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Keywords

high school engineering, invention, cultural historical activity theory

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Extant research and engineering education frameworks call for students to engage in personally meaningful engineering projects; however, there are few case studies documenting the work of young engineers working to design solutions to real-world problems that matter to them. This qualitative case study describes the work of a purposively selected group of high school engineering students (the InvenTeam) ($n = 15$) as they devote a school year to a particularly ambitious invention project: designing and prototyping a device to mitigate deaths occurring when children are left unattended in hot cars. Utilizing cultural historical activity theory as a theoretical and analytical lens, the study triangulates observation, interview, and document data to describe elements of and tensions within the InvenTeam activity system. Data illustrate numerous ways in which invention afforded opportunities for students to apply science, technology, engineering, and mathematics (STEM) knowledge and practices and develop engineering identities. Additionally, data suggest that students' purposes for engaging in the project were dynamic, telescoping from individual, personal aspirations to expanded possibilities for economic and societal impact. Data also illustrate how students assumed defined yet flexible roles within the project's division of labor. Activity systems analysis revealed four main tensions within the InvenTeam activity system: sustaining motivation in the face of technical challenges, community expectations versus student goals, STEM knowledge/skills constrained by specialized roles, and the institutional norms of schooling versus the process of invention. Implications of the case study findings for engineering and invention at the high school level are discussed.

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Introduction

The device isn't working. With only 18 days until the presentation to their funder at MIT, the device isn't working. In one corner of the room, Jeff, the team's Sensor Integration Lead, hunches over code. He's spent the previous week de-bugging, line by line. He knows that getting the device to work depends on getting the code to work. Nora, the Technical Lead, and Beth, a civil engineer, huddle around a circuit board, using a multi-meter to systematically test the circuits connecting the device's five sensors. Nora suggests, "We need to figure out if it's the opto-isolator." After another hour of troubleshooting, they discover that it was indeed the opto-isolator. At a bank of computers, Jade creates a CAD rendering for a 3D-printed case to house the device once it works. Evan, the team's Communications Lead, consults with a graphic designer on a multimedia display to showcase the device once it works. Khalil, the team's App Development Lead, reports that they finally have an IOS app allowing users to receive alerts, "It's not pretty, but it works." As they wrap up the day's work, Jeff lingers over the code, "We're on the cusp." Nora adds, "Yeah. We're close. Really close."

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This is not a scene from a Silicon Valley tech start-up or a university engineering lab. This is a Monday morning in Ms. Green's high school Engineering Applications course. The device, which was indeed working by the presentation at MIT, is the "Baby Saver," a multi-tiered system that detects an unattended child in a hot car and sends a series of escalating alerts including an audible alarm, text messages, and, as a last resort, notification with GPS coordinates to authorities. Troubled by recent deaths of children left in hot cars, students wrote a successful proposal for a grant from the Lemelson-MIT InvenTeam program and devoted a school year to researching, designing, prototyping, and testing a device to mitigate hot car deaths. In the process, this engineering project and others like it disrupt traditional notions of what it means to be a student, a teacher, and an engineer, providing new opportunities to explore a mode of engineering education that invites students to solve problems that matter to them.

Such work is representative of a recent shift in the K-12 education landscape, in which engineering has emerged as a new priority in classrooms across the United States. Numerous states have adopted engineering standards and at the national level, the *Next Generation Science Standards* (NGSS; National Research Council [NRC], 2013) call, for the first time, for the meaningful integration of science and engineering. The *Framework for K-12 Science Education* defines engineering broadly as "any engagement in a systematic practice of design to achieve solutions to particular human problems" (NRC, 2012, p. 11). In describing K-12 engineering practices, the NGSS ask students to consider "potential impacts on people and the natural environment that may limit possible solutions" and to take "a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts" (NRC, 2013, p. 86) into account when developing solutions to engineering problems.

These explicit connections to the sociocultural dimensions of engineering within the NGSS suggest an imperative for students to use the engineering design process to identify, understand, and solve problems in their everyday lives and communities. However, K-12 curricular interventions do not necessarily feature engineering problems that originate from students' lived experiences or communities. Rather, the design challenges students encounter as they engage with engineering curricula often center on hypothetical problems imagined by curriculum developers (Cunningham & Lachapelle, 2011; Gale et al., 2018). Thus, there is a clear need for accounts of what happens in schools and classrooms when high school students endeavor to design engineering solutions to problems that matter to them.

Background Literature

Contextualizing the InvenTeam project requires considering both the current state of engineering design experiences in K-12 classrooms and the aspirations for pre-college engineering education envisioned by scholars within the engineering education community. To this end, the following summary of background literature first highlights key examples and critiques of current approaches to pre-college engineering, then describes emergent frameworks and perspectives on engineering practices and the (re)definition of engineering competency in the K-12 context.

Engineering Design in K-12 Classrooms

When K-12 students are asked to design a solution to an engineering problem, the design challenges set before them generally originate externally, often as part of engineering curricula adopted by schools or districts. In these cases, engineering problems tend to be predefined, with criteria and constraints already outlined for students (Jonassen et al., 2006). Studio-based design experiences tend to occur in informal, opt-in learning spaces rather than instruction taking place in engineering classrooms (McGowan & Bell, 2020). Although the adoption and implementation of popular engineering curricula at scale may increase access to engineering, scholars concerned with equity and the quality of students' engineering experiences have raised concerns. For example, Roth et al. (2001) argue that problem solving becomes constrained by narrow educational goals and recipe-like structures characteristic of many engineering design projects. Similarly, McGowan and Bell (2020) note that the "overstructuring of engineering design problems anonymizes the role that people play using engineering methods to solve problems" (p. 989) where designed artifacts are separated from their creators. Interestingly, this tendency toward prescribed engineering design activities for K-12 students stands in contrast to the trend in higher education toward engineering instructional models that integrate more authentic design practices (Claris & Riley, 2012).

