoy* in the "Group work" category, the insight provided by each was clearly distinct. This comparison represents the advantage – and challenge – of qualitative research. It is possible to gain a deep understanding of a specific setting by participating in it and interacting with those involved, but compiling a vast amount of text-based input and transforming it into an easily digestible bit of information must be accomplished through systematic and repeatable measures.

Because ideas repeatedly put forth by participants pointed to significant points, the frequency with which each participant mentioned a topic was noted to allow areas of emphasis to be better identified. However, multiple instances within the same theme were only counted if responses were not part of the same line of discussion; in other words, it was necessary for specific points to be offered by participants during distinctively separate parts of an interview in order to be accounted for more than once.

Figure 5 illustrates a summary of student responses related to guidance, showing both the total number of times mentioned and the total number of participants to make each type of statement. Most of these statements were in response to the question "Do you receive any feedback about what you need to do to improve?" Yet it is important to note that regardless of the preceding question or discussion, any statement related to teacher guidance was considered for this category. Most statements were connected with eight emergent themes, though three of these themes were only mentioned by two students each. Clarifications of the themes are provided below.

Figure 5: Sample coding summary of responses in student focus groups



- Want more guidance: Students would like to receive more guidance from teachers
- Like freedom: Students like having freedom to problem solve on their own
- Don't need solutions: Students do not expect to receive explicit solutions from teachers for presented and encountered problems
- Poor communication: Teachers do not clearly communicate their ideas (e.g., suggestions, requirements, constructive criticism)
- Need to ask Q's: In order to receive guidance, students acknowledge they need to ask teachers specific questions
- To get on right track: Teachers should help get students on the right track to determine solutions
- Too much guidance: There is an overabundance of guidance given in academy courses
- Good feedback: Teachers offer quality feedback to students

To support the quantified summaries of responses, quotes deemed representative of common themes, those in direct disagreement with the norm, and others considered noteworthy due to unique circumstances were highlighted, allowing for a more tangible understanding of various perspectives. For instance, the two student quotes below illustrate opposing viewpoints on the topic of guidance:

> "Like nobody's every told me, 'Oh, you're actually doing really good in these kind of classes,' or, 'You need to do this or do that.' I don't feel like there's not that much feedback."

> "And I think instead of providing too much guidance, they [teachers] should just allow more time too for trial-and-error and stuff like that so kids can learn themselves how to solve problems instead of having someone hold their hand."

Notes taken during classroom observations, during discussions with the cooperating teacher, and in regards to students' work were compiled on a monthly basis for the purpose of composing "analytic memos," relatively brief preliminary analyses. The purpose of the memos was to facilitate reflective thought about the study as it was transpiring, helping to clarify ideas and shed light on the specific issues,[88] including learning goals, curricular planning, and the classroom culture. As a result of these reflections, unforeseen themes were revealed which, in turn, influenced the research design in such a way that specific areas could be further investigated through more focused observations and pointed discussions with study participants.

In the student focus groups, there were occasional times when social construction of ideas occurred such that a group perspective, rather than individual opinions, appeared to emerge. For instance, when a student noted that she had learned about a particular topic in the course under study, it at times was more likely that others within the same focus group would mention this topic as well. For this reason, when students simply agreed with others and were not perceived to add their own ideas into the discussion, their input was accounted for by applying a half credit to the appropriate theme. The input from students in agreement was thus not completely ignored, yet not given full credit in the coding scheme since doing so would have skewed the results towards those who tended to agree with others often and to those in the focus group of five students.

The data analysis aimed to build a logical chain of evidence towards worthwhile findings. It was necessary to substantiate findings with evidence from multiple sources, a practice of "triangulation" whereby data is collected concurrently and compared among sources as a measure to reduce the risk of invalid findings due to the flaws of a singular method of data collection.[18,88] If, for example, teammates stated that they found group work useful because they were able to collaborate on assignments, these claims could be strengthened or put in doubt by evaluating their written team-based work, by asking for input from the cooperating teacher, by noting their survey responses, and by searching for evidence in the field notes. Once preliminary positions could be verified by input from multiple sources, distinct findings could be justifiably established. Still, because the data was collected, sorted, and pulled from by a single researcher, the credibility of the findings could be cast in doubt, necessitating that validity threats be clearly addressed.

Validity threats

Similar to most qualitative research, two broad types of validity threats existed in this study – reactivity and researcher bias.[88] Reactivity, defined as the influence a researcher imparts on the environment under study and that which is imparted on the researcher by it, was significant. Because I played a very active role during the course, both in the classroom and during lesson planning, the extent to which I influenced the study was far-reaching (particularly compared to traditional ethnographic studies in which researchers attempt to remain detached from the participants). This is not to say that reactivity is entirely undesirable. Indeed, I was able to build close relationships with both the teacher and students during frequent interactions and discussions, allowing for a better understanding of their viewpoints and providing an immense benefit to the case study.

Although I was compelled to fulfill my responsibilities as an aide in the classroom, I made a conscience effort to allow the direction of the course to be dictated by the cooperating teacher. When working with Ms. Foster on the course plans, for instance, I always initially deferred in the decision-making process, allowing her to steer the course in the manner she saw fit before offering support. Still, our frequent pre- and post-class discussions had a clear influence on the course. For instance, I repeatedly broached the subject of learning goals, and this conversational thread led towards deeper discussions of the potential math and science concepts that could be tied into the course. As a result, she began to include more content in the daily warm-up problems.

It was important to include Ms. Foster in preliminary study findings as well. This practice served two purposes: 1) the transparency of the research quickly resolved any initial concerns she may have had about the study, allowing her to remain comfortable with my intentions and promoting honest discourse between us, and 2) her feedback served as a "member check," an important validation strategy which helped support my initial findings and guarded against any misinterpretation of collected data.[88]

In the eyes of the students, I attempted to set myself apart from the teacher by assuming no disciplinary authority in the classroom. When students demonstrated behavior that was not in line with expectations, I intentionally withheld any type of disapproving reaction, with an aim that they would not alter their actions on account of my presence. For example, when students used their phones for non-educational purposes, I refrained from telling them to stay on task. After a short time, the offending students realized that I would not admonish them and, for the most part, they did not appear to change their behavior as I recorded field notes or approached them with questions.

I did attempt to make myself as available as possible to students seeking assistance and often asked eliciting questions, as their inquiries and responses provided an exceptional awareness of their understandings and misconceptions. In addition, because the classroom teacher was relatively inexperienced in the use of power tools, I took on a larger role in the woodshop where the large-scale construction and performance testing took place. I began to interact more with students during this stage of the semester and I was able to build a strong rapport with many. As a result, when they ran into obstacles or generated potential solutions, they often approached me for suggestions. And, because the students did not view me as a teacher, many showed no reluctance criticize the lessons and activities of the course, the instructional methods, and their classmates. This provided an enormous research advantage, allowing for a better perception of their true beliefs.

In addition to reactivity influences, researcher bias undoubtedly affected the data collection and analysis processes. My intentions were to remain as objective as possible, but past experiences clearly influenced my own perceptions of the course. I tended to view the academy as an engineering college preparatory program and therefore held high expectations for the students. When individuals failed to behave as though he or she was at least moderately motivated to pursue a career in engineering or severely lacked basic competencies, it is likely that an overly-critical lens was used during observations. Likewise, because post-secondary engineering classrooms are typically teacher-centered and highly structured, the learning environment may have been viewed too harshly, seen as lacking in control. Since I myself succeeded in teacher-centered classrooms, I remained partial to this mode of education, and as a result, found myself maintaining a desire for more direct instruction.

To mitigate effects from these views in the field notes, an effort was made to identify successes as outlined by the academy's foundational goals, most importantly by finding value in exposure to the engineering profession and positive experiences. Instances of success were therefore credited when students took part in common engineering practices and appeared engaged in enjoyable activities, as displayed through their comments, actions, and expressions. An effort was also made to recognize that traditional education methods did not suit all types of learners. It is important to note that observations served as a secondary data source during the analysis, and findings were not drawn directly from this source, but called upon to provide supporting evidence for other, more reliable data.

To reduce the risk of arriving at erroneous conclusions, specific attention was paid to the shortcomings of specific collection methods, as findings based on sources of common weaknesses may lack credibility. For example, interviews and surveys are both vulnerable to self-report bias. That is, participants may have been unwilling or unable to report noteworthy points out of embarrassment (due to poor behavior or low achievement) or ignorance (due to unobserved events), calling for other types of data for more evidence. Similarly, it was important to take cautionary steps to protect against cherry-picking data that fit any preconceptions caused by personal bias. Steps were taken to mitigate this threat by presenting preliminary findings to academy leaders who contributed to the study, which served to involve participants in the research and helped ensure that data was not misinterpreted.

Aside from these member checks, other key methods to addressed validity threats (as outlined by Maxwell[88]) were those of long-term involvement, the collection of "rich" data, triangulation, intervention, numbers (quantitizing through coding and the simple derivation of other numerical results from the data), and the search for discrepant evidence and negative cases (to help identify any biases, assumptions, or flaws in logic). Most important of all, long-term involvement helped provide more comprehensive information about the setting and its events than any other method.[8] Table 13 summarizes the case study's central validity threats and the methods by which they were addressed.

Table 13: Summary of key validity threats

Data source	*Validity threat*	*Strategies to address threat*	*Rationale*
Observations of students	Student reactivity – different behavior when approached	Long-term involvement – build rapport, no disciplining or assessing	Students more likely to behave normally if they do not feel judged or threatened
Observations of students	Students attempt to hide misunderstandings & do not offer critical views	Long-term involvement – act as a mentor/coach	Students more apt to share challenges & issues if there is no reprisal
Observations of teacher	Teacher reactivity – better preparation/more effort due to observations	Long-term involvement – no critical statements of instruction, be a colleague	Teacher more likely to behave naturally if she does not feel judged
Classroom observations	Researcher bias – only one researcher's perspective	Use as secondary source; utilize interventions & member checks	Supports primary data; researcher presence is always an intervention & can be used for deeper inquiry
Cooperating teacher discussions	Teacher hides course problems or feelings of unpreparedness	Transparency of findings; empathy & supportive comments only	Teacher more likely to share honest opinion if common view shared & researcher perceived as colleague
Student focus groups	Appeasing answers hide misunderstandings & poor behavior	Build rapport; comfortable setting; clarify interview purpose	More apt to reply honestly if non-threatening atmosphere & research purpose is understood
Student focus groups	Student sample unrepresentative and/or does not include all views	Purposive sampling – create groups based on class representativeness	Groups of students with similar behaviors & abilities more effective than random sampling
Interviews & focus groups	Misrepresentation or misinterpretation of comments	Triangulation; semi-structured line of questioning	Support with data not subject to self-report bias; probe for deeper meanings for more clarity
Teacher & administrator interviews	Miscommunication during interviews	Transparency of research; member checks	Participants should be aware of study & have an opportunity to clarify misunderstandings
Student surveys	Inability for students to fully explain reasoning	Triangulation – use focus groups, observations, and teacher comments	Use data not subject to self-report bias, deeper meanings demonstrated by other means
Evaluation of student work	Viewed too critically – from a college engineering perspective	Credit successes as defined by academy goals & as noted by teacher	Misalignment between researcher's & academy's perceptions of success
Literature review	Selection of data that fit researcher's existing goal, theory, or preconceptions	Search for discrepant evidence & negative cases	Biases, assumptions, & flaws in logic can be better identified when focused on finding contradictions
Interpretation of data	Researcher bias – only one researcher's perspective	Coding; member checks; triangulation	Quantitative results support qualitative data; outsiders verify logic & mitigate lone view; agreement among numerous data sources strengthens findings

Claimed contributions

Unlike quantitative studies which aim to determine precise results through probability sampling, settings assessed by qualitative methods are not always meant to be representative of larger populations,[88] although there is "a tendency to approach a case study as if it were a sample of one drawn from a wider universe of such cases."[22(p.90)] The particular setting under study is indeed not proposed as typical, but rather presents an "extreme" case, an outlier due to a number of atypical circumstances.[47] Although the findings are not generalizable in the traditional sense, they still bear significance since "special cases are critically important for understanding the variations that develop and the possibilities that exist in educational policy and practice."[37(p.6)]

Rather than aiming for generalizability, the study was carried out with the objective of providing degrees of "transferability," the practice of applying specific findings (instead of all findings) of one setting to another, depending on the extent of similarity between the two.[37] In order to generate transferable results, a specific context must fully explained through "thick" description, that is, describing a setting in enough detail such that a reader is able to identify which conclusions are applicable to an outside environment.[78] This process by which one judges the likelihood of a study's findings applying to another context (so-called "user generalizability"[91(p.211)]) is necessary because a researcher typically does not possess enough comprehensive knowledge of more than one setting to make direct comparisons to another, necessitating that readers bring their own in-depth understandings to bear.

Connections to this case are most likely to be made by educators also engaged in project-based learning, particularly in classrooms involving engineering-based learning goals and authentic assessments. The emergent findings of this study serve to identify areas in which the learning model is beneficial as well as deficient, where it should be supported or replaced by alternative measures. As noted in the literature, the model may not be advantageous for all students in all learning environments, particularly those possessing weak knowledge bases and poor self-regulatory skills, characteristics of students well represented within this setting. Achievement was seen to be dependent upon a number of important factors, and the study helped better establish the boundaries of project-based learning. Expounding upon the features of the course valued by the students and academy leaders and addressing the difficulties that inhibited learning and instruction will help expand the use of project-based methods.

Recalling the How People Learn framework, the study addressed four key areas of an ideal learning environment:

1. Learner-centered – the role a teacher plays in a project-based classroom is a significant influence, not only on students' abilities to attain understandings and skills, but on their motivations and affect towards engineering as well; fostering a learner-centered environment while also promoting knowledge construction is a complex issue, particularly considering that students' individual capabilities and acceptance of guidance can vary greatly
2. Knowledge-centered – since high school students' factual bases and conceptual understandings are relatively limited, further knowledge acquisition to progress students towards professional behavior is essential in engineering coursework, but design-based projects necessitate the application of a broad scope of information; mastery of content therefore presents an obstacle in project-based environments
3. Assessment-centered – authentic assessments are intended to motivate students and prepare them for the real world by placing them within professionally-relevant contexts, yet by embedding authentic evaluations into hands-on projects, teachers are hard-pressed to directly assess student achievement
4. Community-centered – in design-based courses that replicate the engineering profession, students are expected to work with classmates to come to agreed-upon solutions for ill-structured problems; however, compelling collaborative behavior in an environment that must also provide student autonomy can be challenging

Ultimately, many of the issues dealt with during in the course under investigation lead back to the fundamentals of social constructionism, the idea that group creation of physical products cultivates knowledge construction. This case study explores situations based on this underlying theme and attempts to identify the conditions by which the project-based model succeeds and falters, allowing for connections to similar cases to be drawn, thereby advancing understandings of the learning model and the means by which it is applied.

Broader impacts

Given the rapidly increasing interest in project-based learning and STEM education, it is important to continue to evaluate promising methods for involving students in environments designed to develop their "universal" habits as well as pique their interests through hands-on work in engineering-focused projects. Rather than simply assessing the conditions of the academy, the study serves as a formative evaluation to improve existing practices. These improvements are to be realized by basing future curricular modifications on justifiable conclusions, those which have been determined after coming to a better understanding of student experiences in the academy.[88] Because the academy teachers and administrators expressed a clear desire to enrich the program's instructional practices, the study aimed to take advantage of an opportunity to spur real change, helping to lead students towards careers in engineering and other STEM fields.

At the same time, academy students who decide not to pursue such career paths are still able to benefit since the coursework should compel them to engage in a manner of thinking uncommon in traditional courses. Specifically, problem solving by means of the engineering design process can help lead students to improved critical thinking, creativity, and collaborative abilities. By educating students at a young age to generate unique ideas, consider evidence and alternatives, attempt multiple possible pathways, and iterate for optimization, they become capable of applying higher-order thinking to real-world situations. As a result, they will be more prepared to flexibly react in a rapidly-evolving society.

From a broader vantage point, this study aims to present a clear picture of a singular high school classroom for the benefit of educators who aim to improve or create courses with similar features. Due to a national spotlight being placed on STEM education, the academy has generated an enormous amount of outside attention, and though similar programs are continuing to pop up across the country, there exists relatively little research upon which to base effective course designs and delivery methods. The case study serves to support this decision-making process, particularly significant since academy leaders hope to develop the academy and its feeder programs into a national model.

CHAPTER IV

NARRATIVE

The hovercraft course

The academy courses were initially created by teachers who were tasked with creating instructional, engaging, and developmentally-appropriate engineering curricula. The hovercraft course was no different. Giving students the opportunity to work with power tools and construct a ride-able vehicle was seen as an ideal way to get them excited about engineering. And, due to the absence of state-mandated engineering standards, curricular changes over the years were possible and easily implemented. In this sense, course design followed the iterative process of engineering itself – ideas were attempted, evaluated, and adjusted cyclically. Describing this process, one administrator referred to the first group of students to go through the academy as "guinea pigs," explaining, "We would try it out, see what worked, went back and tweaked it the following semester to re-teach it again. It was a work in progress."

The junior-level course was handed to Ms. Foster who had just finished teaching her first semester within the academy. Ms. Foster's schedule was quite full, and as she repeatedly mentioned during the semester, she wanted to devote more time to the hovercraft course. But with all of her other responsibilities, this was simply not possible, a common theme among the academy teachers. Doing what she could with the time and resources available, Ms. Foster set forth a very general plan of attack, but her horizon for specific lessons extended no more than two or three days out.

The account which follows details the course as it transpired. The purpose of this narrative is to fully describe the context – the environment, the method of instruction, the project, and the interactions, among other phenomena – to convey the experiences and perceptions of the teacher and students.

Day 1: Paper airplane design

The day commenced with two questions being posed to the students. The first question, "Why are you taking this class?" was typically answered in an overly literal sense (e.g., "I am taking this class because it is needed for my STEM certificate.") or in a manner related to the forthcoming enjoyment they expected (e.g., “I’ve heard that this class is fun.”). Answers to the second question, “What do you want to learn or expect to learn in this class?” varied widely. Some individuals pointed to skills they wanted to develop, such as those who wrote, “I want to learn how to problem solve better,” and “I expect to get better at using power tools.” Others were unsure what the course actually entailed, like the student who noted, “I really don’t know what this class is about.” Many expressed a desire to find out more about the engineering profession, including those who wrote, “I want to learn more about different types of engineering,” “I want to learn about how science and engineering relate,” and “I expect to learn more about the details of being an engineer and maybe do some more in-depth and harder builds.” And a few students were quite insightful and demonstrated keen interest specific topics, such as the response, “I want to be able to apply math to physical objects I create. For years I have learned empty math, being able to apply it would be a nice change.” It was clear from the outset that students were bringing a highly variable set of expectations and motivations into the classroom.

After briefly covering the general gist of the course, Ms. Foster segued into an introductory activity. She instructed the students to create a paper airplane that would fly the farthest, the straightest, and stay aloft the longest. She encouraged them to look online for promising designs, an offer that most students heeded. An hour was allotted for this activity, the purpose of which was to get students into an engineering frame of mind, meaning that they were expected to gain practice with the design process.

The activity (and the one that followed) was not well-received, nor were the accompanying lessons, because neither were seen as worthwhile in the grand scheme of the hovercraft project. As one student explained, “I honestly thought a lot of it was just a waste of time because the paper compared to wood is just not even [comparable].” Furthermore, from an engineering standpoint, the simplicity of the project set an unwelcome precedent, one that established a relatively low bar for achievement.

Day 2: Paper airplane performance testing

A brief video covered the main concepts behind heavier-than-air flight during the opening minutes of class. Ms. Foster followed the video with a question-and-answer session to emphasize key vocabulary related to flight, yet she chose not to draw explicit connections to the paper airplane activity. The students were placed into groups of four and given a half hour to submit a final paper airplane into a class-wide contest. The intent was to encourage teammates to collaborate and discuss the pros and cons of each of their crafts before identifying the best features of each and generating an optimized product. This did not take place. Instead, the students continued working independently on their own airplanes, and when the time came, they simply selected the plane which performed best.

Final airplanes were released from a second-story indoor bridge which traversed above the school cafeteria. The performance test was prone to error from a number of different sources, generating wildly inaccurate results that were anything but repeatable. A student from each team was responsible for logging his or her own craft's flight time, and these times were recorded as 4.5, 3, 3.07, 1.45, 5.32, 3.38, and 2 seconds. The manner in which this experiment was carried out was troubling; not only was the experiment entirely uncontrollable, the students recorded measurements haphazardly (e.g., 3 seconds versus 3.07 seconds). This practice reinforced the idea that inexact data was acceptable, the repercussions of which would emerge during future stages of the project.

When assigning grades, Ms. Foster originally intended to follow a typical policy within the academy by categorizing teams based on performance and delivering A's, B's, and C's accordingly. The students had become acclimated to competitive grading, one mentioning, "Our grades are only relative to how other teams do." Said another, "STEM classes are always about competitions." However, recognizing the obvious flaws in the assessment – not only did it foster a non-collaborative atmosphere, the performance results had little to do with knowledge or skill – Ms. Foster decided last minute to scrap these grades.

Although the activity was clearly devised to get students engaged, consuming three hours of class time in the name of engagement was difficult to justify. Opportunities to infuse the activity with math content did exist (e.g., compiling data and calculating averages and standard deviations, creating scatter plots with lines-of-best-fit and bar graphs), but this was not called for in the lesson plans.

Day 3: Ground effect craft design

Ms. Foster showed four short videos and presented a ten-minute slideshow, all of which addressed the topic of ground effect, an aerodynamics term which describes the increased lift and decreased drag created by an aircraft's wings when flying close to the ground. Ms. Foster discussed airfoils and briefly touched on the Bernoulli equation, the Navier-Stokes equations, and Euler's equations, mentioning that the students might see these equations again as college undergraduates. She noted, "You shouldn't worry if you only got some of that. You won't be tested on that, but it's kind of cool."

Because the academy aimed to introduce students to various aspects of engineering, many topics were presented in this fashion, scratching the surface rather than delving deep into content. This practice was brought about during the initial planning of the academy, when faculty members from the partnering engineering college recommended that course plans not get bogged down by highly technical topics. An administrator explained, "At first we were talking about like, 'Oh, we'd have all these different strands – aerospace and mechanical and da-da-da.' And they [the college representatives] really helped us focus in on, 'If you focus on the engineering design process and teach the skills around that, we'll take the specifics when they get there, but we want students to be prepared for that engineering college experience.'" This preparation called for improving students' communication skills, collaborative abilities, and critical thinking.

Similar to the previous activity, Ms. Foster instructed the students to create ground effect aircrafts from paper. The students immediately hopped online to search for ready-made designs and step-by-step instructions. They appeared incapable or uninterested in applying the presented concepts, opting for the most straightforward route to project completion. Ms. Foster confided that she personally disapproved of using the internet in this fashion, noting that if students were constantly handed answers, they would not develop into creative thinkers. More importantly, she explained that when they encountered problems for which there was no readily available answer, they would be less likely to come up with novel solutions.

One student did choose to create a craft without referencing an online recipe. He explained that he wanted to make an attempt on his own before resorting to outside help, and after finding a level of success – though admitting it did not meet the performance of many others – he said that he was proud of his work. I questioned him on specific design features, most of which he readily explained. For features that lacked any justification, we examined their underlying purposes or trivialities. He quickly grasped the discussed concepts and offered some suggestions for improvement, referencing lessons learned from a physics course he had previously taken.

I later spoke with a student who had been struggling to implement a design found online. He asked how his craft could be improved. To gauge his current level of understanding, I asked him to first explain the rationalization behind his design. He shrugged his shoulders. I pointed to a set of small wings protruding from either side of his craft and inquired as to their purpose. He replied, "They look cool." I offered a few suggestions, and though he could not follow my reasoning, he went forward with these ideas. After each slight modification, he asked if it was "good enough." I replied that it had indeed improved, but encouraged him to continue to optimize his design. He simply wanted to reach a satisfactory level to complete the activity.

This type of behavior was representative of a substantial portion of the academy; a lack of student motivation was a problem area noted by all of the teachers. As one teacher put it, "We'll have those kids that just, you know, this is the coolest thing ever and they want to constantly do better and they want to figure it out and they want to do more. And then you have the kids that are the 'good enough' kids, and this is good enough, and let's be done."

After class, I asked Ms. Foster to list the course learning goals. She named several overarching academy goals, explaining that she wanted the students to gain more practice collaborating, handling tools, utilizing the engineering design process, performing research, and presenting in front of an audience. She acknowledged that course-specific goals were fairly undefined. Recognizing value in the current class topic, she suggested that the basic physics of flight could serve as a potential learning goal. But she readily admitted that no assessment was in place to verify students' understanding of this. She expressed further concern that since less than half of the students had taken an introductory physics course, presenting concepts that all could grasp would be challenging.

Day 4: Ground effect craft performance testing

The students were allotted thirty minutes to finalize their crafts before another class-wide competition. Like the previous activity, students were placed into groups and encouraged to optimize a single design to enter into the competition. Some teammates did this, discussing quality design features and negotiating amongst themselves. But others continued to work independently. Worse, several students left the final design in the hands of teammates, playing no role in the activity.

Again, Ms. Foster eventually decided against assigning grades based on the teams' performances because the recorded distances had little, if anything, to do with the students' comprehension of the discussed concepts (after class, she attested that the competitive grading scheme was unfair, that the points assigned were "arbitrary"). Instead, Ms. Foster had the students answer written questions related to the concepts behind heavier-than-air flight. The questions asked students to explain how the forces of flight – drag, weight, lift, and thrust – applied to their crafts, to describe their paper airplane and ground effect craft designs, and to clarify the difference between the two. Although the extended writing assessment was not regarded as an authentic measure, it was an evaluation method the academy teachers occasionally invoked. One student complained, "These questions are freakin' long," but most provided well-organized responses, and Ms. Foster felt that their explanations provided better insight into their understandings. This was true to a degree, particularly when students articulated the relationship between the forces of flight and their crafts, as they were able to connect the presented concepts to their observations. When asked to explain their craft designs, however, students largely offered broad descriptions. The following excerpts illustrate this point:

> *Our ground effect plane was really flat with two wings sticking up in the back and then two under wings in the front. We also placed two paper clips in the front of the plane to give it more weight so that the front wouldn't flip up and then fall. It worked really well, we got second place in the class.*

> *For the ground effect plane, I made a sort of ramp design. I had two blades at the bottom of the plane that gradually got shorter as they got closer to the back. The back was flat so that way all the air would get trapped and go around it and not lift it off the ground.*

These reflections offered little evidence of understanding. Accordingly, Ms. Foster based students' scores on their ability to provide descriptions rather than justifications.

Day 5: Research on flight

The schedule called for the students to spend the class period defining flight-related vocabulary words and writing about the history of flight. While the students researched online, complaints popped up, with several individuals asking “Why are we doing this?” Ms. Foster had no immediate response, as she questioned this much the same.

The curriculum was disjointed, lacking continuity from one idea to the next, and appeared to have little application to the creation of hovercrafts. Ms. Foster made efforts to implement improvements. She showed me a document she had been working on which listed types of flight and types of aircraft. At the top of the page, she had typed: “How will they demonstrate understanding/knowledge and to what depth?” I asked if she expected the students to learn these topics. She replied that she had yet to decide. I asked how this information fit into the scheme of the course. She was unsure.

After well over an hour of internet searches and restatements of discovered text, a student asked Ms. Foster why they had to learn so much about airplanes if they were not even building them. Ms. Foster explained that there were three reasons: 1) she had never taught the course before and the activity was in the curriculum, 2) if standards had been written for the course, the physics of flight would have surely been included, and 3) the hovercraft project would not require the entire semester (meaning that additional tasks were needed to fill the time). The student argued that the assignment was “busy work.” Ms. Foster half-heartedly disagreed.

Day 6: First extended lecture on flight

The daily warm-up questions and progress logs had largely asked the students to write about their observations (e.g., “What was the most interesting thing you learned today about flight?”), a strategy Ms. Foster employed since it allowed her to reach students of all abilities. She argued that everyone could write, albeit with varying elaborative abilities. When math- and science-based questions were presented in the academy, she recognized that these were typically at a relatively low level so that all students could participate, unfortunately resulting in boredom among high-achievers.

Ms. Foster’s colleagues spoke of similar challenges, one teacher saying, “They’re all very spread out mathematically. There’s kids from remedial algebra all the way to like pre-calculus . . . so it’s a little bit hard to say, ‘This kid should be at this point.’” An administrator added, “I think we need to identify which parts of the [math and science] standards have all kids been exposed to. For some, maybe it is repeating it. For some, it is taking it to another level. And yes, that's absolutely a challenge."

Five days into class, the students had yet to complete a single calculation, so I volunteered to create a warm-up question to test their math skills. I originally intended to pose a problem that required them to determine the mass of a rectangular wooden board, given its dimensions and density. Ms. Foster suggested that the problem be simplified. At her behest, they were only required to determine the volume. In addition, she recommended providing them the general equation for the volume of a rectangular prism (volume = length x width x height). The presented problem is shown in Figure 6.

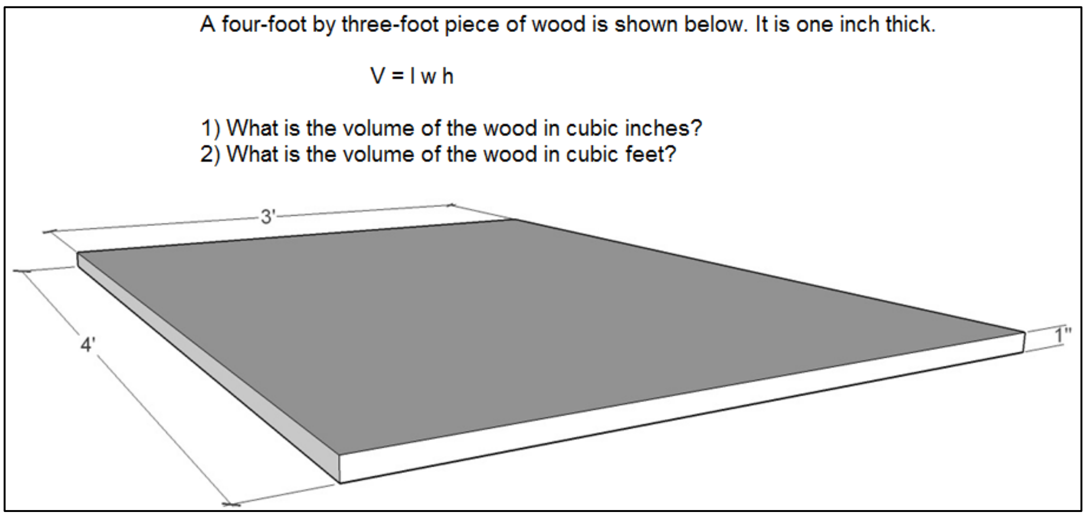


Figure 6: Day 6 warm-up problem

Just one of the thirty-nine students answered both questions correctly. And yet, not a single individual asked for help, though one did complain about having to "do math." The most common mistakes are shown below, represented with actual student answers:

1. Performing calculations across inconsistent units (e.g., 4 feet x 3 feet x 1 inch = 12 feet)
2. Reporting no units or incorrect units (e.g., 48 x 36 x 1 = 1,728 in)
3. Converting units incorrectly (e.g., 1,728 $in^3/12 = 144\ ft^3$)

The erroneous attempts shown were encouraging, relatively speaking, because the students who provided these answers at least made an effort. Many of their classmates, in contrast, quit at the first sign of difficultly or simply chose not to try, content to bide their time, knowing that Ms. Foster would soon present the answer, and also aware that they would not be tested on such a question.

Afterward the warm-up, I presented a slideshow-aided lecture that had been created by a previous teacher which touched on topics such as the significant historical events leading up to the Wright brothers, different types of flying machines, and the physics of flying. To generate discussion, I attempted to solicit ideas on various talking points, but the audience showed little interest. The slides and short video clips dragged on for forty-minutes, during which time no notes were taken.

Once class had ended, Ms. Foster and I again debated the fruitfulness of devoting time to topics that were not directly related to the project. We agreed that these tangentially-related lectures were at least a means to pique students' interest in engineering and provide insight into different types of the profession, one of the academy's academic standards. She noted that it would be wise to assess them on the presented concepts, as doing so would compel greater classroom participation. Yet she believed she had no means to effectively accomplish this using an authentic assessment.

Day 7: Second extended lecture on flight

The lesson plans called for another presentation, and Ms. Foster expressed concerns that the class was becoming too lecture-heavy. She prefaced the day's instruction by telling the students, "I agree that there's a lot of presentations and writing, but there's only so much I can do. . . . Bear with me for the next fifteen to twenty minutes. I'll make this as interesting as I can."

As she paced through the prepared slides, she relied heavily on her wealth of physics-based knowledge, presenting ideas related to fluid flow and airfoils. Some of the material was relatively basic, such as the concept of "stall" in aircraft, but much of the content and terminology, including separated flow regions and the equal transit fallacy, was well above the students' heads. Ms. Foster cleverly interwove three simple yet effective demonstrations into the presentation, illustrating the Bernoulli equation, "auto-rotation" in a helicopter, and an airplane's three axes of rotation. One student later remarked, "I learned how a plane flies and I didn't know that. So I'm actually really happy that I learned that, so that was pretty cool."

Notably, the presentation included a few slides about pressure and offered an opportunity for students to perform a simple calculation to determine the pressure required to lift an airplane. Opting to move along quickly, Ms. Foster chose to skip over the calculation, but she did caution the students that they would eventually be responsible for completing a few calculations on their own, though not too many.

At the conclusion of the slideshow, Ms. Foster introduced the course project. She explained that the students, acting as professional engineers, were being requested to create a device capable of transporting a scientist across a desert habitat which contained "cryptobiotic" soil. This incredibly fragile soil, located in Utah, necessitated the development of a hovercraft. The students were to work in teams of three to design and construct a working product.

After class, Ms. Foster expressed concerns that she had droned on for too long. She was not used to speaking for nearly an hour, as she had done today, even in her physics classes. She wanted the students up and moving, more engaged in the classroom, on their feet, building and experimenting. She remarked that she felt somewhat awkward during lectures because the students did not take notes. But it was difficult to fault them – they sensed no need to record anything because a) they would not be directly assessed on the material, and b) comprehension of the presented information would not directly lead to a better hovercraft design.

Before the bell rang, Ms. Foster had permitted the students to choose their own teammates. She forewarned them of the importance of this selection process since they were expected to work with their teammates for the duration of the semester. Plus, the majority of grades would come from group work. She noted that the project would require building skills, mechanical understanding, creativity, and an ability to use SketchUp, the computer-aided design program used in the academy. But her advice went unheeded as friendship was the only metric used to create groups. Students' thoughts regarding this group-formation policy were later captured, many of whom greatly appreciated the opportunity to choose their own teammates. One explained, "I really don't like being assigned to groups because sometimes you're stuck with people that you can't interact with as much."

But a few individuals were quick to point out drawbacks, one of whom noted that "you can set up your own failure by picking your friends . . ." Others pointed out the lack of authenticity, including the student who stated, "When we go into the actually workforce, we don't get to choose our co-workers." The real downside of this policy was that students were not being challenged to interact with and learn from all their peers. One student noted this issue, saying, "I feel like groups mainly come from your friends. And I really haven't met new people by being in a group with them. I would honestly much rather be assigned to a group instead of just going to my nearby friend and grabbing another friend because eventually it's just who your friends are, not really who you want to interact with and just meeting new people and seeing what skills they have and what you have."

Group formation was a topic to which Ms. Foster had devoted much thought. Allowing students to form their own groups played into the goal of providing positive experiences and cultivating an environment that was learner-centered. She did desire the groups to be evenly balanced, but she recognized the difficulty in this since she had yet to learn each individual's strengths and weaknesses. In addition, she argued that teacher-assigned teams established an easy defense when projects failed to work properly, a common view among her colleagues. She explained, "If students have problems with their teammates and I've created them, then I'm to blame. When they create their own groups, they are more responsible."

Day 8: Group research and individual essays

In light of the previous class period's lengthy presentation, Ms. Foster informed the students that she did not like to lecture for long periods of time, acknowledging that it quickly brought about boredom. She clarified that she still fully expected them to participate in discussions, to be on task, to be on time and working on the warm-up problems at the start of class, and to collaborate with their teammates. Noting that some of them had contributed little in the course thus far, she explained that she would begin to deduct participation points if necessary. Without elaborating, she expected the classroom to become a quality learning environment so that everyone could "get work done and be happy."

For the day's assignment, each student was responsible for composing a one-page essay addressing questions related to the context of the project, including "What do researchers need when observing and studying an environment?" and "What are four possible ways to transport a researcher and his/her tools to research sites within these ecosystems?" The presented task drew several complaints. More than one hour was provided, during which most of the students appeared quite disinterested in the assignment, opting instead to spend much of the allotted time socializing with one another.

Day 9: Balloon-powered prototype construction

Each group was issued an 8”-by-8” square of foam board, a one-inch plastic pipe, a drinking straw, a balloon, and a hot glue gun. They were tasked with creating a working hovercraft prototype by utilizing the balloon to provide a cushion of air beneath the foam board, allowing it to glide along a tabletop. The key design requirements were creating a well-sealed connection with the balloon and ensuring the underside of the foam board to limit friction. In years prior, assembling the craft was the entire activity. But Ms. Foster, seeing an opportunity to incorporate science-relevant practices, extended the assignment, requiring that students design experiments to determine a relationship between the size of the foam board and the maximum weight it could carry while. She created a worksheet to guide the students through the process, asking them to sketch their designs, generate quality data, and create appropriate data tables and charts.

Several groups were able to assemble the pieces without incident and shortly thereafter began designing their experiments. Others struggled mightily, failing to create working crafts after more than an hour of class time. Much of this was attributable to a lack of attention to detail, as students hastily glued their piping to the foam board, disregarding any glue or rough edges that protruded from the underside of their bases, and making holes in the foam board that were grossly oversized.

Due to the diminutive scale of the activity, the assembly process often became the responsibility of just one or two students per group. Collaboration was expected, but not practical, as one student later explained, “I kind of feel like with these projects, like the smaller hovercraft, there was always one of us like sitting out because it just wasn’t big enough for everyone to work on it.”

Consequently, some individuals were completely disengaged from the activity, readily pointing to this issue of “too many cooks in the kitchen” as an excuse for their lack of participation. While understandable, other tasks remained, including planning an experiment, creating a data table, and completing a sketch. But rather than tend to these items – which many viewed as the boring parts of the assignment – several individuals chose to socialize or surf the internet. By contrast, other teams chose to delegate tasks, and those who did tended to submit higher-quality work, as each member had sufficient time to complete his or her individual assignments. This disparity in quality is evident in Figure 7, which shows various team's sketches.

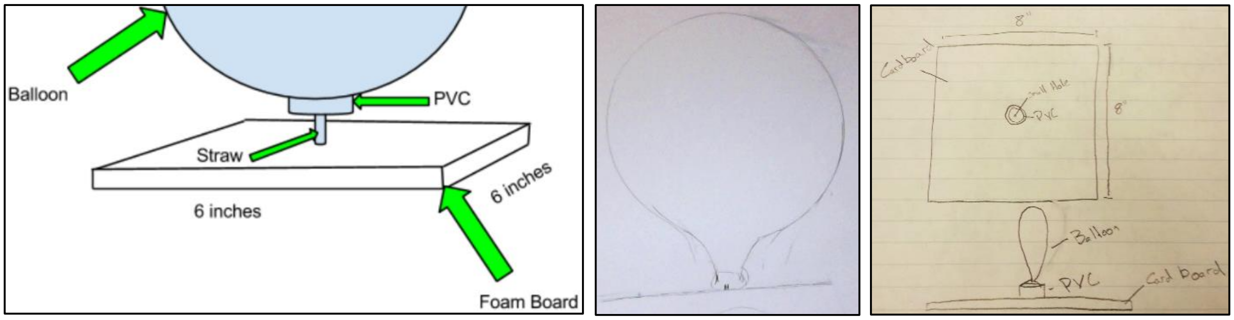


Figure 7: Comparison of submitted sketches for the balloon-powered hovercraft activity

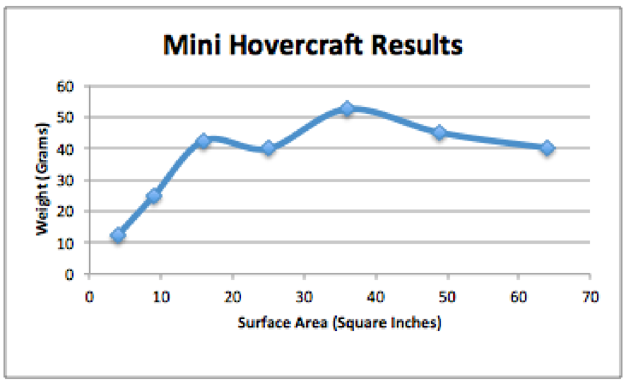
Day 10: Balloon-powered prototype experimentation

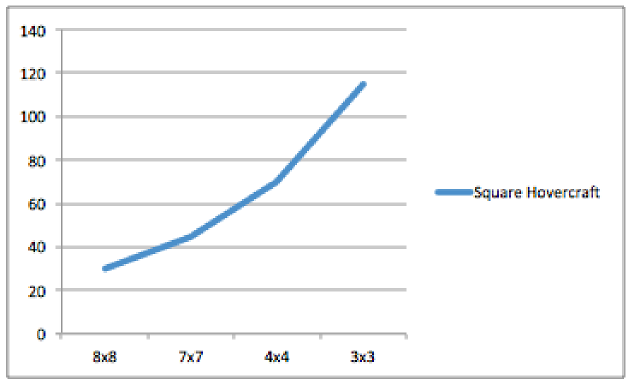
By the end of the period, each group was required to have a finished experiment, complete with data analysis and write-up. If they were unable to finish, Ms. Foster told the students that this signaled they were off task too often and "maybe on your phone too much," a constant battle in the classroom. Four of the thirteen groups would not complete the assignment.