With the introduction of the NGSS, one common entry point to engineering has been through the integration of engineering design challenges in science classrooms. For example, the Science Learning Integrating Design Engineering and Robotics (SLIDER) project explored the outcomes of a problem-based curriculum integrating science and engineering in 8th-grade physical science classrooms (Gale et al., 2018). As a culminating engineering activity, students use LEGO robotics and their understanding of engineering and physical science concepts (e.g., force, friction, acceleration) to design and prototype a braking system to prevent accidents at a dangerous intersection in a fictional town. While curricula like

SLIDER offer potentially effective methods for infusing science classrooms with the practices and disciplinary core ideas of engineering as defined by the NGSS (Gale et al., 2018), scholars raise concerns about the "physics-ification" of engineering (McGowan & Bell, 2020). Specific risks of physics-ification include positioning engineering subordinate to science, devaluing creative aspects of engineering design, inducing anxiety among elementary teachers and teachers without a background in math or physics (Capobianco et al., 2011), and reserving engineering design for students with prerequisite science and mathematics experience (McGowan & Bell, 2020).

At the elementary level, the popular Engineering Is Elementary (EiE) curriculum introduces students to a five-phase engineering design process ("Ask, Imagine, Plan, Create, Improve") that they use to solve design challenges derived from problems in short narrative stories (Cunningham & Lachapelle, 2011). The developers of the curricula clearly acknowledge the societal goals of engineering and the importance of designing engineering experiences relevant to students' lives. Cunningham and Lachapelle (2014) define "inclusive design principles" underlying the EiE curriculum, including the importance of curricula that "foster children's agency as engineers" and "demonstrate how engineering helps people, the environment, or society" (p. 135). Indeed, the EiE curriculum incorporates characters and contexts likely to be familiar if not personally relevant to students. Still, to the extent that students are asked to solve engineering problems that are posed *for* them rather than coming *from* them, even carefully designed curricula lack the relevance and authenticity that exist when students identify and work to solve problems that stem from their lives and communities. Thus, such curricular efforts are illustrative of what McGowan and Bell (2020) describe as "tensions between the situated nature of engineering and the fact that engineering curricula are designed for scale rather than context" (p. 989).

Of course, the population of students and teachers encountering engineering for the first time extends far beyond the reach of any one curricular intervention to include a great many "homegrown" approaches stemming from local school and community contexts. Recent research on the maker movement highlights possibilities for engaging students in meaningful, culturally relevant design projects (Martin, 2015). For instance, Kafai et al. (2014) described a project using electronic textiles to leverage traditional crafting and sewing practices to engage Native American youth in engineering and computing. Another study in this area (Tofel-Grehl et al., 2017) examined the use of electronic textiles in the context of 8th-grade science class and found increased interest in science and positive identity shifts among students who participated in an e-textile unit. While these types of design projects represent critical efforts to forge connections between students' identities and the engineering activities they engage in, they are somewhat limited in the extent to which students are invited to use engineering design to identify and develop solutions to real-world problems.

Competitions such as science and engineering fairs and, increasingly, invention contests represent contexts in which students are challenged to design solutions to problems they identify. For example, the K-12 InVenture Prize asks students working in small groups to develop inventions over the course of several months, after which top inventions are invited to compete in statewide and national competitions (Moore et al., 2019). Although researchers have explored the outcomes of such efforts (Kook et al., 2020; Newton et al., 2018), there is a paucity of research concerning how students engage in engineering practices over the course of an invention project.

Engineering in Practice

Penuel (2014) offers a vision for studying science and engineering *in* practice that informs the current study. Rather than focusing research on forms of science and engineering students engage in *as* practice, in ways that resemble disciplinary experts with the goal of producing *future* scientists and engineers, Penuel calls for research that "focuses on how people use science and engineering *in* social practices as part of collective efforts to transform cultural and economic production" (p. 1). Penuel highlights the importance of a descriptive and analytic rather than prescriptive approach to studying science and engineering education, challenging education researchers to move beyond studying science and engineering for their own purposes, such as determining how best to prepare students to participate in disciplinary science and engineering, to "focus also on participants' own changing purpose for involvement and on their contributions to activities that are focused on transforming communities" (p. 13).

Penuel's conceptualization of engineering in practice resonates with a growing body of research that critically explores youth engagement in engineering. This work pays particular attention to the ways in which youth's engineering experiences are situated within cultural narratives derived from disciplinary practices, historical context, and social structures including race, gender, and class (Leydens & Lucena, 2017; McGowan & Bell, 2020; Moore et al., 2014). One recent case study (Godwin & Potvin, 2017) explores students' critical engineering agency, defined as "an individual's ability to shape the world around them both in their everyday actions (using their knowledge of science and engineering to design solutions for their community) and their broader goals (e.g., pursuing a career in a service-related engineering field)" (p. 442). Based on case study findings, Godwin and Potvin (2017) argue that experiences related to student identity and agency in high school help explain why students decide to pursue and persist in engineering in college. The study also illustrates ways in which high school students benefit from meaningful projects in which they can integrate and apply science and mathematics knowledge to address real-world problems.

Defining Engineering Competency

Following Penuel's advice to adopt a descriptive rather than prescriptive approach to studying students' engineering experiences implies a certain openness regarding what constitutes engineering and engineering competency. If students' own purposes for participating in engineering are centered, rigid notions of what "counts" as engineering and what engineering students should know and be able to do become less privileged (McGowan & Bell, 2020). Indeed, researchers viewing science and engineering education from a situated perspective have advocated against beginning with *a priori* standards for engineering competence in favor of de-settling deeply entrenched expectations that can constrain school-based engineering (Bang et al., 2012).

At the same time, pre-college engineering education is patterned on the history and conventions of disciplinary engineering and conceptions of engineering at the K-12 level put forth in state standards and documents like the NGSS. Recognizing the limitations of the NGSS conceptualization of engineering and the practical necessity of clearly describing engineering practices for educators teaching engineering for the first time, Cunningham and Kelly (2017) propose a set of sixteen epistemic practices of engineering education intended to "capture important aspects of doing engineering and learning about and how to be an engineer" (p. 491). These practices, which were synthesized from research on engineering in professional and school settings, are organized into four non-mutually exclusive categories: engineering in social contexts, uses of data and evidence to make decisions, tools and strategies for problem solving, and finding solutions through creativity and innovation. Critically, even as the core engineering practices outlined by Cunningham and Kelly (2017) provide clarity on what authentic classroom engineering instruction may look like, the framework explicitly situates engineering design work in the social contexts of students' classrooms and communities and encourages students to consider the societal implications of the artifacts they design.

Building on Cunningham and Kelly's framework of epistemic practices of engineering, McGowan and Bell (2020) offer a framework that conceptualizes engineering education in terms of critical sociotechnical literacy. McGowan and Bell argue that equity in engineering education is not simply about expanding access to engineering but also about "re-envisioning engineering as a situated set of practices that depend on diverse types of knowledge to solve novel problems both in and outside of K-12 settings" (p. 988). To this end, they describe a framework consisting of five propositions defining the enterprise of engineering: engineering is situated and place-based; engineering knowledge is embodied and distributed and therefore performative; engineering is synthetic; engineers' knowledge is tacit, emergent, and experiential; and engineering is part of a complex sociotechnical system.

Extant research and emergent frameworks for K-12 engineering hint at the potential for engaging students in personally meaningful design projects as part of their engineering coursework (Cunningham & Kelly, 2017; Kafai et al., 2014; Martin, 2015; McGowan & Bell, 2020; Tofel-Grehl et al., 2017). However, research describing longer-term, youth-driven engineering design projects within the context of high school engineering classrooms remains scarce and there are few instructional models for equitable, place-based approaches to problem solving through engineering. To this end, this descriptive case study explores both the promise and potential challenges that emerge when a group of high school students identified an important problem in their community and devoted a school year inventing a solution.

Theoretical Framework

Cultural historical activity theory (CHAT) serves as the primary theoretical and analytical framework for the case study. Derived from Vygotsky's sociocultural perspective and further articulated by subsequent sociocultural theorists (Cole & Engeström, 1993; Leont'ev, 1978), CHAT has emerged as a powerful, generative framework for analyzing educational change (Lee, 2011; Roth & Lee, 2007). Roth and Lee (2007) comment on the utility of CHAT, stating "this theory is of immense interest to us because it has shown to be fruitful for both analyzing data recorded in real classrooms and designing change when trouble and contradictions become evident in these cultural settings" (p. 188).

CHAT provides both a theoretical lens and an analytical approach that befits the complexities of following a year-long high school engineering project, with a number of conceptualizations of particular value for this case study. By taking activity systems as the fundamental unit of analysis, CHAT provides a structure for analyzing engineering activity while also allowing the flexibility necessary to go beyond simplistic accounts focused on isolated student or teacher outcomes. An "activity triangle" typically used to depict the components of an activity system is presented in Figure 1.

Within this activity system, subjects are defined as individuals or subgroups engaged in the activity system. In engineering classrooms, subjects generally include teachers and students but may also include others who are involved in

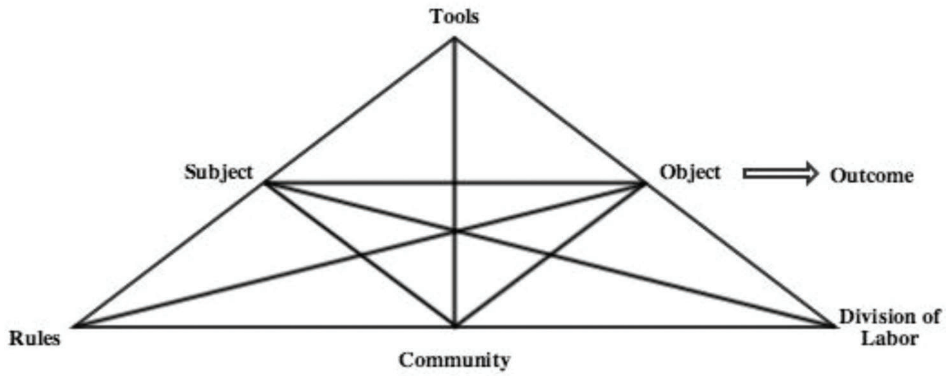

Figure 1. CHAT activity system triangle.

engineering activities, such as volunteers or mentors from industry or higher education. The object is defined as the goal of the activity system or the problem the activity system seeks to address, such as an engineering problem in need of a design solution. The outcome is the consequence of the subject's goal-directed action within the activity system. Outcomes in an engineering education activity system may include learning outcomes, opportunities, or new perspectives gained through participation in an engineering design project. Note that student outcomes such as increased interest or enhanced knowledge or skill flow from the achievement of the object of a project (e.g., engineering a solution to a problem) rather than serving as the object of the activity themselves. Mediating artifacts and tools can be conceptual or practical tools and may include physical resources, technology, or curricula. An engineering classroom may include a vast array of possible physical tools and artifacts in addition to conceptual tools such as understandings of the engineering design process and students' and teachers' prior science, technology, engineering, and mathematics (STEM) knowledge. Community is defined as other people or groups who share the same general object, although they may belong to the activity system at varying levels of influence. In a K-12 context, these may include supporters within the school community and other individuals or organizations that support but are not directly involved in an engineering project. Rules are defined as the norms and sanctions that specify and regulate activity. Within engineering education, these may include school, district, and national policies and standards as well as expectations and norms, both implicit and explicit, for how students and teachers behave and interact in an engineering classroom. The division of labor component is defined as the continuously negotiated distribution of tasks and responsibilities within the activity system. In an engineering classroom, the division of labor may be reflected in the tasks assigned to individuals or groups of students, the roles students assume, and the ways in which expertise and knowledge are shared among students and between teacher and student. Systemic contradictions within activity systems can exert pressures on an activity, resulting in tensions that can either stimulate or interfere with the subjects' attainment of the object (Cole & Engeström, 1993).