Many groups were able to obtain quality data sets, but others were unable to design and conduct controlled experiments, allowing multiple variables to shift during testing, yielding worthless results. Rather than determining a correlation between their craft's surface area and the amount of weight it could lift, for example, one group added layers of foam board atop one another and plotted the craft's base thickness versus the lifted weight, an irrelevant relationship. Of their findings, the group wrote, "The only thing we can learn from our experiment is that thickness and height don't affect the hovercraft at all." These students were given a chance to rework their experiment, as there was sufficient time run new tests, but they declined. They were satisfied that they had met the day's minimum requirements.

The group's failure could be attributed to vagueness in the directions, which asked students to "Come up with a test to determine the relationship between craft size and weight carried." Ms. Foster intentionally left the activity somewhat pliable – as opposed to procedural – to compel the students to think critically about the specific purpose of the experiment and how it would apply to full-size hovercrafts.

Of the thirty-nine students in the course, just two showed decent competency with spreadsheets, meaning that they were able to create graphs without assistance. Although the students were expected to have developed this skill by their junior year, they had in fact never been given a formal tutorial on the use of spreadsheets; they were simply expected to have learned it on their own. I therefore spent much of the class assisting individuals with this process. Although Ms. Foster and I encouraged them to ask for help, many of the individuals who had assumed ownership of the task (typically one student per group) were reluctant to do so, complacent with work that was clearly sub-par. Upon seeing the quality of their efforts, I chose to intervene when possible, offering tips and suggestions to improve their charts. By the end of class, the work of students who had received help was far superior to those who had not, as illustrated by Figures 8 and 9 (note the lack of proper labeling and unnecessary legend on the right plot).





Figures 8 and 9: Scatter plots by individuals who did (left) and did not (right) receive guidance

While the students worked, Ms. Foster assigned notebook grades. Rather than evaluating their daily warm-ups and logs for organization, effort, and accuracy, Ms. Foster chose to leaf through the pages to check the overall appearance and "volume" of writing. This brevity was largely due to her ever-increasing to-do list in both this course and others. By recording each grade quickly, she was able to free up time for more highly-prioritized issues.

After class, I asked Ms. Foster to reflect upon the opening weeks of the semester. She raised three key points for improvement:

1. Learning goals should be categorized by topic (e.g., math, experimentation, CAD) and should be detailed rather than vague
2. In order to elicit the best answers from students, questions should be specific

3. Directions for activities and assignments should be very clear

Her first suggestion was in direct response to our numerous conversations about the genuine purpose of the course. While it was understood that we needed to develop the students' soft skills, the technical learning goals were still unclear. Did the students need to know how to calculate surface areas and volume? Should they gain more experience setting up data tables and generating graphs? Were the physics of flight truly important? We considered these questions and many others, but because Ms. Foster did not know which content and skills would truly be beneficial to hovercraft design, she found herself covering a plethora of topics, many of which lacked clear connections to the project. Compounding the issue were the Academic Standards and Grade Level Expectations, which were too broad to put into practice in the classroom (indeed, when Ms. Foster was questioned on the documents' usefulness, she was completely unaware of their existence).

Her second two suggestions, in many ways, flew in the face of project-based learning, namely that they would institute a greater degree of control in the classroom. But Ms. Foster wanted the students to generate more well-thought-out responses, but her typical line of self-reflective questioning – for example, "What do you think about . . .?" – did not force students to declare definitive or justified answers. Likewise, she expected them to work with greater attention to detail in order to develop their technical skills, but the ambiguity which pervaded the activities allowed the students to complete tasks in manners unrepresentative of professionals. Yet the learning model prized student autonomy to allow for exploration, and being overly specific to elicit precise answers and actions would arguably limit critical thinking and creativity.

Day 11: Fan-powered prototype construction

For the day's assignment, the students were to construct prototype powered by small computer fan, followed by another phase of data collection. I facilitated the activity, and in light of the previous discussion with Ms. Foster, I created a worksheet with step-by-step instructions for collecting the requisite data. Because the number of supplies were so limited – a fan, a piece of 12"-by-12" foam board, a length of tape, a battery, and a plastic sheet – I decided against providing written instructions for assembly, though I did present verbal instructions, using both a physical exemplar and detailed drawing. Still, many groups struggled to assemble their devices, and since they could not proceed to the data collection stage without a properly operating craft, they were forced to work through the obstacles.

It was at this stage in the problem-solving process that teams began to distinguish themselves. Whereas collaborative teammates would attempt to identify root causes and discussed possible alternatives, others simply turned their hands upward and complained that their devices were not working, faulting the provided materials. Several individuals eventually asked for assistance, but Ms. Foster and I, believing that the students were fully capable of overcoming any hurdles, provided little help. This slowed their progress even more, causing frustrations, but they were all eventually able to figure it out on their own.

The activity was designed to generate class-wide data that would provide clues to effective hovercraft features, but it was necessary for the data collection process to be consistent among all groups, a concept that some did not appear to understand. Once teams were ready to begin collecting data, many plowed through the step-by-step procedure with little attention to specifics. One group, for example, used a tack to create holes in the prototype skirt although the directions explicitly stated to use a specifically sized nail. Their resultant data was thus incomparable to others' and had to be thrown out.

The worksheet closed with several questions about lessons learned from the activity. As intended in group-based assignments, many teammates discussed their findings before composing their responses together. Yet because these questions could be easily answered by a single student, the envisioned collaboration did not always transpire, as some students were glad to handle the task themselves while others struggled to elicit contributions from their group members. For instance, a hard-working individual (who had already completed the lion's share of the activity) attempted to include his teammates by asking, "What do we say?" in regards to one of the worksheet questions. He was abruptly met with, "I don't really care." Other unmotivated students exploited the situation in much the same way and dumped the responsibility on the de facto leaders of their respective groups.

Day 12: Fan-powered prototype experimentation

In response to the scarcity of spreadsheet experience among the students, Ms. Foster asked me to compose a set of instructions for creating a basic graph from compiled data. Rather than typing out explicit steps, I suggested that a class-wide verbal tutorial would be more effective. Ms. Foster replied, "They're not trained to do that."

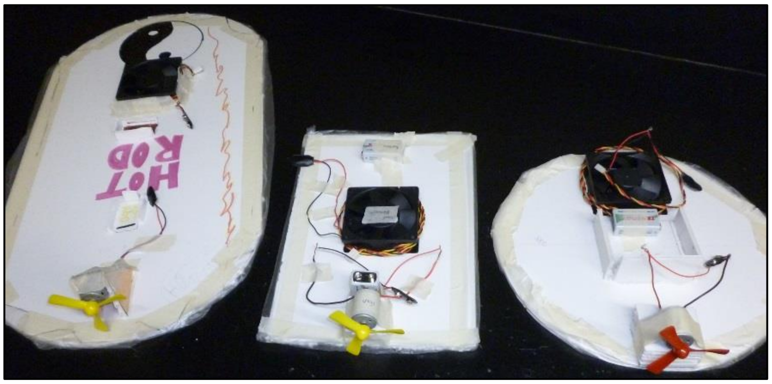
"Do what?" I asked.

"Pay attention," she said. She felt that inattentive students would get too far behind, either giving up in frustration or holding everyone else back, and causing a "headache."

I prepared the written instructions, and the students worked diligently through the activity. Ms. Foster commented that they appeared more engaged than normal. Questions were frequently asked by the students, many of whom wanted to learn more details about the program than the minimum requirements of the task.

Continuing the previous day's activity, the students began wrapping up their experiments and moved on to data analysis. In order to define the relationship between two key variables, it was necessary to calculate the total area of holes in their crafts' skirts, and to do this, they needed to measure the diameter of the nails used to punch the holes. Ms. Foster decided to have the students use manually-operated calipers to take these measurements, a non-intuitive process that required some time for instruction. Rather than conduct a whole-class demonstration, Ms. Foster chose to teach each group separately as they came upon this part of the activity. After fully describing the process and soliciting questions to several groups, Ms. Foster conducted a few informal comprehension checks. Many students were unable to use the calipers properly and it was clear that had gained little from the demonstrations. Although the student-to-teacher ratio was an advantageous 3-to-1 for this instruction, typically one or at most two students per group followed along. The lack of attention was due largely to the fact that students knew they would not be explicitly assessed on this task. In addition, some felt there was no need to learn the procedure themselves as long as a teammate could do it.

In the second stage of the day's activity, students were expected to create a new skirt with an optimized number of holes based on the data they had compiled. After implementing this modification, they were to measure the distance their crafts traveled when pushed with a controlled force, generated by a simple rubber band-powered contraption created specifically for this task (see Figures 10 & 11).



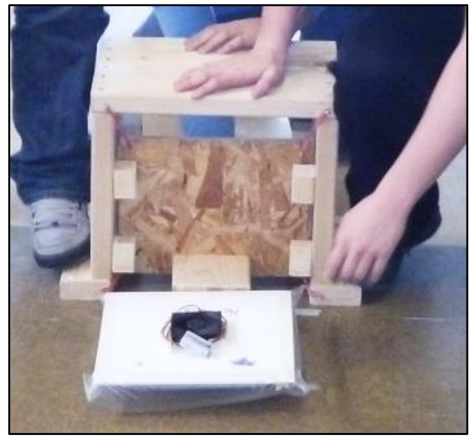


Figure 10 (left): Balloon-powered hovercrafts
Figure 11 (right): Students testing the distance their fan-powered hovercraft is able to travel

Every group was shown how to use the device, but many failed to operate it properly, again failing to control for variables, which resulted in inaccurate data. At one point, two rubber bands on the contraption snapped. Although it was clearly generating a greatly reduced force, students continued to use it, providing measurements that were no longer comparable those of their classmates'. Further prohibiting the comparability of data, some groups recorded their distances in feet instead of meters as was called for. When they attempted to convert these measurements, they committed major calculation errors and provided distances that were incorrect by an order of magnitude or more.

After class ended, Ms. Foster wanted to discuss the two most recent activities and the fundamentally different ways they had been presented. In the balloon-powered craft activity, she designed the task with built-in ambiguity to force the students to think critically before pushing ahead with their experiments. She compared this to the fan-powered craft activity, where the task steps were more explicit. Although she had been frustrated by several groups' lack of progress during the initial activity, attributed to the vagueness of the instructions, she did not feel the latter procedural method was an improvement. She believed that several students were not invested in the activity and were simply "mulling through the steps" with no sense of purpose. Rather than "throwing" the activity at them, she suggested including in the learning process itself. She recommended that asking questions such as "What do you notice about the hovercraft?" and "What different variables can we change?" would have led to better student engagement.

Day 13: Hovercraft lecture & initial designs

Ms. Foster spent thirty minutes presenting pre-made slides about the inner-workings of hovercrafts. The technical information provided on the slides was very brief, giving a very brief overview of the relevant fundamentals. Ms. Foster discussed the basic pressure formula (Pressure = Force/Area) and Newton's three laws of motion in a simplistic manner. She asked students to expound upon these areas, but there was little interest in the audience. Instead of dwelling on this material, she chose to spend more time showing pictures and videos of hovercrafts in action.

Afterwards, Ms. Foster asked the students to brainstorm for their initial hovercraft designs. She explained that each group's basic construction materials would consist of a 4'-by-8' sheet of wood to act as a base and a 6'-by-8' tarpaulin to act as a skirt. Lift and propulsion would be provided by an electric leaf blower and a large fan, respectively. The students were also expected to devise a method to steer. To help guide their brainstorming, she provided an "initial design" worksheet with a series of questions about their craft size and shape, skirt design, required materials, and method of operation. They were required to create CAD drawings of their basic ideas, and they were given the next several class periods to complete this task (see Figure 12 for examples).

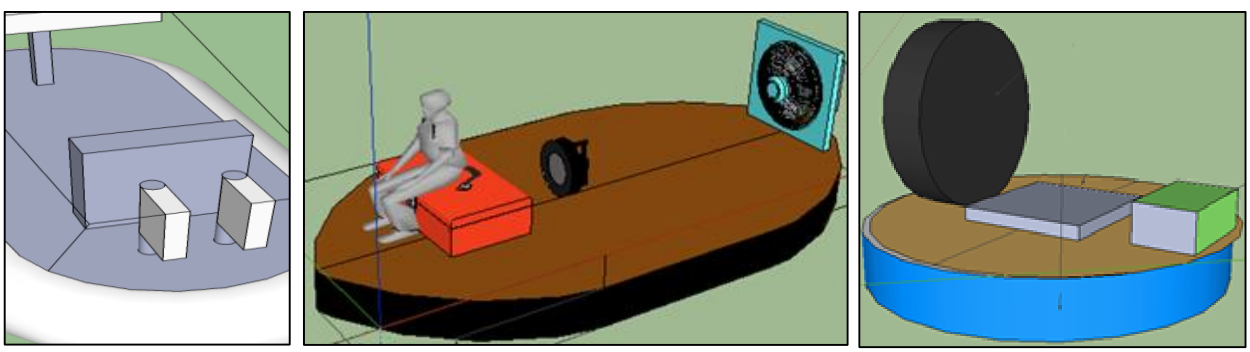


Figure 12: Initial hovercraft designs

After class, Ms. Foster offered her view of how the course had transpired thus far, stating, "Overall, it's going well. I'm having fun and the students are having fun. When building, most people are on task, or at least getting the job done. We've been doing a good job of setting expectations – doing research, keeping notebooks, that data analysis is important. . . . The skills we're teaching are good – Excel, calipers, and data analysis."

She had previously noted difficulty incorporating math-based lessons in the coursework because the true relevancy of math in the project was unclear. I inquired about this. She said, "I think we should include math when we can, when it's applicable. They've been calculating areas in a number of ways. We've been looking at trends with data, more conceptually based."

Although math had not been a major component of the course thus far, and that which had been included was quite basic, Ms. Foster pointed out that the students had largely struggled when presented with math-based questions. Now that she was more keenly aware of their abilities, she regretted not having included more math warm-up problems. Instead of helping them develop their technical skills, she had mainly presented questions designed to compel students to reflect on various topics. As an example, she mentioned the writing prompt "What do you find most inspiring about flight?" that she had posed, an inquiry that she now laughed about. The value of prompts such as this was questionable since nothing came of the students' responses, a few of which are shown below:

> *The most inspiring thing about flight is that humans can not physically do it. That is why we want to.*
>
> *Only a century ago we were inventing the first airplanes, and now we're launching people into space. It will be interesting to see where the future takes us.*
>
> *The most inspiring thing about fight is that we kinda beat gravity in flying up in the air, like 100 to 200 year ago it was impossible to fly and people would always dream that is what makes it really inspiring.*

Ms. Foster's primary concern about including math was its relevance to the project. She said, "I would be open to using more math, but it would have to be relevant. I don't want them to do something random that is not driven by the class, although once in a while this might be okay." She continued, ". . . I don't know a lot of ways that math could be included. It might be good to get ideas from someone else, like what are some 'mathy' things I could do?"

Day 14: Scored discussions

The day's warm-up asked students to measure an object using calipers. Since many of the students had decided to ignore the previous instructions, Ms. Foster and I were forced to start from scratch as we led individuals through the procedure once more. In many cases, students were handicapped by a lack of ability in converting fractions (e.g., understanding that 3/8 inches was identical to 6/16 inches and 12/32 inches), which prevented them from recording accurate measurements. Though warm-up problems were intended to consume no more than ten minutes, the activity required a full thirty minutes. This use of class time greatly displeased Ms. Foster. She attributed much of the problem to students' unwillingness to put forth effort when given the opportunity to work independently, as she felt that many of the students needed direct supervision in order to keep them on task.

For the day's activity, Ms. Foster organized a "scored discussion." The discussion was designed to accomplish two things: 1) evaluate students' abilities to analyze and articulate the data they had collected during the prototype activities, and 2) encourage them to engage more in the classroom. The previous class, Ms. Foster had distributed a list of questions about specific trends in the class-wide data, and she instructed the students to prepare written answers to reference during the discussion. Since this written work was not to be collected, less than one-third of the students completed this task. Still, the discussion was an astounding success.

In sharp contrast to Ms. Foster's previous attempts to elicit involvement, every single student – save for one incredibly shy individual – made contributions during the discussion. Many demonstrated a surprisingly wide-ranging vocabulary and referenced some of the concepts that had been presented during class to support their points. Three students who had not spoken up once during the previous thirteen class periods were transformed into full-fledged participants. A student notorious for partaking in horseplay was suddenly focused. Ms. Foster was extremely pleased with the students' participation and well-articulated responses. Afterwards, she told the class that it had been one of the best discussions she had ever observed. I praised them as well, remarking that their contributions were very professional, and noted that their efforts were quite improved as compared to other days. A student replied, "Well, you gave us an incentive."

After the students had disembarked from the classroom, Ms. Foster spoke about continuing the same level of engagement for the duration of the semester, but realized that this would require more explicit participation points. To track each student's involvement during the scored discussion, we simply made a tally mark each time an individual offered a response, then added a second tally if the contribution was supported with evidence. This rudimentary process would been incredibly tedious to carry out on a daily basis.

Ms. Foster had initially intended to assess participation and collaboration, but she noted that appropriately doing so had proven challenging. For the past two weeks, she had been assigning participation grades for students' efforts during class, distributed at the end of each week and based on her general observations of the class. Nearly every student had received full credit – the average being 95% – which did not align with the concerns she had been raising about students' efforts. For argument's sake, I inquired about a particular student who was consistently late to class, did not complete the warm-up problems, allowed his teammates to complete collaborative work, and was generally off task and disruptive. Ms. Foster noted that he was currently earning a B. I asked if she felt this grade fairly represented his level of achievement, to which she hesitatingly replied, "I'm not sure."

I then referred to the Academic Standards, and read from Standard 2, which entailed collaboration: "Students will master 'working together in teams of diverse members to reach a goal' and 'understanding the role of each individual in a team and taking responsibility for one's role on the team.'" In light of these standards, Ms. Foster acknowledged that a D would have been a more appropriate grade for the student in question. And although she was more cognizant of the fact that some students' efforts were not being reflected by their grades, she felt unable to capture this information in an expedient manner. Notably, she chose not to record any participation points for the rest of the semester.

Day 15: Formative assessment

The day's warm-up problem required students to find the surface area of a wooden ellipse, then establish a proportion to determine its mass. The problem was quite challenging, and since it was directly applicable to the project, the vast majority of students were engaged in solving it. But every student needed guidance, and even with two teachers, the resulting individualized attention expended another thirty minutes of class time.

To gauge the students' levels of understanding on a number of concepts and skills that had been covered thus far, I delivered a thirteen-question formative assessment. Nine of the questions asked students to identify various physical phenomena, ranging from forces of flight to buoyancy to Newton's third law of motion. The students scored relatively well on eight of these questions, the average being 70%, fluctuating from 62% to 94%. Yet the ninth concept conceptually-based question, which asked students to correctly identify the independent variable in the balloon-powered hovercraft activity they had completed, presented a problem. Just 26% answered correctly. This result coincided with the vast number of flaws in their experiments.

Three of the assessment questions were math related, all of which had been previously covered during the daily warm-ups. The first asked the students to calculate the area of a circular hole, a problem which 82% answered correctly. On the second problem, students were required to determine the volume of a rectangular hovercraft base given its linear dimensions, a very basic calculation, yet only 35% answered correctly. The most common error was due to a misunderstanding of units, as many suggested that inches or square inches were appropriate for a volume. The third problem asked students to convert a value from square millimeters to square centimeters, and just 24% were able to do so.

Lastly, the students were tasked with making a measurement reading from an image of a set of calipers. Per Ms. Foster's suggestion, metric calipers were used to avoid the use of fractions. Even so, just 38% of the students answered correctly. The correct answers of the assessment were not explained afterwards, and several of the topics, including the use of calipers, did not re-emerge for the remainder of the course.

Day 16: Student-designed prototype experiments

The day's warm-up prompted students to "Discuss the team dynamics of your group" and to answer the questions, "Are you working well with each other?" and, "Are you happy with your group?" During the group activities, many of the teams had appeared to work fairly well together, but due to the relatively large number of individuals who frequently chose not to fully participate, it was expected that some students would point out issues within their teams. This was not the case. Just one of the thirty-nine students noted anything remotely critical (writing, ". . . we communicate but [teammate] sometimes does not really talk to us"), as all other responses were positive, even from those who were completing nearly all of their respective team's work.

The previous class period, the students had been posed the question, "What other experiment would you conduct?" with regards to their fan-powered prototypes. Based on their written responses, Ms. Foster divided them into temporary teams to investigate these suggested ideas. Upon hearing that they were being tasked with yet another activity, one student called out, "This was supposed to be the fun STEM class!" A second student quickly added "I agree!"

Ms. Foster asked, "You don't think it's been fun?"

The second student responded, "Usually STEM classes have two weeks of research, and then only building. This class has been like eight weeks of research!"

"But we've done lots of experiments," Ms. Foster rationalized, insinuating that that the hands-on experiments should have been enjoyable. But this was not the case. Students' frustrations had been mounting for some time, with grievances such as, "When do we get to build?" being voiced on an increasingly frequent basis. Ms. Foster conceded after class that she was concerned the course was not fun enough for the students. She had wanted to incorporate more enjoyable activities into the classes, but she lacked the time to do so.

Day 17: Student-designed experiment presentations

Frustrations on both sides of the classroom continued to mount. The students wanted to begin building, but Ms. Foster was far from pleased with the students' progress on their lead-up work. She referenced the worksheet that accompanied the fan-powered hovercraft activity, noting that just seven groups had completed it, though the activity had taken place more than two weeks ago. She then brought up their initial design worksheets, and pointed out that only three groups had submitted a CAD drawing. This was initially assigned eleven days prior (by the time the next worksheet was due, only two groups completed it on time).

Five minutes into the day's warm-up, which required that lines of best fit on a series of graphs be evaluated, Ms. Foster realized that several students were not working. She interrupted the class and announced that twenty minutes or more of class time was consistently being consumed for problems that required less than ten minutes, and asserted that the many students had "no sense of urgency." She tried to motivate them by clarifying that the warm-up problems were "not pointless," maintaining that they were relevant to the forthcoming project. She began cold-calling students for answers, purposely choosing individuals who never volunteered to contribute. The first student apologized, explaining he had yet to write anything down because he could not see the board. The second student said that he did not know how to answer. The third offered an incorrect explanation. Others who had been raising their hands were finally called upon and offered quality responses. One student stated that the variables in one graph were "directly proportional." Ms. Foster welcomed this as an "excellent answer," adding, "You didn't have to use that vocabulary, but I appreciate it." She then reworded the student's response into simpler terms.

Before beginning the day's task, Ms. Foster addressed the students' prior complaints about boredom, recognizing that the course project would be more enjoyable than the previous assignments. However, she stressed that their designs were still poorly defined, that they needed to specify dimensions and materials before they would be able to construct their devices. She announced that the building phase could begin in a couple of weeks, eliciting scoffs from several students.

Each team's experiment from the previous class was uniquely designed to gain a better understanding about specific hovercraft features, and the students were to prepare three-minute presentations on their findings. With the impending assessment, most teams worked diligently together, compiling their data into basic charts and discussing which team members would present which information. Two students chose not to work alongside their teammates, catching the eye of Ms. Foster. When she asked why they were not collaborating as expected, one voiced displeasure about her micromanagement, saying, "I feel like you're treating us like little kids. We got this." They continued to work alone.

While the groups presented their data, Ms. Foster asked those in the audience to participate, requiring that each individual contribute at least one question or comment. Although the students' participation was much greater than normal, Ms. Foster expressed dissatisfaction after class. She had expected them to ask about specific design features to gain insight for their own hovercrafts. The more highly engaged students did inquire as such, but others simply asked the presenters to repeat something or posed questions such as "Who is going to drive it?" to earn participation credit. Ms. Foster joked that she would like to prepare a warm-up on how not to ask "dumb questions."

Day 18: Scaled prototype construction

The students were responsible for constructing scaled prototypes of the hovercrafts they intended to build. They showed a solid understanding of linear scaling as they cut accurately-dimensioned bases from foam board. Many of the bases had been designed with integrated curves, however, and the owners of these designs soon realized there was no way for them to accurately re-create these shapes because they had simply drawn the arcs freehand. They had not purposely avoided this aspect of design, they were simply unaware that this level of precision was expected. Still, they proceeded to draw and cut the curves without first establishing relevant dimensions, and Ms. Foster chose not to assess them in this regard.

More troubling, very few groups had any reasoning behind their bases' shapes and sizes. As a result, the students looked to see what their neighbors had designed, and many fell into a pattern of groupthink. For example, although they were permitted create a base of any size, no group used less than two-thirds of the provided 4'-by-8' sheet of wood, resulting in much larger bases than were necessary.

The students also relied heavily on their intuitions, often beginning their responses to design inquiries with "I feel like . . ." and "It seems like . . ." It would have been preferable for the students to justify their product features, but they had little technical understanding upon which to base their decisions. Moreover, Ms. Foster chose not to steer teams towards more effective designs because doing so would have been counterintuitive to problem-based learning. Fostering an open, learner-centered environment in which students could work creatively and come to solutions through their own ventures was at the root of the learning model. Intuitively-designed products had largely worked well in the students' previous academy courses, and from this practical standpoint, any number of base designs could have been successfully implemented within a working craft. Thus, the students were not wholly to blame for their lack of design justification.

Day 19: Critical review preparation

The day started with a problem asking students to find the maximum circular base which could be built from their 4'-by-8' sheets of wood. From this, they were to determine the weight of the base by setting up a proportion, a process they had already practiced in class. Few students were able to answer correctly.

More disconcertingly, less than half of the students even attempted the problem. To highlight this issue, a student who had clearly accomplished nothing since the bell rang was called upon to answer. He replied, "I don't know. You know I wasn't doing it."

Afterwards, Ms. Foster vented in private about her frustrations with the students' behavior, saying, "I don't think I can survive the semester with the current situation." She simply wanted the students to participate, and noted that those who chose not to do so were unfairly holding back others. She called the situation with the warm-up problems "ridiculous" since some students commonly finished the tasks before others opened their notebooks, and acknowledged that too many students were in the habit of writing down the answers only after she reviewed the solutions. She later added, "I wish I could change student attitudes about being on time, being on task, and to stop whining."

By the end of the day's period, the teams were expected to have fully assembled their scaled prototypes and edited their CAD drawings to represent their most recent design changes. They were also required to put together slideshow which detailed their craft features. These three items were to be presented the following class as part of a "critical review" on their initial designs.

As they worked, students asked a myriad of questions, such as how to draw an object in the CAD program, how to assemble a prototype, and how to format a presentation slide. No "why" questions were asked. For instance, a few groups' prototypes failed to move forward because the airflow pathway to the propellers was obstructed. Rather than investigating the situation and probing for the reasoning behind the lack of motion, they instead asked questions such as "What are we doing wrong?" and "How can we get this to work?" This line of questioning did not aim to get at the root of the problem, to better understand the situation. Instead, students were more preoccupied with identifying ways to quickly complete assigned tasks.

Day 20: Critical review presentations

Teams which had worked well together and took full advantage of the allotted class time to prepare their presentations had, overall, created semi-professional-looking slides, complete with appropriately-used images and concise wording. When questioned on their design features, they were generally able to provide some support for their ideas, at times bringing forth basic concepts in their reasoning. For instance, a group using a relatively small base indicated that it would have less weight, thereby requiring less lift force and propulsion.

In contrast, teams which put little thought into their design, or those who had made decisions based on misconceptions, were ill-prepared to accurately support their decisions. A group which had designed a base with a pointed front and back declared that this shape would reduce air resistance, an erroneous claim when considering the minimal speed at which the crafts would move. Rhetoric from these groups was typically unspecific, including contentions such as, "We feel like this skirt design will work," "We thought this shape would be good," "We'll somehow build a box for our rudders," and, "We felt that both a circle and rectangle had pros and cons, so we wanted to use something in between."

Afterwards, Ms. Foster required the students to write at least three comments about their classmates' presentations. A sample of these comments are shown below:

Overall everybody had a good presentation and ideas.

I was disappointed that most groups were using a similar shape for their device, which was the skateboard shape.

I really liked how everyone had original ideas.

The worst groups . . . had nothing in their presentations but lines of text.

For [student's] group I would say they have a really good idea and their skirt design is very interesting.

[Student's] group had the octagon shape design which seemed pretty interesting because it's the only design thats not a rounded rectangle, or circle. They said they talked to people who took this class in the past and said it was a good idea so I'm curious to see how it does.

Many of the groups seemed very unclear of what they were talking about.

Day 21: Center-of-mass calculations

One facet of the project in which math directly applied was in regards to the concept of center-of-mass. While the degree of a craft's success was not dependent upon the accuracy by which its center-of-mass was calculated, many students found this topic worthwhile since the calculations were explicitly connected to their physical product. Ms. Foster spent ten minutes covering how to employ the center-of-mass equation, a relatively straightforward algorithmic procedure. Afterwards, the students were required to complete a center-of-mass worksheet, providing them an opportunity to practice the calculations before applying them to their respective craft designs. The worksheet was assigned as an individual task, meaning the students were less apt to work together (though many did), and while they were welcome to seek teacher assistance, few questions were asked. Owing to these factors – and the fact that Ms. Foster was able to decidedly assess their answers as right or wrong – the students fared quite poorly on what was expected to be a simple assignment, averaging 73%.

While the students were tending to this work, Ms. Foster visited each team to offer feedback on their critical review presentations. The predominant point she emphasized was related to the ambiguity of their designs. Ms. Foster referenced many of their CAD drawings, often pointing out that the placements of numerous parts were "obscure" or seemingly "floating in the air," with no points of attachment. She instructed each team to better establish their designs and required several teams to modify their prototypes to better match their drawings, or vice versa, because the two were misaligned, pointing to a lack of communication between the group members made responsible for the two tasks. One group complained that changing anything at this point would be "too hard" and asked how many points they would lose if they refused to do so.

A team which had been working diligently finished the assigned tasks and was invited to begin cutting out their base. The students joined me in the woodshop – or "fab lab" as it was called, short for fabrication laboratory – located on the ground floor directly beneath the classroom. The vast majority of students had yet to gain extensive experience in the fab lab, with several mentioning they had never stepped foot into the work space. The students worked purposefully, but after thirty-five minutes, they had only managed to make two cuts on their sheet of wood. The vast majority of the teams to follow would require the same level of attention and worked at a similar pace.

A key purpose of the course was to give students the opportunity to become more comfortable with tools and learn how to more accurately fabricate products. Up to this point, the students had primarily worked with rudimentary supplies, including hot glue, craft sticks, and cardboard (about which many complained), and their products had been created without a high degree of precision. Thus this first group in the fab lab, and all of those to follow, lacked basic fabrication skills. Before showing them how to use a circular saw appropriately, I was compelled to begin by demonstrating how to properly measure with accuracy and draw orthogonal lines. These were skills that the students should have already mastered in their math courses; academy lessons and activities were simply meant to reinforce students' proficiencies in areas such as this. However, due to these deficiencies, academy teachers were oftentimes faced with a dilemma. On one hand, they could devote class time to ensuring that each individual was capable of carrying out basic procedures, but this would undoubtedly eat into the time available for the core project. On the other, they could generally overlook these skills to allow sufficient opportunity for engaging with the engineering design process. In most cases, skill-building was downplayed, as this was not viewed to be a central tenet of the program.

Day 22: Base construction

The students were presented with two warm-up problems related to center-of-mass. By and large, they struggled to calculate the correct answers, with many having trouble identifying x- and y-coordinates appropriately. To mitigate this issue, Ms. Foster set up the necessary systems of equations so that the students could simply solve for an unknown variable and plug in numbers. But again, several students made no attempt to solve the problems. At a table of five students, for example, four individuals waited patiently for the fifth, a noted high-achiever, to proceed through the equations himself before making the answers available. The four unmotivated students freely and unabashedly admitted to this. Ms. Foster was not oblivious of this issue and would later summarize that the course consisted of three types of students:

1. Those who tried to solve posed problems and checked their work with classmates
2. Those who waited for others to do the work and then wrote down the answers
3. Those who did not care and did not do the work

Once working on the project, a number of teams prudently finalized their initial designs, gaining approval from Ms. Foster, who then allowed them to begin working in the fab lab. Like they had realized while creating their latest prototypes, the students who had designed bases with curved profiles were unprepared to accurately translate the curves from a paper to a physical piece of wood. Most did not know where to begin, nor were they familiar with the math term "radius of curvature." I demonstrated the necessary steps to several groups, explaining the importance of establishing a curve's point of origin and measuring its specified radius. However, some groups chose to proceed without any instruction and they simply drew freehand arcs once again. As a result, they created asymmetrically-shaped bases.

To strengthen the students' record-keeping skills, Ms. Foster emphasized the importance of logs. At the start of each period, the students were expected to note their daily goals, and at the end of class, they were to compose a three- or four-sentence report about their accomplishments, followed by a to-do list. While intended to force the students to organize their ideas and reflect upon their objectives, most viewed the task as busy work and put little thought into their writings, typically rushing through all three points at the end of each day. A common entry is shown below:

> *Goals: Learn how to calculate center of mass*
> *Progress: We finished the worksheet on mass*
> *To Do List: Calculate the center of mass of our hovercraft based on the objects*

Ms. Foster encouraged the students to expound upon their intentions and achievements, but for most, logs were an afterthought, viewed as a non-essential aspect of the project.

Day 23: Continuation of base construction

The students carried on with the assigned tasks, finishing up their center-of-mass calculations and prototype modifications before moving on to the fab lab. In some groups, teammates communicated well with one another and shared in the hands-on work. Other teams placed too much responsibility upon a single member, which tended to inhibit their progress. In one group, for example, a student had been tasked with creating the base design herself, but she was absent. Because she had failed to include any dimensions in her drawing, her teammates felt they could not proceed.

They did know that their base was to be an octagonal shape (as per the suggestion of a student who had taken the course the prior year), and I inquired as to how they could determine its dimensions. One of the students suggested that they could assume each side to be one-and-a-half feet, then outline the octagon on the wood and "see if it looks right," then make adjustments accordingly. I countered that it was possible to calculate exact lengths, and asked if they were familiar with 45°-45°-90° triangles, content they should have learned in geometry. They replied that they were currently in pre-calculus, and since they had not taken geometry for two years, they had forgotten everything related to triangles. I therefore began from a decidedly elementary level, explaining that there were 180 degrees in a triangle. I pointed out that an octagon could be divided into five equally-sized squares and four identical isosceles triangles, so the length of the triangles' hypotenuses could be relatively easily determined if the overall length of the octagon was known. I covered the steps they needed to take to determine their dimensions, and they both followed along attentively, claiming that they fully understood the procedure. I left them to complete the calculations on their own so that I could assist another group, and by the time I returned, they had outlined an octagon on their wood. But they both agreed that something was wrong.

I reviewed their work, asking pointed questions along the way, and it became more apparent that they lacked basic mathematical understanding. I had hoped that by carrying out the calculations themselves, they would gain much-needed experience. I also wanted them to realize that math could in fact be utilized to solve real problems. But they were falling severely behind schedule and, importantly, I did not want them to become discouraged on their first build day. I resumed the calculations myself, encouraging them to follow along, but ultimately determining the dimensions for them.

After class, Ms. Foster and I again discussed the course learning goals. With several weeks of experience in the course, she felt she had a much better understanding of the project. She stated that the primary course goal was for the students "to work together and build the best hovercraft that they can with the materials provided." She also noted "secondary" learning goals, which were:

a. To understand the science content that had been discussed in class
b. To learn building skills
c. To be able to carry out measurements and math calculations
d. To develop science investigation skills (e.g., "drawing conclusions from data and applying them to the project")
e. To improve teamwork skills, including task delegation

We also discussed the specific knowledge the students could be expected to attain over the remainder of the course. Coincidentally, as part of my official role in the academy, I was responsible for conducting pre- and post-tests to assess class-wide gains over a set period of time. The students would be largely engaged in construction and performance testing in the upcoming weeks, and the measureable knowledge and skills they might gain during this process were unclear. We decided that basic woodshop terminology would be appropriate, and while there appeared to be no more need for math in the project, we deemed it important to evaluate students' abilities in the subject, so two questions that had already been covered in the warm-ups were included. Lastly, although the concept of pressure had yet to be explicitly covered, three questions related to the topic were devised because it was clearly related to the project. We assumed that an opportunity to address the concept would naturally emerge.

Day 24: Preparation for Checkpoint #1 – center-of-mass

Progress checkpoints were included in the curriculum to track teams' progress, keeping students on schedule in much the same manner as would be expected in a professional workplace. Checkpoints also mitigated the potential for procrastination, an issue of which the academy leaders were well aware. An administrator addressed this topic, explaining, "Where I think teachers are fearful is that students sometimes are the best procrastinators and they're kind of going, 'Oh, at the end I've got to rush through and I've got to get all these things done.' But really if they facilitate the learning throughout and they are able to monitor where the kids' benchmarks are . . . then I think that's not a problem."

The first progress checkpoint required the students calculate the center-of-mass of their respective crafts with the fan, leaf blower, and ten-pound toolbox positioned atop their bases. To verify their calculations, they needed to then balance the crafts on a plastic bucket which was to be placed at their centers-of-mass. Ms. Foster originally intended for the students to determine these locations solely mathematically, but this created challenges for teams with bases of more complex shapes. Ms. Foster allowed these teams to bypass some of the math by having them determine the center-of-mass of their bases experimentally, significantly simplifying the process.

Midway through the period, all of the groups had finished cutting out their bases, save for one. This particular team had become bogged down trying to figure out how to accurately measure and draw the outline of their base, but they had not once asked for guidance (though I had repeatedly offered) and were largely forgotten in the chaos of the fab lab. Consequently, they were far behind schedule, and I felt obliged to intervene. I showed them exactly what they needed to do to complete their base. Yet only a few minutes later, they had changed their minds, inexplicably deciding on a new shape for their base, although this would no longer match their CAD drawing or prototype. This practice of making alterations during the building process was common across the academy, as students had become accustomed to frequently modifying their designs as they sought out improved features. But these constant alterations were in direct opposition to an important component of engineering – building a product to specification. Upon realizing that many students' creations were continuously in flux, Ms. Foster faulted herself, remarking that she had not mandated that the students establish and build to specific dimensions. She later instituted a policy that required students to complete a design change form before making major modifications, but the students largely ignored this condition and continued to build on the fly.

Taking over for the group once again, I sketched out plans on paper, explaining that they needed to determine a radius of curvature and describing the algebraic steps required to determine their point of origin. One of the students spoke up, stating that she could not follow the math and needed to review the steps more slowly. Though she had never requested help before, she revealed that she was often lost during the warm-up problems and was not able to make sense of much of the math that had been covered during the course (of the six problems on the formative assessments which required calculations, she had answered just one correctly). I reviewed the procedure once again, and while her teammates were prepared to move forward, it was clear that she still did not understand, requiring more clarification. Over the course of forty-five minutes, this team was able to make one cut and draw one arc.

Despite this student's struggles in math, she noted on the end-of-course survey that a benefit to her time in the academy was that "I learn to do better math and understand math better than in my actual math classes," an encouraging sign. Unfortunately, she also wrote, "Freshman year I really wanted to be an engineer and go to [the partnering college] that is the main reason why I join STEM but then how some STEM classes are and what engineers do that was boring to me."

Day 25: Checkpoint #1 – center-of-mass

At the beginning of class, Ms. Foster checked each group's center-of-mass calculations. Because each group's design was unique, assessing each set of calculations for accuracy would have required an extensive amount of time. Ms. Foster therefore decided to assign scores based on appearance, allowing her to grade each team's work in just a few seconds.

Two groups had yet to complete this work. A member of one of these groups claimed that her teammate had taken the calculation worksheet home to finish it on her own, but had failed to finish it. Members of the other team stated that they were unaware that any such worksheet was due, a not entirely surprising revelation considering that these students rarely paid attention when Ms. Foster covered each day's requirements. I offered this latter group some pointers, explaining that they needed to establish an origin before applying the center-of-mass equation. They reacted as if they were hearing this information for the very first time. I referred to the example problems Ms. Foster had covered in previous classes, but again, they claimed to have no recollection of these, one stating, "I'm not saying we didn't do it, I'm just saying that I don't remember them." Due to their general lack of engagement in the class, Ms. Foster chose not to provide them more help. Later, when they saw Ms. Foster assisting another group, they became upset, feeling that they were not receiving their fair share of guidance.

The groups who had completed their calculations prepared for the progress checkpoint. The circumference of the plastic bucket upon which they were required to balance their craft assemblies was large enough to provide room for error, yet challenging enough that accuracy in both their measurements and their math was necessary. The owners of those that were able to balance on the bucket cheered and high-fived each other, delighted to see their calculations come to fruition.

Once each team completed the checkpoint, they were provided the remainder of the period to continue working on their crafts. Most took advantage of the time by preparing for the next checkpoint. Others, realizing that they would not be assessed again for four more class periods, made no real effort to make more progress.

Day 26: Construction of mounts

The students worked industriously on their leaf blower and fan mounts, though their progress was slow. Their substandard construction skills continued to impede a faster advance, but more significantly, their inclination to overlook details forced them to continuously re-modify their designs. In some cases, brainstorming sessions resulted in lofty ideas that could not be constructed in a practical manner, and I attempted to steer these groups towards more easily implementable plans. Those who plunged forward without first seeking feedback were at times rebuffed by the tools themselves – bandsaw blades snapped due to improper use, jigsaw blades were bent by students attempting to drill holes with them, and one student's efforts were wasted as he attempted to sand wood with a scouring pad.

Overall, the students had become much more engaged since the construction phase began. Three key features stood out as the underlying reason for this. First of all, as opposed to the lessons that took place in the classroom – when Ms. Foster was forced to constantly reminded them to pay attention and stay on task – many teams now began working before the bell rang and needed no encouragement to remain busy throughout the ninety-minute periods. Students would later note that they overwhelmingly preferred the fab lab over that of the classroom, recommending that more classes take place in this open environment.

Second, many were developing a stronger rapport with their teammates, and while this at times led to more socializing than project work, this aspect of class was viewed quite favorably. Said one student, "I really do love working in groups and that's something I like about STEM. I'm able to hang out with my friends while we work and so it makes STEM more enjoyable. It makes me want to come to class."

And third, the autonomy they were provided project was well received by most. Ms. Foster chose not to intervene in the students' work, allowing them to manage their projects as they saw fit. Explained one student at the end of the semester, "I personally liked the level of freedom we had in this class. In other classes there's been a lot more of a teacher's watch over your shoulder a lot more."

Day 27: Unit conversions

Before continuing on with their mount assemblies, Ms. Foster presented ten basic unit conversion problems, another warm-up that consumed the first thirty minutes of class. The students, even those in upper-level math, made several fundamental errors, but with some guidance, most were able to reproduce the procedure. But not everyone. Ms. Foster spent much of the time working with a single individual who could not grasp the concept, constantly held back by his weak foundational knowledge. For example, after double-checking that, "One foot is twelve inches, right?" the student stated that one cubic foot must equal twelve cubic inches, a common misconception (it equals 1,728 cubic inches). Ms. Foster and his teammates attempted to explain the conversion procedure in a myriad of ways, and but he continuously jumped to erroneous conclusions. After some time, his teammates chose to give him the answers.

Another student, seeing no connection between unit conversions and hovercrafts, asked why they needed to learn the procedure in the first place, a question frequently asked about many of the warm-up problems and activities. In truth, there was no pragmatic application of the lesson in the project; it was simply included to strengthen the students' math abilities. Ms. Foster offered a general reason, saying, "I want you to have some number sense." The students were not satisfied by this reply.

Math continued to be a point of frustration for a large number of students, and any posed problems that included calculations were immediately met with groans. From Ms. Foster's standpoint, identifying practical ways to incorporate more math into the project was a perpetual struggle. Not only did she want to consider integrating calculations and analyses directly applicable to the project, remaining accommodating to students with a wide range of abilities was a major constraint. Although she did not believe the math content had to cater to the lowest achievers, she was concerned that overly-challenging content would hurt some students' attitudes. She reiterated that a central aspect of the program was accessibility, that it was necessary to ensure that all types of students could benefit by participating in the classes. Under the current academy conditions, she found this to be largely true. She explained, "I guess the way I appease myself [laughs] is the idea that okay, you have students at different levels all working on kind of the same project, and you can find ways of trying to incorporate this content, this math, this kind of extra stuff. And if like the lowest-level kids only get exposure and a little bit of practice then that's good for them. And the kids in the middle get a little bit more from it. And the kids who are really psyched on it and really pay attention and really think about it, they kind of grab on more. . . . And that's possible with the projects, which is nice because everyone kind of has access to them. They're doable."

Day 28: Continuation of mounts

The entire period was devoted to building. The majority of the students were wholly engaged in the work, and they were gradually becoming more accustomed to handling the tools. Their craftsmanship depended largely on the degree of attention they were willing to commit to their projects, with some students making precise measurements and cuts based on detailed plans, while others gave little forethought, choosing to use crayons or fat-tipped markers to sketch rough outlines of their parts, resulting in wavy edges and split wood. The consequences were more than aesthetic; detail-oriented students were more likely to secure a tighter connection between their leaf blower and base, and they typically encountered fewer durability issues. Students who did not prioritize quality construction were more apt to face torn skirts, weak joints, and broken fasteners, all of which required time away from optimizing their designs.

Prior to designing and fabricating their mounts, the teams were required to select one of three available fans to generate propulsion. One fan generated a force about three times stronger than the others, but Ms. Foster chose not to announce this, anticipating that the students would at the very least conduct a side-by-side comparison of the three before settling on the most powerful option. But just five of the teams did this, all of whom subsequently selected the strongest fan. Three other teams chose to use this fan as well for various reasons. One group reasoned that the fan would be easy to mount onto their base (a somewhat valid justification) while another wanted to balance out the weight of the driver, and thus based the decision on which fan was heaviest (a poor justification since overall weight inhibited performance). A student from a third group chose the fan because it "looked powerful," though he and his teammates had yet to actually turn it on.

The five teams that did not select this fan would later complain that their fans were much too weak, as if they themselves were not at fault. Three of these teams selected a standard twenty-inch box fan, claiming that it would be the easiest to mount to their bases. Though an important consideration, they failed to realize that this fan was quite weak, and thus failed to think critically in a manner representative of an engineer.

Likewise, the remaining two groups chose to use the third available fan, the smallest of those provided. One student justified his team's decision by pointing out that it was the lightest, again an important consideration, but the benefit of this was negligible as compared to the correlating loss in propulsion. The other group asserted that this small fan was in fact the strongest, an erroneous and unverified claim.

Ms. Foster decided not to intervene in this decision-making process. By allowing the students to realize their own shortcomings, the students were being compelled to realize the importance of weighing all available evidence before making decisions, and it was hoped they would assume more responsibility for the work. While this did transpire in some cases, the poor choices made during the design phase had severe repercussions later in the project. This unfortunately led to frustrations and, ultimately, negative experiences in engineering.

Day 29: Checkpoint #2 – leaf blower and fan mounts

Before class, Ms. Foster mentioned the pre-test and upcoming post-test, specifically the content related to pressure, asking if there was any way to incorporate this content into the project in a practical manner. She had struggled to find a natural segue. I suggested a few weak ideas for doing so, but none were critical to the project. We decided to revisit the matter later. It seemed that the motivation for addressing pressure at this point was strictly for the sake of the post-test.

The students were required to show Ms. Foster the mounts they had constructed in order to pass the second progress checkpoint. With the impending deadline, the students worked hastily to receive full credit for their efforts, and all but one group were able to complete the tasks by the end of the day. Several mounts were well-constructed, planned out beforehand and strongly connected to the base, securing the blowers and fans with innovative latches and other types of fasteners. Conversely, several were shoddily built – comprised of a bevy of odd materials including bungee cords, rubber bands, duct tape, string and cable ties – constructed in a rush to stay on schedule and meet the minimum checkpoint requirements. These teams received full credit.

Day 30: Skirt design

To generate sound skirt designs, several groups referred back to data that had been collected during the prototyping phase of the project. Though this experimental data was not always conclusive, an effort was made to identify the most effective design features. Data related to the distance that a craft hovered above the floor, called the "skirt depth," was the most convincing, the trend being that craft performance increased when skirt depth decreased. The more meticulous groups typically fashioned skirts that aligned with this finding.

To fashion their skirts, each group had received a standard 6'-by-8' blue tarpaulin, the dimensions having been provided weeks earlier. Once these tarps were unpackaged, two groups were immediately forced modify their designs since their base lengths were also eight feet, prohibiting any slack in the skirt once attached to the base perimeter. Similar to the fan-selection oversights, Ms. Foster was well aware that these groups would encounter this issue, but she again chose not to intervene. She reasoned that their errors would compel them to recognize the importance of detailed planning, an outcome that was not observed. Instead, the students expressed frustrations, one of them complaining, "Engineering is so hard!"

Day 31: Skirt testing

As the students continued to create and attach their skirts, I asked an individual from each group, "What skirt depth did your team design for? Why?" The question was intended to assess the students' reasoning behind their designs, but the striking detail that emerged was that many individuals were completely ignorant of this essential parameter. Eight of the thirteen students who were questioned were unable to state the depth, much less provide justification. These students deferred to teammates instead, revealing that their groups were not collaborating as expected.

Students who did provide justifications, both those directly questioned as well as those covering for teammates, most commonly cited the data sets from the prototype experiments as expected. But several were unable to offer any explicit reasoning behind their decisions. One such student, for example, answered, "We're not really sure, it just seemed good." Another group, which had originally designed for a two-inch skirt depth, suddenly changed it to six inches because they "felt like" a larger dimension would work better, providing no further defense. Yet regardless of their reasoning, the reality was that achieving lift did not necessitate a deep understanding of any fundamental concepts. So long as a team properly sealed their skirt and secured the leaf blower to their base, they were likely to achieve success.

Yet one group, despite putting in a great deal of effort, was unable to make any progress towards the checkpoint and finally asked for guidance. I offered them hints to get them on the right track, but this subtle prodding provided them no benefit. After a long while, I reluctantly decided to explicitly show the next step the needed to take. Shortly thereafter, part of their leaf blower mount disconnected from the base because they had relied heavily on duct tape to make the attachment. They were forced to resolve this newly-discovered connection issue, setting them even further behind schedule. Wrote one of these students in her log, "Our greatest concern for the final testing is not being able to finish on time."

Worried that the students were becoming overly frustrated with the project, I discussed this group's struggles with Ms. Foster after class, explaining that they did not seem capable of problem solving on their own. Ms. Foster believed that in their case, handing them the solution was probably reasonable. She was pleased that these students were at least trying, noting she was rather dissatisfied with the efforts of others. She had been stressed about the remainder of the course, concerned that she had not provided enough time in the fab lab. But after recognizing that several teams regularly stopped working with twenty minutes or more left in class, she stated that the fault would lie with the students if they were unable to finish.

Day 32: Continuation of skirt testing

Once teams achieved lift, they would immediately attach their fan, expecting to see their craft accelerate down the hallway. This did not happen, and complaints were voiced, infrequently at first, then more regularly. A few individuals, who spoke with students who had taken the course the previous year, reported back that those crafts had not worked well either. Still, plenty of work days remained and Ms. Foster stuck with her hands-off approach, providing an opportunity for the students to discover a solution themselves.

In light of these complaints, Ms. Foster conducted a quick internet search and found that fans used for do-it-yourself hovercrafts typically provided airflow in the range of 400-1,000 cubic feet per minute; the strongest fan offered in the course was less than 100. Ms. Foster noted that although the students were enjoying the project, it would be "really sucky" and a "bummer" if they were unable to propel the crafts forward simply because the fans were too weak. In light of this new information, Ms. Foster said, "I feel like I'm lying to them."

As students continued to run into the propulsion roadblock, the number of requests for help grew rapidly. Several individuals became noticeably upset and complained that the amount of guidance was inadequate. Realizing that Ms. Foster was reluctant to offer assistance, they began to pester me for hints, insisting that I was maliciously withholding information. Yet many of these teams had not made any real attempts at identifying a working solution. They tinkered briefly without success, believing that if an immediate solution was not readily available, the teacher was consequentially responsible for provide alternatives. A team unable to overcome a balance issue, for example, insisted that I provide them suggestions for resolving the problem. I asked, "So you want me to give you an answer?"

"No," one of them replied, "We want a list of ideas so that we can pick one." This approach towards problem solving did not foster critical thinking.

The students were capable of addressing this balance issue on their own, but they were behind schedule, frustrated, and simply wanted to move past the problem without expending any more class time. The issue was caused by recent modifications they had made to their base, after which Ms. Foster had instructed them to redo their center-of-mass calculations to provide a better idea as to where their driver should sit. But they were reluctant to do so, having excessively struggled with the first set of calculations. One complained, "This is the hardest project I've ever done."

Day 33: Checkpoint #3 – lift

All of the teams were able to pass the third progress checkpoint with little trouble. Yet the next checkpoint – propulsion – was a much greater challenge, as many had already realized. The majority of the students were hard at work for the duration of the class, brainstorming for possible design improvements and implementing agreed-upon ideas. However, since they had three more classes before the upcoming assessment, several individuals became complacent, accomplishing little for the day. By this point in the project, Ms. Foster had largely ceased to encourage these students to stay on task.

While I fielded questions and assisted with construction, I made a point to ask one individual in each group, “Are the holes in your skirt the same as in your prototype?” Overall, the students responded confidently, much more aware of their teams’ designs than others had previously demonstrated. Several knew the exact diameters and locations of their holes. A few did fail to take their prototypes into consideration when creating their skirts, one such student saying, “No, we really didn’t think about that.”

Towards the end of the period, a group achieved the breakthrough needed – their craft was able to propel itself forward. This group had succeeded by strictly limiting the depth of their skirt, as suggested by the collected prototype data. The news quickly spread throughout the class; now that the class was aware that propulsion was possible, the number of complaints decreased.

Day 34: Problem solving for propulsion

Now that they were three full periods ahead of schedule, the team which had achieved forward motion the previous day spent a large portion of this class and the next playing Hacky Sack. When I questioned Ms. Foster as to how they would be assessed in light of their actions, she replied, “This ‘flows’ more into the participation grade, which I haven’t been noting. I don’t think that I should punish a group for figuring it out early. And I can’t blame them for not working and not wanting to ruin it.”

As Ms. Foster alluded, a major limitation of the hovercraft project was that the materials did not lend themselves to endless iterations. As opposed to other academy courses which allowed students to make numerous changes without penalty, those in the course under study were often afraid to drastically alter their designs, particularly their bases and skirts. Doing so was not trivial. Due in large part to the students’ lack of fabrication experience, modifications often consumed an extensive amount of time, and more significantly, the changes may have been non-reversible. Ms. Foster mentioned that she wished the students would take more risks, but from the students’ perspective, creative ideas did not necessarily translate into quality performance. And, since they were not assessed on their creativity, but on their products’ ability to perform, there was no external motivation to generate unique ideas.

Day 35: Continuation of problem solving for propulsion

Aside from seeking guidance and taking note of successfully-functioning crafts in the classroom, many groups relied heavily on a process of trial-and-error. Some put a great deal of thought into this process, progressing through a series of iterations in much the same way as professionals would do so. One team, for example, made single incremental changes, careful to alter only one variable at a time, and measured the remaining frictional force of their craft by utilizing a spring scale (see Figure 13). The scale's recorded readings offered insight into the effects of their modifications, thereby allowing them to base future design decisions on sound reasoning.

Figure 13: Using a spring scale to measure friction

The groups that engaged in detailed practices such as this were in the minority. More commonly, students made adjustment after adjustment hoping to realize a radical performance improvement that would lead them towards a clear solution pathway. Because they evaluated each iteration by feel and intuition rather than any quantitative method, they had little justification to support their changes. Oftentimes, these iterations offered no observable changes, and it was not uncommon for teams to devote hours of class time to wholly unproductive efforts, both in terms of project progress as well as attainment of knowledge or skills. A student who practiced this mode of problem solving, for instance, frustrated that her team had failed to make any advances for several periods, said in exasperation, "We're making bigger holes because we don't know what else to do."

Meanwhile, a team which had been working with clear design intentions, tending to details and devoting time to quality craftsmanship, saw their efforts pay off as their craft began moving forward slowly along the fab lab floor. They began to cheer and high five, one exclaiming, "This is great!" They immediately began working towards the final checkpoint.

Day 36: Checkpoint #4 – propulsion

With the remaining project days running out, it became apparent that an opportunity to address the concept of pressure would not naturally emerge as hoped. The students had consequently gained no concrete knowledge on this topic, forcing Ms. Foster to acknowledge that it would need to be covered by traditional means, through direct instruction and a worksheet. She opened the class with a simple calculation they could easily handle, then segued into a brief lecture. She presented three slides to discuss the definition of pressure and how it is calculated, the various applicable units of measurement, and a short example problem. The entirety of the presentation lasted eight minutes, yet only about half of the students paid attention.

Ms. Foster passed out a worksheet that contained sample problems about pressure, providing an opportunity for students to gain a better understanding of the concept. She announced that it would be due in a week. The students were not pleased with this new assignment, which they perceived as being tacked on to the end of the project for no apparent reason. A student in the back of the class – and out of Ms. Foster's earshot – complained, "What the f---? C'mon man." His neighbor put his hands up in frustration and said to no one in particular, "Why?"

It is noteworthy that at the end of the semester, when students were asked about what they learned in the course, pressure was one of the most prominently discussed topics. But several individuals were critical of the way in which it was presented since there was no application of the delivered content. One such student said, ". . . she talked about physics, like the pressure stuff and the hovercraft kind of separately. And I feel like she should have brought them together. Like we should've been doing like the pressure to figure out how to build our hovercraft instead of just like pressure worksheets and then building our hovercraft."

Others asserted that the worksheet was much too difficult and they learned little from it. Yet the problems simply required basic arithmetic and application of the pressure formula (Pressure = Force/Area), and little could be done to simplify them further. Once the worksheets were submitted, Ms. Foster graded very leniently, yet the average score was 72%. Aside from the group-based initial design worksheet which averaged 70% because so few groups completed the requisite CAD drawings, the pressure and center-of-mass worksheets were the semester's two lowest-scoring assignments. Notably, these were the only two assignments that required individuals to provide exact solutions to posed problems.

Before conducting the fourth checkpoint, Ms. Foster made a point to announce that she had noticed many students off task on a regular basis, that they were not taking full advantage of the allotted time to improve their devices. Yet once in the fab lab, it immediately became apparent that the students would not heed her advice. Because there were only two leaf blowers and three fans, the queue to use the shared equipment became increasingly longer as the final days approached. Since most teams had become overly reliant on the trial-and-error process, they believed their only path to success was through a cyclical process of incrementally testing and modifying, meaning they needed constant access to the equipment. Many believed there was little they could do otherwise and therefore cast blame on the lack of resources.

Four of the thirteen crafts were able to pass the propulsion checkpoint. Ms. Foster decided to assign grades to the others based on a sliding scale relative to the measured frictional force remaining. Several groups on the cusp of success, with less than two pounds of friction preventing them from forward motion, earned the equivalent of a B. Those with higher levels of remaining friction were assigned lower grades.

Day 37: Second-to-last build day

Now that the majority of groups were officially behind schedule, students sought out more guidance and rushed to test as many options as possible in hopes that they would discover a viable solution. Students from two groups which had fared remarkably poorly on the previous checkpoint asked for help. These students' efforts were not lacking, they simply failed to identify the design changes necessary for improved performance. To explicitly demonstrate a feature of their respective skirts that significantly hampered them, I referred them to another group's craft, pointing out the manner in which air was evenly distributed underneath the skirt. In both of their own skirts, they had placed holes along the sidewalls, directing airflow laterally rather than providing an air cushion between the skirt and floor. I asked eliciting questions to help guide them, but the students were unable to discern this major shortcoming. With time running out and their frustrations building, I decided to point out their flaws and directly ushered them towards a path of improvement, a decision that conflicted with the guidance strategy that Ms. Foster had been employing.

After these groups had taped over the unwanted holes (see Figure 14 for an example), they re-tested their crafts to observe the effect of the modifications. The crafts were still unable to move forward, but the remaining frictional force, which was measured at 7.5 pounds on both crafts, had dropped to 3.5 pounds and one pound, respectively. While these developments helped raise their spirits, the guidance they received did not help improve their critical thinking skills.

Figure 14: Skirt holes patched with duct tape

Shortly thereafter, a well-performing group became the first to create a successful steering mechanism. Upon seeing this new breakthrough, a student from a group I had been working with complained, “I hate my life! Why can’t ours do that?!” A fellow teammate later griped, “I hate this class. I actually like this class, but I’d like it a lot more if ours worked.”

While most of the underperforming groups focused on modifying the holes on the bottom of their skirts, enlarging them and patching them in hopes that a functional configuration would soon emerge, one group took a different approach. Like the others, this group had been solely fixated on the size and number of holes in their skirt for the past several days, with little to show for their efforts. After noticing that a successfully-working craft had made use of excess airflow from the leaf blower by allowing much of it to escape out the back of the skirt, thereby providing additional propulsion, they decided to try a similar idea. Before doing so, I asked them to check the frictional force remaining with their current design, which they measured to be three pounds. They then cut short lengths of plastic piping and inserted them through the rear of their skirt, gluing them to the underside of their base (see Figure 15). When they were prepared to test again, they inexplicably decided to use a different fan.

Figure 15: Piping added to the back of a craft to improve propulsion

If their craft performed better or worse, I asked the students, how would they know if this was due to the plastic tubes, the different fan, or some combination of the two? They were not quite sure how to respond, and their quizzical expressions obliged me to once again cover the importance of altering just one variable at a time between tests. After re-mounting their original fan, the students measured the remaining frictional force to be one pound, meaning that the additional propulsive force amounted to two pounds. I asked the students to explain what was happening. Their answers were:

1. Because the craft was not moving anywhere, there was clearly no propulsive force, so the lower measurement must be due to less friction; this was perhaps caused by less pressure in the skirt, making it looser and not as hard against the ground
2. It was unclear as to whether the added pipes were adding propulsion or reducing friction
3. The pipes were obviously aiding in propulsion

Each of the students came to the conclusion that more pipes should be added, and while this was in response to the improvement in performance, just one of the three (student #3) demonstrated comprehension of the situation. Had they been left to construct new knowledge on their own, it is likely that they would have come away from this recent development with very different understandings. This scenario, and many others like it, revealed the importance of teacher intervention to ensure students made proper sense of their observations.

Yet doing so was oftentimes a painstakingly slow process, one which required intense devotion to a single group (or even a single student).

Day 38: Final build day

Most of the groups worked feverishly to finalize their crafts before the final checkpoint. Several inched closer and closer to achieving functionality while those who had already achieved this status accomplished little. Ms. Foster suggested that they begin working on their presentations, but knowing these would not be due for several more class periods, the students resisted, choosing instead to socialize and play on their phones.

Day 39: Checkpoint #5 – steering

The fifth and final progress checkpoint was designed to evaluate the crafts' steering mechanisms. Because so few teams had demonstrated an ability to travel forward, they were first required to re-attempt the previous checkpoint, then make an effort to maneuver their devices around three cones spread out over fifteen feet in the hallway. Ms. Foster noted that she would be "super liberal" with grades, meaning that their maneuverability did not have to be perfect, she simply wanted to see that they were able to turn left and right. She announced that the crafts should already be finished, that they needed to present a finished product, and they would have no additional time to make further modifications. As soon as the students entered the fab lab, however, they scurried about, making last-ditch efforts to generate presentable products. A group that had struggled to achieve propulsion, had subsequently ignored the steering aspect of the project. They began cutting out cardboard "flaps" (see Figure 16) that would be held along the sides of their fan to act as rudders, a course of action that accomplished nothing and prompted Ms. Foster to record in her notes of their performance, "Worst turning rudder system ever, does not work."

The overall results were less than satisfactory. Some teams' craftsmanship was so poor that several crafts fell apart during the test. The very materials the students had been cautioned about using were now causing havoc – rubber bands snapped, taped joints separated, strings and cable ties broke, and mounts which had been glued and re-glued countless times failed once again. Some underperforming students argued that their substandard results were indeed adequate, offering innumerable excuses as to why their crafts did not work as expected. Ms. Foster, in turn, became more and more frustrated and told the students that they needed to demonstrate achievement rather than give excuses. In truth, the hallway tile had recently been waxed, resulting in a slight increase in friction, and the students were understandably upset about this. But many attempted to cast all of the blame upon this single circumstance, conveniently overlooking their countless hours of unproductive class time. Ms. Foster did not as easily forget this.

Figure 16: A team's last-ditch effort for steering – cardboard "flaps"

Seven of the thirteen groups were able to demonstrate an ability to turn, though three of these were only able to do so with no driver on board, and just four were able to move forward, the same number as the previous checkpoint. The atmosphere during these final performance tests, normally a time of excitement in the academy, was quite despondent. Students were frustrated. Ms. Foster was frustrated. The vast majority of her notes were negative, such as "fan fell off," "wood broke for fan attachment," "super unsteady," and "things falling apart." And yet the average checkpoint score was 90%.

In their final logs of the course, Ms. Foster required that each student complete an eight-sentence reflection on the project, including a summary of their final performance, a comparison to other groups, and a statement of modifications they would make if given the chance to do so. While the intent of the assignment was to compel the students to reflect upon the strengths and weaknesses of their projects in preparation for their upcoming presentations, most students provided very cursory accounts, with little demonstration of knowledge gained. A reflection somewhat representative of the class is shown below:

> *Overall our final test didn't do to[o] bad. The force it took to move our hovercraft ended at 4 pounds. This is about average compared to other groups, some did better and some did worse. However our hovercraft wasn't able to turn without the driver. Most people were able to turn their hovercraft in the class. If we were able to start over we would fix*

the skirt and use a different fan. The fan we used didn't give us enough force and having more holes in the skirt will give us less friction. That is why overall our hovercraft performed around average compared to the class.

Much like the atmosphere in the fab lab, the students' reflections were quite negative, with many pointing to conditions out of their control or rationalizing that they had in fact done satisfactorily, as compared to their classmates. Examples of these views are shown below:

> *If done differently I would start the project earlier in the semester as many groups started running into unexpected difficulties. I wish our group did better than we did in this class because this sounded like an awesome class, and it only turned out to be an alright class.*
>
> *Compared to other groups ours did about average on final test day. A lot of groups weren't able to get theirs to move at all.*
>
> *. . . in the future, serious consideration should be given to the unfortunate circumstances that presented themselves to certain groups.*

As they had been doing throughout the semester, students seldom expounded upon the reasons behind their failures, demonstrating a lack of understanding of the physical setting in which they had been participating. More often, they offered a description of their observations and provided overly vague speculations about ways to improve their crafts, as shown in the examples below:

> *I think we could have came up with a way to better our propulsion. I am not sure how we could have done it, but if we spent more time contemplating the fact I am sure that we would have been able to find a way.*
>
> *If we were to have the opportunity to finish our project to make it better, I would keep adding more holes till it worked.*
>
> *Our group did not do very well in this class. We struggled a lot with getting our hovercraft to do what we wanted it [to do]. Our project lifted off the ground but it didn't move forward or turn.*
>
> *We had all of the elements to complete the checkpoint they just didn't work together to make it happen. We had the fan attached and working as well as the leaf blower. We had thrust and a steering device it just didn't work. We didn't have enough thrust to move us with the amount of weight we had.*

Day 40: Slideshow presentation preparation

Students were allotted the entire ninety minutes to prepare their slideshow presentations. Most teams chose to delegate specific topics to specific team members so that each individual could prepare the information that he or she would be presenting. In other groups, a single individual completed the majority of the work, though this was not always due to a lack of motivation from teammates. One student complained that he had been purposely blocked him from editing the slides, to which his teammate responded, "I don't want [him] to mess anything up."

These types of issues with group work were a common source of frustration among Ms. Foster and her colleagues. To cultivate a learner-centered environment, the teachers were inclined to let the teams work through projects themselves, placing the responsibility of problem resolution squarely on the students' shoulders, an approach that applied to teamwork as well. Yet the outcomes of this strategy did not always transpire as envisioned, illustrated in the following teacher's comments: "There's the person who will let everybody else do the work for them and there's the person that will want to try to do the work for everybody else because they don't trust the group to do well enough."

Days 41 & 42: Slideshow presentations

The development of quality presentation skills was stressed in the academy, and at the end of every semester, students were required to showcase their projects in front of their classmates. Due to this experience, most of the students had become more comfortable with public speaking and were able to articulate their thoughts fairly well.

Several classes prior to their presentations, Ms. Foster had provided the students with a rubric so that they knew exactly which points to cover. Unfortunately, they overlooked many of these points due to a lack of attention to detail – a weakness that had hampered their progress throughout the project – dropping most of their scores. For example, the rubric called for a budget sheet listing the additional supplies that the students had incorporated into their hovercrafts, a requirement that only five groups addressed. The rubric also mandated that the students include a table or graph in their slides. Just two groups did so.

While much of the course had been upbeat – the students had truly enjoyed the opportunity to work freely in the fab lab – due to the many failures on the final two checkpoints, a large number of students were clearly unenthusiastic about presenting their work. One student captured this palpable lack of excitement by opening his group's presentation with, "The whole thing was just a sham and didn't go like we hoped." Another stated, ""We didn't expect it to pass all the way, but we expected it to do better than it did."

Several individuals took to finger-pointing, declaring that the cause of their problems was due to a lack of build time, a poor connection between the prototypes and the full-size crafts, a constantly absent teammate, or a lack of tools. For example, a student stated, "With an extra tarp, we would have been more bold and done a lot more experiments." Another said, "There was a lot of sitting around because we were always waiting for something, the leaf blower or the fan, and so we really didn't know what to do."

Yet like their written reflections, the students seldom drew upon any conceptual understandings to identify the root cause of their shortcomings. Instead of addressing the underlying fundamentals of the project, they frequently conceded that they progressed through the decision-making process with little reasoning upon which to base their judgments. One student, for instance, explained that "we didn't really know what would work" for her group's skirt design, so she and her teammates "started cutting a bunch of holes in it."

Two groups explicitly talked about resorting to a trial-and-error process because they were out of other options. A student from one of these groups acknowledged, "For about three class periods, that's all we did, just add more holes and see what it did." Added a student said during a following presentation, "We did the same thing as [his] group and were just guessing where to put the holes. And by the time we had gotten to the final checkpoint, we had made too many holes and it didn't work." (See Figure 17 for an example of this strategy.)

Figure 17: Bottom of a skirt created by a team reliant on trial-and-error

A few groups even acknowledged they could have worked a bit harder during the course. When discussing ways they could have improved their projects, students listed statements on their slides to this effect, including, "Use time more effectively," "Work more efficiently," and "[be] 100% confident in our ideas, Better planning, Time management, More testing."

The presentations were designed to provide students an opportunity to disclose the knowledge they had gained while participating in the project, but like their written reflections, they typically provided a general overview of their work, with no real insight into their decision-making processes. Accordingly, Ms. Foster graded them on whether or not they addressed each of the points on the rubric, not how well they demonstrated their understandings, as this would have been quite subjective, requiring an extensive number of inferences to be made.

Day 43: Post-test

A post-test identical to the pre-test given seven weeks prior was distributed at the beginning of class. Students made marked improvements on all of the questions, a summary of which is shown in Table 14.

Table 14: Percentage of students answering correctly on the pre- and post-tests

Question description	*Pre-test*	*Post-test*
1. Identify a "circular saw"	53%	66%
2. Identify a "bandsaw"	50%	58%
3. Identify a "sawhorse"	6%	53%
4. Identify a "jigsaw"	69%	82%
5. Define "pressure"	25%	61%
6. Identify appropriate units for pressure	28%	50%
7. Convert 5 m^3 to cm^3	17%	29%
8. Set up a proportion to calculate the weight of a circular base	61%	71%
9. Apply the pressure formula	17%	42%
Class average	*36%*	*57%*

Aside from the first four questions in which the students were simply expected to identify various tools used in the fab lab, no concepts related to the remaining questions were applied during the project. Rather, these topics were presented by manner of direct instruction, and thus these improvements must be attributed to students' exposure to these ideas via warm-ups, lectures, and worksheets. Had this content been more critical to the project and incorporated in such a way that the students were required to master it in order to construct a successful device, then student progress could have been attributed to the project-based model, and much higher gains may have indeed transpired. But practicality dictated otherwise, as even in retrospect, there were few procedures or conceptual understandings that every group encountered during the hands-on work, and thus little to be assessed by traditional means.

Day 44: Poster presentations

The students' final assignment required them to exhibit the work they had completed over the course of the project on a display board, complete with CAD drawings of their prototypes and final products, the calculations they had used, a budgeted list of materials used, their performance results, and any future modifications they would make. Like the slideshow presentations, the poster session was designed to act as an authentic assessment, providing the students an opportunity to experience an aspect of engineering that they might carry out as college students or professionals.

Again, the project descriptions were cursory, with little to no explanations as to how the hovercrafts actually worked. For example, under a heading titled "Device Performance," a group displayed the following accounts:

> *Because our device was not able to move forward the steering checkpoint was not acquired as well. We performed poorly because we were not about to move forward therefore we were not able to steer. However, without the driver our rudders (steering system) was very successful and our hovercraft was able to maneuver easily and turn. Overall the device performance for our hovercraft was not a fail but not the most successful.*
>
> *Leaf blower blows air through a hole in the board into the tarp skirt*
> *Holes make air pocket under skirt to levitate hovercraft*
> *PVC pipe and box fan propel hovercraft forward*
> *Tool box and [Student] help balance the center of mass and control hovercraft*
> *Cardboard rudders direct airflow to turn hovercraft.*
>
> *Leaf Blower → Blows Air → Inflating Skirt*
> *Fan → Blows Air → Propels Craft*
> *Lazy Susan → String Stirring [steering] → Rotation*

From these descriptions, there was little evidence to accurately assess the students' understandings of their physical products, again leaving Ms. Foster to assign them credit if they simply addressed each point of the rubric, regardless of the soundness of their explanations. The same was true in the "future design modifications" of each team's poster, as shown in the following examples:

Group A:
- *Make skirt tighter*
- *Less holes*
- *Make the board shorter from the start*
- *Not use Zip Ties*
- *Release pressure from the top*
- *Start with better fan*

Group B:
- *Attach the Skirt as securely as possible*
- *Make sure the skirt fits perfectly*
- *Switch out maneuvering device to a rudder system*
- *Take some extra time to craft everything well*
- *Make the board smaller*
- *Make sure the fan propels us forward or find another way*
- *Have a lighter person in the group*
- *Do more background research*
  - *Different types of skirts, hovercrafts, maneuvering devices*

Group C:

> *One thing we would like to change is the weight of our hovercraft. We would greatly decrease the size of the deck and we would be more aware of the extra weight we were adding with construction. We would also slightly change the skirt design. Instead of cutting a large hole in the skirt, we would cut one long strip and wrap it around the perimeter of the deck. Stability was also an issue, so we would add a chair to prevent the driver from moving around.*

These modifications may have in fact led to better performance, but there was little support as to why this may have been true. Clearly, the students had become accustomed to making claims without evidence in their previous projects, a non-disciplinary practice that had been carried through into this course. Without this evidence, evaluating the knowledge they had attained was impractical by such authentic measures.

CHAPTER V

SAMPLE STUDENT PROFILES

The following profiles are intended to offer examples of individual experiences in the course. Four students were selected for in-depth investigation, each possessing distinct abilities, backgrounds, and motivations. Each of the students perceived the course features in a unique manner, influencing their classroom actions and subsequent levels of achievement. The students' progressions through the course, along with their personal reflections on their experiences within the academy, offer extensive insight into the learning model.

It is important to note that no individual who was representative of the class's unmotivated students was not profiled. While including such a student was intended, potential candidates did not often provide genuine or insightful direct input, as they were more apt to conceal their poor behavior and give themselves more credit than was deserved. However, some direct input from these types of individuals are included in the following sections, specifically those who served as teammates of the students profiled.

"Cassandra"

Cassandra was a mature, well-organized student with a higher-than-average work ethic, reflected by her cumulative 3.6 high school GPA. She had performed similarly well in the academy, attaining a slightly higher 3.8 GPA in the five STEM courses she had completed, and she was regarded by her peers to be a very capable teammate. She came to class prepared, asked clarifying questions when in doubt, and fully participated in discussions. She was one of the best public speakers (if not the best) of all junior-level academy students, possessing a rather large vocabulary and natural ability to vocally articulate her thoughts.

Motivation

Cassandra spent her freshman year at a nearby high school which featured an International Baccalaureate program. She half-jokingly mentioned the allure of a free laptop computer drew her in to the academy (she did come from a family of low socioeconomic status), but Cassandra's fundamental reason for transferring was grounded in her belief that a STEM-focused education would provide her better preparation for a career in medicine, a field she planned to pursue in college. Two years into the academy, she was fairly dissatisfied with her decision to enroll. She had struggled to find a true purpose in the academy, commenting, "At this point I feel like it would just be background knowledge for me to revert back to. I don't know, with certain projects, I feel like they're not really applicable to life."

When she initially entered the program, she expected to be immersed in science content on a daily basis, helping her to build a foundational knowledge base that would readily apply to the medical field. She did not anticipate the high concentration of hands-on projects and felt that she had not acquired a substantial amount of useful information. She explained, "The only class that did meet my expectations was the biomedical engineering class. And even with that, I thought it was just more, I don't know, just more engineering-wise. It wasn't very science-based as I thought it would be." She later joked, "There's barely any bio . . . other than the word 'microscopic.'"

Rather than focusing on the "E", she believed all STEM areas should have been evenly represented. She stated, "I would like more variation among classes . . . basically the core STEM classes that you have to take, it's the same class, just a different project. I feel like content-wise it's the same so more variation among that [would be nice]." And yet, while several of her friends decided to drop out of the academy due to their dissatisfaction with the hands-on work – "They're like, 'I can't build stuff,'" she said – Cassandra had chosen to remain. Yet her decision to complete the academy requirements was spurred more by a desire to supplement her resume than any real interest in the coursework. Looking back, she said, "I still would have joined because it does sound appealing diploma-wise and to colleges. But I don't know, sticking with it is just kind of 'ehh' now because it's not very science-based I guess. It's just more technology-based and engineering-based."

Cassandra's lack of interest was not a symptom of overly challenging subject matter – she did not find STEM courses to be difficult and she was able to understand the basic physics behind hovercrafts. And while some of her dissatisfaction could be attributed to her general indifference towards engineering and a desire for more medical-related content, the most telling reason behind her discontent stemmed from a disconnect between the presented material and the hands-on work. Cassandra simply viewed the material as extraneous to the project, and therefore not worthy of coverage. In the hovercraft course for instance, she saw no reason for the instruction to delve into concepts such as airfoils and buoyancy since flying and hovering were, from her perspective, completely different. Reflecting back on the lectures about flight, she said, "I mean it did introduce us to transportation devices, but overall, we could have done that in a slide, talking about cars can transport us, airplanes can transport us." Somewhat ironically, though she pined for more science content, she would have preferred to have scrapped the vast majority of the lecture material.

Nor was she simply interested in hands-on work, as she viewed the introductory activities of each course in an equally critical light. In recalling a previous course, Cassandra noted, "I know in my robotics class we did an egg-drop project which was super irrelevant to us making robots. I didn't see how it applied and it wasted a good week of school." She spoke similarly of the hovercraft course, noting that the paper airplane and ground effect craft activities "did drag a bit." Her expectation for the course was merely "to learn how to make a hovercraft." The assessment structure served only to support Cassandra's belief that course content provided little purpose, as the focus on product performance and presentations de-emphasized factual knowledge. Consequently, not only was there no intrinsic motivation for her to learn the material (building a better product), there was likewise no extrinsic motivation (grades).

One feature of the hovercraft course that did motivate Cassandra was the opportunity to work in the fabrication laboratory. She explained, "I liked that we were down in the fab lab and everyone was working hard and you could look around and you could bounce to other groups and you could see their progress. I liked it a lot. . . . It makes you feel more engaged."

It is noteworthy that Cassandra preferred this type atmosphere over that of the classroom *even though she had no interest in fabrication.* Whereas in the classroom she participated in discussions and activities, she was much less productive in the fab lab because she believed power tools were "scary." Because the other female in her team was similarly intimidated by the tools, Cassandra allowed her team's only male to complete the vast majority of the physical labor (coincidentally, in the only other group comprised of two females and one male, the females also said they were "scared" to use the tools and deferred to the male). Still, like many of her classmates, she wanted to begin the building process much sooner in the semester, listing one of her favorite parts of the course as, "Finally getting to build." From responses such as this, it was clear that even for those students predisposed towards traditional learning, the appeal of an open, non-traditional work environment was much preferred.

Collaboration

Cassandra enjoyed working in groups, stating that teammates who worked together were more capable of creating successful projects. She also believed that teammates were incredibly important in the academy courses, and wrote that the best teammates were those who were "always working hard and not just slacking off" as well as "competitive and driven to make and finish a great product." And while Cassandra remained relatively engaged throughout the semester, she appeared at times to be overly reliant upon her teammates, seemingly unable to take the lead on individual tasks. Her comments about group work help support this view to a degree: "You can always come to a consensus with someone, and it just works. Like I've never had anything that has completely failed because there was always two other people or three other people to kind of help pull you along if you are falling a bit behind. And vice versa."

In the initial stages of the project, Cassandra's team progressed well. In fact, her group was the very first to begin working in the fab lab since they had completed the prerequisite design tasks so efficiently. She wrote that she and her teammates "always manage to come to a fair consensus of what to do," and that, "We all contribute ideas and work together to complete and succeed on assignments." The truth was, however, that the team advanced through task delegation; Cassandra and her teammate "Stacy" completed the necessary paper-based work while the third team member, "David," was responsible for the hands-on work and CAD drawings. Consequently, they failed to gain genuine collaborative experience because they did not actively work together.

Notably, when Ms. Foster did deliver individual assignments, Cassandra and her teammates were still inclined to view assignments as group work. For instance, Cassandra and Stacy completed the center-of-mass worksheet together, then shared their answers with David. The team members viewed such task delegation as a necessity since there were oftentimes multiple tasks assigned concurrently. Explained David, "We can't sometimes just all work on it because sometimes [they've] got to be doing the center-of-mass worksheet while I have to go work on the prototype because it's due next class and we haven't started it yet."

The negative effects of task delegation began to surface during the construction phase of the project when the students were expected to collaborate for several consecutive weeks. Because much of the work was labor intensive, David gradually assumed more and more control over the project, fracturing the group's cooperation and slowing their progress. By the end of the project, Cassandra and Stacy found it difficult to work with David. Then, when each group was expected to create a final presentation and CAD drawing, David initially refused to help, telling his teammates, "Well I built the whole thing."

Stacy later complained, "We tried to help . . . like when he was building the rudders, I was just sitting there and was like, 'David, how can I help?' And he was like, 'No, I got it. Don't worry about it.' And I was just like, 'Okay.' So then he expects to do all that stuff and we did a lot of the calculations . . . and it just doesn't seem correct that he gets to do all the fun part, the building."

Not only did the divide-and-conquer strategy generate hostilities within the group, they also failed to gain the intended experience in developing their skill-sets. David gained little experience in math, for example, while Cassandra and Stacy avoided much of the fabrication and all of the CAD work. An exchange between Cassandra and Stacy perfectly captured a major drawback of this strategy:

> *Cassandra*: Well, I feel like that's the point of teamwork, is like whatever skill you have, that's what you should apply it to. So if Stacy and I aren't too good at cutting or we can't build a certain thing, I feel like that's what David was useful for. And whereas he didn't really quite know how to calculate some of the math that went into it, that's where Stacy and I came in. And I feel like that's what made our team a good team, like we were efficient and effective, but-
> *Stacy*: But then what happens when you get thrust into a group where none of us can cut, none of us can do that? Then you're screwed because you're like, 'Well, I always had him who could do it.'
> *Cassandra*: That's true.