This case study focuses on exploring the nature of the InvenTeam project when viewed as an activity system. The purpose of the study is twofold. First, the study aims to identify and provide a rich description of the components of the InvenTeam activity system. Second, the study explores the tensions that become evident as the components of the activity system interact. Thus, the study addresses the following research questions:

1. What are the components of the InvenTeam activity system (e.g., subject(s), object(s), outcome(s), tools, rules, division of labor)?
2. What tensions arise within the InvenTeam activity system?

Methodology

This qualitative study employs a single embedded case study design (Yin, 2013) with the goal of developing a contextualized understanding of an invention project as it unfolded within one school community.

Setting

Following a unique case sampling strategy (Merriam, 2007), STEAM Charter School (a pseudonym) was purposively selected as the research site for the case study. STEAM Charter School, located in a major metropolitan area in the southeastern United States, serves over 1800 students in Pre-K through 12th grade. The school is divided into Elementary (Pre-K through 5th grade), Junior (6th–8th grade), and Senior (9th–12th grade) Academies. Although significant community revitalization has occurred in recent years, the school community remains predominantly low-income with the majority (56%) of students eligible for free-and-reduced lunch. Eighty-seven percent of students at the school are Black; 7% are White; 3% identify as two or more races; 2% are Hispanic; and 1% are Asian.

Although subject to many of the same conditions and challenges prevalent in public schools across the country (e.g., standardized testing, poverty, scarce resources), STEAM Charter School is widely recognized for its STEAM-PBL instructional model and its robust engineering design program. The school utilizes project-based learning (PBL) as its primary mode of instruction, with a focus on integrating STEAM (science, technology, engineering, arts, and mathematics) disciplines. The school has a well-established engineering design program including engineering design courses at every grade level (K-12), initiatives to involve students in engineering and design outside the classroom (e.g., makerspaces, clubs, competitions, community events, internships) and the option to pursue an Engineering Career Pathway at the Senior Academy level. The school is one of the top performing schools in the state and reports academic performance outcomes exceeding those of other schools in the district serving similar student populations. For example, in 2020, the school's graduation rate was 98% and has been between 95 and 100% each year since the Senior Academy opened. The school provides intensive counseling and support for college and career development, resulting in similarly high (90–100%) college acceptance rates among each graduating class.

Project Context

The Engineering Applications Course

Within STEAM Charter School, the InvenTeam project was pursued in the context of the Senior Academy's Engineering Applications course, the third of four courses included in the school's Engineering Pathway. The course follows the introductory foundations of engineering and technology course and an engineering concepts course in which students continue to build their understanding of fundamental principles of engineering, areas of specialization within engineering, and the application of tools and procedures as they complete hands-on engineering design projects. Following the Engineering Applications course, students complete the pathway by participating in an engineering internship course. The State's Department of Education describes the Engineering Applications course as one in which "students will apply their knowledge of STEM to develop solutions to technological problems," adding that "solutions will be developed using a combination of engineering software and prototype production processes" and that students will complete a capstone project to demonstrate their depth of knowledge of the engineering design process.

The InvenTeam Project

Although it is not uncommon for STEAM Charter School students to design and prototype inventions for class projects or competitions, as a year-long, student-led project tackling a technologically difficult design challenge, the InvenTeam represented a particularly ambitious project. The project had its inception the previous school year when Ms. Green presented the opportunity to her students and a subgroup of students volunteered to participate in brainstorming, problem scoping (Watkins et al., 2014), and development of the proposal submitted to the Lemelson-MIT InvenTeam program. The idea to invent a hot car death mitigation device was one of several options the team considered and was ultimately agreed upon in light of concerns with the originality and feasibility of two other ideas being considered, a robotic crossing guard and an invention to protect against home invasions.

Following the announcement in the fall semester that the class had received one of fifteen Lemelson-MIT InvenTeam grants, students in the Engineering Applications course devoted the remainder of the school year to the project. As detailed further below, students worked in teams and assumed specific roles according to various aspects of the project, including both technical and administrative objectives (e.g., sensor integration, app development, fundraising). In February, following weeks spent testing the various sensors that comprise the device (e.g., motion, infrared, ignition), students gave their first formal presentation of their design at a mid-grant technical review attended by members of the school community, school partners from industry and higher education, and Lemelson-MIT representatives. Once students on the sensor teams had successfully tested and developed Arduino code for individual sensors, the majority of the spring semester was spent coding and troubleshooting the integration of the device's sensors and developing a working iOS app. The resulting device integrated multiple sensors to detect the presence of a child in a vehicle, monitor temperature, and send escalating alerts (audible alarm, text to vehicle's owner, text to authorities) as certain temperature thresholds were reached. Other objectives during the spring semester included designing and 3D printing a housing for the device, fundraising for the team's trip to the Lemelson-MIT EurekaFest event in June, and creating a video and a model featured in the team's multimedia display at

EurekaFest. The following school year, three InvenTeam students continued refining the invention and submitted a successful application for a provisional patent as part of an independent study.

Participants

The InvenTeam was comprised of 15 students (identified using pseudonyms). Eleven students were juniors and four were seniors, and the class included six students who identify as female and nine who identify as male. All students had participated in prerequisite Engineering Pathway courses prior to enrolling in the Engineering Applications course.