Cassandra became well aware of this downside, noting that she felt underprepared for the upcoming senior design course, fearing that she lacked essential skills that would soon be necessary. Still, due to an unwavering focus on task completion, she continued to rely heavily on teammates rather than develop her own abilities. This was made clear on the end-of-course survey when both David and Stacy (who tended to take the lead in their respective areas of strength) noted that a team of three was sufficient for completing the project. Cassandra, on the other hand, recommended that an extra teammate would have been more appropriate.

Skill-set

Although Cassandra had an uncanny ability to verbally express her ideas with clarity, a skill that shined during class discussions and presentations, much of her written work was less polished. Her logs and summaries were absent meaningful reflection, as they lacked the same depth provided in her verbal descriptions. For instance, after an activity in which the students were introduced to heavier-than-air flight, she wrote:

> *Overall we did pretty well. My group and I had not ideas down, or an initial design. We came up with a plane glider last minute and performed pretty well. We traveled pretty far, however not as straight.*

Later, after a prototype activity, she wrote:

> *Today we did okay, our hovercraft worked, it just wasn't as efficient was it could've been. During final testing our thrust force was off so our device curved toward the wall. This most likely happened because there were last minute notches add in, therefore it most likely affected the lift force.*

The quality of these musings was quite representative of those by her classmates (and probably a bit more detailed than average), consisting of generalities and followed by somewhat-educated guesses as to the source of any problems. When content was presented in a traditional manner, Cassandra clearly understood the science, as demonstrated by her class discussion responses and formative assessment results. And yet, owing to the grading structure of the course, she was not compelled to reference or apply concepts to justify her design decisions as should have been expected of an engineer- or scientist-in-training. Instead, her written work was more a narrative of observations. As a result, the disconnect she noted between content and the hands-on projects was not bridged.

There were exceptions to this, as she did attempt to include scientific justifications in her written reflections in a few cases during the semester. In these instances she attempted to draw upon her background knowledge to support her observations, but she struggled to provide clarity, as illustrated by her following explanations:

> *The ground effect must be concaved and more flat in order for our device to basically scope [scoop] air underneath and allow it to lift. Our glider however was more evenly distributed in weight and the lift from the surface (ground) was a lot greater. The wings pointed up allowing more air dynamics.*

> *We were able to prove that our propulsion device has a systematic ventilation system allowing our device to hover.*

Typographical and grammatical errors notwithstanding, there was no basis to use much of the included terminology, which only served to provide confusing and erroneous accounts. Nonetheless, she received full credit for her work.

Similar to her views of science, Cassandra regarded math as largely irrelevant in the academy, though she had found some value in "how to apply classroom equations to real life situations." Regarding the level of difficulty, she said, "I don't think we've done anything harder than algebra one, which sounds kind of bad." However, in the course's few measures of mathematical aptitude, Cassandra failed to demonstrate a solid understanding of basic concepts. For instance, she was unable to accurately determine the center-of-mass of her team's hovercraft, a skill that required comprehension of coordinate systems and basic algebra. And while she was generally able to apply simple formulas properly, she consistently struggled with unit conversions. However, since the success of the final product was not directly tied to mastery of these skills, she continued to view the project as detached from mathematics and found little reason to improve in these areas.

Problem-solving strategies

When Cassandra encountered obstacles during the course, she commonly looked to projects around the classroom for promising ideas. While a worthwhile strategy – and one recommended by academy teachers to varying degrees – Cassandra too often relied on others' designs, skirting a need to think critically for herself. In one instance, when teams were tasked with creating ground effect crafts, Cassandra and her teammates were unable to come up with an effective design on their own. Rather than working through the design process, they created a carbon copy of another group's. This latter craft, which had been constructed, tested, and modified to identify an effective craft shape, wing placement, weight distribution, and launch technique, rewarded its creators by travelling the farthest distance in the class. Yet, with very little effort, the craft assembled last minute by Cassandra's group performed remarkably well.

Later in the project design phase, when the students were required to select one of three provided fans to mount atop their crafts, Cassandra's team selected a box fan. When asked to explain their reasoning, they noted that the fan was the lightest of the three and thereby required less force to move forward, a valid explanation. But they also claimed it was the most powerful, a more important measure, and one which the team did not validate themselves. Instead, they relied on a classmate who had mistakenly come to this conclusion.

After spending hours of class time creating a mount specific to the box fan, Cassandra climbed aboard the craft while her teammates prepared for its initial propulsion test. When the fan was switched on, she braced herself, half-expecting to be launched down the hallway. The craft went nowhere. "Who said this was the strongest fan?" she asked, looking to place blame elsewhere for her team's decision. They eventually decided to switch to the stronger fan, which necessitated even more class time.

During the initial weeks of the project, when the students were required to carry out algorithmic tasks – CAD drawings, prototypes, and center-of-mass calculations, for instance – Cassandra's team advanced with relative haste. But when they were required to conduct more heuristic tasks, such as determining effective methods for mounting the fan and leaf blower, generating propulsion, and constructing a steering mechanism, they struggled to achieve a high degree of success. To address situations which were not straightforward, they relied heavily upon a strategy of trial-and-error. Unfortunately, the three teammates displayed little mindfulness in their approach and simply resorted making alteration after alteration with little reasoning behind these modifications. When they found themselves behind schedule, their activity increased, but they lacked a well-thought-out plan, depending on their instincts instead. Cassandra explained during the group's final presentation, "We just kind of cut out what we thought we needed to reduce friction."

They did make improvements, but their modifications proved too incremental to produce a working device. Had Cassandra and her teammates consulted the class's aggregate data from their prototype tests, for example, or conducted controlled experiments on various individual features of their hovercraft, their potential for creating a successful product would have greatly increased. Rather than practicing such disciplined inquiry, however, they approached challenges from a different frame of mind, one which prioritized task completion, regardless of the pathway.

Falling in line with this viewpoint, Cassandra continuously sought out the easiest courses of action for arriving at solutions. While simplicity is often a hallmark of quality designs, high-quality work was not an outcome of Cassandra's efforts. In lieu of fabricating custom hovercraft parts, for instance, Cassandra and her teammates chose to use duct tape, wood glue, bungee cords, string, and pre-cut scrap wood to affix the fan and leaf blower to the base. The resulting low-quality mounts, constructed with little attention to detail, became a major source of frustration when they began falling apart later in the semester. In the students' defense, these mounts did meet the minimum guidelines set forth by the lesson plans, which did not require students to appropriately design, plan, measure, and build as would be expected of an engineer.

Adding to Cassandra's frustrations was a belief that the level of guidance in the course was insufficient. She acknowledged that she did not always expect to receive direct solutions to her inquiries, but she did expect "more interactions" with the teacher and "more solid answers." Cassandra felt a need for more and clearer feedback, even if it was critical feedback, because "that helps us move forward and find the solution," she explained.

Summary

During much of the semester, Cassandra appeared to be a model student – she participated in discussions, submitted her work on time, and was rarely off task. Of the thirteen course assignments which more or less required completion (as opposed to comprehension or product performance), she accumulated 138 points out of a maximum 145, the missed points due primarily to less-than-elaborate writing in her engineering notebook. She felt that her problem-solving abilities had improved as well, commenting, "I feel like no matter how many times we failed, I feel like there's always a solution that you can come up with. So what I've learned personally is, ways to like persevere out of those hard situations and just really find a solution that will at least help you move on." And yet, her true effort and output was lacking.

Cassandra was not fully engaged in the course. She did not aspire to fully comprehend the presented physical or mathematical concepts. She expected the purpose of each lesson and activity to directly build towards the construction of a functional hovercraft and failed to see any value in anything not explicitly aligned with this goal. In essence, she was oriented towards performance goals. Rather than attempting to utilize any investigative methods supportive of disciplined inquiry, she searched for the quickest path to product success. By heavily relying on classmates, the teacher, and a guess-and-check strategy, she was simply looking outwardly rather than inwardly for solutions. Her higher-order thinking skills were not being engaged as intended by the learning model.

Cassandra's approach to problem solving was visible in a suggestion she made for improving the course: "We all had similar designs, I would've like to see different hovercrafts so that when my team and I fail, it's not because of not cutting more holes in the skirt. I would've like to see more unique designs." Aside from pointing to a general lack of creativity among her classmates, her statement revealed a strong dependency on outside ideas as well as a guess-and-check strategy. However, because she and her classmates were rewarded for their performances rather than their critical thinking capabilities, they viewed these problem-solving strategies as efficient methods for identifying solutions. Consequently, they were not forced to reason their way through the design process, and thus failed to construct their own knowledge as intended by the learning model.

It is perhaps fitting, then, that Cassandra's team was unable to create a working hovercraft by the end of the semester. In describing future modifications they would make, the team wrote:

> *If we had more time we would attempt to make our hovercraft lighter, we could do this by decreasing the overall size of the craft. Another thing we would want to do is to decrease our depth down from six inches to as small as possible. Finding a way to reduce friction would help our hovercraft a lot, this could be done by reducing depth or adding more holes. If given more time we would try different skirt designs such as wall skirt or donut.*

Again, the Cassandra and her teammates largely provided guesses as to what they expected to work, and if afforded more time, it could be expected that they would continue with their trial-and-error strategy until something worked.

Cassandra was a highly-capable student, but her views of the course did not align with project-based learning. Rather than highlighting a need to build successful hovercrafts, placing an emphasis on specific content, skills, and habits-of-mind may have helped Cassandra reorient her goals from performance to mastery, thereby improving her ability to construct her own knowledge. Cassandra finished the course with an A–.

"Rick"

Rick joined the academy because he was "thoroughly interested in engineering." The promise of guaranteed acceptance into the partnering engineering college was a "huge factor" in his decision to enroll, as he was fairly certain that he would indeed pursue an engineering degree upon graduation. He was hard-working and highly involved in class, and had earned all A's in the academy. He carried a 3.8 overall GPA.

Authenticity

Rick's expectations in the academy were centered upon gaining practical experience as preparation for college and eventually a career. He wrote, "The purpose of the STEM academy is to further our knowledge in the field of engineering." He identified clear connections between the profession and coursework, recognizing that classroom tasks were designed to simulate real engineering projects, noting, "Working through the problem and then coming up with a reasonable solution to fit within the budget, the time frame, the height constraints, width constraints, all that, it really opened my eyes to what real engineers have to do in that they have to work within certain parameters. But in those parameters, you can have all the freedoms you want."

In the same vein, he recognized a competitiveness among groups within the STEM classroom and perceived this to be reflective of realistic situations outside of school. He tended to view this aspect of the environment in a more positive light than many of his classmates. He explained, "I think that competition represents real life pretty well in that you're not going to be the only one working on a project. And if you can come up with something cheaper and better than the other guy, then you deserve a better grade."

But even with this understanding of authenticity and the significant role it played in the academy, Rick still believed that the functionality of physical projects was overemphasized in the coursework. Because "it is school and we're all working towards knowledge," he argued that the successful functionality of products should have been less stressed. He held the common notion that "the last project has a lot riding on it, and if you don't do well then your grade suffers tremendously." While true to an extent, the impact of product performance on a students' grades was in reality much less prominent, and yet the emphasis placed on physical products gave them a perceived value higher than their true worth.

Grading aside, Rick's main grievance was the manner in which effective problem solving was presented. He considered the utilization of trial-and-error to be an inauthentic manner by which to identify effective designs, writing that the process "is not a realistic application of engineering in the world." Rather than providing the students with multiple opportunities to iterate, he recommended that designs should be based on some justification and fully established before any fabrication commenced. Rick saw the process of disciplined problem solving as significantly more valuable than creating a successful product. He elaborated, "I think we should also start freshman year more with a math background and walking through the problems before we actually try something. And teaching us more equations in order to further prepare us for our classes coming later in high school. And just teaching us how to walk through a problem before you start it."

Rick was an anomaly among his peers, being the only student who "strongly disagreed" with the statement, "The best way to learn is by trial-and-error." Instead, he wanted to determine if his designs would perform well before implementing them. He stated, "When you think about a real-life project, you have to work within the budget and you can only do it one time. So if you just screw it up, you screw it up bad. You can't go back."

He traced the academy's emphasis on trial-and-error back to the freshman course, calling it "more of a building class than an engineering class," referring to the numerous hands-on activities designed to engage students in the design process. He explained, "There's not as much focus on the actually like preparation math, and it was more of a trial-and-error in the beginning instead of, you get one time to do it, and you have to do it right the first time, so you got to make sure you triple check all your calculations to make sure you put everything in the right spot."

He viewed the hovercraft course much more favorably, calling it his favorite course, a key reason being that it compelled him and his classmates to "do it right the first time" because "you have one board, one tarp, and if you screw it up, sorry." He believed this type of project, one in which students could not endlessly iterate again and again due to a lack of time and materials, better matched the real world, and said, "It should be like that in every class." In his view, being "able to walk through it with Popsicle sticks and hot glue and if you screw it up, you pull it off and you try it again," was not an appropriate way to engineer.

Owing to his time in the academy, Rick had come to sense that engineering was being presented as a process in which a person simply builds and iterates, an entity completely separate from the other STEM subjects, this disjointedness due in large part to the lack of math and science necessary for completing engineering projects. He suggested time and again that coursework should more heavily focus upon background research, believing that if relevant concepts and practices were emphasized from the start, "It becomes more doable, more achievable to make something that works really well."

Problem approach

Due to his background, Rick was already experienced with construction basics, allowing him to effectively guide his team during the building phase of the project. Most importantly, he paid acute attention to detail, which translated into carefully-designed prototypes and a well-crafted hovercraft. As compared to most other teams who consistently struggled to execute their designs – attaching mounts, adhering the skirt, assembling steering mechanisms – Rick and his teammates expended significantly less time troubleshooting issues due to poor craftsmanship, providing more opportunity for overcoming design flaws.

Rick and his teammates made a conscientious effort to improve their device by thinking through each encountered issue before implementing their designs. When the team's craft failed to provide enough forward thrust, for instance, he logged, "Our greatest concern for the final testing is the forward momentum problem. Our group has discussed weight elimination and funneling the air to create more pressure. We've also talked about [redirecting] air from the leaf blower." Comparatively, another student facing the same issue wrote, "Our biggest concern for final testing is to move forward and [to] pass the class! We will address this by continuing to work on it!"

With a detail-oriented approach, Rick was able to identify specific areas of weakness in his team's design, thereby affording him the opportunity to remedy a proper course of action. Importantly, because he clearly disclosed his team's intentions and supporting reasons, evaluating his level of comprehension was relatively straightforward from an instructor's point of view. It was also possible to quickly identify any errors in his plans and offer pointed feedback to appropriately support his efforts.

Of all the students in the course, Rick was most apt to make an attempt to apply his understandings in a practical manner by connecting his past knowledge with the observations he made in class. Even so, he found little applicability in the concepts presented, noting for example that science "wasn't vital" in the scheme of the project. He explained, "We didn't have to draw back on those [presented concepts] and just remember and say, 'Hey, alright, well we learned this, so we need to do this.' We didn't have to do that very much at all."

Despite all of his valuable qualities, Rick did at times fail to work and problem solve in a manner befitting a highly-achieving engineering student. Much of this lackluster conduct was related to group work, as assignments were sometimes left unfinished or completed incorrectly due to a lack of individual ownership. Rather than working together on the center-of-mass worksheet, for instance, Rick left the task up to one of his teammates. This student, appointed the team's math guru, made a slight calculation error, ruining the team's chances of successfully passing the associated progress checkpoint. The unsatisfactory result led Rick to place blame on his teammate, failing to hold himself equally responsible.

In another unfortunate case, Rick attempted to game the assessment system after Ms. Foster insisted his team increase the rigidity of their fan mount. Rather than seek a permanent solution, Rick encouraged his teammates to make a temporary modification, saying, "It's just so we can pass the checkpoint. That's all it's for. Later we can take it off."

While these less-than-ideal actions were few, Rick more frequently struggled to adequately handle the performance issues his team faced with their products. As he put the finishing touches on their prototype, for example, Rick boxed in the propulsion fan on each side save for one, which served to separate the fan from the planned area for the driver's seat. When the fan's battery was switched on, he was surprised to see the prototype remain motionless, not recognizing that he had inadvertently cut off all of the airflow to the fan. I intervened to show him the flaw.

Later in the semester, when the team's full-size craft was having similar propulsion issues, Rick's team decided to cut rectangular holes out of the base as a means to reduce its overall weight. It was a well-founded plan, agreed upon by the three teammates after discussing its merits as compared to alternative ideas. Yet the team made no attempt to verify the plan's true effectiveness before readying a jigsaw to cut the holes. I asked them if it was possible to determine the actual weight which needed to be eliminated in order to achieve forward motion. After brainstorming for a moment, they were unable to identify a method to do so. I offered a few hints, suggesting that a simple experiment could be conducted to determine this necessary weight reduction, but they remained stumped. Rick said jokingly, "We're not very smart. Could you just tell us?" I provided more revealing clues to no avail, and it was clear they would not conjure up a suitable course of action in a reasonable amount of time. I finally relented, telling them that they simply needed to turn on the craft without its driver (when the fan's thrust was powerful enough to set the craft in motion), then add weight to the base until it ceased moving forward.

These examples of inadequate engineering practices are not meant to diminish Rick's ability as a student, they are intended to help illustrate the point that even those most suited to project-based learning are still in need of appropriate guidance. In Rick's case, his educational experience and self-regulatory capabilities allowed him to effectively work through most problems with little need of assistance. And yet, some supervision was necessary to help steer his ideas down worthwhile problem-solving pathways and to ensure that he completed tasks properly.

Rick was not overly pleased or displeased with the amount of guidance he had received in the academy. Because he was determined to overcome obstacles himself, he did not often look to the teacher for help. But in some cases, direct guidance would have improved his progress. When he and his teammates were searching for potential solutions to the propulsion issue, for instance, they discussed a plethora of options, many of which were based on misconceptions. Rather than intervening at this point, Ms. Foster decided to leave the students to their own devices, noting privately, "I hear a lot of bad physics ideas, but I've decided not to say anything." Had she chosen to step in, her help may have saved the team from hours of fruitless work, and their chances of creating a working device would have greatly improved. But doing so would have reduced the learner-centeredness and investigative atmosphere Ms. Foster was attempting to cultivate.

The lack of help was not lost on Rick, who suggested that more guidance would have been well received at times to "get us on the right track to something that might work a little bit better." But he also acknowledged the importance of student-led exploration, explaining that teachers should act "kind of like a spark to get something rolling in our heads. . . . Not telling us, 'Hey, you need to do this, this, and this to make your thing work.'" Instead, Rick believed teachers should ask questions such as, "Hey, what if you thought about this?"

Overall, he believed that the academy was preparing him and his peers for the types of issues they could expect to face outside of school. He explained, "I think that a STEM graduate has a certain element of preparedness, meaning they know how to problem solve in the real world. And they can be given a problem and they can work through it enough to find a solution to the problem that's cost-effective and will work."

Collaboration

Each time a major design decision needed to be made, Rick and his two teammates put their heads together to hash out a plan before taking action. When it came time to assemble their steering system, for example, they made a point to first discuss a number of possible options. By establishing and communicating a set plan, the team members ensured that everyone was on the same page during construction and assembly. This is not to say there were not disagreements. They often had conflicting ideas, enough so that Rick said jokingly one day, "We argue about everything." Still, by talking through the foreseeable benefits and consequences of each proposition, they were able to compromise. When appropriate to do so, they divided the workload so that they were all consistently working on the craft. As a result, they made clear strides on a daily basis (see Figures 18 and 19 for images of their project).


Figure 18 (left): Rick's hovercraft undergoing performance testing
Figure 19 (right): Rick and a teammate working on their base

Rick disagreed with many of his classmates who claimed that four or even five member per group were needed to accomplish all of the required tasks. He believed three members per group was appropriate, not only for the hovercraft course, but for all academy courses. He stated, "Three is the magic number for groups. Three allows for enough work for each person, and four there can be a slacker. With three everybody has to work or else the project doesn't get done." He placed blame on the work ethic of those who made little headway when given time to work.

Rick was fortunate to have teammates with similar work ethics, abilities, and aspirations as himself. As each of the group members expressed, a lack of motivation was an issue among their peers. Rick noted that unmotivated students were particularly prominent during their freshman and sophomore years, and their presence severely diminished the learning environment. Although this issue was had been greatly reduced by their third year, Rick believed that several of his classmates were apathetic to engineering. In his mind, an outcome of this was a dichotomous learning environment comprised of motivated and unmotivated students. As he explained, "There's definitely a split atmosphere where there's some people that need the grade, for one. Two, they actually enjoy the class. And three, they actually look forward to it and they're like, 'Alright we have STEM today, I'm excited.' Then there are the people that have somewhere else better they have to be, and they really just don't care. They're there just filling space, breathing oxygen. They're not trying at all."

He went on to note that because the program was "progressively harder and being more labor intensive and just more challenging, it weeds a lot of the people that don't belong in the classroom." He continued, "I mean I hate to say it, but there's some people that just don't want to be there. And it's not fair to the rest of us." For this reason, Rick was vehemently opposed to the academy's group grading policy, arguing that he and his classmates deserved individual grades based on their own contributions.

Rick and his teammates contended that too many unenthusiastic students were being allowed into the academy in the first place, and recommended that measures be taken to mitigate this problem. Said one of his teammates, "[A] suggestion I would have is just making the STEM Academy a little bit harder to get in to. I know freshman year, anybody really who applied got in and, I mean, that's just [trails off, then laughs]." His other teammate suggested similar modifications, saying, "I think adding some kind of thing to make it not as easy to get into would be very beneficial. Especially to the beginning classes, where things aren't as good. But they'll be much better I think when the people who actually want to be there are there."

Conclusion

Rick came into the course expecting to improve his knowledge of engineering practices. The actual performance of his craft, while important, was secondary to learning. He participated in the classroom in a nearly ideal manner – he engaged in lessons, made daily progress on his team's device, and worked closely with his classmates. He even helped teach them at times. When a teammate of his was intimidated by the prospect of using a circular saw, for instance, Rick walked him through the steps, telling him, "You need to learn how to do this."

Perhaps most importantly, Rick had a great attitude. He routinely made comments such as, "I really like this class," and, "I wish we could work on this all day." His teammates shared in his passion, and the three genuinely enjoyed coming to class. In his notebook, Rick logged, "Our team dynamic is good and uplifting. My group is fun and easygoing. We all are working well together and laughing the whole time while being productive. We have finished all projects to date and have worked efficiently. All pieces of work are accounted for. I'm very happy that I'm with this group." Even after major setbacks, Rick kept a positive outlook, often reminding his teammates that "this is going to work" by the end of the semester. The three wholeheartedly believed they would create a well-functioning device.

But in the end, despite the aptitude of Rick and his teammates, their attempts to apply practical knowledge in a disciplined manner, and all of their diligent work and attention to detail, the team's hovercraft did not work. Their disappointing outcome was largely due to the complexity of their craft – while well-constructed, it was simply too heavy to propel forward.

Product performance clearly did not tell the whole story of student achievement. Though his team's device ultimately failed to meet the performance benchmarks, Rick surpassed expectations in nearly every other facet. When reflecting upon the course, he believed he had improved upon his fabrication skills, learned how to work within a team, gained a better sense of using small-scale models, better understood math formulas and "the raw principles of engineering," and learned "how to overcome problems as they arise." He also had an awareness of the connections between the academy and the world outside, saying "That stuff is vital for the rest of our engineering careers." Had Rick been graded largely on the performance of his product, few of the gains that he made could have been captured. Fortunately, in his case, he and his teammates were able to articulate the ideas behind their design choices as well as some of the reasons for their crafts' failure.

Owing to the manner by which Rick approached problems and worked in concert with his team members, he did indeed gain relevant engineering experience. However, those with different expectations and problem-solving strategies experienced the course in a completely different manner, and therefore came away from the course with a very different view of what it actually means to be an engineer. Rick saw value in fostering a learner-centered environment designed to offer an inside view of the engineering workplace, as he believed this provided clarity for students unsure about pursuing a degree in the field. He explained, "[Academy students] have a narrowed perspective on what they would like to do later in their career, meaning if they want to be an engineer, then they know it. . . . They have a better idea of the workload, they have a better idea of what the material's going to be, they have a just a more narrowed focus on what they want to be eventually and potentially." Because students are coming away from the academy with such sentiments, it is vital that the projects do indeed align well with the engineering profession so they understand what it is they could pursue.

In many ways, Rick was much like any other student in his class; he greatly appreciated the two aspects of the course the academy founders specifically incorporated as a means to engage students – physical products and group work. He wrote, "The best parts of this course were the hands on work and the fun that we had in the classroom." For Rick, however, part of the "fun" was the challenge that was presented. This was evident as he explained why the hovercraft course was his favorite in the academy. He said, "Alright, here's the project, here's the material you can use, solve the problem. Make it as cost-efficient and as material-efficient as possible. And I like that challenge being you have think it through. What are you going to use? And how are you going to make it work with the materials that you're going to make it as cost-effective? And just being able to put your hands on tools and actually put time and effort into something and effort into something and just watching all your hard work come to fruition, it's very, very rewarding. Very gratifying." He was one of the few students who was able to find gratification from the course even though his group's craft failed to perform as expected. Had his peers carried this same outlook, steering each group towards success would not have been necessary. But because most others became overly frustrated due to their lack of substandard product performances, helping to ensure they achieved some semblance of success was critical to achieving the affect goal of the academy.

At the end of the course, Rick wrote in his notebook, "Our group performed pretty well. Of the other groups we had the most fun. We were able to keep a light hearted attitude while repeated failures plagued us." He and his teammates discussed getting together over the summer to build another hovercraft.

"Marie"

Marie was an accomplished student. She had accumulated a grade point average just above 4.0, and though she had performed slightly less well in the academy (with a 3.7 GPA), she had been recognized as an outstanding STEM student for her effort and attitude in a previous course. When outside educators visited to learn more about the program, she, along with Cassandra, had been selected to serve as a student representative. With all that she had achieved, Marie's impetus for originally enrolling in the program was somewhat surprising – she merely wanted a free computer. As an incoming freshman, she had no expectations, admitting, "I didn't even really know what the STEM academy was."

During her tenure within the academy, Marie had come to believe her most significant gains were achieved by use of the engineering design process, which led to improvements in her critical thinking. In describing her newfound ability to problem solve, she recalled a time at home when an object became lodged in a pipe. She explained, "There was no possible way for me to get it out. But I feel like having STEM, being able to think of ideas, I was able to come up with some kind of tool to push it out. So in that moment I was like, 'Oh, I probably know how to do this because of STEM.' It was such a small thing, but I feel like STEM has taught us how to come up with solutions to problems easier."

Three years into the program, Marie had come to understand that "The STEM academy is to prepare our minds so that we are able to think like engineers," and she was seriously considering pursuing an engineering degree after high school.

Initial design

Marie viewed group work as a highly important classroom feature, one which was preparing her for a professional career. She explained, "I feel like working with a group is really good for us just because we know how it's going to be when we move on after high school. Like when you get a job, you're always going to have to be working with other people and you have to know how to be able to deal with other people . . . and how to solve problems all together."

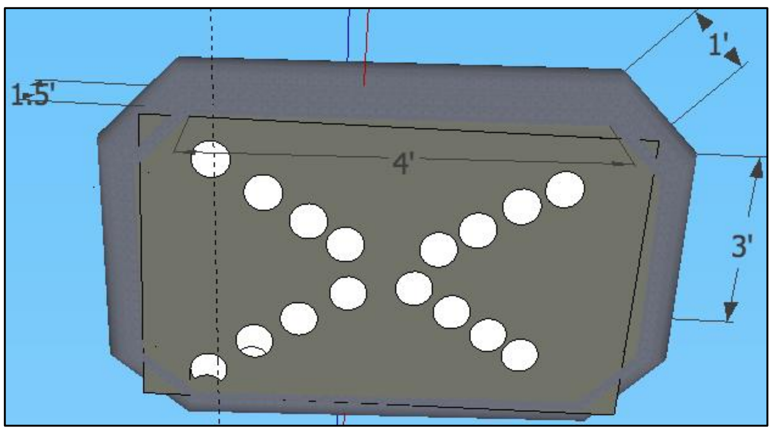
But like many of her classmates, Marie saw a major flaw existed within the group-centeredness of the classroom, that being the potential for having an unmotivated teammate. She believed that a number of her peers needed to increase their efforts, writing at the beginning of the semester that it was important to have teammates who were "hard working because you do not want to be doing all of the work. It is important that everyone contributes to the team." Still, when it came time to select her own teammates, Marie chose to partner with friends who were far from industrious. These teammates soon labeled her as the "brains" and "CEO" of the group while calling themselves the "builders," and the vast majority of the paper-based group work fell on Marie's plate.

When the first CAD drawing of the project was assigned, Marie initially passed on the task because she had limited experience using SketchUp. But her two teammates refused as well, both claiming they had never learned how to use the program properly. Ms. Foster intervened, insisting that they needed to improve their CAD skills and suggested they work on the drawing together. Marie's teammates continued to make excuses, and after a minute of bickering amongst themselves, she relented and took on yet another responsibility. She wrote in her log that day, "As a team we all have very poor sketchup skills and we do not know what we are going to do. I am finally going to have to teach myself how to use google sketchup."

Yet Marie was already in the midst of completing a worksheet for the team and, reluctantly, her teammate "Victor" agreed to take over the CAD assignment. Instead of generating a drawing from scratch, however, Victor simply imported a hovercraft from the program's online library, then made a few modifications in an attempt to personalize it. Upon seeing the drawing's intricate details, Ms. Foster was quick to realize that Victor had not completed it himself. She asked why he had not created his own drawing. He explained that since he had never been taught the program, he used this strategy as a workaround. He claimed it had sufficed in his previous STEM classes. "Yep, ten out of ten every time," he said.

Ms. Foster insisted that Victor begin again. But rather than create a unique design, he imported pre-made parts and assembled them onto a base that he did in fact draw himself. Although Ms. Foster disapproved of this new tactic, one that she considered it to be along the lines of "stealing," she did not explicitly disallow it because she recognized the students lacked experience, and the practice became widespread in the class.

Yet Marie was displeased with the quality of Victor's work, and once finished with the team's worksheet, she began to create her own drawing. Unfortunately, her lackluster CAD skills prevented her from even creating a basic layout, and she eventually decided to abandon the task. For their critical review, the group presented the drawings shown in Figures 20 and 21.



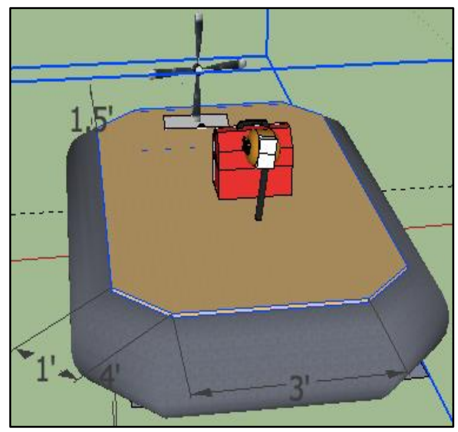
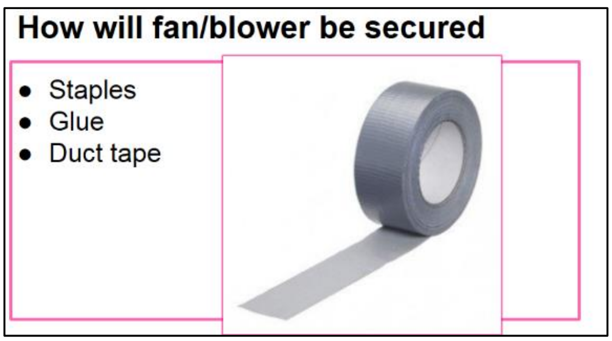


Figure 20 (left): Bottom view of Marie's team's craft design
Figure 21 (right): Top view of Marie's team's craft design (note the pre-made parts)

While Victor was busy with the CAD assignment, the team's third member, "Aaron," was assembling and testing the team's physical prototype. Marie began to compile slides for their upcoming critical review. Although these tasks were intended to be completed collaboratively, Marie and her teammates worked in isolation, an issue of which Marie was keenly aware. She wrote, "My team and I work okay together. . . . We distribute the work pretty evenly but sometimes one person does most of the work. For instance, on one of the templates we had to fill out I did most of the work but one day when we were testing Aaron did most of the work."

Marie finalized the slides well before her teammates completed their own respective tasks. Rather than offer them assistance, she began reading a novel. I asked to review her work. She had clearly followed the provided rubric which required that items such as the skirt design, mounts, and weight distribution be addressed. But her wording was extremely unspecific and difficult to follow. On a slide entitled "How will fan/blower be secured," for example, she had created a bulleted list that simply read "Tape, Staples, Hot glue" (see Figure 22). On another titled "How will the weight be balanced," she wrote "Torque" followed by "Example: a lighter person can balance with a heavier person if the lighter person is sitting further away from the pivot point." This statement did not address the topic, it simply described a center-of-mass problem that had part of a warm-up problem. On a third slide, she described the craft's weight distribution with the ambiguous statements shown in Figure 23. She had essentially attempted to cover the rubric topics in the broadest terms possible, giving little attention to the team's actual design.



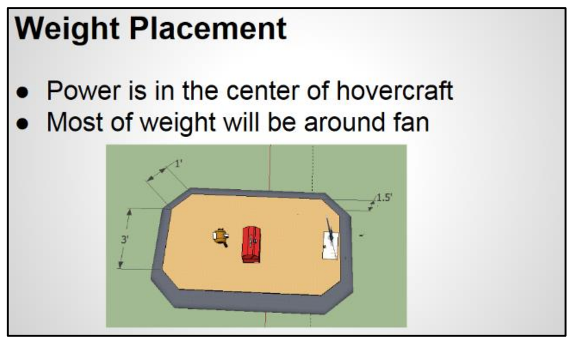


Figure 22 (left): Marie's slide describing her team's mounts
Figure 23 (right): Marie's slide describing her craft's weight distribution

When questioned on this ambiguity, Marie replied that she did not write because she had not spoken about the design specifics with her teammates, both of whom were sitting within a few feet of her. She admitted that she was not sure what Ms. Foster wanted to see in the presentation, and rather than asking for clarification, she decided to simply write in "some words," as she put it. As compared to her peers, Marie was less inclined to seek help. Rather than ask clarifying questions, she was content to complete assignments without fully understanding the content or requirements. Surprisingly, she placed part of the blame on Ms. Foster, reasoning that she had not provided adequate motivation. At the end of the course, Marie explained, "I feel like my connection with her [the previous teacher] was a little bit stronger because I've had her for longer and I was more comfortable asking her questions or talking to her about certain things. I feel like also her expectations for me were a lot higher, so I feel like in her classes I would work harder. Unlike in this class, I didn't really know Ms. Foster that well so I was just kind of like, 'Ehh, whatever.'" Marie's sentiments were largely a result of Ms. Foster's method of facilitation, which prized autonomy. This hands-off approach, while in line with learner-centeredness, was clearly not effective for all students.

During the group's critical review presentation, the group's lack of collaboration was made obvious by discrepancies among Marie's written descriptions, Victor's CAD drawing, and Aaron's prototype. The dimensions in the drawing did not align with those of the prototype, and Marie's slides described the shape as a "curved rectangle" although the CAD drawing displayed a rectangular base with corners cut at 45-degrees. Later, while describing the team's steering system, Marie presented a schematic she had found online which showed the basic components of a well-designed hovercraft. The craft assembly included a part labeled "thrust duct," which was a fan shroud used to increase the velocity of the airflow. Ms. Foster asked the group, "Who can tell me what a thrust duct is?"

Marie stated that the drawing had been included only as an example of a possible steering mechanism; the team had yet to discuss their own specific design and planned to handle the task when they arrived at that particular stage of the project. Ms. Foster explained that the purpose of the critical review was to present a set plan, not to show outsiders' designs.

Marie and her teammates received just 74 of 100 possible points for their work, the fewest of all thirteen groups. Ms. Foster later spoke to the team about the prevalent inconsistencies, telling them, "I think there is a lack of communication among you," and explained that some of the words used on their slides were very unclear, at times confusing. Ms. Foster's feedback, as written on the team's score sheet, is shown below:

- *name of shape is odd – no curves in it*
- *"power" is in center – what is this?*
- *what will fan holder be made of?*
- *what size? rope from where?*
- *Should not be "etc" on materials*
- *balance how – "put something over here" ← what object?*
- *what weight will be around fan? → location unclear*
- *Dimensions Marie said do not match w/ sketchup*
- ***<u>stole</u>*** *design of rudders from offline but <u>unclear understanding</u> of how it will work*

Before they would be allowed to begin the building process, Ms. Foster required Marie and her teammates to establish a more detailed plan. This set them behind the rest of the class, but they fully acknowledged that their designs were too vague. Said Victor, "We still need to talk about a lot of stuff." Marie agreed, "Yeah, we still need to get ourselves together." Yet for the duration of the semester, the details of their design never came into focus, and they continued to devise plans in broad terms (remarkably, Marie included the same "thrust duct" drawing in their final presentation).

The team gradually fell further and further behind, and Ms. Foster began to blame their lack of progress on a poor work ethic. They were incessantly off task – they socialized, texted with friends, and perused the internet – and, as opposed to many of their classmates, they appeared generally disinterested in the project. Although Marie had previously been a model student, she now seemed unable to focus. Ms. Foster remarked that she was being "tainted" by her teammates.

Moreover, the group isolated themselves from the rest of their classmates. Ms. Foster encouraged them to work alongside the others, hoping this would keep them on task, but her requests were ignored. A few weeks into the project, Ms. Foster regretted having allowed the students to create their own groups. She felt that the three were incapable of working together and noted that they constantly made excuses when asked about their inability to complete work on time.

Construction

The day before the first checkpoint, which required the groups to balance their crafts at the center-of-mass, Marie was absent. Without their leader, Victor and Aaron completely disengaged from the class. Ms. Foster intervened and suggested that they tackle the center-of-mass worksheet. To Ms. Foster's great displeasure, they replied that Marie was in charge of the calculations and there was nothing they could do without her. Before the following class began, Marie arrived to complete the worksheet, which she had yet to begin. She received substantial guidance, ensuring that her measurements and calculations were accurate. As a result, the team's craft balanced perfectly, yielding each member full credit on the assignment.

Once in the construction phase, Marie and her teammates continued to generate fuzzy notions from which to fabricate unspecific parts, and they showed no appreciation for craftsmanship. Duct tape became their favorite building material, and rolls of it were consumed in futile attempts to fasten their parts together. The attachments incessantly failed, requiring an unending cycle of reinforcement. Likewise, they relied heavily upon glue, and spent one entire ninety-minute period attaching blocks of wood to their base, squandering valuable class time because they were literally waiting for glue to dry. Rather than evaluating and testing various design features, Marie and her teammates were consequently forced to spend an exorbitant amount of time troubleshooting construction and assembly flaws. As a result, they were the only team unable to finish their mounts on schedule.

The team eventually settled upon steering their craft by attaching a fan atop a wooden mount. The mount itself was attached to the rear of their base by a single screw, which acted as a pivot point, allowing the fan to swivel. It was an effective design – one they had adopted from another team's craft – yet instead of moving on to the next phase of construction, the team became inexplicably fixated on reducing friction between the mount and base, a trivial concern. To address the issue, they covered the surfaces in contact with duct tape, which only served to increase the friction, making the fan more difficult to rotate (see Figures 24 and 25 for images of their craft). Then, as a means to fasten the fan securely, they ran plastic cable ties underneath the mount, which tore into the tape, further binding up their steering system. Hours of class time were consumed on this issue. Similar construction-focused concerns continued to slow their progress.


Figure 24 (left): Marie's team's fan mount
Figure 25 (right): Marie's team's craft during performance testing

When the mounts were finally in place and the skirt was sealed to the base, Marie and her teammates set out to test the hovering capability of their craft. But they did so without first creating holes in the skirt, believing that the craft may have been able to hover without them. They turned on the leaf blower and watched as the skirt rapidly inflated, pressurizing to the point that the wooden base began to bow severely. The skirt's seal suddenly burst, sending the craft crashing back to the floor. As intended by the learning model, the students learned through failure, although continuous failures such as this consumed a large portion of class time.

After they had re-sealed the skirt and cut several quarter-sized holes from its bottom, their hovercraft rose for a second time. However, the total area of the holes was insufficient for the large volume of air being pumped in by the leaf blower. The seal began to slowly separate once again, and the craft sank. Marie and her teammates appeared puzzled, uncertain as to what was causing the problem. I placed my hand along the separations, bringing their attention to the skirt's failure points, but they believed the relatively small gaps were trivial. I trusted that they would resolve the issues themselves, but they did not know how to proceed and simply waited for further instructions. Such scenarios played out continuously during the project, causing them great frustration. Ms. Foster expected the students to overcome obstacles on their own, yet she believed they too quickly gave up, neglecting opportunities to develop their problem solving skills.

Math & Science

Marie consistently struggled to demonstrate a solid understanding of the content presented by Ms. Foster. Fundamental physics concepts discussed in the opening weeks of the semester evaded her, and her math ability was exceptionally weak, as evidenced by her performance on the formative assessments (she correctly solved just two of seven math-related problems), the answers she provided during class warm-ups (she once calculated the center-of-mass of a 3.5-meter-long lever as "92.5"), and her limitations during the construction process (for example, she needed help using a ruler properly).

In addition, Marie commonly failed to support her arguments with evidence, which at least partially accounted for her propensity to take a surface approach to product design. Rather than first establishing a plan, she preferred to "just go for it" without thinking through all of the consequential steps. In many cases, this was indeed an effective strategy. After the first activity of the course, for instance, Marie wrote, "Our airplane did really well. Victor just built the airplane in a matter of seconds and it turned out to be a good design. I did not expect to do as well as we did." But as the semester wore on, laying out plans and justifying designs became more critical, and Marie came to the realization that vague intentions did not translate into workable solutions. Her struggles were documented in her daily logs, some of which are shown below:

Our goals are to come up with a sol[i]d idea for our hovercraft because right now it is a little sketchy.

The part that is the most unclear to me is the way we are going to steer our hovercraft and I do not understand the length of the skirt. In our google sketchup we do not have rudders attached to our hovercraft so therefore we have no way of steering our hovercraft. Also in our google sketchup our skirt is really long and I don't think that is what we planned.

Goals: to come up with ideas to improve our hovercraft performance. Right now the ideas we have are very broad.

Goals: My goal for next class is to finish the Google Sketchup completely and to be certain of what we are doing. Right now we are really behind on where we are supposed to be.

My greatest concern for our project is that the tarp is not attached well enough and that it might be too big. We already attached it on and now we have to cut out holes. I really hope it works out in the end because if it dosent then it is going to suck.

When the project began, Marie initially made strides to design with purpose. For instance, she attempted to size the holes of her team's prototype skirt with great care, and because she did not initially understand the process for doing so, Ms. Foster reviewed the steps with her, clarifying how to calculate the proper diameter of each hole. After Marie had worked on the calculations for some time (Victor and Aaron chose not to help), I reviewed her work and noticed several errors. I walked her through the steps a second time and explained that once she found the necessary diameter, we could select a suitable nail to create appropriately-sized holes in the skirt of her prototype. When she was again provided time to work through the process herself, she instead chose to ignore the calculations and simply used a "random nail" to make the holes, negating all of the guidance she had received.

Marie's limitations in math and science posed a barrier to proper engagement with course content, and she became susceptible to avoiding knowledge application and logical reasoning. When asked why her team decided to create a base with dimensions of 4'-by-6', for instance, Marie replied, "I don't know. It seems kind of medium, like if we used the full board it would be too big and if we used something smaller it wouldn't lift enough." Later, after they had modified their original skirt, I asked Victor to explain the team's decision to use a skirt depth of six inches. He immediately deferred to Marie, claiming that she had confirmed that this dimension would work effectively. Upon hearing this, Marie said, "I just kind of picked a random number. I think six inches looked good."

These intuitionally-based decisions had served Marie relatively well during her tenure in the academy. But as a consequence, she had come to perceive math and science as extraneous facets of engineering. She explained, "I feel like you kind of just do what you see or what you would feel what works for your projects. Like if you think that would work, you kind of just have that instinct that something's going to work. You don't actually know the research behind it. I feel like that's how our projects are made and I feel like with math, you don't really use it that much. Like it's just kind of something that's just there. I mean, I guess you do have to do calculations, like when teachers tell us to, but when you're actually building your project, it's not something you think about. Neither is science."

When asked to suggest possible academy improvements, she wrote, "I think that incorporating Science and Math in a way that we understand would be really great," but she was hesitant to recommend increasing the quantity of this content. She appreciated the emphasis on physical products and did not want to steer the program towards a more content-heavy format. She explained, "I feel like the best parts of the STEM academy are just that coming to class, you're always working on a project, like on something. It's really hands-on, so it makes class a lot more fun than having lectures. Because I feel like if we had lectures on engineering, that would really suck. STEM would be super boring. So I feel like having it just be hands-on has been really fun."

Marie pointed to the beginning of each semester, when coursework was more math- and science-laden, and described the lessons as "really boring." She conceded that the content was "kind of useful," but argued, "I feel like building is a lot more fun and it makes class go by a lot faster and I feel like you learn a lot more that way." Instead of presenting concepts through direct instruction, she suggested that content needed to be directly intertwined with hands-on work. But she understood that doing so was not straightforward, as is evident in the following discussion:

> *Todd*: Any recommendations to improve this course?
> *Marie*: I don't know. To improve the STEM Academy – I feel like this is very contradictory – but I feel like we should somehow use science and math more. Because it's called science, technology, engineering, and math, and I feel like it's very just engineering. Like we don't-
> *Victor*: Just building.
> *Marie*: Like science and math aren't really that important. So I feel like somehow incorporate it more, but in a fun way. Which I don't know, I feel like it's really hard.
> *Todd*: So how do we do that and not have lectures?

Marie: I don't know honestly. I feel like maybe while people are building, somehow maybe give some kind of, I don't know, like a packet or something that a student has to complete that has science, technology, engineering, and math involved with it. Or maybe homework that is more science-y and math [hesitates] I don't think that's good. I don't know if the other students are going to like the more homework, but I feel like just somehow have science and math [laughs].

Todd [directed at Victor]: How would you feel about more homework and more science and math content?

Victor: I don't know. I'd be a little bummed out, but at the end of the day it's homework, so you got to do it.

Notably, although the idea of pursuing engineering in college appealed to her, she was not interested in improving her math and science knowledge. In fact, the academy's additional requirements in the subjects was one of her primary complaints. She said, "What I just didn't like is that there's just so many other classes that you have to take to get your STEM certificate which, I mean, makes sense . . . but it just a hassle because you have to take a lot more science than other people, or like AP sciences and more math I think than other people. So I feel like that's been a struggle. In the end, it's going to be good for me, but it's just been a little bit tougher."

Guidance

After Marie and her teammates enlarged their skirt's holes following the two seal blowouts, they intended to test the craft again, this time on a large concrete patio just outside the fab lab. I asked them to consider why this might not a suitable location. They suggested that its downward slope could interfere with a controlled test, an accurate observation, then incorrectly guessed that the hardness of the concrete would play a detrimental factor as well. After several hints, Marie realized that the concrete's roughness was disadvantageous, yet the only downside she noted was that the concrete could potentially damage the underside of the skirt. I explained that surface roughness promoted friction, a force they wanted to avoid, then instructed them to conduct the test in the hallway adjacent to the fab lab. After hauling the craft inside, they switched on the motors and watched excitedly as the craft rose and the seal remained intact. After a brief moment of pride, they quickly realized that the fan was too weak to propel them. At this point, the students were expected to come to the realization that the depth of the skirt needed modification, as suggested by the prototype data. Yet Marie and her teammates were again unsure how to proceed.

After receiving more guidance, they tightened their skirt and the remaining frictional force decreased. But their craft was still incapable of moving. Once again, the students were expected to problem solve on their own, and it was assumed they would realize the need to divert more airflow backwards in order to generate forward motion. However, Victor suggested that they put holes along the sidewalls of the skirt. When I questioned his rationale, his reasoning was nondescript: "I don't know. I think just because there aren't any holes here." Marie disagreed with his idea, but she herself could not articulate a convincing argument. Victor pestered Ms. Foster for hints, but she was unwilling to capitulate and stated that the design was up to him and his teammates to decide. Victor responded, "No, that's for you to decide since you're the one giving the grades."

But Ms. Foster held her ground, and without any additional assistance, Marie soon thereafter relented, allowing Victor to add holes to the skirt's sidewalls. Once he had done so and the leaf blower was powered on again, the new holes bled huge quantities of air, drawing airflow away from the lower holes and worsening their performance. They did not know the next logical step they should take. Once more, I chose to provide help, and noted that the leaf blower expelled a large amount of air into the skirt. I explained the air had to go somewhere and asked, "Where does it go?" Marie answered, "It goes back up," and stated that this was how the craft was lifted. Unsatisfied with this answer, I explained that the air filled the skirt and generated a high pressure zone, forcing air out the skirt's holes and creating a nearly-frictionless air layer between the skirt and ground. But Marie and her teammates were unable to make any connection between this explanation and their design. To compel them to realize that their sidewall holes were inhibiting the craft's performance, I continued to pose eliciting questions. These attempts were fruitless.

I encouraged them to spend some time discussing the situation in order to properly address their lack of propulsion. This frustrated them even more, and instead of brainstorming or conducting a series of controlled experiments – as was expected of engineers-in-training – they simply stopped trying.

At the end of the course, reflecting back on the provided guidance, Marie had a split assessment. She noted on a survey, "I think this course is great but maybe a little bit more guidance [would be helpful]." And when asked if she received adequate feedback, she replied, "I don't really think so. Not that much in this class as I would in other classes, like a science class or math class or an English class. Because in those kind of classes, I feel like the teachers talk to you about how you're doing. They tell you what you need to work on. And, I don't know, in STEM classes, I haven't really had that, like a talk. Like nobody's every told me, 'Oh, you're actually doing really good in these kind of classes,' or, 'You need to do this or do that.' I don't feel like there's not that much feedback."

At the same time, she recognized the need for autonomy, particularly in upper division courses. She explained, "I feel like for our freshman year we got a lot more guidance, but that's because it's our freshman year and we need that guidance. But now that we're going into other harder engineering classes, if we decide to become engineers in college or whatever, we're not going to have the guidance. . . . so kind of just letting us be on our own, little by little, I feel like is good."

Victor reiterated these sentiments, saying, "We kind of wanted you to help us, like give us step-by-step stuff to do, but you guys wouldn't, you guys would just tell us like, 'I don't know.' . . . We kind of had to figure out on our own and you guys left alone in this class, which was a good thing but a bad thing for us because that's just how it's going to be out in the real life, I guess you could say, because we're going to be out there alone and stuff." He later noted, "I have received like a little guidance and stuff. In this class, especially like you and Ms. Foster, you guys helped us out a lot. You guys try to like give us little pointers, but not give us the full answer which really bugged us. But it worked and now you got us thinking . . ."

Final checkpoint

Marie's team showed little promise for passing the final checkpoint as the end of the semester neared. After initial modifications to their skirt design yielded discouraging results, they chose to make few additional design changes and spent the final days of the project passing time in conversation and decorating their craft. On the day of the final test, hoping to attain any degree of success, Marie and her teammates tried a multitude of variable combinations to achieve forward motion. They reoriented the fan. They tried a different fan. They tried without a fan. They tried different leaf blower speeds. They started at different locations in the hallway. They changed drivers. Victor pushed off the floor when he thought Ms. Foster was not watching. These attempts continued for more than half an hour.

Then, after Victor oriented the fan just right, adjusted his body weight to the perfect position, and started exactly where a slight gradient in the hallway began, it began to move. In fact, it completed the required twenty-foot distance in seventeen seconds, faster than any other group. Marie and her teammates were ecstatic. Marie later wrote, "My group did a really good job on our final test. . . . We went forward in 17 seconds and then we were able to go through the course with some difficulty. I was extremely surprised because I did not think it was actually going to work since we had not really tested that much previously, but I was wrong. When I saw that our hovercraft did work I got really happy."

Passing the checkpoint provided Marie with a sense of achievement. During the team's final presentation, she said, "It actually moved and that caught us by surprise. . . . We were really proud of ourselves at that point." She later explained that one of the best parts of the course was "just the fact that we built a hovercraft because when I first thought about it, I was like, 'How are we going to build a hovercraft? That's impossible.' But after we were able to do it and we completed it, it kind of made being in this class worthwhile and fun."

In addition to these positive experiences, the social aspect of the course added another layer of enjoyment for Marie. While presenting her team's final project, for example, she stated that she and her teammates "had a lot of fun" and "had a lot of time to talk and it was a good class to come to." She later wrote, "The best part of this course was my group." Yet these positive facets of the course did not necessarily foster learning, as shown in the following dialogue:

> *Todd*: Why do you feel that you worked harder [in previous courses]?
> *Victor*: [Interjecting] Well, I think that it's just because we had a good time.
> *Marie*: Yeah. . . . I don't know, maybe because I feel like this class was actually really fun for me. Like in past classes I've been with people that I don't really talk to that much, I don't know. And also just because it was [the] last semester so I just kind of didn't really care as much I guess. But I just feel that working with Victor and Aaron made me-
> *Victor*: We made class fun.
> *Marie*: Yeah, it made class more fun.
> *Todd*: So compared to the biomedical class [her most recent academy course], did you have different motivations? Less motivation?
> *Marie*: Yeah, I feel like I had more motivation in that class just because it was just me and [another student] and [she] is really quiet, so we both had to split the work. And I feel like it was a lot more work also. And then with this class, I don't know, I told them [Victor and Aaron] more what to do and then they would just do it. And in biomedical, I would think of something to do and then I would do it.

Marie also found fault with the academy assessment structure, arguing that grades should have reflected effort over performance. She explained, "I don't think they're fair because sometimes people work really hard and their projects don't turn out to work. Like I know my sophomore year, I was with two other people, and we had to make solar water heaters. And I know that we worked so hard on it, so hard, and our idea was great and everything, but just in the end, it didn't perform well. So I don't think that that's fair if we worked so hard. And it's like there's not enough time to fix your project, so I don't think it's that fair."

In light of this disappointing experience, Marie's decision to put forth little effort after facing numerous challenges in the hovercraft course are understandable. To remedy this issue, she suggested that effort play a larger role in the grading scheme, saying, "I just feel like the teacher should watch more. I feel like it should be more participation and hard work. Teachers just need to pay more attention. Not just on the performance." Ironically, because her team had managed to meet the minimum requirements on nearly every progress checkpoint, her performance grades were higher than any other assessment type, having earned 97 of a possible 100 points.

Conclusion

Marie was a high-achieving student, evidenced by her schoolbooks chock full of note tags and a lofty grade point average. She fully recognized the importance of a learner-centered classroom. She understood the need to become self-sufficient and made efforts to complete her work independently. But due to the classroom expectations and the dynamic of her team, she did not conduct herself in a manner befitting someone truly motivated to pursue engineering in college. She repeatedly avoided opportunities to think critically, and as the course progressed, she became less motivated to work hard. And due to her team's ambiguity during presentations and their failure to address points specified on the accompanying rubrics, Marie and her teammates earned just 157 points of an available 200 on their presentations. This helped drop Marie's grade to a B, low by her standards.

Still, Marie felt the academy courses were generally not challenging enough. She believed the classroom atmosphere was "middle school-y," elaborating, "I feel like teachers still really take care of us [again, illustrating a contradictory view of the provided guidance] and the projects that we're given, I don't know if I would say [the courses are] as hard as they could be. I feel like just being juniors or seniors next year, I feel like we should be able to do more." She continued, "It just kind of still feels like we're not really doing engineer things. But maybe we are because I don't really know that much like what actually engineers do." Her disappointed outlook was captured in her response to the statement "I'm glad I joined the STEM Academy." Marie selected a three out of five.

By disregarding related math and science content, planning without specificity, and ignoring the intended engineering design process, Marie was indeed "not really doing engineer things." Subsequently, not only was her mode of problem solving unsuitable for the learning environment, she failed to gain an appreciation of the engineering profession. To truly achieve at a higher level, Marie required a greater level of teacher involvement, as she was falling below expectations in both conceptual understanding and motivation. These undesirable outcomes are illustrated by her response to the question, "What have you learned in this course?"

> "I feel like I learned not so much how hovercrafts work because even if you ask me like now, I wouldn't know how to answer. . . . in past STEM classes I worked a lot harder than I have in this one, but we still didn't do that bad. So like Victor said, sometimes the simplest idea turns out that it can work. You don't have to think so hard or work so hard to get a good grade or to have something work well."

"Travis"

"I think the middle school I went to really pushed STEM and kind of sold me on it," Travis explained as he reflected on his reasons for enrolling in the academy. "I didn't really know what I wanted to do coming into high school, so I think I just joined STEM because I thought it would give me good opportunities after high school."

According to Ms. Foster who also had him as a physics student, Travis consistently scored the highest in his class on his physics tests. He was a very hard-working student, exhibited by his 3.9 overall and 3.8 STEM GPAs. He wasted no time in the classroom, always busy working on the assigned tasks, and his abilities and diligence were fully recognized by his peers, many of whom wanted to team with him.

Group work

Like Marie, Travis partnered with two classmates who had shown little initiative during the opening weeks of the semester. Ms. Foster reasoned that Travis may have purposely selected unmotivated teammates, explaining, "He chose to be with [his teammates] who are slackers . . . but they allow him to do his own thing, and this could have been exactly what [he] wanted." Predictably, Travis completed the vast majority of the assignments. He created designs, constructed prototypes, conducted investigations, and filled out worksheets. His group was essentially a one-student operation. When the class moved to the fab lab to commence the build process, a time when many non-participatory students began to take part in group-based work, his teammates were still largely unwilling to lend a hand, making Travis responsible for the entire project.

Travis did not appear to purposely dominate the group by overtly preventing his teammates' involvement or ignoring their advice, and the two showed no signs of dissatisfaction. They simply stood idly by, permitting Travis to work alone. Initially, Travis was content with the situation. He refused to note anything critical about his teammates, even giving them credit when none was due. During the first weeks of the project, for example, he logged, "Our group's dynamics are very good. We work well together because we are friends. I think two of us contribute the most to ideas because we are here everyday, but, when everyone is here, we are mostly on task. I am very happy with my group." He later wrote, "The team dynamics of our group are pretty good, everyone wants to present ideas and participate. I also think that we are working well together [and] everyone has their tasks, no one is just doing everything. Overall I am happy with my group, and would be fine to continue working with them." Importantly, he found value in teaming with others, noting, "I think working in groups is definitely necessary in STEM classes and it's good to learn how to work in groups."

As the semester wound down, however, his teammates' detachment became even more pronounced. Still, Travis showed no outward signs of frustration, but he did begin to distance himself from the two by asking for instructor feedback and making executive decisions without first consulting with them. His teammates' lack of motivation began to discourage him, but still, he refused to explicitly criticize their behavior. Even at the end of the course, after Travis had put together both the entire slideshow and poster presentations, he showed extreme constraint. He wrote in his notebook, "Towards the beginning of this class I think that the work was fairly evenly distributed. But, as we started construction, I feel that I did take on the bulk of the work. I think this was mostly due to absences of my other two partners. We did collaborate in most of the ideas, though. Recently, I had to create the entire presentations on our hovercraft. So, while I believe I did most of the work, when everyone was here, we mostly worked as a team got things done efficiently."

When pressed to share his views on group work, however, his true feelings emerged. He was one of just three students to select "strongly disagree" for the statement "All STEM students work hard on their projects" and he noted that two students per group would have better sufficed for the project. He was most irritated by the group grading policy in the academy, finding it unfair that his teammates received full credit when they contributed little to the project. He recognized that group grades were intended to compel collaboration, but he found a major fault with this strategy, explaining, ". . . I think that [group grading] prepares you for real life. But at the same time I think that, especially in high school, there's no motivation if you have a member of the group that doesn't want to do anything. There's no motivation for him to do anything, and he still gets the same grade as someone who does work a lot. So I think for a high school class, there needs to be more individual grades within a project like this that reflects more on the person, not the whole group." He reinforced this view by awarding himself the highest score on the peer-assessment, though his teammates each awarded themselves the most credit on their own score sheets (illustrating why the teachers placed so little value in such measures).

Travis's case represented a key reason the teachers were dissatisfied with the grading scheme. Travis was wholly engaged in the project from beginning to end, completed all of the individual work on his own and on schedule, presented his findings well, and came away from the course with positive experiences. He accumulated 95% of the total possible points, earning an A. Yet due to the high proportion of group work and the relatively large number of completion grades, one of his teammates received a 91%, good enough for an A– (and because the school dropped pluses and minuses, he finished with a grade identical to Travis). The third team member, who had five missing assignments, two late assignments, and did not even keep a notebook to record warm-ups or logs received a B.

Understanding

On day one, Travis wrote about the course, "I'm not sure what to expect, but I would like to learn more science based engineering, such as chemistry or physics." He, like the other high-achieving students in the classroom, hoped to gain a better understanding of the connections between science and engineering. At semester's end, he was quite unsatisfied in this regard.

During the opening weeks of the course, when lectures were a more prominent component of the curriculum, Travis was fully engaged. He asked inquisitive questions and attempted to draw links between discussed concepts and the daily activities. He made clear gains in this style of learning – on the first formative assessment, which covered several topics presented over these initial weeks, he answered all thirteen questions correctly, one of only two students to do so. However, during the latter part of the course, when the classes were more hands-on and learner-centered, he acquired less knowledge, at least as measured by the next formative assessment, as he answered just three of nine questions correctly.

Travis will need a strong foundation of factual and procedural knowledge if he decides to enter the engineering field. But if the bulk of academy courses do not lend themselves to supporting such a foundation, he may be ill-prepared to do so upon graduation. Though Travis was well ahead of most of his classmates, he still had many areas of weakness. This was most prevalent when math-based questions were presented, as he consistently struggled to handle the problems at a level befitting a student of his caliber. During daily warm-ups, for example, he used the wrong units, made careless calculations, and employed erroneous formulas. On the center-of-mass and pressure worksheets, he did much of the same. Because these tasks factored little in the gradebook and project, he devalued their importance.

When Travis originally joined the academy, he anticipated that coursework would mirror that of the core subject offerings, explaining, "I think I expected it to be a lot more like a math or science class. Learning stuff and then being tested on it." While he was surprised to find this not to be the case, he had come to appreciate the gains he made in other areas. He elaborated, "And what I actually learned is more – the stuff that I remember anyways, or I'm going to remember – is like critical thinking stuff, creative thinking, problem solving. All that stuff which I think is good for engineers now." Still, he "strongly agreed" that "There should be more math and science in STEM courses," and when asked about the importance of the subjects in the academy, he replied, "Honestly, I don't think really you need either and that's something I wish was better about STEM."

As a result, he viewed the courses as unchallenging, "strongly disagreeing" with the statement "STEM courses are too difficult." He commented, "I expected it to be a lot harder actually. [The classes] challenge like your thinking and stuff, but they don't challenge you as like other classes do with tests and stuff." Despite these claims, he believed that traditional assessments were not necessary in the academy. He continued, "I've learned a lot of stuff regardless of being tested on them. Learned a lot about engineering and, I don't know, I think my critical thinking, my creative thinking is better now."

Such sentiments are a huge boon to the academy since improvement in these areas is a key learning outcome. Still, like his struggles in math, Travis demonstrated key deficiencies in his approach to problems, as illustrated in the following section.

Problem approach

Two of Travis's greatest qualities were his high value of project research and his attention to detail. Through his efforts during the allotted research time, he identified practical designs to test and evaluate during the prototyping stage. Afterwards, during the critical review session, he presented two promising skirt designs to the rest of the class, generating a lot of interest from his peers.

When he initially began constructing the base and mounts for his hovercraft, he paid due diligence to the dimensions specified on his plans as well as the total material cost, one of the few students to do either accurately. He spent an extra day constructing these items due to their complexity, and though his team was docked points for finishing the task behind schedule, the quality of his work ensured no issues with the steering mechanism would emerge, saving time in the long run. And although Travis paid a similar amount of attention to his leaf blower mount, it failed to work reliably, hampering his ability to conduct performance tests. Likewise, his skirt design, after demonstrating great promise on his prototype, performed poorly.

Yet Travis prized the trial-and-error process. Early in the project, for example, he logged in his notebook, "For our hovercraft design, I think the part that is most unclear is the weight distribution of the materials on top of our hovercraft. The main reason we are having this issue is because we won't know the exact distribution until we get our final materials. Once we do though, I think we will solve this problem through trial and error." To address the inadequacy of his skirt design, he made incremental adjustments and tested their effects, a systematic strategy reflective of science- and engineering-based investigations. But he did not work mindfully – he never re-evaluated the quality of his design nor generated fresh ideas based on his observations. Over several class periods, he had little to show for his efforts. Rather than implement a new design, he was convinced that his device was always on the cusp of success and therefore devoted nearly all of his efforts over the final weeks of the project tweaking his design, only to see it consistently fall short of his expectations.

I decided to intervene and asked the group about the skirt depth their original design specified. Travis answered, "We didn't really think about that," explaining that "it was not something we planned for." I referred him to the prototype data and pointed out other skirt designs in the classroom, hoping that he would realize the major defect in his own. Yet he was still staunchly committed to his original ideas, and his ensuing modifications deviated little from his initial design. He generated a flurry of activity over the final project days (his group, by far, consumed more duct tape than any other), but made little progress.

At the end of the semester, when reflecting on his experiences in the course, Travis did acknowledge some drawbacks of his method of approaching problems. He explained, "I think mostly, I've learned a lot about the engineering process and what kind of things engineers go through. Because more than any other class, I think this class being like a large-scale project, I've learned a lot about the trial-and-error process and how you have to really research stuff beforehand because when you're dealing with large-scale stuff, it's not so easy to go back and it costs a lot of money. And it takes a lot more time than some of these other small-scale projects that we were doing in other classes." Still, he "strongly agreed" with the statement "The best way to learn in STEM is by trial-and-error."

Guidance

Travis sought out assistance when he struggled to understand a certain concept or when one of his physical models failed to operate. He was not overly reliant on help, falling more within the expected boundaries of the learning model. That is, he utilized the teacher as a resource, someone with whom he could discuss his observations and ideas.

While he worked through his craft's issues, Ms. Foster and I pulled less-capable and less-motivated students along so as to keep every group roughly at the same stage of development. Travis made note of this, disagreeing with the amount of additional assistance that other groups were provided. Much unlike many of his peers who believed that the teacher's guidance was insufficient, Travis would have preferred that even more autonomy was given. At the end of the course, he explained, "I actually think that there was plenty of guidance in this class and actually maybe a little too much. I think that the teachers – and this is mostly how it is – should provide the background information for kids going into a problem and then they should be able figure out a way to solve it. And then when they run into issues, they have somebody to ask, but they shouldn't help them too much."

A key reason Travis enjoyed the academy was because he and his classmates were afforded a relatively large amount of freedom in the classroom. He drew contrasts to non-academy courses, saying, "I think the teachers in other classes just really hold your hand and guide you through most of the stuff and I think the STEM teachers don't do that, which is probably what they should do. I like it a lot better in STEM." In lieu of more guidance, he suggested that more project time be provided, as he believed this change would have yielded greater results. He explained, "I think instead of providing too much guidance, they should just allow more time too for trial-and-error and stuff like that so kids can learn themselves how to solve problems instead of having someone hold their hand."

Travis also believed that academy students should have been required to possess better math and science capabilities as a prerequisite. Like many others, he would have preferred if more content was included in the projects, but he wanted this content to have come directly from his math and science courses, thereby both building a bridge among the subjects as well as providing more opportunity for product design and construction. He complained, "You don't really need anything coming into them [academy courses], math or science. I think just like they basically teach you everything you need to know at the beginning."

Conclusion

Because Travis devoted so much time to his team's skirt design, he lacked adequate opportunity to ensure that other facets of his craft worked well. The problematic leaf blower mount encountered during the first few classes of the building phase was never corrected, leaving the skirt with unreliable air pressure. Travis attempted to correct this issue last minute by creating a tube with his leftover tarpaulin material, duct taping it to his base at one end and using rubber bands to cinch the other end around the leaf blower outlet. The shoddy craftsmanship stood in stark contrast to the parts he crafted at the beginning of the project, and the rubber bands constantly broke. The final checkpoint did not go over well. (See Figures 26 and 27 for images of Travis's craft).

Figure 26 (left): Bottom view of Travis's craft
Figure 27 (right): Travis struggling during performance testing

The modifications he had made since the previous checkpoint – when he was very nearly able to overcome friction and move forward – were in fact detrimental. His craft, still with a skirt that was much too large, strained to simply hover. Once up, it was so unstable that the sides of the base repeatedly slammed down onto the hallway tile. Travis attempted to keep the air flowing into the skirt, but needed both hands to hold the leaf blower in place, limiting his ability to balance the craft and preventing him from steering. After watching him struggle for several minutes, Ms. Foster was compelled to tell him to stop; she did not even attempt to measure his craft's performance. He was understandably disheartened with his results, later concluding his notebook entry with the following:

> *As this class comes to a close, I am slightly disappointed in my group's performance. We were confident coming into the build, but that quickly faded as we realized our hovercraft wasn't living up to our expectations. For the final test, our hovercraft was not able to move and even had a hard time hovering. . . . The only thing that I really wish would have been different is the amount of time we got to build our hovercraft, as well as my group's time management. I would have liked to do much more testing on my hovercraft to fix the issues and perfect it. Building a functional hovercraft would have been more satisfying.*

Due to the hard work Travis had put into the hovercraft, Ms. Foster awarded his group 24 of 25 points on the final checkpoint. The leniency of Ms. Foster's grading, as well as an understanding that product performance was not overly emphasized in the gradebook, helped Travis stay relatively positive about his end result, and he came away from the course with many positive experiences which, like his peers' sentiments, largely came from the hands-on aspect of the course. He said, "I like the fab lab. Actually I love the fab lab. I think all the STEM classes should be in here . . . that was a good experience for the future." He later wrote, "The best parts of this course was definitely the building process of the hovercraft. I enjoyed using power tools and building a full-scale device." After three years in the program, Travis was certain that he would pursue some type of STEM degree in college, likely in engineering. He explained that although he knew little about the field before entering the program, "now I'm staying in it because I think I want to be an engineer. It's kind of gotten me interested in it."

Travis's experiences indeed gave him a better appreciation of engineering, but had also adopted some poor classroom practices. For example, he largely ignored the use of math and science, and he did not collaborate with others, though this latter issue was not entirely his fault. Most concerning, he was convinced that the trial-and-error process was the best way to engineer. He proposed time and again that in the future, more time should be allotted for hands-on project work, as it was his belief that all issues could be overcome with enough iterations. In response to a solicitation for academy improvements, for example, he wrote, "My only suggestion would be to begin [the] building processes earlier. While researching is an important part of the engineering process, I imagine more time should be spent on trial and error with many different prototypes that would allow for a more tested final product."

Travis's self-reliance was uncommon in the academy. And while he firmly believed that his creativity and critical thinking ability had greatly improved in the academy, he clearly required a greater degree of interaction with the teacher to better develop his knowledge base and problem-solving habits. Because he simply tried to push his initial design through the project, he was not challenged to genuinely reflect on the true merits of his ideas. The learner-centeredness of the classroom therefore did not align well with Travis's actions, providing him an inadequate learning environment.

CHAPTER VI

DISCUSSION

The following sections detail the most significant topics to emerge from the study, as related to the research questions, supported with representational and salient quotes. These topics have been placed under three main headings: building, math and science, and the classroom environment.

Building

Motivation

"I thought the beginning of the year the projects and classes were a little bit slow and too much research. I just like to build."

– Hovercraft course student

More than any other aspect of the academy, the students enjoyed constructing physical products, indicated by the students during the focus group interviews and surveys (see Table 15). This unsurprising outcome aligned with the heart of project-based learning, at least as the model was implemented within the academy, as it intended to draw students into engineering by use of hands-on work.

Table 15: Students' favorite aspects of the academy and hovercraft course

Best parts of academy – Focus group		*Best parts of course – Focus group*		*Best parts of course – Survey*	
Topic	*# Students*	*Topic*	*# Students*	*Topic*	*# Students*
Building	13	Building	4	Building	19
Learning about STEM subjects	5	Product is large scale	4	Group work	9
Problem solving	3	Riding craft	4	Testing craft	6
Being challenged	3	Applying M&S	4	Designing craft	4
Being creative	3	It was simply fun	3	Satisfaction of creating craft	4
Classmates care about learning	3			Product is large scale	3
Group work	3			Riding craft	3

The academy's heavy emphasis on product design and creation was immediately evident when students entered the program as freshman, as their first-year experience was designed as "a teaser course to get them interested" in engineering and to let them see that "this is kind of fun stuff," as one teacher explained. Yet the emphasis on engagement often relegated technical knowledge and skills to secondary aims. Thus, when Ms. Foster attempted to include more of what she considered to be appropriate lessons and activities for engineers-in-training – including lectures on supporting content, background research to bolster initial ideas, and controlled experiments to identify promising design features – many students found this to be unnecessary and irrelevant. The students were simply not accustomed to the extensive preliminary work that Ms. Foster was endorsing. Rather, they had become familiarized with building, testing, and iterating, key steps of the engineering design process, but certainly not the only steps. Because the hovercraft coursework delayed product construction in lieu of supportive activities, individuals made numerous objections. In effect, students became unsatisfied with the course the more it began to resemble authentic engineering work.

Though the hands-on work undoubtedly helped retain students within the program, this highlighted aspect of the curriculum motivated some to remain for a non-ideal reason. For example, five students, all females and all interested in pursuing degrees related to medicine, were greatly encouraged to apply as eighth graders. As one the students explained while reflecting back on an academy presentation she had attended in middle school, "They were like, 'Oh yeah, if you want to be in the medical field it would like benefit you.' And I want to be somewhere in the medical field, so that's why I joined." Three years into the program, there was a general feeling of dissatisfaction among these students, even a belief that they were somewhat misled as to the content of the courses. They anticipated that the biomedical engineering course would provide insight into the medical field, for instance, but instead came to view it as one that it largely resembled a robotics course. In response to a question about the usefulness of this course, a student explained that it was "probably not helpful, but it was kind of fun to mess around."

None of these five students had any interest in engineering. Yet they had decided to remain in the academy because they enjoyed building. Two explicitly pointed to hands-on work as the *only* factor keeping them in the program, one of whom stated, "[Building is] probably why I stayed in STEM, otherwise if it was like just learning, I probably wouldn't stay. Because I can go take anatomy at [another high school] or something to pursue my profession alone, but building's fun." Consequently, hands-on work did not enhance these students' engagement with engineering practices; rather, it was viewed as an enjoyable environmental feature that motivated them to remain despite a lack of interest in the profession. (As a side note, two of these five individuals decided to quit the academy after the hovercraft course. The other three decided to remain, particularly because they wanted to improve their college applications.)

Expectations

"I entered the academy because I am very interested in science, but what I didn't know is that STEM is basically just engineering."

– Hovercraft course student

An affinity for hands-on work did not factor into most individuals' decisions to apply to the academy. In fact, this aspect of the coursework was barely mentioned when students reflected back on their initial reasons for enrolling, illustrated by the focus group responses categorized in Table 16. Other, more ideal reasons – such as an innate interest in math or science, a desire to become an engineer, or a hope to learn more about engineering and related fields – had a much larger impact. By no coincidence, the students noted that their expectations for the coursework were quite different than what they experienced. Not a single student in the focus group anticipated the amount of hands-on work that was incorporated into the curriculum. Rather, many students believed that the STEM fields would be equally represented.

Table 16: Focus group results – Reason for joining & Expectations

Reason for joining		*Expectations of academy*	
Topic	*# Students*	*Topic*	*# Students*
Interest in math and/or science	9	In general, academy not as expected	11
To improve college application	7	More STM expected	8
Desire to become engineer	5	Amount of building unexpected	6
To investigate different careers	4	Did not expect just engineering	3
Enjoy building	3	Expected to learn more about what eng's do	2
Presentation in high school	3	*Academy is as expected	0
For a free laptop	2	*Amount of building is as expected	0
More opportunities after graduation	2		

These responses present a misalignment between students' expectations and their classroom behavior. That is, they reported a desire to improve their knowledge and skill-sets as well as gain an understanding of engineering practices, yet when Ms. Foster made strides to do this, there was palpable push back. Ms. Foster explained, "I think some students really appreciated, I guess, maybe some of the more content-oriented goals and the work that went into those, and others were really impatient with them."

Many students were simply uninterested in learning by traditional means when the prospect of hands-on work beckoned. Moreover, when students were engaged in building, much or all of the content that was intended to support their designs was ignored. A student commented on this peculiarity, saying, "You don't keep that in mind. You're just like, 'Oh, we're just building something that hovers.' I think that idea just gets lost." Because calculations and concepts were not utilized or referenced during the hands-on component of the project, mastery of these items was not reinforced as designed by the learning model. As a consequence, knowledge acquisition was hampered, a point later noted by the same student: "The other thing, you don't learn much information. Like in other classes you're soaking in stuff and you're tested on it, but this you just [learn] one [idea] per week about like endometriosis or the soil and then you kind of forget about it until you have to put it on your presentation. And you just know you're building something."

The enjoyment of, and distraction by, physical construction was not lost on the teachers, who contended that the students' ever-present expectation of partaking in hands-on work created an atmosphere in which redirecting students' attention elsewhere was quite challenging. In discussing this obstacle, one teacher explained, "Right now, some of them, it's fun build time and that's what STEM classes are. And so they come in with that mentality and they don't feel they need to learn anything because it's just about building." This teacher suggested that a sizable number of students remained in the program "because classes are fun" and "because they get to come and screw around and build stuff."

Another teacher, one who also taught within the math department, said of her academy courses, "I notice that when we give them lectures or try to teach them something, they get really bored really easily and really distracted. And they're level of focus in that class for learning a math problem is way less than . . . in my math class . . . I mean they should be able to go for a little bit, but I think for them after like two minutes, they're like, 'What? This isn't math class.'"

At the same time, much of the focus on building could be attributed to the manner in which coursework was presented. Ms. Foster, for instance, spent more time reviewing the project schedule and outlining the hands-on tasks (262 minutes) than she did lecturing on content (156 minutes), thereby implicitly downplaying underlying fundamental knowledge and emphasizing the importance of the physical product. This was no anomaly in the academy; all five of the teachers freely admitted that, as an effect of the project-based learning model, highlighting task completion often took precedence in the classroom. Described one, "I suppose on a day-by-day basis, we usually have a goal up on our slides for them. But I do think that usually my goal has to do with what I think they need to get done that day and not our overall learning goal."

Contrary to many students' beliefs, the primary purpose of each academy course was not to build a functioning product. Instead, the products served as mediums through which knowledge could be attained and skills and habits could be practiced, supported by kinesthetic learning in a contextually-based environment. Whether or not a group of students could successfully build a working hovercraft was, in many ways, irrelevant; it was the knowledge and experience derived from the project which were truly valuable. But, as a teacher asserted, the students often perceived "completing the task" as the singular goal, explaining, "That's always been one of the difficulties I think with it, is, 'Does the project work?' really the goal of the class? . . . I don't know that they see the underlying knowledge that comes along with achieving the project."

This is not to imply that the students viewed the academy as a vocational program, one in which building a successfully-operating product was the end-all. Many, fortunately, believed that more content should have been included in the curriculum, as shown in Table 17. However, there was opposition to lectures since students saw this as encroaching on their building time. As a result of Ms. Foster's extra content- and skills-focused lessons, thirteen students recommended in the open-response survey that more build days be added to the course curriculum, compared to just six for the academy at-large.

Table 17: Open-response survey – Suggestions for improvement

For the course		*For the academy*	
Topic	*# Students*	*Topic*	*# Students*
More build time	13	More science	8
More/better materials	11	More build time	6
More physics/research	6	Better materials	6
More guidance	5	Course options other than eng.	5
No intro projects	4	None	4
None	4	More math	3
Less research	2		
More math	2		

Misrepresentation of engineering

"Previously, I would've said [math and science skills are] not as important. And now I would say it's more important, simply because again when we started, some of the curriculum was designed more around – there's no right way or politically correct way to say this – but it was more of get them to have fun and experience the fun side of engineering, and we weren't selling what all of engineering actually requires."

– Academy administrator

Many professional engineers spend much of their time creating mock-ups and prototypes from which to generate new ideas and optimize their designs. Several of the academy leaders, understandably, noted that engaging the classes in similar activities put students in the shoes of real engineers. Said one administrator, "That's one of the things that I really enjoy is that they get hands-on, a more of a practical sense of what it's like to be maybe an engineer and at such a young age where you don't often get that with a lot of other subject areas or courses."

Ms. Foster believed that the hands-on projects provided a pathway for individuals to better connect with engineering, placing them in situations similar to those encountered by professionals, and providing an opportunity to learn about various aspects of the field. She explained, "These classes are designed to introduce you to a number of topics, to let you get interested, to see all the cool things you can do." Product construction, in her view, was an effective means by which students could become motivated to pursue engineering or other STEM-related careers. She continued, "What if they're like, 'Oh man, what if I do this now, imagine what I can do later kind of after I put in this work.' I guess that's how I would want to sell it to them."

But many engineers do not work with their hands. Engineering is design-focused field, and one in which professionals depend upon foundational understandings of the physical world for making sound decisions. By placing so much emphasis on physical work, students were exposed to a derivative of engineering that, in many ways, was not truly representative of the profession. Some of the academy leaders had come to realize this shortcoming. An administrator pointed out, for instance, "Now it's really about what technical skills – math, science, technology – do you need to be able to truly access engineering at a higher level. . . . Because if we just keep having kids build stuff, well they're done, they got that. I mean after fifth grade, they've got that."

Presenting engineering as a predominantly hands-on field was a disservice to the students. Because the academy strived "to show what engineers do on a daily basis," as one student wrote, many students spoke of product construction and engineering as one and the same. Those only interested in the building aspect of courses, who had little to no interest in the underlying fundamentals of the projects, may have in fact been better suited for vocational studies. Likewise, students uninterested in physical tasks were likely to be disenchanted by the prospect of a career heavy in hands-on work. Individuals who enjoyed mathematical modeling and experimentation, for example, should have been encouraged to pursue STEM-related fields by the curriculum, not dissuaded by it. This issue was touched on by several focus group participants; the following dialogue captures one of these student's views on the matter:

> *Todd*: If you knew what you know now, would you still have joined the academy?
> *Student*: I don't know, maybe. Because to graduate with a STEM diploma kind of thing would be good to have on my resume. So that's kind of the reason [laughs] I stuck with it while so many of my friends quit. I wanted to finish what I started.
> *Todd*: Why did they quit?
> *Student*: Because . . . they pretty much said it was like stupid and it didn't meet what their expectations were. . . . They just didn't think it was so much building, hands-on, and stuff like that. They thought it was just going to be more like, oh you take more science classes and math classes.

This point of concern necessitates reflection upon the true purpose of the academy, which was by a large degree for "students to be exposed to the engineering design concept and then have kind of the coordinating qualifications to get into engineering college," as one administrator explained. The projects were designed to interest the students in STEM-related fields, yet without an emphasis on developing disciplinary understandings and capabilities, there was question as to whether the coursework was truly readying the students for technical careers. The academy was not intended to mimic that of a college program, but its perceived misalignment with traditional STEM education spurred this re-examination of the curriculum, a topic touched on by another administrator, who said, "And so I think as of recently in the last two years for sure, we've had to really take a hard look at, are we really preparing them to be better qualified than other candidates for . . . engineering school . . . or to even go into the workforce with a better skill-set?"