Ms. Green was in her fourth year teaching engineering at the school during the InvenTeam project. Although she was a relatively new teacher, with a background in civil engineering, Ms. Green brought a wealth of expertise to her instruction. She had been involved in several professional development initiatives focused on enhancing PBL in STEAM disciplines. As the Senior Academy's lead engineering teacher, Ms. Green implements a vertically aligned engineering design program in which students are challenged to complete increasingly sophisticated engineering projects as they progress through the engineering course sequence. Although certain grade level projects may be repeated with different groups of students each year, Ms. Green emphasizes student agency, often encouraging students to take the lead on the conceptualization and implementation of ambitious engineering projects. For instance, in the year following the InvenTeam project, Ms. Green received a grant to support another year-long project in which students in her Engineering Applications course designed and constructed a Tiny House (Gale & White, 2019). Ms. Green had worked with each of the students in the class in at least one additional year-long course prior to the Engineering Applications course.

In addition to students and Ms. Green, the project involved a number of volunteers as ancillary contributors to the InvenTeam's work. These volunteers, recognized affectionately by students as "VIPs," included other teachers or staff at the school who assisted with particular phases or aspects of the project as well as experts who consulted with students on particular questions or issues they encountered. For example, as the students were preparing their final presentation, they worked closely with another teacher at the school with engineering and graphic design expertise to develop a 3D model of a car to display their device. Another critical VIP was Mr. A, a software engineer who volunteered in the classroom, spending considerable time helping students develop code and troubleshoot their device.

Students also recognized me as a VIP in their engineering classroom and recognized my role as helping to document the work of the InvenTeam. This VIP designation served as an important reminder to carefully consider my positionality as I collected, analyzed, and interpreted case study data. Having spent the previous 10 years conducting various grant-supported research projects at the school, I began the project with a high degree of familiarity with the school setting, in general, and with Ms. Green and some of her students, in particular. For example, in a previous project evaluating the school's professional development model, I spent several days traveling with a group of STEAM Charter School teachers, including Ms. Green. Several members of the InvenTeam were also participants in a longitudinal case study I was conducting that involved interviewing students over the course of their high school careers (from 9th to 12th grade). As such, by the time the InvenTeam project started, I had developed a close rapport and fairly extensive understanding of this particular subset of students' previous educational experiences and future goals. In some ways, my close relationship with Ms. Green and her students enhanced the validity of the study, allowing more access and more candid conversations about the project than may have been possible had we begun the project as strangers. At the same time, given my generally positive preconceptions of Ms. Green as a teacher and the students with whom I was familiar, I had to take seriously the potential for biased interpretations of the case study data. Similarly, as a White woman affiliated with a university, it was important to continually reflect on the ways in which my privilege, life experiences, and history of schooling necessarily influenced my perspective on the project.

Data Sources

The study triangulates four data sources: participant observation, interviews, survey data, and documents.

Participant Observation

Participant observation (DeWalt & DeWalt, 2010) was conducted weekly in the Engineering Applications classroom over the course of the second semester of the year-long project, with a total of 13 observation visits. Observations typically lasted the duration of the class period (90 minutes) with two additional two-hour observation sessions conducted during Saturday work sessions near the end of the semester. While conducting observations, I assumed a moderate participation role (DeWalt & DeWalt, 2010) such that I was identifiable as a researcher and familiar to the students but only occasionally interacted with students or Ms. Green, primarily through the informal interview procedure described below. Observations utilized a semi-structured field note guide, which was pilot tested during the months prior to observation and designed to identify and describe the components of the activity system in the Engineering Applications classroom. In addition to observations conducted in the classroom, informal observations were conducted at school events featuring the InvenTeam, including the project's mid-grant technical review at the beginning of the semester.

Interviews

Interviews were conducted with students and Ms. Green. In order to minimize disruption, the majority of student interviews took the form of short "design discussions" occurring over the course of the project. In these two- to three-minute discussions, students were prompted to describe the particular engineering task they were working on and, periodically, to comment on the overall progress of the team. A total of 26 of these design discussions were conducted over the course of the semester and each student in the class participated in at least one design discussion.

Two students, Nora and Khalil, who participated in the project from its inception the previous school year, participated in three semi-structured interviews lasting approximately 40 minutes. These interviews were conducted at the beginning of the project during proposal development, at the end of the Engineering Applications course, and the following school year during the subsequent Independent Study course. In each interview, students were asked to reflect on their role in the project and factors influencing how the project was progressing.

Similar to student interviews, a 60-minute semi-structured interview was conducted with Ms. Green at the end of the school year. In this interview, Ms. Green was also asked to reflect on the project and describe factors influencing how the InvenTeam project transpired in her classroom. In addition, informal interviews resembling the student design discussions were conducted with Ms. Green in conjunction with participant observation. These informal interviews generally involved Ms. Green providing commentary on student activities and updates on the project's overall progress. Longer semi-structured interviews were audio-recorded and transcribed for analysis. Design discussions and informal interviews with Ms. Green were audio-recorded; however, given the brevity of these discussions, they were not transcribed but rather reviewed to confirm main points and key quotations captured in field notes.

Surveys

At the end of the semester, all 15 students completed a short online survey including three open-ended items. The first item asked students to reflect on what they learned by participating in the project: "What is the most important thing you've learned by participating in the InvenTeam project? Please share specific examples." The second asked students to share advice for other engineering students or teachers: "What advice would you offer other engineering students or teachers considering a project like this?" The third item invited students to share anything else they would like people to know about their InvenTeam project.

Documents

An array of documents was collected as a secondary data source. Documents include student engineering design logs, project planning documents, the InvenTeam project blog, documentation of project events, local press coverage, student- or teacher-generated media (e.g., photographs, recordings, video, social media). Messages shared using a group text messaging application (GroupMe) provided documentation of discourse among InvenTeam members over the course of the project.