A major weakness of the academy was a lack of coordination with the school's math and science departments, an issue of which the teachers and administrators were well aware (one stated that the three programs operated in "silos"). However, the wide-ranging abilities of the academy students, a symptom of its inclusiveness, presented a barrier to alignment among the programs. Any time a topic from geometry or physics was included in an activity, for example, it was necessary for a teacher to fully uncover each kernel of knowledge because it could not be assumed that all students already possessed that understanding. This greatly slowed the pace of coursework and limited the depth to which teachers could delve into subject matter.

Students were aware of the lack of overlap among the departments, one noting that "There should be a better bridge between the STEM, math, and science courses." Two high-achieving individuals suggested that separate content-only courses be established in conjunction with the math and science departments, providing a means for academy students to better grasp the fundamentals of the projects before steeping themselves in the hands-on work. They found the application of knowledge in specific contexts to be highly rewarding, yet believed the academy projects were in short supply of this. One explained, "I think then they could put into more of a concept-based lesson where when you're doing a math problem you're actually solving for this. You're not just solving a math problem, but you're going to see how it applies in engineering. Same with science. This is the concept of velocity, you can use it in this kind of situation. And I think if we can get math and science and the STEM classes that we have already now to start working together, I think that could really produce something that we could be much more advanced than where we're at now."

But academy leaders were reluctant to shift the focus of the curriculum from a predominantly hands-on program to one that aligned better with professional practice, as they were concerned students would become less engaged in the classroom. This point is illustrated in the following exchange:

> *Todd*: Do you think including that math and that science content will hurt or help their attitudes towards engineering?
>
> *Administrator*: It's a good question. And that's the fine line that we're trying to balance. We don't want to turn too many people off of the idea of engineering, but at the same time we don't want to sell them on a false sense of what it is to be an engineer. And so that's a very strange happy balance that we're trying to always keep in the back of our minds.

Math and Science

Learning goals

"And when we decided it was just an elective, and the content wasn't the primary focus, then it kind of opened it to what are other things and skills that we kind of think are important?"

– Academy teacher, on establishing the academy curriculum

Ms. Foster's inability to articulate the learning goals of the course was representative of a systematic problem within the academy – learning goals were simply not specified in the lesson plans. This uncertainty, commonplace among the academy teachers, inhibited them from designing activities to strengthen students' understandings and skills and prevented them from explicitly relaying course goals onto their students.

This issue caused a host of problems during the hovercraft course. Lectures tended to be unfocused and covered a wide swath of information, some of it far beyond the grasp of the students (e.g., the college-level Navier-Stokes and Euler equations). And much of the content was, at best, tangentially-related to the project. The students, aware that they would not be directly assessed on their understandings of the presented ideas, had no reason to take notes, and no more than one-third of them showed interest during lectures.

The academy's Academic Standards provided a general overview of the expected outcomes, but lacked adequate specificity for practical use. Standard 3, on "STEM skills and knowledge," for example, addressed the application of math and science with the statement, "Students will master the ability to apply knowledge and skills of math, science, technology, and engineering to solve a problem." Mastery in this standard was described as an ability to a) "Identify, analyze, independently seek, and apply content knowledge necessary to solve a problem," and b) "Explain and justify how the content knowledge applies to their solution." The Grade Level Expectations carried the same degree of ambiguity, requiring that sophomores "use provided STEM related content and resources to complete the required project." By the end of their junior year, the expectations stated that successful students were those who "are aware of, and can independently seek, STEM related resources to complete projects and assist with design needs."

By painting learning outcomes in broad strokes, the teachers were provided with ample freedom to include content as they saw fit, but the obscurity and lack of enforcement of these standards and expectations also allowed the teachers to easily overlook specific areas. For instance, prototyping and foundational math and science concepts were seen to have little application in robotics courses. In fact, it was possible for students to navigate through the first three years of the academy without independently completing a CAD drawing or setting foot in the fab lab, a disparity prevalent to the senior design course teacher, who noted that students' skill-sets were riddled with holes.

Furthermore, teachers found it challenging to evaluate students in many of the standards. One of the documents' authors discussed this obstacle, calling the standards "difficult to fully implement." He offered

Standard 5 as an example, which covered the "Development of Communication Skills." He posed the question, "What does that mean for the junior-level course, in terms of now they're at this level of communication, and what does that look like?" As a result, the documents were ignored, and course learning goals remained wholly undefined. One of the authors later admitted that after writing the two documents, ". . . we probably haven't looked at [them] again since."

Significance of math and science

"I wouldn't say that you have to be any genius at either one [math or science] to complete the projects. . . Just anyone who's willing to work should be able to do it."

– Hovercraft course student

Stemming from the undefined learning goals in the course, connections between the physical product and the included math and science content were often murky. The vast majority of the presented course content, while generally related to hovercrafts and useful for supporting a well-rounded knowledge base, was indeed not directly applicable to the design and construction of a successful device. Thus, students who were solely motivated to create working products found little reason to value this content. Lectures covering airfoils, buoyancy, and a host of other topics were typically considered nonessential. Hands-on activities leading up to the project construction phase, while more engaging, were viewed likewise.

The most glaring example of this disconnectedness was the topic of air pressure. It was initially assumed that the pressure formula would be utilized within the project, allowing teams to more easily justify design modifications and rationalize their observations. But this assumption failed to materialize. Ms. Foster, in response, deemed it necessary to present the topic in a traditional manner, yet its inclusion in the project was anything but seamless, taking place well after the primary design phase and lacking applicability. This prompted several students to voice complaints, such as one who noted, "I think that since we built something that used pressure and we learned about pressure than we should have done pressure calculations to design the hovercraft." Added another, "She covered both the things [pressure and hovercraft design] fine and taught them well, but she made them seem like they were kind of two different worlds almost and didn't really help us connect the dots I think."

These concerns were valid, and with more available time for lesson preparation, the relevance of pressure to hovercraft functionality could have been strengthened. But no matter how strong the connections, the reality was that students could have constructed a working craft without any knowledge of pressure, begging the question, should the topic have been included in the project?

This question centers on the heart of project-based learning, whereby students should be expected to utilize fundamental concepts and apply technical procedures to support their physical designs, an ideal with which Ms. Foster readily agreed. By completing successful projects, students should then be able to establish their comprehension of these concepts. "But then the truth is," Ms. Foster explained, "is that a lot these projects you don't need to understand everything to do, you just don't. You can watch a YouTube video of how to assemble this and build a lot of those things." Without a need to apply knowledge in the creation of products, both the students' motivation for acquiring the knowledge as well as the teacher's ability to perform authentic assessments were compromised.

Aside from watching online tutorial videos, Ms. Foster and her colleagues discussed the propensity for students to rely heavily on their intuitions rather than any hard math or science when designing their devices. Regarding the structural engineering course, for example, a teacher noted, "In terms of doing complex math, I think with torque they could do it mathematically, but they could also do it by feel. They could say, 'Oh, this is too much.' They don't have to know exactly how much it is and they can adjust it. So I'd say that they'd have to have a general sense of math, but I don't know that they have to be an A student in math to do well in the project."

Another teacher in the academy expounded on this issue, saying, "So much of the projects that we do, I want to say, are kind of more tinkering-oriented, where if you just kind of have a general sense of how things kind of work, you probably can come up with a solution without doing any type of really in-depth analysis ahead of time and say, you know, is this going to work? I mean they just kind of sort of have a feel for it."

This presented a major problem for designing worthwhile projects – if only the math and science that was deemed vital for the successful completion of products were incorporated into lesson plans, it stood to reason that very little content would be presented in the academy. Therefore, to ensure the students were confronted with some new knowledge, at least so they could gain a better sense of the types of areas in which engineers were involved, it was necessary to identify points in the project where disciplinary information "fit" appropriately. Thus, topics that could be tied to the project or observed in some fashion were deemed worthy of inclusion.

These requirements were indeed met by the concept of pressure. The topic was used throughout the sciences, included a degree of math, and the "hardness" of a craft's skirt could easily be observed and related to a resultant lift force. The associated lecture and worksheet were designed to supplement these observations and further develop students' understandings of the concept, including its relationship with force and area, its units of measurement, and examples of other situations to which it could apply. These traditional classroom tasks, while inauthentic, were indeed necessary to ensure that all students encountered and reflected upon the topic, as expecting them to *discover* this more detailed knowledge by their own endeavors was beyond reasonable. Their engagement with the project could, however, *reinforce* this knowledge.

This reinforcement would have been strengthened if they were required to apply the concept in some manner, as the teachers and administrators recognized. But, as one teacher mentioned, "It's really hard, for example, to bring some strong math skill-sets into some of these topics." Designing projects such that math and science skills were a critical component had yet to be effectively accomplished in the academy. For instance, just one of the four freshman-level projects required math, "But the other [three projects]," a teacher commented, "no I think they could be bad at math and science, but be good at construction and iterating and learning from your mistakes and good at adjusting things and have a great project at the end." The students' initial experiences in the academy therefore exposed them to a version of engineering that required little planning, thereby creating a perception of the profession that they still possessed as juniors.

After the introductory weeks of the hovercraft course, math and science were often discussed only during the warm-up problems, neglected for the rest of class. Like the pressure-related lesson and worksheet, students were frustrated by the inclusion of these daily problems, which they viewed as irrelevant in the scheme of the project. They saw no purpose in toiling over content that could not directly apply to designing a better device, and several complained that they only served to cut into their build time. Said one student, "I think this is the biggest [course] where like, for the warm-ups, that was a lot more math than I've done in any of my other ones. Although I feel like with the warm-up it kind of put us at a disadvantage for not having enough time. Because I feel like if we did have a little bit more time, some of us more would have gotten moving and turning."

Although the students entered the academy expecting to learn a great deal of math and science, they ultimately came to view the two subjects as generally inconsequential during the development of their projects, as illustrated in Table 18. As one student explained, "None of the classes I've been in in STEM, I've really had to use math, only like a little bit, but that's kind of the basic stuff. We kind of just have to like think of good ideas and build . . ." Added another, "As far as I've seen in STEM, you don't actually have to be that good at math. Maybe one person in your group has to be, but even then, it's not crucial."

Table 18: Focus group responses regarding the importance of math and science in the academy

Sample questions: *How important is it to be good at math and science to complete projects?* *Do you consider math and science when designing projects?*	
Topic	*# Students*
Little/no math used	16.5
Want more math and science	13.5
Little/no science used	13.5
Math can be useful in some instances	9
Physics can be useful in general	6.5
Teacher should explicitly tie M&S to E	3

One positive outcome that emerged from this line of questioning was that the students truly did want math and science to be a more integral part of the curriculum (also see Table 16), sentiments that aligned with those of the administrators and teachers (eight of the nine explicitly stated that more content was needed). Likewise, the statement "There should be more science and math in STEM courses" (1 = strongly disagree, 5 = strongly agree) was met with an aggregate response of 3.78 from the students. Just seven students disagreed with this statement, and these students generally demonstrated no real interest outside of the building time. At the other end of the spectrum, many of those who tended to participate during warm-ups and lectures made statements similar to that of the individual who suggested, "Students should see how science concepts affect the design and calculations of projects. And more time should be spent on calculations to support the design."

Several focus group participants did note instances when math and science was useful during their academy tenures. However, those who found value in science spoke of its usefulness only in generalities, and pointed to the benefits of physics though they had little to no experience in the subject themselves. That is, they held a *perception* that an understanding of physics was useful in the projects. On the other hand, individuals who had taken a physics course found their background knowledge to be of no real advantage. This discrepancy is apparent in the following two representative comments about the importance of science in the course:

> *Student without physics experience*: "Like that physics worksheet, the pressure one, I had no clue what I was doing. So I feel like maybe that this class should be required after like you take physics. Like you need a physics course to complete this course because it's a lot of mental [work] with the pressure and the force. It doesn't seem like mental [work], but our thing's not working."
>
> *Student with physics experience*: "In this class, it was important to understand, as far as science goes, that the air needs to be captured under the hovercraft. But a lot of the actual equations and the concepts, you didn't have to understand them as much, you just had to know kind of what was going on. It's wasn't crucial to fully understand the science behind it."

As the first individual alluded, some students were inclined to point to their lack of background experience when they were unable to complete tasks or when their devices failed to perform. This particular student found it easy to place blame elsewhere even though the knowledge needed to complete worksheet was fully covered by Ms. Foster during class (the student chose not to pay attention during her lecture) and, as illustrated by the second quote, understanding science was not essential for creating a functioning craft.

Though more students were innately interested in science, math was more frequently cited as useful during projects. This usefulness was attributed to the applicability of calculations such that results were physically observable when integrated into projects. A simple example of this was the center-of-mass checkpoint. Although in reality a working hovercraft could have been created without identifying its center-of-mass, because the teams were able to see their paper-based work validated when their crafts balanced at the specified locations, many students found this exercise to be worthwhile. This exercise well represented an authentic assessment, but unfortunately, this was the only assessment during the entire semester in which accurate calculations were necessary to carry out a physical task. As a result, Ms. Foster lacked leverage in motivating the students to value the math lessons. Speaking on the importance of content relevance, she noted, "So how . . . we con them [laughs] into the learning part is teaching the concepts so they're applicable." Ms. Foster fully recognized the practicality of the situation, noting that better comprehension of disciplinary content would not inevitably lead to better-performing products, yet it was important to her to increasing the students' disciplinary knowledge. She continued, "I mean maybe it's only small degrees of improvement on their project. Or maybe it won't even improve their project, but they're just understanding better."

Assessing for understanding

"You can be in a team with somebody and two of your team members could know what's going on and your project does well and you just got a good grade. And I have no idea that – well, I have some idea – but I have nothing in place to say, 'You don't know,' you know?"

– Academy teacher

The teachers in the academy struggled to assess for understanding. Due to the group-centeredness of the classroom, the vast time devoted to the development of products, and the lack of traditional assessments, students were able to pass the courses without truly demonstrating their own capabilities. Although four of the teachers suggested that conducting written tests would have provided a more reliable evaluation of students' knowledge, there was a reluctance to shift away from the authentic assessment measures upon which the program was first established.

While the courses were designed under the assumption that a successful product performance equated to a successful use of the engineering design process, meaning decisions were weighed based on applicable knowledge and evidence discovered via disciplinary practices. The reality that students were capable of creating working devices by lesser means pointed to an inconsistency between the idealized version of the learning model and practicality. A teacher gave a simple example of this, pointing to the paper airplane activity used in the hovercraft course. He explained, "There's physics involved, but are there really any good physics [equations] that are really going to accurately predict who's going to win ahead of time? Not quite, and sometimes when you really try to [include] the physics, there's some other thing factor that comes into play that makes it not work, and then they get frustrated." The teacher went on to point out that while it would have been preferable to include more content, "I don't think their background science and math really help them with their projects . . ."

To account for this misalignment issue, Ms. Foster chose to weight presentations more heavily, allocating 32% of the students' overall grades to these tasks versus just 19% for product performance. In her opinion, it was more important for individuals to possess an ability to communicate the ideas that went into their designs and the observations they had made, ideally tying those observations to the topics that had been discussed in class. She noted, "So if they don't have a clear understanding of the concepts and the math involved with it, it's really hard to talk effectively about those things."

Still, presentations fell short of her expectations. Rather than providing sound reasoning for their initial prototypes or explaining their strategies to overcome unforeseen obstacles, teams essentially described their crafts, gave brief synopses of their progress, and listed their performance achievements. Whether or not they incorporated appropriate concepts or demonstrated logical thinking during the design cycle was not explicitly communicated nor evaluated. Ms. Foster commented on this issue, saying, "At the moment they're not really being graded on what they learned per se. I think they're being graded mostly on their project and how it works and how they presented it at the end and how they're able to talk about it." Thus, the students were not held accountable for justifying their designs.

Ms. Foster pointed out that while the authentic assessments did not map well to measuring comprehension, she did believe the scores she gave were relatively fair. She explained, "I feel like you could look at their grades and the best grades would be the ones who learned the most. I would feel confident to say that. But . . . 'learned' kind of implies that now they can do these things, and I don't know that the grading really reflects that." Referring back to the learning goals that Ms. Foster identified mid-way through the semester – content knowledge, craftsmanship, and collaboration, as well as skills in math, data analysis, and experimentation – very little was in place to actually assess students in these areas. Consequently, there was a clear separation between the aims of the course and the attributes being evaluated.

The root of this problem is that it is simply not possible for physical objects to capture the knowledge and effort that students put into them. A teacher offered an example of this issue, saying, "I have a senior design group – their project was nothing by the end, but they did a lot of programming creating an app and learning how to use Bluetooth and Arduino and they learned a whole heck of a lot by doing it. But the end result . . . if I look at that I'd say they didn't do anything."

Ms. Foster touched on this issue as well by comparing the type of grading system she envisioned for the academy to that which currently existed. She presented two hypothetical scenarios that would lead to the same grade:

> *Ideal assessment*: "[They have] an A because they can calculate these things, they know what pressure is, they know how to use these tools, they know how to build a hovercraft."

> *Current assessment*: "[They have] an A because they did a good job building a hovercraft, they presented it well, which means they probably knew how to use the tools. They probably did all their work. And they did a good job at refining everything."

By rewarding or penalizing students for their performance of their creations, their focus was drawn away from the true learning goals, resulting in poor engagement, particularly during lectures and class discussions. And since the utilized authentic assessment strategy fell well short of accurately evaluating understandings of course content, students were presented with another reason to undervalue math and science in the academy. Thus without aligned assessments, there was a lack of extrinsic motivation, and in the eyes of Ms. Foster, the students' efforts were subsequently inadequate.

Rigor

"It's not necessarily I just want to get rid of the bad kids. I do think the level of expectation could somehow be higher . . . So you have a choice – you can continue to behave the way you are and be disrespectful and disrespect the space and the people here and then ultimately get kicked out or you can choose to kind of step it up . . . I don't know if there's a really good means to kind of handle that right now."

– Ms. Foster

Just one of thirty-seven students agreed with the statement "STEM courses are too difficult," the average response being 2.26 (1 = strongly disagree, 5 = strongly agree). Similarly, thirteen of the nineteen focus group interviewees reported – without being directly asked – that they felt unchallenged by the coursework. The program leaders did indeed want to challenge the students. Yet increasing the rigor of the curriculum, while seen as a method by which to improve students' understandings, was also viewed as exclusionary, one teacher mentioning that she was "torn" between wanting to include more content on one hand and wanting to offer opportunities for low-achieving students on the other. From Ms. Foster's point of view, the demand of the curriculum was bounded by the overall culture of the high school, which by its nature was undemanding. She explained, "The norm would be different at a different school, but not even all of the core classes require homework or have limited amounts. So I guess [the academy is] fitting with the norm of the school."

In addition, Ms. Foster viewed traditional tests and positive engineering experiences as somewhat mutually exclusive, noting that the introduction of such assessments would constrain the potential for enjoyment. She explained, "And then I think with the spirit of the program, the idea is that rather than test, the test is their project and the test is presenting it . . . And also like kind of one of the overarching goals for STEM programs, or at least the way they sell them, is like kids up, kids building things, kids engaged. So tests don't suit that scenario as much."

One unfortunate outcome of this strategy, as acknowledged by the teachers, was the establishment of relatively low expectations. This is not to say that authentic measures could not have held students to high standards, yet the manner in which assessments were carried out did not demand deep understanding of content. For example, rather than assigning technical reports demanding the incorporation of multi-step calculations and the utilization of spreadsheets for data analysis, the math required of students was kept relatively basic. The following summarized responses from focus group participants represent the students' general feelings about the rigor of math in the academy:

- You just need to know how to divide and use a calculator
- Knowing the equations is more important than knowing math
- You just need common sense
- You just need a math whiz in your group
- You do calculations, but not for the project
- You just need general knowledge of math
- You're given equations and you just need to plug in numbers

In line with the project-based model, the assignments were heavily focused upon the reflection of one's work, whereby classroom actions and observations were described, but understandings were not necessarily demonstrated. In the hovercraft course, the only tasks which required students to declare definitively correct answers were three worksheets, representing just 6% of the overall course grades. Notably, students fared worse on these assignments (78% average) than any other (see Table 11).

By comparison, most other grades were based on task completion and remaining on schedule, affording students experience in teamwork and time management, important skills for engineers. So as not to discourage students or leave them with disappointment, Ms. Foster assigned quite lenient scores to the students' work. The hovercrafts which completely failed to operate, for instance, were still assigned a B on the final performance checkpoint. This leniency that was common throughout the academy. Said one of Ms. Foster's colleagues, "It's really hard to get an F in one of these classes, and even a D. You know if a project gets completed and they've been doing minimal work in turning in assignments, then they'll at least have a C probably by the end, if not a B."

Yet the repercussions were evident, as illustrated in Table 19. Not only were a non-trivial number of students disengaged from the coursework, poor behavior was also an issue. From Ms. Foster's point-of-view, an appropriate measure was not to "get rid of the bad kids," but instead to raise the "level of expectation." But a method for doing so while maintaining a learner-centered atmosphere and without excluding lower-achieving students had yet to be identified.

Table 19: Teachers' comments regarding student participation

Topic	*# Teachers*
Many students not trying	5
Difficult to assess participation	4
Poor behavior is an issue	3
Can't motivate students	3
Participation grades focus on poor behavior	3

It was clear that the atmosphere being fostered within the academy catered to students' desires for autonomy, and while plenty of students possessed the self-regulation needed to make strides in such an open learning environment, many did not, as pointed out by a teacher who said, "So right now students come into the engineering classes, and this is really obvious . . . it's so laid back, they're all comfortable, they just want to relax." To establish an environment that was more conducive to college preparation, the teachers discussed the likely outcomes of shifting towards a more traditional classroom. "I know that they would know more if we did that [gave written tests]," predicted one teacher. "They would be a lot more serious about the class because in that class, definitely there are kids who are goofing off in there or maybe not as focused as they should be . . ."

Achievement

"I think mostly I have learned to problem solve. Very often a problem comes up in the group, whether with team members or the project, and I have been able to help counter those problems so that we can move on."
– Hovercraft course student, on what he learned in the academy

As shown in Table 20, students largely identified with transferrable skills and universal habits-of-mind when asked to reflect upon the gains they had made during their three years in the academy. These achievements will undoubtedly serve them well in engineering and related fields, particularly those related to teamwork and critical thinking. Notably, the students generally did not find that their knowledge bases had expanded, as they seldom mentioned improved math or science skills. And unfortunately, five focus group participants explicitly stated that they still did not have a clear understanding about the type of work that engineers actually do, as they noted that professionals certainly do not spend the vast majority of their time creating objects from cardboard, hot glue, rubber bands, and other basic supplies.

Table 20: Students' self-identified gains in the academy

Survey		*Focus group*	
Topic	*# Students*	*Topic*	*# Students*
Build skills	16	Problem solving	10.5
Teamwork	14	Design process	10
Problem solving	10	Critical thinking	8
Design process	9	Teamwork	6.5
Creativity	5	Build skills	6
Science content	5	Not what engineers do	5
Math skills	4	Creativity	3
Critical thinking	3	Presenting	2
Communication skills	3		
Computer-aided design	3		

The students' responses align relatively well with those of the academy leaders (see Table 21). When asked to discuss the strengths of the program, the administrators and teachers spoke primarily about skills and habits. The acquisition of factual knowledge, conceptual understandings, or procedural skills (e.g., CAD, experimentation, fabrication) was not mentioned.

When asked to reflect upon specific knowledge they had gained in the hovercraft course, the students did identify a number of topics about which they believed they had attained better understandings, including pressure, forces, and center-of-mass (see Table 22). Although they may have not mastered this material, exposure to these topics is likely to support their general understandings of math and science, thereby diminishing the learning curve the next time they encounter these concepts in other contexts.

Table 21: Program strengths as viewed by academy leaders

Topic	*# Admin*	*Topic*	*# Teachers*
Design process	4	Teamwork	5
Teamwork	4	Problem solving	3
Creativity	3	Creativity	3
Problem solving	3	Critical thinking	2
Have more responsibility	3		
Critical thinking	2		
Communication	2		

Two notable concerns did emerge from this particular data set. First of all, the project-based model operates under the premise that students will come to discover knowledge on their own as they engage with projects. Because each hovercraft was created with somewhat of a unique strategy and design, it was anticipated that individual teams would uncover novel understandings during the engineering design process, drawn from distinct experiences encountered in their work. However, no student made any mention of newly-attained knowledge that had not been directly presented by Ms. Foster. That is, students only noted gains if the teacher had overtly covered the material.

Table 22: Students' self-identified gains in the course

Survey		*Focus group*	
Topic	*# Students*	*Topic*	*# Students*
Build skills	13	Forces	6
Pressure	12	Not how HCs work	5
Forces	10	How HCs work	4
Center-of-mass	7	About pressure	3.5
How to build a HC	7	Center-of-mass	3
Teamwork	5	Not about pressure	2
How planes work	5		
Design process	4		
How HCs work	3		

Secondly, while four focus group participants explicitly stated that they had come to learn how their hovercrafts worked, *five* individuals acknowledged that they were still uncertain of the fundamentals behind hovercrafts at the end of the semester. One of these students further explained his discontent in the open-response survey, writing, "This course would be better if we could delve deeper into the science and math of how the hovercraft works. We did touch the surface but it bugged me that I couldn't fully understand what was going on." From statements such as this, it was clear that some students were not well-suited to unearth new understandings on their own or make connections between their observations and the science concepts discussed in the classroom, pointing to a greater need for teacher involvement.

Environment

"I enjoy the STEM classroom environment. It's a lot lighter than a lot of my classes because it's a little more – I wouldn't say carefree – but it's a little bit more relaxed, and then not everyone's trying to cram for some test or something. They're just working, everyone's having fun. Having a good time building and designing. So I think it's just a good atmosphere."

– Hovercraft course student

The classroom atmosphere created by Ms. Foster was very well received, as illustrated in Table 23. Students enjoyed working with others and having freedom to work at their own paces. One noted that he appreciated not being "treated like a child" in the fab lab, that he was entrusted with responsibilities not offered in other courses. Many cited the community-centeredness of the projects as a rewarding feature. Wrote one, "Getting to do the project with my friends was a large bonus. I had fun every time I came into class." While some believed that they could have accomplished more in the course with fewer teammates, most agreed that teams of three or four were most appropriate, the average group size suggested by the students being 3.3 members.

Table 23: Focus group participants' comments about the learning environment and group work

Learning environment		*Group work*	
Topic	*# Students*	*Topic*	*# Students*
Enjoy environment overall	9.5	Enjoy group work overall	8
Like freedom to move around	8	Leads to a stronger project	7
Some classmates do not work	7	Teamwork is an important skill	5.5
Like working in fab lab	5	Should choose own groups	5
Freshman year was very poor	4.5	Should work in area of own strength	3
Like competition	4		

Not only did students enjoy working alongside their peers, they generally understood the importance of teamwork. A student explained, "I really enjoy working in a group because I kind of tend to fall into a one-track way of thinking . . . It also creates potential for a much stronger and better designs because you have three people looking at it from three different ways, rather than just one person looking at it their way only."

The academy leaders generally agreed, pointing to the team-focused aspect of coursework as one of the key strengths of the learning model. One teacher commented, "I think group work is wonderful because in my experience, students learn more by talking to each other than they do by just trying to learn something from the teacher or a book or whatever."

Assessment in a group-based classroom

"It was because of him honestly that I got the grade that I got in that class. I don't know, I guess there's no way that the teachers can monitor every little thing that everyone's doing, but I just think that sometimes that people benefit from others and they don't really deserve the grade that they should get. Because I know I did not deserve an A in that class, because all I did was like screw things in and make a poster, pretty much."
– Hovercraft course student, discussing a previous academy course

A major point of contention in the academy was the issue of group grades. The study participants had split views on this divisive topic. Among administrators, one agreed and two disagreed with the current group grading policy, the fourth claiming that it depended on several issues. Notably, Ms. Foster was the only teacher in favor of group grades, though she did have reservations, calling it a "flawed system because students can do very little and still pass on the work of their teammates." As for the other teachers, one was non-committal on the issue while the three others were against the policy. The students were similarly divided – the average response to the statement "All team members should receive the same grade on a project" was a middling 3.12 (1 = strongly disagree, 5 = strongly agree).

The students and academy leaders in favor of group grades generally offered justifications similar to that provided by an administrator who said, "I would say I'm still a fan of that idea simply because it's almost a lesson in how to work in groups and take responsibility as a group for the performance . . ." Students opposed to this policy typically pointed to past or current teammates who had been awarded grades they had not earned. A few openly admitted to receiving high marks for projects to which they themselves had contributed little. Unsurprisingly, several suggested that effort play a larger role in the grading scheme.

The teachers did indeed want to include more participation points. They generally viewed such grades as a practical way to increase student classroom involvement. Yet participation points were perceived as subjective measures by the students and their parents (as well as by the teachers themselves to a degree), and consequently, many were inclined to argue for higher scores, believing that an instructor's assessment of effort was malleable. As one teacher explained, "I've given daily grades in some of my other classes, and sometimes there will be pushback because they feel like it's open for interpretation. Like what does 'on task' mean? Like if I'm writing something down but I'm talking to my neighbor, am I being on task?"

As a result, participation-based assessments were downplayed in the academy, typically accounting for about 10% of overall grades. In the hovercraft course, participation accounted for just thirty points, less than 6%. Ten of these points were assigned according to Ms. Foster's general observations of individual engagement, distributed in two five-point installments before she decided to discontinue her efforts. The other twenty points were assigned during the scored discussion; while this activity allowed for a more systematic method of accounting, the process was incredibly time-intensive, thereby limiting opportunities for adequate instructor involvement.

The general observation and systematic approaches employed by Ms. Foster each presented flaws, and neither proved to be sustainable. In the academy as a whole, when participation points were assigned, teachers generally distributed grades at infrequent intervals as they saw fit, making no written record to support these scores. This is not to say that the teachers' assessments were inaccurate. On the contrary, they believed that due to their high level of involvement in the classroom – leading discussions, assisting groups with fabrication, providing advice and encouragement – they had a solid grasp on each student's effort. But it was the lack of justification that prevented these grades from being more prominently used, particularly when parents became involved. Said one teacher, "So do I feel like I could give them a grade that correctly assesses how much they've participated and how much they've helped their group? Yes. Do I feel like I have a good handle on that? Yes. Do I feel like I could justify their grade to their parents with actual physical evidence? No."

Ms. Foster voiced similar frustrations about the assessment structure, pointing out that there was nothing in place to differentiate among teammates. She explained, ". . . say it was like a really good project, really good job. Two good students and one slacker – like one person who clearly wasn't doing anything – I don't know what to do there." Her thoughts were reiterated by a colleague who stated that students receive group grades "because you would have a really hard time proving this one student should receive an A versus another student [who] should receive a C even though you know that this student worked really hard and this student didn't." She continued, "I think we'd have a lot of parent complaints if we did something like that. Definitely." Consequently, grades were often unrepresentative of individual contributions, implicitly reinforcing the poor efforts of those less involved. Complained one teacher, an individual's grade "doesn't always tell the full picture. It doesn't show us what their level of engagement is with the project."

Aside from appeasing argumentative students and their parents, Ms. Foster felt that the obligatory recordkeeping of individual contributions affected her own actions in the classroom. In her view, focusing on students' behavior for the purpose of assigning grades essentially boiled down to docking points for poor conduct. Rather than interacting with all students, she felt that she might be less attentive to the needs of those who were consistently on task. She explained, "I think the thing that makes me sad about it is then you're keeping track of negatives and you may not necessarily even be bothering to keep track of the positives just because . . . these guys are fine so I'm not even going to worry about [them]."

Another teacher spoke along similar lines, pointing out that she wanted to assess students on their contributions during class, yet from a practical standpoint, she believed that doing so ultimately hindered her ability to teach well. She explained, "There's so much interpretation . . . Unless you make it really stringent and you say, 'Participation is one, bringing your book to class, two, having your warm-up done once the bell rings, three . . .' But how hard is that to grade thirty kids? And then you're not even focusing on what you're focusing on, so it's kind of beside the point."

From the long-term substitute's perspective, allocating just ten percent of a student's grade to participation was inadequate; in her previous engineering courses, participation constituted thirty to forty percent. She claimed that this relatively high proportion was necessary for classroom management, particularly in a team-based environment. She said, "I think it holds the kids accountable, because if they don't have a participation grade, then they're getting graded on a group project . . . How do you hold them accountable?"

Compounding grades based on classroom contributions were expectations that students should collaborate with one another, a key learning goal of the academy for which there was no established method of assessment. The teachers viewed collaboration grades as completely impractical. Not only did they cite the extensive time that would be required to evaluate each student's collaborative abilities, they were unable to monitor exchanges among teammates without influencing the students' behavior. Explained one teacher, "I can't listen in on every conversation that's happening throughout the room. And as soon as I get close, it actually changes the whole dynamics." Collaboration thus went unevaluated in the academy.

Individual accountability

Todd: How do completed projects demonstrate student comprehension of the learning goals?
Ms. Foster: I think that can be very hit or miss, that if you're going on performance alone, it doesn't give you the full picture, especially if you start talking about the particular members of a group. It could be very much the case that one of three students really knows what they're doing and the rest, kind of just hanging out.

As previously noted in Table 19, a lack of participation was a significant problem in the academy. The teachers noted that this apathy was fostered by community-centeredness of the classroom, as some individuals were "willing to let to let their group do everything," according to one teacher. Another estimated, "I'd say seventy percent of the kids are trying to actively do it and thirty percent of the kids are just trying to get by."

During the initial years of the program, disciplinary skill development played a much lesser role in the classroom, and less motivated students quickly learned to game the system once realizing they could receive passing grades without fully participating. "I think it affected students because for a little while when we had so much emphasis on just the performance of the device and the group itself, kids were starting to see that 'Timmy' could get away with doing nothing and get the same grade," an administrator explained. "And so why would I want to offer my help or do more on my end if we're all going to end up with the same grade?"

To address this shortcoming, a concerted effort was made to place more responsibility on individuals "so that not every students' grade is reflective of just the performance of the device, and it's not just the group's effort, but it becomes more of an individual student's effort," he continued. But without a practical method for identifying each team member's specific contributions to group work, these assessments went untouched, and teammates continued to receive identical project grades. Instead, more "personal responsibility pieces" such as "making sure that they're getting other things turned in on time" were assigned and tracked. That is, students were being held accountable for task completion. In the hovercraft course, this meant writing brief reflections and answering the daily warm-up questions and logs, which did not necessarily lead to knowledge or skill acquisition. Still, it was possible for unmotivated students to accomplish little during the projects and still receive decent grades – aside from one individual who was perpetually absent, all of the hovercraft students earned a B or better – and their lack of effort was not lost on their classmates. As it stood, several high-achievers were dissatisfied with the learning environment that was cultivated, and questioned the academy's admission requirements. One wrote, "A suggestion I have is to make the STEM program more selective as a program instead of allowing anyone to get in. This will create a more focused atmosphere among the STEM students."

While plenty commented on the lack of participation within the classroom, at no time did a student mention a classmate's lack of ability as cause for concern. In other words, individual weaknesses, in math or computer-aided design for example, were not seen to hamper the learning environment. Rather, when students aired grievances about their peers, they pointed solely to behavioral issues, not aptitude. These sentiments are illustrated by the following student's comments: "Contribution and participation is just a major thing. I see lots of people slacking off in STEM and I don't believe they should get the same grade as the people who actually try. And even if they don't succeed, at least they're trying and learning."

But the teachers, with a desire to reach out to students of all abilities and motivations, were disinclined to shift the academy towards what may have been considered a "weed-out" program even though they recognized that removing disruptive students would have provided clear benefits. In discussing a particularly low-achieving group, for instance, Ms. Foster illustrated these conflicting ideals, saying, "I think they struggle and complain a lot. Does that mean they shouldn't be in the academy? No. If they want to be, they should do it. So I guess I don't have this expectation that every student has to be awesome or to be on task every second." She later noted, "Maybe if the expectation was a little bit higher, so if students like them would just step it up a little bit, I feel like overall that would kind of increase the environment."

Ms. Foster attempted to mitigate these behavioral issues by frequently encouraging teammates to work together through their projects, to rely on one another so that the bulk of responsibilities did not fall upon one student's shoulders. Yet rather than working in concert with each other, teams often chose to delegate tasks. As a consequence, students did not gain the intended collaborative experience, nor did they gain develop their disciplinary skills as expected. When Ms. Foster distributed the group center-of-mass worksheets, for instance, most teams simply passed off this assignment to a single member, typically the individual most adept in math. Those who could have most benefitted from the assignment therefore gained no practice. Some of the students saw no problem with this situation, as the following discussion demonstrates:

> *Todd*: Okay, so let me ask this, do you think that all the members in a group should get the same grade on their assignments?
>
> *Student A*: Yeah, because it's a team.
>
> *Student B*: And I didn't see it as too big of a problem because I think it's just like a time thing. Like if everyone in the group did the center-of-mass calculations, I'm sure we could all go through it and explain it to each other if we needed to. But because the time we have and all the stuff we want to do in each class, we have to split up the roles. And so I think we all should get the same grade because we all do different jobs. They might not be the same or take the same skills, but that's more how it would reflect in real life, I'd assume, because everyone would work in a group and you would just work to your strengths.
>
> *Student C*: I agree with that. It's just like a collaborative kind of thing. Everyone just works together to get everything done.

From these comments, it is clear that the students overlooked the importance of developing their technical abilities in the academy, as efficient task completion was more highly prioritized. One of these students did acknowledge, however, that because only one of them completed the worksheet, the other two essentially learned nothing from the assignment, a drawback he believed Ms. Foster could not recognize. He explained, "I think that once we fill out that center-of-mass form, I think the teacher just assumes that we all just know how to do it."

One method of promoting accountability, as supported by several academy leaders, was through a "checking in" process, whereby teachers would frequently and purposefully interact with students, discussing specific areas of projects to determine each individual's level of involvement and comprehension. A teacher who noted, "I think kind of through me talking with them while they're working on stuff I can get more of a feel for the individual understanding," utilized these interactions, but only in a formative teaching mode. That is, individuals were not formally assessed based on these discussions. There simply was not enough available class time to evaluate student competencies in a fair and systematic manner.

In some cases, when faced with tasks that required knowledge or skills beyond their comfort levels, students simply passed the work off to teammates. Said one such individual, "I was really lost a couple times when we were doing different things and I was like, 'It's all up to you two because I have no idea what's happening.'" With this ability to defer difficult task to others, the coursework did not hold individuals accountable, and among the teachers, there was a general feeling that students did not possess a sense of ownership over their projects or their grades (see Table 24). By lacking ownership, Ms. Foster believed that students were more apt to find fault in the circumstances surrounding their work, either placing blame upon their teammates or the conditions of the project itself when their devices did not perform well.

Table 24: Teachers' comments regarding student individual accountability

Topic	*# Teachers*
Can't assess individuals	4
No ownership of grade/project	4
Individual work = accountability	4
Need more individual work	3
Tests would lead to accountability	3

In light of these repercussions, one teacher suggested that group grades should be virtually eliminated within the academy. But determining individual contributions remained a major limitation in project-based classrooms. She explained, "If you could actually get that individual piece accurately and get an accurate representation of what did that person contribute to that final project –ideas versus building versus knowledge and understanding of it – I mean that should their whole grade, you know? And then the project would be just a small portion like twenty percent and then eighty percent would be the individual. It's just so difficult to get that – an accurate representation of what that person contributed."

Problem solving

"I feel like the Stem Academy's purpose is to teach critical thinking more than anything. Which I think is a very big aspect in Engineering."

– Hovercraft course student, writing on the purpose of the academy

Nearly across the board, the study participants believed that gains in critical thinking were one of the key strengths of the academy. During student focus groups, for instance, eleven of the nineteen students noted that their problem solving abilities had improved, while eight offered critical thinking as a notable benefit to their time in the program (see Table 20). These gains were frequently attributed to the students' experiences within the engineering design process. In this regard, academy courses were viewed by teachers and administrators as a no-lose situation, being that even if students chose not to pursue engineering or another STEM field, they would still benefit from the critical thinking skills they attained. This advantage was noted by an administrator who said, "They may not all want to be engineers, but those skill-sets that they're learning are applicable to any career or anything that they want to try and do in their lives."

Another administrator spoke similarly, asserting that the learning model paid dividends because it carried value outside of the classroom. She explained, "I think one of the strongest parts is project-based learning. I definitely feel like that is more relevant to what they're going to really see in their world and they also have more responsibility in their own learning. I think that they have more relevance so it's more engaging to students."

When reflecting upon the skills they had gained in the academy, students frequently pointed to changes in their thought processes, noting that they possessed more confidence to tackle encountered issues. Said one, "Without the STEM class[es], I wouldn't be introduced to just brainstorming and how we would work through a problem. It's one thing I really liked about the STEM academy, is kind of having the freedom to do and try what we wanted. That's one of the skills I'll take out of this class." Said another, "I like that it's a different way of thinking, like problem solving and it's engineering. It's not just sitting there. It's not boring. You get to do a lot."

Unfortunately, due to the difficult nature of explicitly assessing a student's problem-solving skills, these professed gains went unmeasured. Rather, the success of a team's final product was intended to implicitly correlate its members' abilities to problem solve. Yet this correlation was subject to numerous outside circumstances, and it was unreasonable to assume that a functional device proved quality problem solving skills. To illustrate this point, it is worth considering the manner in which students addressed the obstacles they faced, their predominant approach being trial-and-error. This method of working through projects was highly revered among the students, with responses to the survey statement "The best way to learn in STEM is by trial-and-error" averaging 4.01 (1 = strongly disagree, 5 = strongly agree). This preference for what oftentimes amounted to a lower-order thought process was due in large part to its effectiveness in the courses. Instead of identifying and implementing promising design features substantiated with sound reasoning and scientifically-backed justifications, students had learned that most, if not all, obstacles could be overcome if they attempted enough different design iterations. Explained one student, "I was expecting [coursework] to be a bit more math-based and not so much of the hands-on learning. But I've come to appreciate the hands-on learning more than just sitting down and doing the equations and thinking about it so much, rather than doing some trial-and-error. So it wasn't what I expected but I ended up liking it more than what I thought I was getting into."

Aside from this strategy's lack of need for "thinking about it so much," students employing trial-and-error often consumed excessive amounts of class time for each iteration. In the hovercraft course, it was not uncommon for teams to expend one to two full class periods modifying their devices to try an idea, only to realize that their skirts' holes were still too small or their fan could not swivel freely. During this time, when they were adjusting the size of their skirts or reconfiguring their mounts, for example, the students were acquiring little to no knowledge or skills. It is arguable then, that from the standpoint of developing students' understandings, the hours devoted to this type of physical labor were not an effective use of class time.

Yet due to the relative success the students had been able to attain in the academy projects without first substantiating their designs through calculations or analyses, the learning model was supporting students' manifestations that trial-and-error was *the* way to engineer. That is, they came to view the design process as one in which an engineer evaluates a series of ideas until a benchmark is achieved. One student who shared this viewpoint explained, "I learned that hovercraft design, like engineering, was that sometimes it's not a bad thing to go with the flow and take some risks because it may work in the long run. And you may not know what to do, but it might work and just don't be afraid of putting out ideas out there and if they work, they work. And if they don't, back to step one. But that's just part of engineering."

Unfortunately, this perception of the engineering process prompted some students to again avoid ownership over their work. These individuals alluded to the idea that the performance of their devices was largely dependent upon circumstances out of their control. One such student explained, "It's like engineering's not going to be perfect the first time. That's like the point of this is trial-and-error. And we're graded on our trial-and-error. Like if it fails, we get a bad grade." For this reason, many students noted that the key necessary ingredient for success in the academy was adequate time.

In stark contrast to the vast majority of the class which held trial-and-error in high regard, five individuals believed that this problem-solving strategy did not align with professional engineering. Unsurprisingly, these students tended to reflect more deeply on their product features in efforts to fully comprehend their observations. Several had been exposed to engineering outside of school. At times, these students voiced displeasure over the direction of the course, believing that more emphasis should have been placed on research and the fundamentals behind the operation of their devices. One of these students explained, "But the specific ideas that we've been learning is definitely the trial-and-error . . . I would've rather we worked on calculations in the beginning and seeing if – like for the leaf blower – seeing if the force over area that would support us . . . All the math behind it, I really wish that was more stressed in the classes." Other suggestions included making the project "more scientific and calculated rather than trial-and-error," "to focus more on the background research" because "trial-and-error is not a realistic application of engineering in the real world," and "to do math to figure out the best surface area to weight ratio, so that we could know if a bigger or smaller board would work better for the lift of the craft."

Guidance

"I think that's one thing that STEM teachers struggle with – really most of our project performance is just reflected in the grade. And throughout our project they don't really give too much advice or guidance on what exactly we should improve on in our craft. They just say, 'Well, you're struggling in this area, go figure that out,' and we get the B or whatever it is on the test day. And so if we got more help throughout, I think we would be able to learn from that better."

– Hovercraft course student

The quantity and quality of guidance offered in the academy was one of the more divisive issues among the students. In response to the statement "STEM teachers provide enough guidance during projects," the average response was 3.38 (1 = strongly disagree, 5 = strongly agree). Yet fourteen of the nineteen focus groups students claimed that there were at least some areas in which Ms. Foster and her colleagues could have offered more assistance, while just two claimed that too much guidance was provided (see Table 25). At the same time, twelve focus group students indicated that they enjoyed the level of freedom they received in the classroom, creating a challenging environment for teachers' interventions to be met with appreciation.

Table 25: Focus group participants' comments about guidance

Topic	*# Students*
More guidance desired	14
Enjoy autonomy	11.5
Teachers don't need to provide solutions	10.5
Feedback is unclear	8.5
Important to ask specific questions	4
Guidance should get students on right track	2
Too much guidance provided	2
Quality feedback was provided	2

The students well understood that they would not receive explicit solutions to overcome problems they faced in the classroom (noted by eleven focus group participants, a surprisingly high number since a question specific to this topic was not posed). They did, however, expect to receive more direct answers to their questions, and many felt that there was a lack of communication and feedback from Ms. Foster. One student, in describing her frustrations with this, said, "And when we'd be like, what do you think that we could possibly do, she'd just be like, 'Oh well, just think about it and try to fix it.' And that's just not really the answer I'm looking for."

From Ms. Foster's point of view, and in alignment with the learning model, students were expected to work through the activities nearly autonomously, with little instructor interference. Ms. Foster self-admittedly took a "laissez-faire approach," choosing to offer little guidance towards potentially-successful design modifications, and leaving the responsibility on the shoulders of the students themselves. In response to this hands-off approach, many individuals became frustrated with what they considered to be a lack of attention. It was therefore suggested that Ms. Foster and the other STEM teachers should have been more proactive in the classroom. One student, for example, said, "I think they should go and like try to help out groups more. Like go out and see, 'How's your hovercraft working?' And, 'Do guys have any like questions that I could help you with?' Because it was mostly just, she talked to us on the day of the checkpoint, and if it didn't work, she would say, 'Oh you need to try and reduce the friction,' or something. . . . we were kind of on our own."

Yet providing an appropriate amount of guidance was a delicate balance between ushering students down a suitable path versus challenging them to think critically for themselves. Due to the students' wide-ranging abilities and motivations, this balance varied team to team, and identifying the point at which to intervene was not well-defined. While some shared in the viewpoint, ". . . I think it's something really important, for us to learn how to fend for ourselves," others were quick to point to a lack of guidance for their underwhelming product performances.

Finding this balance between freedom and guidance was an issue with which all academy teachers struggled. Students were expected to apply their understandings to proceed through projects to the best of their abilities, but identifying the point at which teams could no longer make effective progress was an inexact science, and one that was not always correlated well with the manner in which students sought out help. That is, some individuals, by their nature, were disinclined from asking questions – either due to pride or shyness or an unwillingness to disclose their misunderstandings – while other were over-reliant on instructors and put forth little effort to problem solve on their own. Complained one teacher about this issue, "It's like I don't know how much to tell them and how much to clue them in on and how much to even teach them. We also are not a hundred percent sure how much we should teach them about building this thing, or is that something that they should explore on their own?"

Further compounding the situation was the vast amounts of time that students commonly consumed while exploring various designs. This teacher continued, "And then, with our time constraints, will they even be able to complete their project unless we teach them this but we want them to learn about on their own?" Ms. Foster often questioned the same issue, wondering if it was worthwhile to allow students to pursue ideas that were clearly bound to fail, but would have provided an "aha" moment. Learning from one's mistakes was a critical feature of the design process, but this often came at a cost, notably the time expenditure and frustrations that accompanied failure. On the other hand, leading students towards a successful end product to build their confidence and provide them with a positive, fulfilling experience did not always align with challenging them to construct their own knowledge by thinking critically through problems.

Gender issues

"I think to some extent when they're in there with a bunch of boys, especially ones that are unfocused, it kind of sours their taste of what engineering is. I've had some kind of tell me that in the senior class. While it's okay for the program to help some people decide that that's not what they want to be, I don't want the program to be the reason why they don't consider it [engineering as a career]."

– Academy teacher, on issues faced by female students

This case study did not intend to identify differences between males' and females' classroom experiences, yet there were substantially fewer females in the class (just 12 of 39) and these individuals tended to have a less favorable view of their experiences in the program (as shown in Table 26). A few key outcomes emerged that compel elaboration on the subject.

Table 26: Survey items with clear gender differences

Statement (1 = strongly disagree, 5 = strongly agree)	*Females*	*Males*
STEM courses are too difficult.	2.59	2.12
There should be more science and math in STEM courses.	4.18	3.62
STEM teachers provide enough guidance during projects.	3.09	3.50
I'm glad I joined the STEM Academy.	3.36	3.88

First of all, the female students in the hovercraft course were clearly less apt to engage in hands-on work, particularly in the fab lab when power tools were made available. In the three mixed-gender groups, the males completed the vast majority of the builds though they themselves did not possess any more construction experience than their female teammates. The two all-female teams, as pointed out by Ms. Foster, were consistently behind their classmates, their devices failing to achieve even a moderate level of success, owed largely to their inhibitions with construction.

Accordingly, the female students found the academy courses to be more difficult than did their male counterparts. Due to this perceived difficulty, the females believed that a greater degree of teacher involvement was necessary. In addition, they were less satisfied with the amount of science content included in the coursework, many of them having enrolled out of interest in the sciences. Suggested one of these students, "Add more diverse classes... the only representation in this academy is the E! so we can get more science classes because a lot of students want to do things that involve more science."

Lastly, whereas several male students frequently identified their classroom experiences with those that existed outside of school, the females were less apt to do so. This discrepancy was most prevalent during the focus group interviews when the topic of authentic assessments was discussed. Eight males noted that they appreciated the product performance grades. They compared these measures – particularly the competitive component – to the engineering profession. Explained one, "Overall in other STEM classes that I've had, it's been fair because if you failed, well you blew your shot. You just lost to a competitor and now they're going to sell their design to a company."

In contrast, several females pointed out that they were adamantly opposed to competitive grading, claiming that they were not comfortable being compared to their classmates. One such individual stated that some of her peers simply "have the gift of engineering," and it was unreasonable to expect her to compete with these students. The females much preferred grades based on their efforts rather than their product performances.

Creativity

". . . not enough groups took enough risk with their designs to try to come up with something totally out of the ordinary. . . . they would see that one idea would work and so they would start to scrap immediately what they were thinking of doing [so they could make] something that they knew would work."

– Academy administrator

A final issue that should be addressed is one of creativity. Although this topic was highlighted by six academy leaders as a key strength, just three of the nineteen focus group students mentioned creativity as a beneficial feature of the program. The administrators' and teachers' view of creativity was thus vastly different than the students', and several study participants pointed to specific classroom practices which limited greater appreciation for this critical component of real-world engineering.

As part of their problem-solving strategies, students often relied upon ideas from classmates, past students, and the internet for design ideas. Rather than brainstorming for novel ideas themselves, they were more motivated to produce items that worked, spurred in large part by their orientation towards task completion. Remaining on schedule and achieving performance benchmarks was highly stressed in the classroom, and those who chose to pursue untested designs were at risk of falling behind. In some cases, teams were actively encouraged to rely upon outside sources. A teacher spoke on this topic, explaining, ". . . I said [to the students], 'Use the internet for ideas, there are ideas out there, you don't have to re-invent the wheel, you want to make it a little bit better and see how you can apply it."

It was often the case in the academy courses that when a team did incorporate a novel and effective idea into their product, it was imitated by a number of teams. After the first craft demonstrated quality propulsion, for example, others began to carefully inspect its design, and over the next several days, some crafts began to more closely resemble one another. Another team of students, the first to incorporate a Lazy Susan-type turntable into their design, commented that their idea was soon adopted by many of their classmates. An excerpt of this discussion is shown below:

> *Student A*: We get feedback from . . . others, and like that's good-
> *Student B*: And they try to help us, and we try to help them I guess. And you just even see a lot of things that work and don't work and-
> *Student A*: As soon as people saw us use the Lazy Susan, everybody-
> *Student B*: Yeah, everyone hopped on that bandwagon to use that.
> *Student A*: I guess that's kind of the point of this class.

The academy's assessment structure pushed students to pursue proven ideas. A team which may have generated a well-thought-out and original product, but one which ultimately failed to function, would not have earned a quality performance score. A student mentioned this issue in the end-of-course survey, writing, "I almost feel like you're punished for trying new ideas, because new ideas seldom work, and you're graded on performance." Because the grading system did not reward students for risk-taking or thinking outside the box, teams were reluctant to try new ideas. In the hovercraft course, this fear of failure was readily observable, as many students were seemingly unwilling to implement a design feature until it had first been proven by another, a point brought up by Ms. Foster.

Still, the academy teachers desired to establish a learning environment that cultivated creativity. In fact, the importance of creativity was offered as justification for the lack of traditional written assessments. That is, to allow students to autonomously explore unique areas of interest, it was deemed necessary to promote investigations of creative and untested ideas, and this was seen to stand in opposition to learning discrete facts and procedures. A teacher explained, "In the STEM program, I feel like our intent is to make them be creative. We want them to ask questions. We want them to be inquisitive. We want them to explore. We want them to be interested in solving their problem and interested, along with that, engineering. And so there isn't necessarily a structure for that. And I feel like that goes along with the intent for them to be creative and not give them like, well now we're going to say you have to do this test and you have to know these facts and you have to know this."

CHAPTER VII

FINDINGS

The findings outlined below provide a framework for the practical benefits and limitations of project-based learning, with regards to the manner in which it was implemented in the course under study. Detailing the progress of a specific course in earnest is intended to provide educators with an understanding of the contextual factors at play within a design-based high school engineering course, allowing for awareness of potential pitfalls that should be taken into consideration and helping to shape realistic classroom expectations. A well-founded understanding of these characteristics, which help define the boundaries of the learning model's capacity to advance student abilities, have permitted academy leaders to more justifiably implement curricular changes. It is hoped that this insight will support the design and modification of similar STEM-focused courses such that the expectations of all of those involved – most importantly, the students – are met.

Research question #1: What were the perceived and potential benefits?

The perceived and potential benefits of project-based learning, as observed in the case under study relative to the academy and course goals, are discussed below. Table 27 summarizes these benefits.

1. *Positive experiences:* In general, the students were satisfied with their decisions to enroll in the program. They responded with an average of 3.73 in regards to the statement "I'm glad I joined the STEM Academy" (1 = strongly disagree, 5 = strongly agree), with just three students in disagreement (although, to be fair, many individuals noted non-ideal reasons for remaining). As intended by the original design of the hovercraft course and the academy curriculum in general, the students often engaged in activities that resulted in positive experiences. The classroom freedom provided by Ms. Foster, in her efforts to generate an open learning environment, was highly prized by the students, and they appreciated the opportunity to manage their projects as they deemed appropriate. Teams were able to work at their own paces so long as they met various progress checkpoints, replicating the engineering profession and requiring that time management

skills be developed. This openness was a critical component of the inquiry-based classroom since it permitted those motived to engage with the course material to do so through their own endeavors, helping to promote self-reliance. Particularly during phases of craft construction and performance testing, students were highly involved in the classroom. For example, some teams chose to begin working before the bell rang and needed no instructor encouragement to stay on task for the duration of each ninety-minute period. However, most of their enjoyment was derived from hands-on work, which was not often related to professional engineering. During instances when students were tasked with researching hovercraft fundamentals, carrying out procedural experiments, and compiling data, for example, they were often disinterested in fully participating. While the learning model showed great promise for motivating students to delve into projects (as supported by the literature), the students were not exposed to a true sense of engineering, as many equated engineering to one of building and/or the trial-and-error process, and several individuals noted that they lack a clear sense of the profession. It is therefore necessary to create stronger ties between the physical projects and math, science, and the use of technology during the development of projects.

2. *Inclusive learning environment:* Students with wide-ranging backgrounds, language capabilities, math skills, and science-based understandings were all provided an opportunity to succeed in the course since it was possible to create a working product without prerequisite understandings or skills. Like all academy courses, any content that was deemed necessary for completing assignments was explicitly covered. Similarly, students were not rigorously assessed on their abilities to, for example, build to specification or generate professional CAD drawings. Individuals who would have normally been excluded from partaking in engineering coursework were able to engage in hands-on, group-based projects, introducing them to a new way of learning and interacting with others. An administrator praised this accessibility, noting that second language learners and special education students were able to prosper in the project-based learning model. She added, “We have some students that are on the autistic spectrum that are quite successful within the STEM

Academy. They wouldn't be anywhere else. They wouldn't be accepted as readily for their talents and their skill-sets. And they're also learning those social skills that they need." However, this inclusiveness lowered the bar of expectations, and individuals' weaknesses in key areas – including many of the skills described below – limited Ms. Foster's ability to delve deeper into the underlying fundamentals. In addition, the pace of the course moved along slower than Ms. Foster expected; had the students been proficient in scientific investigations, for instance, the product design phase could have been carried much more efficiently, allowing for a more professionally-relevant experience. Thus, while the learning model can be employed to engage a classroom of students with very different competency levels, doing so is likely to diminish an instructor's ability make connections to content that is developmentally appropriate for all.

3. *Course goals:* The learning model's applicability towards the course learning goals, as noted by Ms. Foster and supported by the Academic Standards of the academy, are described below:
    a. *Science content knowledge:* While Ms. Foster attempted to bring relevant scientific concepts into the course, this did little more than "expose" students to new ideas, as it was not necessary to truly engage with the content in order to successfully complete the project. Importantly, students were not seen to discover and learn new knowledge as they engaged in the design process. The lead-up activities and project did, however, provide an opportunity for students to apply and reinforce math and science concepts (again, provided that these concepts are directly applicable in the project).
    b. *Science investigation skills:* Because the groups were compelled to work through issues with little instructor interference, there was an overwhelming belief from all study participants that gains in critical thinking skills were a significant outcome of the course and the academy in general. Students asserted that they possessed greater abilities to address problems, both those presented formally through project requirements and those which unexpectedly arose during the engineering design process. Because Ms. Foster hoped that students would become more adept at drawing conclusions from collected data and applying this knowledge

in their projects, she structured the preliminary prototype activities as a means for students to gain experience with conducting controlled experiments, taking measurements, and analyzing data. However, during the initial design phase, many teams simply chose to ignore the findings from the class-wide data in favor of problem solving through less desirable techniques. Likewise, though the students were given the opportunity to conduct experiments and collect data at any point during the project, none of the thirteen teams did so, revealing that the students placed little value on a more disciplined and strategic approach. In order to ensure that students engaged in disciplined inquiry – a key component of critical thinking – it would have been necessary for Ms. Foster to mandate that students' support their design decisions be supported with hard evidence, forcing them to conduct further research, continue to run a number of controlled performance tests, and compile sets of measurements, the very types of activities that students had complained about in the beginning of the semester. Such a curricular modification would have diminished the openness of the learning environment, but the students had repeatedly demonstrated a lack of mindfulness as they chose suboptimal problem-solving approaches and decisions.

c. *Math skills:* Like the potential for science content, the learning model provided clear, relevant opportunities to connect the importance of proper measurement, mathematical computations, and data analysis. But in large part due to some individuals' limited abilities and the emphasis placed on positive experiences, the students were not required to carry out their projects in manners reflective of professionals, thereby negating opportunities to create designs with clear dimensions and build to these specifications, to compile and organize performance data in spreadsheets, or to identify trends relating dependent and independent variables. Ideally, math could be used to predict product performance in an engineering classroom, but this is not often easily accomplished with products designed and created by high school students. However, collecting and analyzing experimental data is always possible with physical products, and tapping into this available opportunity is a major advantage of the learning model. But again, this was only seen to take place when mandated by the instructor.

d. *Building skills:* The project provided students with opportunities to gain experience with prototype construction and the use of power tools, features of the course that highly engaged the students. Although it could be argued that such work is not professionally relevant since practicing engineers typically do not build products themselves, gaining a clearer understanding of the manner in which products are created provides designers-in-training with better insight into benefits of the prototyping process. It is important to note that students' crafts often failed due to poor craftsmanship (as opposed to poor designs); devoting more time to their woodshop skills would have likely yielded improved performances and less frustration, but this is time that cuts into more professionally-relevant activities.

e. *Teamwork:* Although several individuals acknowledged that they were initially averse to teamwork before entering the academy, the students learned to value and enjoy working alongside their peers, a key feature that generated positive experiences in engineering. Many had come to view teamwork as a necessity for completing complex projects, and recognized the significance of interdependence, believing that their project outcomes were of higher quality than would have been achievable working in isolation. The most natural team strategy employed by the students was task delegation, as it was often impractical for teammates to work on an individual task, and labor division was viewed as a more efficient manner of completing individual assignments. As a result, the students attained less collaborative experience than intended. Still, the learning model demonstrated great potential for developing students' abilities to work in teams – a key academy strength, as noted by the teachers, administrators, and students.

f. *Creativity:* Although one of the purported strengths of project-based learning is the opportunity for students to seek creative pathways towards project solutions, this was not seen to hold true in the hovercraft course. Because students were graded on their product performance, they were reluctant to pursue novel ideas, instead choosing to push forward with more conventional design features. While it is important that students gain an appreciation for project management and find satisfaction in the successful completion of a project, they should be rewarded for ingenuity.

Table 27: Benefits of project-based learning in the hovercraft course

Academy goals	*Perceived benefits*	*Potential benefits*
Positive experiences	Good, but highly dependent upon hands-on activities (rather than engineering tasks)	Good, if math and science content can be better connected to project
Inclusiveness	Good, all students given opportunity to successfully complete project	Limited, if higher-level concepts are included
Course goals	*Perceived benefits*	*Potential benefits*
Science content knowledge	Poor, students "exposed" to content, mastery not required	Good, for reinforcing concepts directly connected to physical product
Science investigation	Poor, students chose non-ideal problem-solving strategies	Good, if instructor mandates disciplined inquiry and design justifications
Math skills	Fair, relevant math tasks completed, but students did not rely on math during design or evaluation	Good, provides context for collecting and analyzing experimental data
Building skills	Fair, building seen as highly engaging, but students not held to rigorous standards	Fair, developing building skills should not overshadow more important engineering skills
Teamwork	Fair, students worked together, but typically delegated tasks	Good, but necessary for instructor to compel students to truly collaborate
Creativity	Poor, students reluctant to try novel ideas due to emphasis on product performance	Good, if students rewarded for ingenuity

Research question #2: What obstacles prevented expected achievement?

Although the centerpiece of the learning model – product construction – provided the course participants with an enjoyable, unique experience, it also presented unwanted influences. The ubiquitous prospect of hands-on work tended to detract from students' ability to focus on presented course material, overshadowing their original motivations for enrolling in the academy, most importantly, their interests in math, science, and engineering. As noted by the focus participants, very few joined the academy out of a desire for hands-on work, and none of the nineteen expected the products to play such a large role in the classroom. By their third year, they had become accustomed to spending the vast majority of their time assembling, modifying, and testing physical devices, and the teacher's attempts to deliver lessons on related math and science content were commonly met with disinterest, many individuals perceiving such procedures and content to be an infringement on their build time.

The central tenet underlying constructionism – that hands-on work supports engagement with and comprehension of associated content – was therefore not widely demonstrated under the conditions of the course. Students did not perform well on the formative assessments, worksheets, or warm-up problems, partly due to an overall lack of motivation to complete this traditional written work. Math and science content was indeed desired by the students, yet to provide adequate motivation to engage them in the material, it was necessary for quality product creation to demand mastery of incorporated disciplinary knowledge and skills. All five of the teachers and three of the four administrators noted that there was a clear need for more math and science incorporation. But from the teachers' standpoint (noted by two of the administrators as well), doing so was inherently difficult, in part because completing high school-accessible projects did not require practices such as mathematical modeling and physics-based analyses. The utility of delivered content therefore fell short of expectations, and it was entirely possible to create functioning devices through "tinkering" without any application of technical knowledge. Lacking a critical need to develop understandings of particular concepts or procedures, students had little incentive to learn the material. This falls in line with the How People Learn framework, in which Bransford et al. note that generating enjoyable environments may increase engagement, but engagement does not guarantee the acquisition of knowledge or skills.[19]

In some cases – depending on the connectedness of a particular task to a presented lesson, the teacher's level of guidance, and the awareness of a student – hands-on work did reinforce course content. This was clearly evident during the first progress checkpoint in which students were required to calculate their hovercrafts' centers-of-mass before finding it experimentally. Students noted the clear connection between the two tasks and many pointed out that this checkpoint was worthwhile. Conversely, though the students observed the effects of pressurizing their crafts' skirts and later completed a worksheet about pressure, several complained about a disconnection because they were not required to apply and verify any pressure-related concept. Reinforcement of discussed content took place when students were able to physically observe the phenomena, but more often, the hands-on aspects of the project simply served to motivate students to focus on creating products capable of passing performance benchmarks, regardless of the application of their understandings. As supported by Slough and Milam, hands-on work did not necessarily support "minds-on" efforts.[118] Resultantly, many students did not come to discover new knowledge through their endeavors, contradicting a purported benefit of open-inquiry in a learner-centered classroom.

Not only were there few math and science content pieces integrated into product designs, students generally eschewed the importance of disciplined inquiry practices such as prototyping, experimentation, and data analysis in favor of "winging it." Student-built products were therefore not so much engineered as they were created through iterative processes of trial-and-error. This common classroom practice presented a wild misrepresentation of the engineering profession, an implication being that engineering equated to "building stuff," with little forethought required for generating workable solutions. One outcome of this approach to problem solving was the belief (noted by 17 of the 19 focus group participants, and supported by the quantitative survey) that the academy was unchallenging.

In truth, much of the content to which the students were exposed did contain challenging concepts, but the students were not required to demonstrate understanding of these underlying issues. The students' written accounts and presentations, expected to represent real-world engineering practices, accomplished little more than provide surface accounts and ambiguous descriptions of their design processes and project outcomes, yielding little valuable insight into their abilities. Similarly, finished products – intended to serve as authentic assessments – consequently fell short of providing teachers with adequate information for evaluating student understanding. Not only were few disciplinary concepts integrated into teams' designs, student achievement of engineering learning goals needed to be inferred from their products' appearance and performance, an impractical task. The authentic assessments therefore needed to be supplemented by traditional assessments; as Chappuis et al. suggest, while performance assessments (including presentations) may represent professional practice well, it is not feasible to conduct such assessments for every individual in a course.[27]

It must be recognized that physical products cannot tell the full story of student learning, as it was possible for a team to create a working product with little content or skill mastery. Similarly, failure to achieve a performance benchmark may have been attributable to, for instance, a student's inexperience with construction tools rather than a misunderstanding of disciplinary concepts. This was made clear by the students' attitudes towards the grading policy of the academy, in which a plurality of them noted that grades were generally unfair (15 = unfair, 13 = fair, 7 = so-so). Students in disagreement with the policy pointed out that there were too many uncontrollable circumstances (e.g., teammates' efforts, poor building materials) to yield accurate grades of their own abilities and contributions. During the academy's curricular design phase, it would have been wise to take into consideration recommendations put forth by Wiggins and McTigue, proponents of the "backward design" approach to creating cohesive educational units, who asserted that assessments must pass the following questions to truly align with the learning goals an instructor intends to measure:[137(p.53)]

1. *Could students do the proposed assessment well but not really have mastered or understood the content in question?*
2. *Could students do poorly on the specific assessment but really have mastery of the content in question?*

If the academy's performance assessments in their current form were held to these high standards, it is unlikely that many of them could be used, since ensuring that the physical outputs of students perfectly represent their intellectual capabilities is not reasonable. This is not to indicate that the academy courses should have been without progress checkpoints and performance benchmarks; such assessments helped keep teams on tasks and created an authentic environment. But these measures did not disclose sufficient evidence of student learning or non-learning, and should not have constituted a large component of the assessment structure. This discrepancy was noted by two of the administrators, one who questioned, "[Are] our assessments actually measure what we're wanting them to learn?" Rather than asking, "How can we measure this?" – a common question that drives assessment[108] – Ms. Foster needed to consider what areas were worth measuring and to determine what it was that the students were to learn be completing the project, as it is common in project-based environments for teachers and students to lose track of the real goals of the coursework.[11,118]

The hands-on aspect of coursework did help with retention to a degree, but this retention was not always ideal. In some cases, students chose to remain in the academy solely for the enjoyment of product construction. And as pointed out by a teacher, ". . . I think that may even increase their numbers because students hear that it's easy and you get to play with the computer and do games and, you know, it's not that hard, and you just build stuff." At the same time, the heavy emphasis on physical work deterred others, particularly those more interested in the application of math and science. Hands-on work thus failed to engage students in the expected manner, arguably encouraging students ill-suited to the field while discouraging potential future engineers who preferred more abstract learning.

The group-centeredness of the academy presented additional issues within the learning environment. Partly due to the emphasis placed on task completion, project responsibilities were often divided among team members and worked on in isolation. While task delegation is an important facet of teamwork, students habitually chose to work within their comfort zones when given the opportunity, meaning that students avoided developing their weaknesses – oftentimes in areas of mathematics, computer-aided design, and fabrication – deferring to teammates who possessed more experience in these areas. Low-achieving students thus commonly became overly dependent upon their peers, which resulted in very dissimilar skill-sets among students at the same grade level. Furthermore, by delegating responsibilities intended as group work, students did not practice collaboration as intended. That is, all members of a group did not necessarily contribute to the decision-making process required of complex problems.

In some cases, hard-working students came to be exploited by those less motivated, a common issue in team-oriented classrooms,[65] and the issue exacerbated by the grading policy of the academy. The teachers deemed it impractical to evaluate students in action due to a host of logistical issues, meaning that participation and collaboration went largely unassessed, and individual contributions of group-generated work could not be easily identified. The teachers were therefore limited in the capacity to extrinsically motivate individuals by use of the gradebook.

Although in an ideal world, the success of students' products would reflect their abilities and efforts, this did not hold true since product performance was dependent upon a number of factors, including the conditions surrounding a project and its particular constraints, the availability of tools and supplies, and the quality and quantity of guidance. Many course participants, sensing that these outside factors played a dominant influence on their work, were quick to point elsewhere when their devices failed to meet expectations. For example, the following excuses surfaced in the course under study:

- A teammate did not contribute or made poor decisions
- A particular math or science course had not been taken yet
- There were physical circumstances that did not allow for envisioned designs to be created (e.g., a lack of adequate materials)
- Initial attempts in the trial-and-error process had yet to succeed, so more time was needed
- Insufficient guidance was offered by the teacher

Students were thus predisposed to redirect blame elsewhere when faced with challenging problems, an outlook that led some individuals to avoid taking ownership over their work. To at least mitigate the complaints about poor teammates, teachers often allowed students to choose their own teammates (which unfortunately led to behavioral issues and groups of vastly different skill levels). This mitigation strategy was explained well by a student who said, "When you pick groups, you know how the people are like. So if things don't work out you can just be like, 'Oh, it's my fault because I picked them.' And you can't blame the teacher and be like, 'She put me in this group, that's why this happened.'"

Research question #3: What tensions were generated?

Four key areas of tension existed within the academy, inhibiting the teachers' abilities to design lessons and facilitate classes in such a way that the needs of each of their students was met. These seemingly incompatible academy features are outlined below.

Positive experiences and Inclusiveness vs. College preparation

Engaging students in "fun" engineering activities through hands-on work and providing a learning environment accessible to students of all ability levels consistently conflicted with goals of college preparation. While product construction did not unavoidably necessitate that content be minimized, the reality was that math and science were indeed de-emphasized. The students largely viewed lectures, research, discussions, and procedural labs as unexciting relative to product construction and performance testing, and academy leaders feared that if more content were included, the program would become too rigorous and exclusive, diminishing the opportunity for lower-achieving students to pursue engineering. As a result, the teachers limited their coverage of math and science. This general lack of core content is not unique to this particular case, as it has been previously noted that students engaging in project-based classrooms seldom engage in deep mathematical modeling and often have a less rigorous understanding of the underlying fundamentals.[94,103,129]

In a similar vein, traditional written homework and tests – an effective manner by which individual understandings could be objectively assessed – were perceived to conflict with the goal of cultivating affect towards engineering. Yet without such measures, teachers lacked leverage for motivating students to focus on developing their knowledge bases and technical skills. By jumping into projects without solid understandings of related fundamentals or investigative skill-sets, students generated designs with little supportive validation and addressed problems through undisciplined inquiry. Although such efforts had proven successful in past projects, the students generally struggled to identify functional hovercraft designs, with just four of thirteen teams able to create working devices. Ironically, the overemphasis placed upon enjoyment at least partially accounted for poor output, leaving the majority of students dissatisfied about their accomplishments.

Guidance vs. Autonomy

Fostering ingenuity was a delicate balance. On one hand, Ms. Foster attempted to compel teams to work through their own problems by offering substantial project autonomy. On the other, it was necessary to guard against student frustrations, caused by frequent futile endeavors and slow progress. The level of freedom provided in the classroom was intended to promote knowledge discovery and represent an authentic working environment, but the students were unlikely to "stumble upon" new understandings as they engaged with the project, nor were they likely to connect their observations with presented course content. Only through the teacher's interventions were they forced to think in terms of the related fundamentals. In addition, students were often unable to overcome encountered challenges, thereby necessitating further guidance. By asking eliciting questions, offering hints, and providing feedback, the teacher was able to address these issues, yet in doing so, the onus of learning shifted from student to teacher, and opportunities for individuals to problem solve on their own were diminished.

Moreover, it was entirely possible for a team to gain valuable experience and develop practical skills while also creating a product that utterly failed. If students had been more oriented towards mastery – as put forth by the achievement goal orientation theory[35] – their perceptions of engineering would have been less dependent upon achieving performance benchmarks. However, as noted by Harlen, the manner in which a teacher presents a task heavily influences students' motivation,[56] and by focusing on the daily tasks to be completed, Ms. Foster inclined the students more towards performance goals. As such, it was necessary to help students improve their products' functionality to ensure they viewed engineering in a positive light.

The crux of the guidance situation falls upon identifying a suitable amount and type of assistance to offer students, as well as an appropriate time at which to provide it. These decisions are often challenging because every individual possesses a different level of ability, self-regulation, and motivation. Offering too much guidance may hinder students' abilities to work independently, making them overly dependent upon the teacher. Yet compelling students to become self-reliant by offering too little guidance increases the potential for product failure, which may lead to frustration, diminishing students' positive experiences in engineering.

Collaboration vs. Individual accountability

Obtaining an understanding of and appreciation for working in concert with peers was perceived as one of the most prominent strengths of the academy. The vast majority of assignments were group-based, intended to compel students to depend upon one another, learn from one another, and gain a better sense of the social aspect of professional engineering. But as was often the case, students divided project tasks according to their strengths. Which such task delegation is indeed representative of an engineering workplace, professionals spend years honing their skills and typically work within their respective areas of specialty. Students, on the other hand, must first develop these skill-sets, and to do so, they should be expected to engage in all facets of a project, including the design, fabrication, evaluation, and any calculations or data analysis which can help support decision-making.

In addition, due to the challenges inherent in determining the individual contributions in group projects, as pointed out by Zhang and Ohland,[140] students were not held accountable for their own work. Less motivated students were thus able to work only in their areas of interest, which tended only to be the hands-on coursework, while eluding tasks that typically required skills more representative of those required by engineers. In some cases, individuals wholly relied upon their teammates for completing the vast majority of the assigned work, a common problem in similar settings.[65] Individual assignments were seen as a means to improve accountability, but the collaborative nature of the academy prevented the teachers from relying heavily on such measures.

Although there was an understanding among the teachers that knowledge and skill acquisition was important for the students' development, there was concern that time devoted to these areas would diminish teams' abilities to complete complex projects, illustrated in the following teacher's comments about a third-year course: "It would be nicer to have the junior-level classes a little bit more . . . rigorous in the build, where they have to learn a few more skills to be able to build well. But it's hard to put that into a semester-long class where they have time to really kind of develop those skills." Availability of class time was thus a major constraint on supporting both individual and team-based skills.

Task completion vs. Acquisition of knowledge and skills

The creation of working products was viewed as the predominant purpose of the course, a viewpoint explicitly stressed by the academy assessment structure and implicitly communicated by the teacher's actions. The utilization of products to implement authentic assessments was well-founded, but basing students' grades largely on the functionality and presentation of their devices yielded unexpected consequences. Most significantly, the students came to focus solely on craft performance, often disregarding the importance of the knowledge and skills the crafts were intended to support.

In addition, these assessments did not require students to explicitly demonstrate their attained understandings or skill-sets. Instead, students were simply *exposed* to new areas – related math and science concepts, various engineering design practices, basic computer-based and fabrication tools used by engineers – without being held accountable for mastering them. As long as students were able to complete assignments on time, irrespective of their true gains, they were rewarded. As a consequence, teams often looked for ideas which had already been proven to be successful or relied upon trial-and-error, strategies perceived to be direct pathways to solutions. Conversely, the implementation of untested, unique solutions was seen to be a greater risk, since unverified product features were more likely to fail, resulting in lower performance grades. This mindset did not foster creativity.

Still, meeting deadlines and presenting a finished product to a client is an important aspect of engineering. Providing students with an unending supply of class time and materials to pursue numerous creative ideas would not have presented an authentic environment, a point brought up by a student whose father worked in a STEM-related field. He said, "Because engineering, it's not just some free for all. [I] can't just go out and build whatever I want using however much money I need. That's not the real world and how it works." It was therefore important for students to stay on schedule and work within the time and budgetary constraints of the course, which helped support their time management and organizational skills. And yet, this effort to replicate the engineering field detracted from students' development in other significant areas.

All five of the teachers noted that they prioritized the daily agenda over that of the course learning goals, actions that were consistent with Ms. Foster's in the hovercraft course. But at a large part of this shortcoming could be attributed to the lack of concrete learning goals in each of the courses, an issue pointed out by three of the teachers. As stressed by Dweck, learning goals must be explicitly communicated[36]; four of the teachers stated that they failed to do this.

CHAPTER VIII

CONCLUSIONS

Overview of the project-based learning model in the academy

The academy founders' establishment of project-based learning as the program's educational model was well grounded in that heavily kinesthetic coursework provided a natural corridor into the world of engineering, opening student's eyes to a new way of engaging with subject matter. In many ways, the classroom environment nurtured by the teachers well represented an adaptation of a professional workplace, allowing students to take on more responsibility and developing their self-reliance. Regrettably, clear limitations were exposed in the learning model particular to the manner in which it was utilized, diminishing the expected student outcomes.

The predominant finding realized from this study which adds to the existing body of knowledge challenges the purported benefits of project-based learning and constructionism in general. Specifically, the creation of physical products can be a major deterrent to learning core math and science concepts in an open-inquiry classroom, as students were not observed to discover new knowledge through their independent endeavors. While they may have been highly engaged in hands-on activities, this engagement did not result in improved understandings. *Project-based learning should therefore be utilized as an educational strategy to apply and reinforce students' existing knowledge, not to attain new knowledge.*

This limitation is further discussed in the following two subsections, which compare the idealized version of the academy learning process to that which was observed in the classroom.

Idealized learning process

The project-based model was intended to provide a framework for academy coursework, utilized in conjunction with the engineering design process. The idealized process, illustrated in Figure 28, is detailed below.

A complex problem set within a real-world context provided the setting for each course. A novel solution to the problem, generated by the development of a physical product, was to motivate students to engage in the classroom. This motivation depended upon two important factors: 1) a mastery goal orientation,[35] and 2) a direct connection between presented content and the product. Before delving into the project, it was imperative for students to realize that products served primarily as vehicles for learning, not as an end goal in and of themselves. Then, by compelling students to recognize the significance of applying disciplinary knowledge and skills in the project, they were expected to be driven to learn course content and relevant skills.

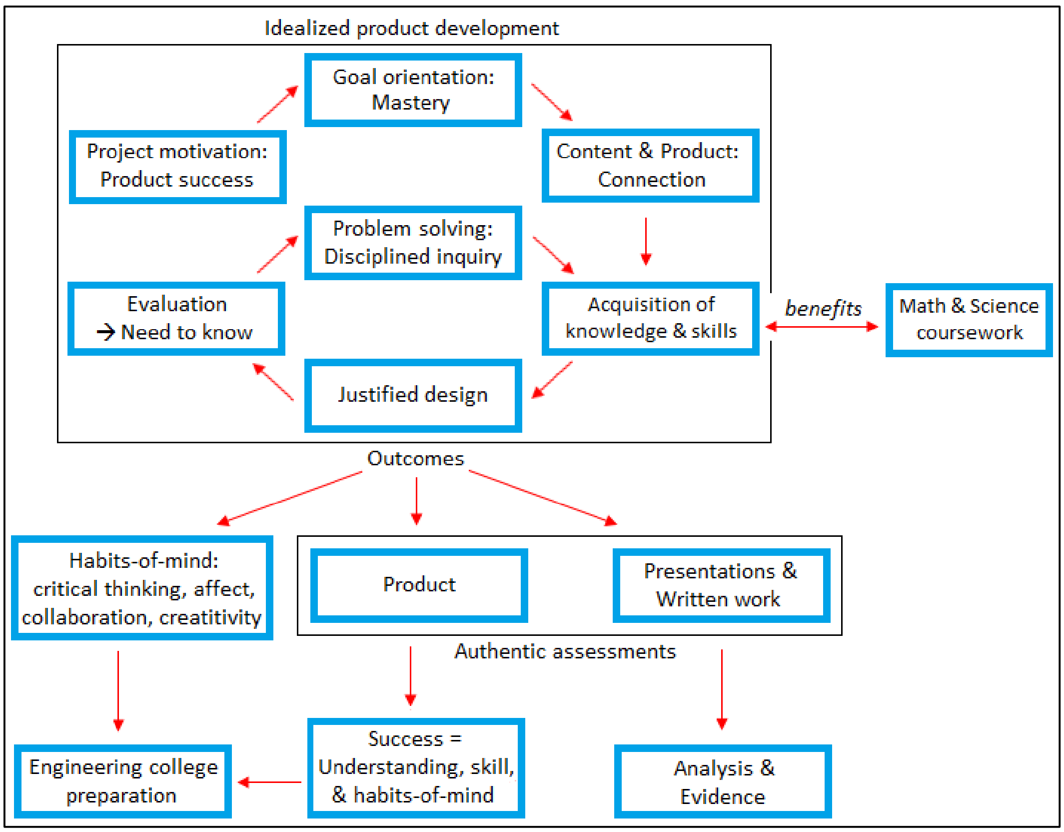


Figure 28: Idealized learning process within the academy

Because design-based projects often require the application of a wide range of knowledge,[28,114] it was important to encourage students to bring their background knowledge into the project (particularly from their math and science coursework) as well as apply newly-attained understandings to establish well-founded, justified designs. By applying this knowledge, their understandings could be reinforced, thereby reciprocating benefits back to their math and science classes. After fabricating initial prototypes based on their designs, students were to evaluate the effectiveness of specific design features and their products overall. Areas in which they fell short should have spurred them to troubleshoot encountered problems, as suggested by

Felder and Brent,[42] accomplished through gathering evidence in disciplined manners and making sound decisions. Previous gaps in knowledge or misconceptions could then be realized and corrected before the next product iteration, falling in line with the constructivist learning theory,[71] which was expected to yield an improved design. These latter steps were to be iterated in an effort to optimize the design, dependent upon available time and resources. Taking all of these contributions into account, students' inquiries were expected to closely follow the steps outlined by the engineering design process.