Data Analysis

Following data collection, Yamagata-Lynch's (2010) suggested method for activity systems analysis guided the iterative coding of interview transcripts, observation guides, open-ended survey data, and documents. Specifically, this approach combines an open coding process to identify major patterns and themes along with selective coding to identify how data represent the components of the activity systems model (Figure 2). Coding followed a sequential qualitative analysis process (Miles et al., 2019) in which a provisional start-list of codes was initially developed based on several iterations of reviewing interview transcripts, field notes from observations and design discussions, and documents. After drafting this initial coding scheme, I completed a first round of coding that involved continually refining, combining, and adding codes based on whether and how well they reflected prevalent issues across multiple data sources and types of data. As I was the sole coder for the project, in order to ensure the trustworthiness of my coding I enlisted a colleague who was generally familiar with engineering education but had not participated in the study to independently code a subset of three interview transcripts and two sets of observation fieldnotes. Following our coding of those data, we met to review any discrepancies and make final revisions to code definitions. I then utilized the coding scheme to code the entire dataset using the NVIVO software program. Finally, I applied selective coding to identify specific object-oriented activities reflective of components of the activity systems model. Data were then assembled in conceptually ordered meta-matrices (Miles et al., 2019) in order to interpret patterns and themes related to the activity system. Using these matrices, I developed a CHAT diagram

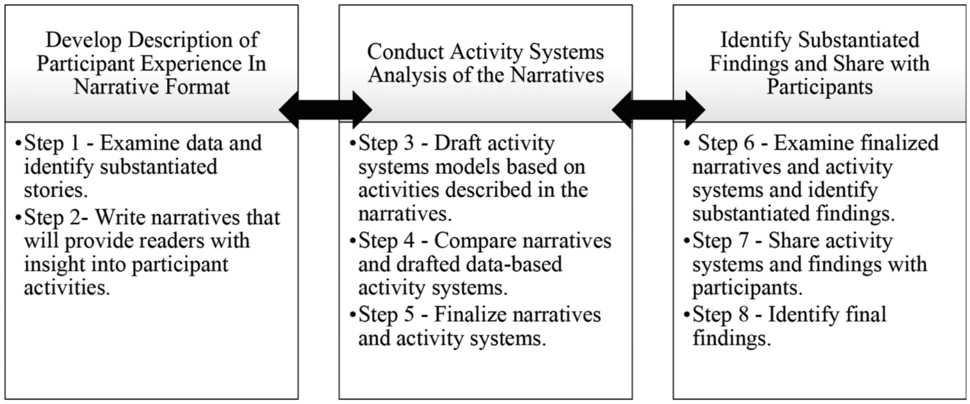

Figure 2. Steps to identify narratives and activity systems. Adapted from Yamagata-Lynch (2010).

illustrating the InvenTeam activity system and followed the process recommended by Yamagata-Lynch (2010) to draft thick description of participant experiences in a narrative format and subsequently describe activity systems from these narratives.

Findings

Results are presented by research question below, beginning with a summary of the components of the activity system (Research Question 1) followed by a summary of the tensions evident within the activity system (Research Question 2).

Elements of the InvenTeam Activity System

Figure 3 depicts the elements of the InvenTeam activity system, with tensions within the activity system denoted as dashed lines (a)–(d). Table 1 summarizes each of the components of the InvenTeam activity system. The following subsections describe four components of the activity system that were most salient in data: STEM knowledge as a tool; roles and division of labor; the object of a working invention; and outcomes: engaging in epistemic engineering practices and refining engineering interests.

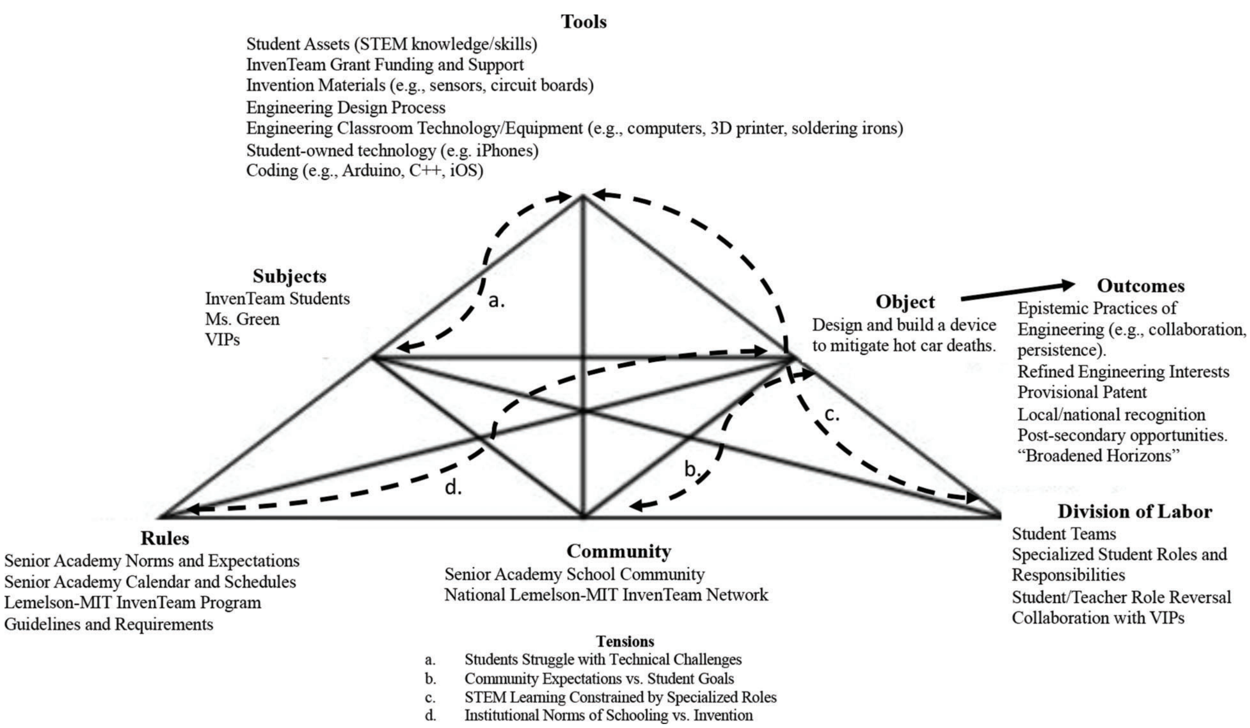

Figure 3. The InvenTeam activity system.