This process was to yield three outcomes, the most significant being improvements in students' habits-of-mind. The openness and learner-centeredness of the projects were intended to support creative problem solving, thereby advancing students' critical thinking abilities in real-world situations. Likewise, the community-centeredness was to provide students with valuable collaborative experience. And the entirety of the hands-on, group-based experience was expected to improve students' affect towards engineering.

The verbal and written communication pieces and the physical products generated by students were intended to replicate basic engineering work, serving as authentic assessments. Through presentations, written reports, and essays, students were provided the opportunity share insight of the analyses and evidence used to arrive at their final products, including the critical design decisions and actions taken towards optimization. These elaborated forms of communication were to be rooted in the math and science content relevant to the project, allowing teachers the ability to directly evaluate students' understandings and some of the skills they incorporated into the engineering design process, including those in computer-aided design, experimentation, and data analysis.

The physical products were meant to disclose students' abilities further, as the success of a product's performance was expected to correlate well with the level of understanding incorporated into its design. And though only students' fabrication skills could be directly observed by evaluating the products, other disciplinary skills, understandings, and habits-of-mind – most notably those of critical thinking, creativity, and collaboration – could be inferred through evaluation of the product. For example, a team of students could be credited with gaining experience in collaboration because, as noted by a teacher, "If they have a completed project, then they had to have worked somehow together."

Ultimately, successful product performance, attained through applied knowledge and disciplinary skills, in concert with habits garnered through quality utilization of the design process, was expected to generate interest in the engineering field and prepare students for the rigors of college.

Observed learning process

Due to limitations within the project-based model, the idealized learning process did not come to fruition. Rather, the observed learning process, as illustrated in Figure 29, skirted key components of product development, resulting in undesired outcomes.

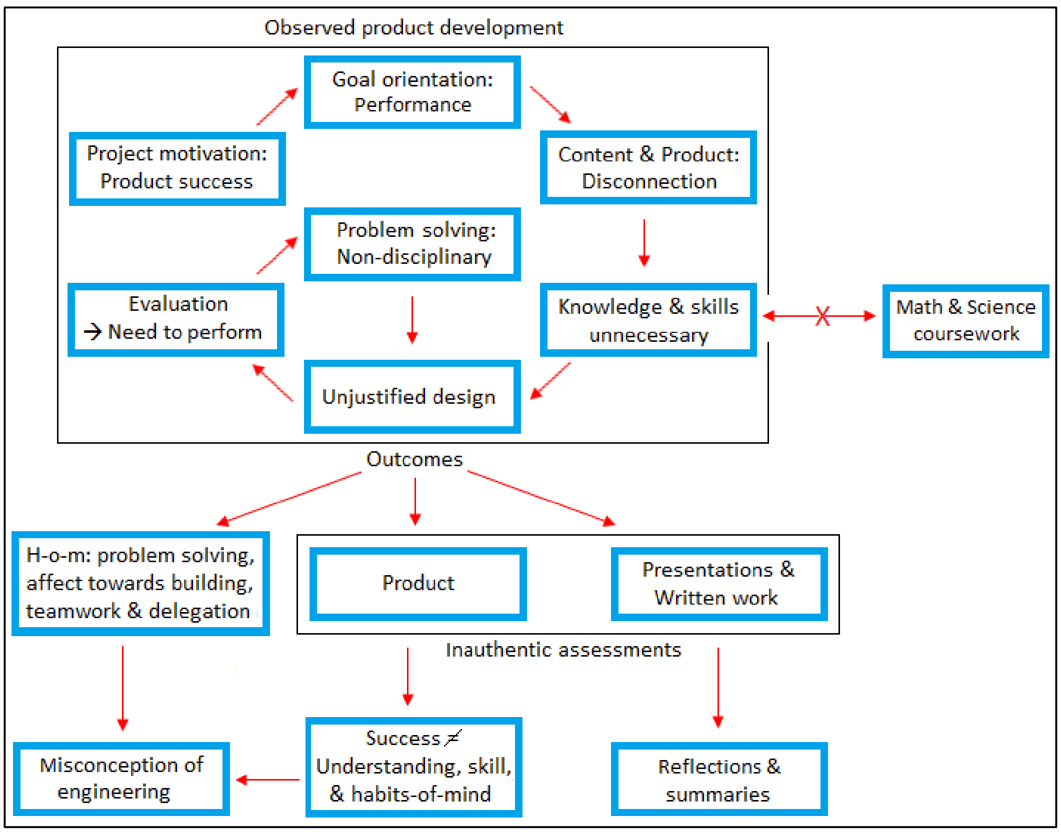


Figure 29: Observed learning process within the academy

The first deviation from the intended process transpired due to the overwhelming prominence given to products, both explicitly through the assessment structure and implicitly through the curriculum. By orienting teams towards performance goals, they commonly sought the easiest routes to meet the project requirements, regardless of educational gains. Students were further influenced by the lack of requisite knowledge or skill application during product development. As a consequence, students were unmotivated to master the math- and science-related content originally deemed relevant to the projects, and were less apt to bring in outside knowledge from their math and science courses. Without reinforcing course content in project work, the reciprocal benefit of supporting students in their math and science courses was weakened.

Lacking a need to apply fundamental understandings to achieve project success, teams had little need to justify their product designs, often relying on their intuitions instead to develop their initial prototypes. After evaluating their products, students were inclined to search for effective ways to improve their performance, often favoring non-ideal problem-solving strategies. These included borrowing ideas from outside sources, relying heavily on teacher-directed guidance, and most commonly, trial-and-error. By taking these measures, students could not necessarily be expected to gain new knowledge or skills, meaning that subsequent design modifications would continue to lack justifications. Although students were often capable of completing projects in this manner, the steps of the engineering design process were not followed as intended.

The outputs from this process were consequently of lower quality. The students did gain experience in problem solving, yet without connections to conceptual understandings or disciplinary investigative skills, the available evidence to support critical thinking was greatly reduced. Likewise, the students acquired teamwork experience, but their collaborations were often weakened by a heavy reliance on task delegation. Due to this division of labor, individuals avoided opportunities to fully develop their skill-sets. Still, students were often engaged in the course, although this engagement was largely due to hands-on activities.

The outputs generated by the students fell short the aims of authentic assessments. The verbal presentations and written work, rather than outlining the details behind selected product design features, were little more than reflections and synopses of project proceedings. This surface communication did not provide the expected disclosure of students' attained knowledge or the methods of inquiry utilized to optimize products. Similarly, the functionality of finalized products offered scant insight into students' applied understandings, nor did it always correlate well with students' demonstrated skills and habits. That is, teams which collaborated well together, utilized relevant data, attempted to draw connections to science-based concepts, and considered the benefits and repercussions of their ideas before implementing them did not necessarily generate well-functioning devices. On the other hand, those who exhibited none of these high-quality traits were still capable of achieving product success. This misalignment, along with a high focus on hands-on work, promoted an inaccurate picture of the engineering profession.

Changes within the academy

Fortunately, the teachers and administrators of the academy, in recognition of the observed shortcomings, were willing and able to make modifications to the curriculum. They acknowledged that the original intent of the academy, which focused more heavily on increasing enrollment and creating enjoyable experiences, needed re-examination. Said one administrator, "I think we've met the needs of what we started out to do, and now we need to raise that bar."

To address some of the weaknesses identified within the program curriculum, the academy leaders instituted several changes within the past school year, all of which highlighted the importance of developing students' individual skill-sets. The most prominent modifications were made to the first-year curriculum, as it was believed that students who were already predisposed to academy courses may not have been accepting of radical changes. The freshman course was expanded from one semester to a full year, much of the additional time devoted to improving students' abilities in the following areas:

1. *Computer-aided design*: each student was held responsible for completing tutorials and generating their own drawings, with heavy focus placed on using accurate dimensions
2. *Fabrication*: students were required to gain experience with measurement and construction, providing an opportunity for them to gain a better understanding of how products are assembled and helping to make the fab lab more accessible to all
3. *Drawing connections between projects and the professional world*: more attention was placed on the authenticity of coursework with the goal that students will have a better understanding of what engineers do on a daily basis
4. *Experimentation*: preliminary stages of projects required more collection of data to better support design decisions, the importance of controlling variables during experiments was stressed
5. *Spreadsheets*: tutorials were offered to introduce students to the basics of spreadsheets, which were then utilized for the collection and analysis of project data

6. *Technical reports*: individuals were required to compose reports that were reflective of professionals and included data tables and charts, summaries of analyses, and elaboration on the reasoning behind design decisions

Although much of the included content still remained unnecessary for creating physical products, the teachers were more cognizant of the need to connect math and science content with the project at hand. Importantly, students were held more accountable for their understandings and accomplishments. Brief content quizzes on presented procedures and concepts were given for the first time in the academy, and tasks were less often assigned to groups, forcing all students to submit their own work. In effect, some activities more closely resembled cooperative learning than collaborative learning. That is, classes were still designed such that students pursued goals collectively, but coursework was more structured to place responsibility on individual achievement.

These actions fell more in line with a shift of the academy as a whole, as it was moving more towards becoming a college preparatory program and away from being an introductory one. Explained an administrator, “And so now it’s become much more of a pressing issue that they are able to correlate the math that’s required for some of these projects and why it’s required and how it’s going to help them. And same thing with the science now, trying to talk a little bit more about the sciences behind what it is they’re doing and why they’re doing it.” Said another, “They’ve definitely done more than we did at the beginning. Oh my gosh, we didn’t do hardly any.” Beginning with the 2015-16 school year, second-year students will no longer have the option to select from a variety of course options; they will all be required to take the same full-year course. The intention of this change is to engage students across a greater spectrum of material while helping to ensure they build consistent, transferrable skill-sets.

The academy’s commitment to inclusiveness is the critical program component which endures as a persistent challenge to improving overall student achievement. While the academy leaders fully appreciate the difficulty of designing and facilitating projects for individuals with greatly dissimilar abilities, they are devoted to serving students across the entire school population. In fact, some noted that the academy should reach out to even more students. In the words of one teacher:

> "This is kind of my big dream of the STEM program, would be to modify it. Because like I said, I think there's kids we're missing. Kids that should be in here. And they're kids that maybe academically they struggle in math or academically they struggle in science or maybe they're not the best writers or whatever. They're missing some of those academic pieces coming in as freshmen so they're not immediately seen as, 'Oh, you're a STEM kid.' And I would like the program to, while allowing [them] to do the group work and the presentation work and stuff, also somehow reinforcing those weaknesses that they have. And kind of getting their math skills up, getting their science knowledge up or their writing skills or whatever so that they're not getting pulled out of the program because they're doing poorly in math. And they're not getting pulled out of the program because they're doing bad in English. That they're being able to be supported by the program . . ."

Meeting the needs of these students while also challenging high-achieving students will continue to present obstacles, but this is the pathway the academy leaders have chosen to pursue, a commendable endeavor. Much like the engineering design process itself, the curriculum will undoubtedly undergo numerous future modifications in an attempt to optimize the learning environment. In recognition of this ongoing process, an administrator declared, "So the work will never be done. We're never going to be done with the STEM academy."

General outcomes of the case study

The lessons learned from the study are intended to provide outside educators an in-depth example of project-based learning in action in a high school environment. It is hoped that the benefits, limitations, and potential tensions detailed above can provide guidance to those interested involved in similar settings. The case study serves not only to support high school curricula and facilitation, but at the college level as well, particularly first-year projects courses which possess many of the same goals as the academy, these being to engage curious students in engineering-like projects and spur their interest in the field, while also building their communication, collaboration, and critical thinking skills.

It is important to note, however, that major differences exist between these types of college courses and those of the academy. From a logistical standpoint, for example, there is not a pressing need that college students complete their project work during class time, which provides a huge boon to facilitation and guidance. Since it is less necessary for instructors to push teams along to keep them on schedule, students are made more responsible for their own work, offering a more authentic environment. From an assessment standpoint, college instructors have more opportunities to meet with teams outside of class to discuss the details of their individual projects and the dynamics among team members. Such discussions allow for any significant problems to be addressed and, importantly, for student understandings, participation, and collaboration to be assessed in an authentic manner, either for formative or summative purposes. Assessments such as these, which are still likely to be viewed as subjective measures, are also less likely to meet resistance, particularly from students' parents.

In spite of these differences, numerous connections can be drawn between the two settings. If product construction is to form the basis of coursework, it is still important to orient students towards mastery goals since the propensity for focusing solely on improving the outcomes of performance tests will exist. And, although college students can be expected to be more committed to their educations, hitchhiking can still be a major shortcoming of group projects. It is critical to address these issues, particularly if project aspects are intended to introduce students to, or reinforce their abilities in, technical areas, as it cannot be expected that all incoming freshman have the same experience with certain tools, equipment, and software. The guidance that is provided and the autonomy that is offered, much like in the academy, presents a challenge for instructors as well, as some individuals will require more assistance than others, although adequate freedom will still be necessary to allow students to work through the engineering design process and learn from their mistakes. Eliciting adequate information about individuals' abilities via authentic assessments is another area of concern for college instructors, since many of the same problems that plagued Ms. Foster and her colleagues are likely to be experienced.

It is therefore important for both high school and college instructors to have a solid grasp of the project-based learning model as it relates to design-based engineering coursework. The following section outlines a framework of the student inquiry process that can aid with comprehension of the learning model.

Pathways of the inquiry process in project-based learning

Based on lessons learned from the case study in conjunction with previous research, it is apparent that achieving engineering habits-of-mind through project-based learning requires that certain student-centered and environmental conditions be met. These conditions are modeled as a series of "filters," each with its own set of constraints, illustrated in Figure 30 and outlined below.

In order to appropriately address ill-structured situations, it is first necessary that the classroom environment be inclined towards learning. If students are overly concerned with reaching performance goals, they are apt to give excessive attention to task completion, making them susceptible to shortcut deep investigations by overly relying on their instincts and through problem-solving tactics such as trial-and-error and borrowing proven ideas from other sources.

Students who are instead oriented towards mastery can be expected to generate initial product designs substantiated by deep knowledge bases and disciplined investigations. If students also possess a degree of self-regulation such that they reflect appropriately upon the aims of a project and demonstrate maturity to work without direct oversight, they hold the basic ingredients for practicing inquiry in a manner representative of professionals.

Conversely, students with limited understandings of underlying fundamentals should not be expected to create designs founded on sound reasoning. And, if incapable of identifying quality design features though disciplined investigations, students will likely have insufficient evidence to justify their decisions. Even for those with adequate background experience, if unable to stay on task without the direct oversight of an instructor, proper utilization of the engineering design process is doubtful. If any efforts are made, these unequipped individuals are prone to relying on the same strategies as those overly focused on performance goals. Thus, for individuals with shallow knowledge bases, unrefined skill-sets, and/or low self-regulation, an inquiry-based environment is unlikely to lead to effective learning. These observed actions in the hovercraft course fell closely in line with findings from other research, principally that students who are involved in explorative learning without thinking analytically,[99] who fail to constantly question, reflect, and re-question,[12] or who do not demonstrate mindful behavior during trial-and-error,[5,76] are not engaging in project-based lessons as expected. Most importantly, there was a greater need for self-regulation practices; students were too often off task, and had Ms. Foster attempted to micromanage each group (an impractical responsibility), this would have misaligned with the openness demanded by the project-based model.[100,135]

Still, students needed more direction from Ms. Foster, a point repeatedly brought forth during the focus group interviews, in which 14 of the 19 participants suggested that guidance was lacking. Nine of these students explicitly noted that feedback from the teacher was generally poor, meaning that Ms. Foster's attempts to create a learner-centered classroom had shifted too far in that direction, and more teacher involvement was important for the students to both create successful products as well as understand the key principles behind their creations.

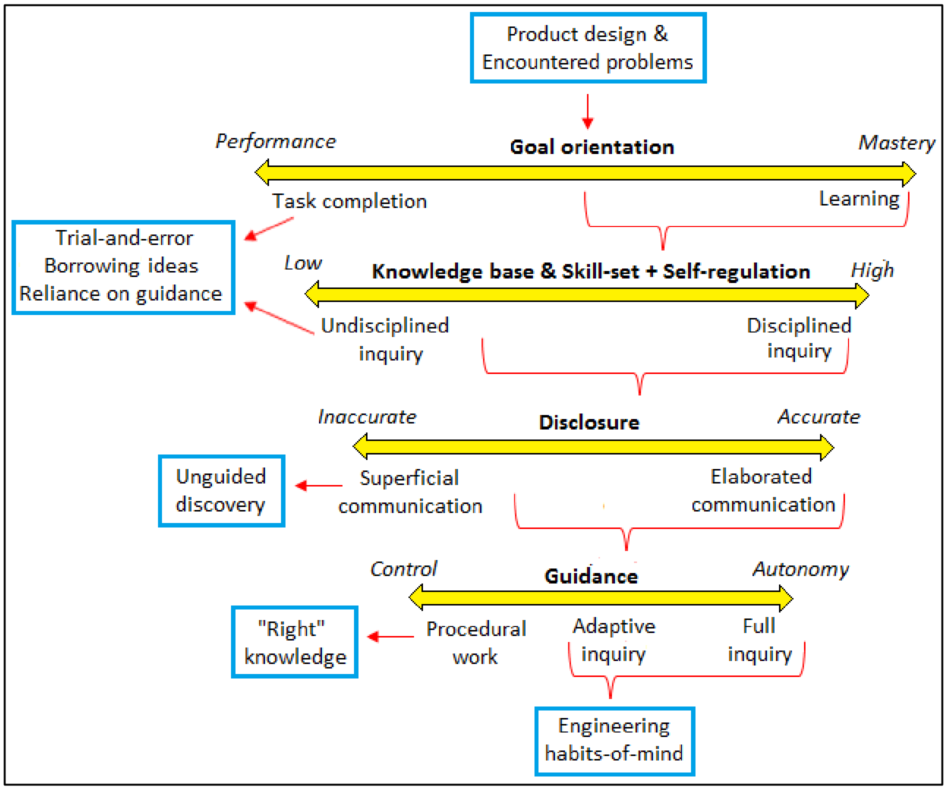


Figure 30: Pathways of the inquiry process in project-based learning

Next, students must be compelled to disclose their understandings, effectively accomplished through forms of elaborated communication. One-on-one and class-wide discussions, written reflections, essays, technical reports, and verbal presentations all possess potential for relaying this information to course instructors, granted that students' applied knowledge and decision-making processes are well-articulated. Although it is possible for an instructor to infer student understandings by monitoring classroom actions and evaluating products, such indirect measures are subject to inaccurate interpretation. Communication which only serves to superficially describe a project and its outcomes are much less useful, as a teacher cannot be expected to correct student misconceptions that are not disclosed.[31] If a teacher's guidance is absent or misdirected, students may venture into "unguided discovery," whereby excessive time is expended while exploring unproductive ideas, heightening the potential for frustration.[106] This issue is exacerbated if students have inadequate knowledge bases, limiting the opportunity for making informed decisions.[52]

The final filter is dependent upon course learning goals. Engineering projects designed to direct every student towards engagement with essential material require learning environments with a higher degree of oversight. Depending on the imposed constraints, controlled projects may in fact be too procedural to truly represent authentic contexts. While this may lead to better understanding of specific content, directing students towards the "right" knowledge both misaligns with project-based learning and is not representative of the engineering field, primarily because real-world problems offer multiple solutions and require broad application of knowledge.[103] Ms. Foster supported this finding, noting that projects could be designed to result in improved understanding of concrete concepts, but called these types of projects "very precise" since they would necessitate procedural actions, as opposed to an open-inquiry learning environment.

Classrooms that offer excessive autonomy, on the other hand, may allow teams to practice "full inquiry," but expecting high school students to come to quality solutions solely through their own endeavors is usually unreasonable, hence the need for teacher interventions.[97] This guidance, intended to steer students towards promising solutions, represents "adaptive inquiry," providing a pathway for students to experience engineering without possessing the capabilities of professionals.[39] Teachers should engage thus in formative practices to make students' thinking visible and scaffold activities to give students a better chance to engage with complex problems.[23,118] Appropriate levels of guidance offer students the opportunity to effectively explore creative avenues, ideally compelling them to engage their critical thinking skills and recognize the importance of collaboration. Deep engagement with projects in this manner, supported by but not wholly dependent upon successful product creation, aims to provide students with positive classroom experiences.

Proposed remediation

The teachers within the academy were presented with a monumental task – to create and improve a four-year high school engineering curriculum while simultaneously teaching both within the academy and in their home departments. Lacking the available resources (e.g., time, training, money) to properly establish a coherent course plan, the courses evolved organically with little oversight. As Ms. Foster's case demonstrated, academy teachers had little available time to prepare lessons and activities, and were free to make changes as they saw fit, and they often did so without consulting administrators, or even other STEM teachers. By comparison, the Project Lead The Way program is constantly under review by educators and researchers, and its teachers receive two full weeks of specialized training for each semester-long course. The hovercraft course, which was taught by yet another new academy teacher in the spring of 2015 (and, again, one without any experience in engineering or project-based methods), resulted in the same shortcomings that were observed during this study. This is not to place blame upon the teachers – their proverbial plates were full with other courses, after school programs, school sports clubs, mandatory professional development, and loads of meetings and paperwork. The assumption that the teachers would be capable of optimizing the STEM courses on top of all of this was not reasonable.

No systematic feedback loop existed to provide teachers with reliable information upon which to base curricular changes. This was in large part due to the assessment policies of the academy; that is, the grades delivered to the students were not reflective of their individual understandings or skill-sets, and without this information, it was difficult for a teacher to note the areas that needed to be strengthened and those which should have been eliminated. At the same time, accurately measuring students' soft skills and habits-of-mind was a common affliction among both pre-collegiate and college engineering courses. In addition, the academy teachers were severely limited in implementing changes due to the ambiguity (and ensuing neglect) of the Academic Standards and Grade Level Expectations. Ensuring, for example, that "Students can use, implement, and fully understand the engineering design process to complete projects" without giving further clarification of what this entailed was a key reason the founding documents were largely forgotten.

While the teachers faced struggles outside of the classroom with regards to curricular development, the challenges posed inside the classroom were even more foreboding. Rather than focusing on the application of math and science, the limited abilities of a large subsection of the students prevented real engineering from taking place. In the academy as a whole, some students were unable to use computers efficiently, some were C students in grade-level math, and some spoke English as a second language.

Providing a further challenge, many students refused to view math and science as an integral part of the academy, and they utterly shut down when these core subjects were broached. Of course, stronger links between the projects and subject matter would have likely improved this situation, but even in projects in which such links were more explicit, some individuals still lacked the motivation to engage in the material. A clear example of this phenomenon regularly occurred in a freshman project whereby the students are responsible for creating a hot air balloon capable of lifting a small video camera. Taking into account the weights of the camera and the balloon materials, as well as the densities of the balloon's hot air and the environment's cool air, the students are given an equation to determine the minimum balloon volume required. It is perhaps the most direct application of math in any academy project. And yet, many students are resistant to learning how to apply the equation, and once they do determine the minimum volume, some teams build balloons that are in no way reflective of their calculations, instead choosing to rely on their gut instincts. Even though this singular equation is taught and applied several times over the course of many weeks, the students struggle to show mastery of it, instead relying upon teammates whenever the equation is presented in class. During the past two years, for example, just 37 of 165 students (22%) have correctly answered a formative assessment question at the end of the unit which asks them to apply the equation.

According to the learning model – and the formative teaching mode in general – the teachers should have identified this weakness during the project and addressed the situation. Yet with the multitude of other classroom activities and the heavy focus on constructing a working hot air balloon, the basic core skills were often overlooked. And, as seen in the hovercraft course, students were much more apt to ask for help when their products were unable to reach expected benchmarks, not when they were unable to carry out computations. Overall, the teachers needed to provide more oversight, though doing so in classrooms of thirty students is arduous.

Taking all of this into consideration, key areas of remediation for the academy include the following (these recommendations also hold true for educators planning to initiate similar programs):

1. *The title of the program should be very clear*. By calling the academy a "STEM" program, students were preconditioned to believe that they would be engaging in classes more akin to those they had

taken in math and science. Because the program is meant to prepare students for engineering, it should be labeled as such. On the other hand, if a program is designed to engage students in hands-on work that may improve their critical thinking and collaborative abilities, but does not entail a large degree of math and science, it should not carry the title of engineering.

2. *Teachers should be solely devoted to the academy and given adequate training and time (and compensation) for further development of the curriculum.* By splitting time between the academy and other departments, the teachers were not fully invested in improving the academy's offerings.
3. *The learning goals of the academy must be more explicit and measureable.* While many of the courses touch on components of the Academic Standards and Grade Level Expectations, there was nothing in place to declare that students were performing as expected.
4. *The importance of product functionality must be greatly minimized.* Teachers were unable to turn students' attention to connected content when coursework and grades constantly pointed to the physical products.
5. *The initial academy courses should focus on improving students' skill-sets.* If students are to engage with engineering at a deeper level, they must better develop their math and science skills. Improved communication is necessary with the school's math and science departments to better support curricular coherency for STEM students.
6. *Expectations should be high and the coursework rigorous.* By designing the first-year of the academy as a "teaser course," the teachers set the precedent that STEM classes were highly focused on constructing physical devices. By setting high standards, the students will come to demand more of themselves; those in the program simply for the enjoyment of "building stuff" will either choose to put in more effort or decide that engineering is not for them.
7. *Math and science content should be "forced" into the projects through design constraints.* Requiring that products fall within certain parameters such as area, volume, cost, and weight, and that designs be validated with measured data will compel students to engage with underlying concepts. There is likely to be some pushback from those who want to create devices that fall outside the

constraints, but if students understand that the purpose of the projects is to improve their skill-sets (rather than to simple build functional devices), and realize that real engineering work always comes with constraints, they will be more likely to work within the set parameters. At the same time, there should be some leeway for individual cases, as the constraints should not limit students' creativity.

8. *Creativity should be rewarded.* As long as students have a reasonable justification for pursuing outside-the-box solutions, they should be encouraged to implement creative designs. Lessons can still be learned from ideas that end in failure, and students should not be punished for these failures (provided that they are able to articulate the new understandings they gleaned from the process).
9. *Students should be* ***very specific*** *with their designs and should be required to build to their stated specifications.* Students too often "design on the go" without adequate forethought put into their products. By emphasizing the importance of details, students will learn to specify exact materials and dimensions, as well as gain improved fabrication skills.
10. *Students should be required to justify all design components and modifications.* Similar to the previous recommendation, students too often create products with no real reasoning behind their creations. By forcing them to identify the reason for each of their decisions, they will be compelled to look deeper into the underlying concepts.
11. *Guidelines should be established for properly requesting and providing guidance.* Rather than simply asking, "What should we do now?" students should be required to ask specific questions about discrete aspects of their projects. Teachers, for their part, should be clear about their role as a facilitator during project time, and should aim to interact with each individual on a daily basis so that students do not feel neglected.
12. *Project tasks which lead to skill development should be completed individually.* Tasks such as carrying out calculations, creating CAD drawings, or developing spreadsheets should not be assigned to groups, as it is unlikely (or impractical) that each student will engage equally with each task. Tasks

that do not lead to clear gains (e.g., the creation of basic prototypes) or those which are often collaborative by nature (e.g., conducting experiments) should be assigned to groups.

13. *Traditional assessments should supplement authentic assessments.* Evaluating students' knowledge and skills solely through observation and performance tasks does not reveal adequate information about individuals' understandings and non-understandings. Written work and quizzes should be included in order to directly measure students' capabilities.

These recommendations are by no means meant to indicate that if these changes are made, the academy courses will run smoothly, without major setbacks or need for further reflection and adjustment. Hands-on and open-inquiry classrooms, by their nature, are chock full of commotion and unexpected issues, and continuous revamping is necessary if students are expected to engage in engineering practices while also developing their skills and habits-of-mind. These recommendations aim to place a greater emphasis on the true purpose of an engineering classroom, shifting attention away from pure enjoyment, and allowing the teachers to incrementally improve the curricula and support the students.

While the hovercraft course did show promise for offering an engaging project as intended, a critical concern of the project entailed the inability to quickly test and collect data on a multitude of design configurations. In some cases, teams devoted one or two full days to implementing an idea, only to discover that their changes provided no improvement, and worse, little was to be learned from their efforts. This issue raises an important question of the project-based learning model – is it worthwhile for students to devote hours of class time to the construction and modification of their products when, in many cases, minimal knowledge is to be gained? If students spend weeks building hovercrafts but cannot define pressure and apply its most basic formula, is the project truly worthy of the engineering label? If the aim of the course is to impart knowledge and skills, then the answer is no. Such a project cannot be declared to be valuable if the extensive hands-on work does not lead to intellectual achievement.

Because the hovercraft students were largely unable to demonstrate gains in understanding and skill, it is recommended that the core project of the course be greatly modified so that more time is allocated to tasks representative of the engineering profession and less time devoted to the physical manipulation of tools and supplies. Hovercrafts could still serve as the course topic, but students would create scaled down crafts, with the context being that a scientists' tools (rather than the scientist herself) are to be transported. The same concepts (e.g., friction, lift, pressure) would be included, but adequate time could be devoted to a more substantial uncovering of each topic. The supplies would cost substantially less, though students would still be provided the opportunity to learn to use woodshop tools, and more data could be collected and analyzed from the students products because iterations would require drastically less time. To provide the "cool" factor to hook students, the downsized crafts could be outfitted with remote controlled servos (which the academy already possesses for use in its robotics courses).

It is important to note that while the difficulties associated with iterating in the hovercraft course are presented in this study as detrimental the students' progress, engaging in projects that are easily iterative should be facilitated with care. If students are allowed to continuously test design variations without reflection upon their observations, they are likely to formulate inaccurate impressions of the engineering field. In a freshman-level academy project, for example, students are required to develop small-scale wind turbines, and testing apparatuses allow numerous tests to be run in a relatively short amount of time to determine the optimum number of blades, blade length and surface area, and pitch angle. While this project setup allows for a clear segue into the importance of controlled experimentation and the ensuing data analysis, students are also provided the opportunity to identify quality designs simply through physical tinkering, with no real need for a systematic inquiry process. These types of projects led several students in the hovercraft course to voice complaints about their experiences in the academy. Stated one such student, "It's mostly been trial-and-error [in courses prior to the hovercraft course]. And to be able to walk through it with Popsicle sticks and hot glue and if you screw it up, you pull it off and you try it again." This highly iterative process can lead to understanding, but as was seen in the course under study, it is necessary for the teacher to intervene such that students iterate mindfully (rather than taking a guess-and-check approach) and to ensure students see the connections between their products and the underlying concepts.

Future work

This case study is intended to provide insight for designing and facilitating effective high school engineering courses. Through developmentally-appropriate curricula which balance learning and engagement, students should be expected to become both more prepared and eager to enter engineering degree programs. There will, of course, be students who are not well-suited to the field, nor enthused by it, and it is better for these individuals to come to this realization during their high school studies rather than a year or two into costly post-secondary tenures. Yet their reasons for abandoning interest in engineering and other STEM-related professions must be valid, such as an aversion to demanding math- and science-based coursework or preference for an alternative field. Grounds for eliminating engineering as a potential career should not be due to an unappealing environment brought about by disorder in the classroom, teammates who consistently shirk responsibilities, or a lack of adequate guidance. Likewise, coursework should not be so intensively hands-on that students who prefer abstract learning are turned away. In essence, the engineering classroom should fairly represent the profession. Efforts should indeed be made to portray engineering in a positive light, but these portrayals should characterize the field in earnest such that students with the potential and motivation to succeed as engineers are drawn in and rigorously trained. Students should not remain within an engineering program because they perceive the field to be something it is not.

There is still much to be learned about project-based engineering education. As a result of this case study, seven key areas emerged which call for further investigation. First of all, guidelines for introducing disciplinary concepts and skills into hands-on projects must be better established. Ideally, these important aspects of engineering would seamlessly integrate into a given project, and could be supported by the use of constraints to ensure specific parameters are met, much the same way codes and budgets shape true engineering work. It is often more prudent, however, to apply knowledge and skills to peripheral aspects of projects, for example, in the form of technical reports and schematic drawings, and the development of detailed rubrics to support such work is essential. While perhaps not as engaging as fabrication, it is important to identify a practical means to improve students' technical abilities. This is not to imply there is no place for product construction in engineering classrooms, but hands-on work should not overshadow the importance of learning.

Second, it was readily apparent that students' aversions to math generated significant disinterest in the course. When math-based problems were presented, a large portion of the class chose not to participate, many voicing that they were "not good at math" and therefore should not have been expected to solve equations or conduct calculations. Yet the application of math is a promising feature of project-based work because, ideally, students should be able to reasonably predict the outcomes of some performance measures. Explicit and observable connections between paper-based work and physical testing are sorely needed for students to acknowledge the importance of improving their math skills, even if they are not innately interested in the subject. Because low abilities in math commonly present a roadblock to entering engineering degree programs, designing projects that heavily rely upon math is perceived as a natural support for students in this regard. But more work is needed in this area, and it would be worthwhile to investigate the effects of making math a dominant component of project-based coursework. As compared to current projects, where math plays a minor role, would students be more capable of succeeding in engineering? And, perhaps more importantly, would they be more or less motivated to pursue careers in the field?

Third, it should not be assumed that high school students are naturally equipped to conduct efficient investigations in complex contexts. Proper practices of disciplined inquiry should be modeled and explicitly addressed through direct instruction, carried out with an end goal of enabling students to develop unique quantitative and qualitative methods for identifying and evaluating promising product features without guidance, in manners similar to professionals. Strategies for instructing high school students about disciplinary problem-solving tactics would allow teachers to foster critical thinking skills, making students less apt to resort to trial-and-error. But is it possible to emphasize more procedural problem-solving techniques while also fostering creativity?

Fourth, an effective protocol for providing students with appropriate guidance should be outlined, as clear communication of a classroom's guidance policies is likely to reduce teachers' uncertainty and mitigate students' frustrations. Determining when and how to intervene during student investigations can be challenging, particularly since fostering a learner-centered environment is constrained by time limits, and the reality is that some students proceed through projects extremely inefficiently. It is vital that students understand they are expected to make honest efforts to overcome encountered problems before seeking help, but teachers cannot allow them to persist in unpromising pathways such that no learning takes place. Students should be encouraged to solicit pointed feedback by posing detailed questions; inquiries such as "What should we do now?" should not be viewed as acceptable. Teachers, for their part, need a clearer grasp of the type of guidance they should offer relative to individual abilities and project learning goals. Recommendations for providing unsolicited advice should also be clarified.

Fifth, if project-based learning is to gain a stronger foothold in engineering and K-12 classrooms, it will be necessary to demonstrate concrete improvements in students' habits-of-mind, most importantly critical thinking and collaboration. Without proof of achievement, many administrators and instructors will be reluctant to incorporate project-based methods into their curricula. Ideally, assessments would allow educators to objectively evaluate students' abilities in these areas, thereby providing clear, measureable benefits. These measures should be logistically undemanding such that instructors are not inhibited in their capacity to facilitate projects.

Sixth, although engaging students in hands-on projects at the high school level can help motivate them to consider engineering and other STEM fields as potential career paths, many students make these decisions well before high school. Thus, a large number of students have already opted out of this career choice by their freshman year. Educators involved in K-12 engineering, including the academy's administrators, have realized this, and have implemented design-based projects in middle school and even at the elementary level. Outcomes from these efforts deserve in-depth examination, particularly a comparison of the abilities and outlooks of students who enter high school engineering programs who have already been exposed to project-based learning versus those who have not. Are they more equipped to succeed in high school? Are they more likely to enroll and succeed in engineering college? Longitudinal studies on these issues would help shed more light on the beneficial effects of design thinking at the lower grade levels. And importantly, more well-defined engineering standards could be established for each level, helping to support the design and facilitation of project-based lessons and allowing for better integration with core math and science curricula.

And seventh, the most natural extension of this study would be to continue to follow those of the case study's thirty-nine students who chose to pursue STEM fields after graduating from high school. Determining the facets of the academy that they found useful and the skills and habits they rely on could then be stressed at the high school level. Of course, noting the areas in which they felt underprepared would need to be strengthened.

For these guidelines to prove useful, educators must first determine the critical learning goals against which students are to be measured. These may include mastery of mathematical procedures and scientific concepts, investigative proficiency, appreciation for STEM-related careers, collaborative experience, and written and verbal communication skills. Each learning goal should be prioritized such that adequate class time is allocated appropriately. In order to truly achieve the learning goals, students must understand that the underlying purpose of product creation is to come to understand content related to the project and develop disciplinary skills and universal habits that will serve them in the future. This mastery orientation can be fostered by directing more attention towards the connections between projects and related math and science content, as well as by requiring students justify their design decisions with evidence. Task completion and physical performance should be de-emphasized in favor of understanding and technical precision, while the investigation of creative ideas should be rewarded, even those which fail to achieve performance benchmarks.

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APPENDIX

Student focus group questions:

1. Why did you join the STEM Academy? Is it what you expected?
2. Before you started taking STEM classes, what specific knowledge and skills did you think you'd learn? What have you learned so far?
3. What have you learned in this course?
4. Do you think [the teacher] has a good idea of all the knowledge and skills you've learned in this course?
5. Do you think the grades you receive in STEM classes are fair? Should all students in a group get the same grade on a project?
6. Do you receive any feedback from your STEM teachers about what you need to do to improve or anything like this? What about in this class?
7. How do you feel about working in groups?
8. How do you feel about the STEM classroom environment?
9. Describe your interactions and relationships with your STEM teachers and how they compare to your teachers outside of STEM.
10. How important is it to be good at math to complete projects in STEM?
11. What about science? Do you take into account the scientific ideas the teachers talk about in class when you're designing your projects?
12. What are the best parts of the STEM Academy?
13. What are the best parts of this course?
14. Do you have any recommendations to improve the STEM Academy? What about this class specifically?
15. What skills and knowledge does a student with a STEM Academy certificate have that a typical graduate doesn't?

Teacher interview questions:
Note: Questions for the cooperating teacher and the long-term substitute are slightly different

1. Could you tell me a little about your background?
2. What's your involvement with the STEM Academy?
3. What are the goals of the STEM Academy? What is the expected skill-set of a student graduating with a STEM Academy certificate that sets him/her apart from a typical graduate?
4. Do you think students are obtaining this skill-set?
5. Talk about a specific STEM course that you've recently taught. What were the learning goals of this course?
6. How did you communicate these learning goals to the students?
7. Did you think the students understood the learning goals and worked towards them?
8. How do completed projects demonstrate student comprehension of the learning goals?
9. Talk about how you assess students.
10. Do you think you're able to accurately assess what each individual has learned in a course?
11. Should all students within a group receive the same grade on a project?
12. Do you think each student feels accountable for his/her own grade?
13. Have you tried any assessment methods that have failed? If so, why did they fail?
14. Would you like to incorporate any assessment methods but haven't done so because of some obstacle? If so, what types of methods and what were the obstacles?
15. How do you give your students feedback?
16. Why are there few homework assignments and written tests in STEM?
17. Compared to your classes outside of STEM, how are your interactions and relationships with your STEM students?
18. What type of classroom environment is ideal? What is a typical environment?
19. What are your opinions about group work?

20. How do you address situations when, for example, students don't participate, don't show any understanding of the important concepts, or constantly distract others?
21. In your opinion, what are the strongest parts of the STEM courses?
22. If you had the ability to do so, what would you change about the STEM courses?

Administrator interview questions

1. Could you tell me a little about your background?
2. What's your involvement with the STEM Academy?
3. Why was the STEM Academy created?
4. What are the goals of the academy? What is the expected skill-set of student graduating with a STEM Academy certificate that sets him/her apart from a typical graduate?
5. Do you think the students are obtaining this skill-set?
6. How important is it for students to be good at math and science to complete their projects?
7. How do completed projects demonstrate student comprehension of the learning goals?
8. Should all students within a group receive the same grade on a project?
9. How can teachers ensure individual accountability?
10. How should the teachers address situations when, for example, students don't participate, don't show any understanding of the important concepts, or constantly distract others?
11. What are the strongest parts of the STEM courses?
12. Would you like to change anything about the courses?

Likert-type survey:
On a scale of 1 (strongly disagree) to 5 (strongly agree), indicate the number which best represents your feelings towards the following statements:

1. All team members should receive the same grade on a project.
2. I'm glad I joined the STEM Academy.
3. STEM courses are too difficult.
4. There should be more science and math in STEM courses.
5. STEM teachers provide enough guidance during projects.
6. All STEM students work hard on their projects.
7. The best way to learn in STEM is by trial and error.

Open-ended survey:

1. What is the purpose of the STEM Academy?
2. What knowledge and skills have you learned in STEM? Be specific.
3. List any suggestions you have for improving the STEM Academy.
4. What is the purpose of this hovercrafts course?
5. What knowledge and skills have you learned in this course? Be specific.
6. List any suggestions you have for improving this course.
7. Was the grade that you received fair? Why or why not?
8. What were the best of this course?
9. List any changes you would make to this course.
10. How likely are you to pursue a STEM degree in college?
11. If you already know which degree you want to pursue, what degree is it?