Table 1
InvenTeam activity system definitions and components.

CHAT component definitions	InvenTeam activity system components
Subjects: The individual person or subgroup of people engaged in an activity system.	– InvenTeam students (n = 15): eleven 11th grade, four 12th grade. Nine male, six female. All began course with strong interest in and previous experience with engineering. Three students continued working on project following year as Independent Study course. – Ms. Green, Senior Academy (9th–12th grade) engineering teacher. In her fourth year teaching, had taught all students in at least one additional year-long engineering course. – VIPs (volunteers from industry, disciplinary experts, teachers).
Object: The goal of the activity system or the problem the activity system seeks to address.	– Design and build a device to mitigate hot car deaths. – Set in students' Lemelson-MIT InvenTeam proposal.
Outcome: The consequences of the subject's goal-directed action within the activity system.	– Engaging in epistemic practices of engineering: working in teams, persisting in the face of failure, seeing themselves as engineers. – Refined engineering interests—confirming or disconfirming interest in specific fields of engineering. – Provisional patent—applied for and awarded during subsequent Independent Study year. – Local/national recognition for initial InvenTeam award and invention. – Post-secondary engineering opportunities: e.g., leveraging InvenTeam experience in college, internship applications. – "Broadened horizons": e.g., special opportunities for travel.
Tools: Conceptual (abstract) or practical tools. Includes physical resources, technology, curricula.	– Student assets: STEM knowledge and skills – Lemelson-MIT InvenTeam grant funding and technical support. – Invention-specific materials (e.g., sensors, circuit boards). – Engineering design process. – Engineering classroom technology and equipment (e.g., computers, 3D printer, soldering irons). – Student-owned technology (iPhones, laptops). – Coding (e.g., Arduino, C++, iOS).
Community: Other people who share the same general object, though they may belong to the activity system at varying levels of influence.	– Senior Academy school community (families, teachers, students, administration). – National Lemelson-MIT InvenTeam network.
Rules: Norms and sanctions that specify and regulate activity.	– Senior Academy norms and expectations regarding teacher and student roles, how space and resources are used. – Policies and schedules governing how time is used and allocated during the school day and over the school year. – Lemelson-MIT InvenTeam program guidelines and requirements.
Division of labor: Continuously negotiated distribution of tasks and responsibilities.	– Teams based on both technical and administrative priorities (e.g., sensor integration, app development, fundraising). – Specialized student roles/responsibilities: aligned with student strengths/interests, shift according to project needs. – Student/teacher role reversal: students hold specialized knowledge/expertise, which they often impart to teacher. – Collaboration with VIPs: sustained work with volunteers (other teachers, experts from industry).

STEM Knowledge and Skills as a Tool

The knowledge and skills that students brought to the project represented perhaps the most vital tool in achieving the InvenTeam's object. From the project's inception, it was evident that the level of difficulty and scope of the project meant unusually high expectations for the InvenTeam, going far beyond the standards for the Engineering Applications course. Analysis of daily design journals (DDJs) illustrates how students applied and deepened their STEM knowledge as they researched, designed, prototyped, and tested the device. One of the more technically difficult aspects of the project was the selection, testing, coding, and integration of the device's sensors. DDJ entries detailing the work of student teams charged with exploring the viability of the device's infrared sensor demonstrate how student knowledge both emerged from and contributed to their design work. One student on the team reports extensive research on heat radiation, with detailed notes documenting new understandings about how humans radiate heat, estimates for heat radiation for different sized people, and differences between thermal and infrared radiation in humans. Another student's DDJ outlines procedures for testing the precision of infrared sensors, with the goal of "seeing if the sensor can measure to a certain degree of exactness." In this example, the students applied their existing understanding of experimental design to conduct a series of investigations in which they compared readings from their infrared sensor to known temperatures of heated water and a person in various conditions. Additional questions students explored at this phase included whether using more than one sensor generates more exact measurements, whether the car's interior size affects measurements, and how the thickness of any cloth or blankets covering a person may influence measurements.

Importantly, the knowledge students applied was not limited to formal, disciplinary understandings acquired in previous STEM courses but also included tacit knowledge gained through everyday experiences. For example, several students most invested in coding the device's sensors drew upon experiences gained through computer science summer camps or other informal experiences coding, playing video games, or working on computers as hobbyists. In another instance of drawing on funds of knowledge, John drew upon his interest in media and videography as well has his contacts and knowledge of the school community to identify sites to shoot each scene of the video for the team's multimedia display.

Roles and Division of Labor Within the InvenTeam

At the beginning of the project, one of the first orders of business was for students to apply for specific roles. Although the general description of each role was predefined, roles were somewhat fluid as the division of labor shifted according to the needs of the project. For example, once the project reached its ambitious goal of raising the nearly $25,000 to fund the team's trip to the Lemelson-MIT InvenTeam EurekaFest event in Boston, the Fundraising Lead turned her attention to assisting the sensor team with soldering the device's circuit board.

Roles also tended to correspond to students' perceived strengths and interests. Khalil noted that his willingness to take on the task of designing an iOS app that would interface with the device stemmed from his interest in computer science and experience with app development in a summer program. Nora described how her strengths as a researcher made her an effective Technical Lead:

> I like to research. Whenever we had a problem, I didn't mind going through different forums looking at other people's experiences that they asked questions about. I guess that's the strength that I brought to it. Also, not minding being stuck on something…I like working on it. I didn't like getting stuck, but we had to get it done. It was just a thing we had to do. That's how I looked at it. It was frustrating, but I didn't want to give up.

Although students were asked to take on specific roles early in the project, Ms. Green also allowed time for leaders and new roles to "emerge." In a post to students' design journals early in the project, she notes "I'm looking for a Technical Lead to emerge in the next two weeks. This person will be the manager of all of the technical team. Roles are still flexible. I'm also looking for a Communications Lead to emerge." Similarly, the project's blog, written monthly by the Communications Lead, often discussed contributions of team members according to their roles. For example, the project's November blog states:

> Based on their work, three leaders have emerged on our team. Jasmine, who is already our team's Project Manager has agreed to take on the role of Sustainability Lead as well, and Nora and Khalil have emerged as leaders in their technological areas. Khalil is spearheading GPS integration and Nora will be leading the charge on infrared sensing.

Team members identified closely with their titles, especially when presenting to an external audience. Each of the team's presentations, including their final presentation at MIT, began with InvenTeam members introducing themselves by stating their name and title. In practice sessions leading up to their final presentation at MIT, Ms. Green emphasized the importance of all students being able to clearly articulate how the invention works, regardless of their particular area of expertise and role on the project. At the same time, students prepared to field particular questions related to their areas of expertise. For instance, because he had overseen the testing and coding related to the temperature sensor, the group decided that Jeff would be the one to handle any questions about the device's temperature sensors and how the device was coded to trigger certain events once the temperature in the vehicle reached certain thresholds.

Although students generally embraced their particular roles within the project, they were not always satisfied with the division of labor, occasionally indicating frustration with teammates' commitment to the project. In the weeks leading up to the MIT presentation, individual students exerted pressure on teammates to increase their level of involvement. In a GroupMe chat about the team's final work session before the MIT trip, scheduled after the end of the school year, Jordan urges his teammates to "step up":

> I think all the people that don't have any roles right now need to step up and ask what they can do to help, 'cuz either way it go even if "u finished with your part" or not, we all gone look stupid on stage if EVERYTHING isn't done.

Lawrence then asks "what can I do to help?" adding, "honestly, if u sitting at home doing nothing and not even asking how's the device goin', you trifling."

Object: A Working Device

Observation and interview data suggest that students' own purposes for engaging in the project were varied and dynamic, telescoping from individual, personal aspirations to expanded possibilities for economic and social impact. Students remained committed to the overarching object of designing and building a device to mitigate hot car deaths and continued to raise the issue of hot car deaths in formal presentations and public statements. For instance, the InvenTeam's blog entry for November concludes with the statement "at the end of the day, we all have one common goal; to reduce the loss of life caused by children and pets being left in hot cars." However, interview and observation data indicate that students rarely referenced hot car deaths as they worked on the device, instead focusing intently on meeting their deadline for the MIT presentation. In practice sessions for the mid-grant technical review and the MIT EurekaFest presentation, Ms. Green and the parent audience asked students to increase their energy level to convey a sense of urgency and to "remember why you are doing this." Ms. Green confirmed this shift in focus from "saving babies" to designing a working device:

> After the initial idea, we pretty quickly got off of the saving babies focus. That was the point of our device, but we got focused on designing the device. Our new mission wasn't "save babies." It was finish the device, get a device working. And then we've definitely lost track of that. Save babies. Even in our PowerPoint presentation, it says next steps. And the two things that were in there were, get a patent and get it in cars. We never said save babies.

Outcomes: Engaging in Epistemic Practices of Engineering

The InvenTeam experience afforded numerous opportunities for students to engage in epistemic practices of engineering (Cunningham & Kelly, 2017). While individual students engaged in each of the sixteen epistemic practices of engineering at some point in the project, the most prevalent practices evident across data sources and over the course of the project were in the category of epistemic practices related to solving problems as members of a team: working well in teams, persisting in the face of failure, and seeing themselves as engineers.

InvenTeam Collaboration Both students and Ms. Green cite learning to collaborate effectively as one of the most important outcomes of the project. In her year-end interview, Ms. Green contrasts the development of technical skills with the value of collaboration:

> I think the skills aren't as important. I mean the technical skills…It's about being a part of a team and how you can either mess up or improve team dynamics by your attitude and collaboration, and kind of the impact that you can have as an individual on a team and on a team's success. I think those are all really important pieces that they learned. I think it was a lot like an industry project, which was cool.

Ms. Green's reflections were echoed by student survey responses, with twelve of the fifteen students discussing collaboration as one of the most important things they learned as a member of the InvenTeam. Students frequently discussed the high degree of interdependence within the team and the relatively high stakes for collaborating effectively. For example, Jordan stated that:

> The most important thing that I learned about while participating in the InvenTeam is the importance of teamwork skills. Everyone had their own individual role, but if everyone had not done their own individual part, this project would have been impossible to complete.

Although the members of the InvenTeam placed a high value on collaboration, the InvenTeam navigated its fair share of collaboration challenges. In interviews, Ms. Green, Khalil, and Nora all describe a rather contentious beginning to the project, in which students had difficulty coming together around the problem they would propose to solve. Ms. Green describes this conflict during the problem identification phase, stating that "there was a rift between these kids that I didn't know about. In the beginning of the project, we were at a stalemate about what we were going to pursue. And it was a really challenging environment." Students' reflections and observations of sustained, successful episodes of collaboration provide ample evidence that the team was able to overcome this initial stalemate to collaborate effectively over the course of the project.

Persisting in the Face of Failure Next to collaboration, persistence was the outcome most often touted by InvenTeam members and Ms. Green. At the beginning of the school year, Ms. Green held a community meeting in which she asked families and students to sign a contract, explicitly setting the expectation that the InvenTeam project would require a level of commitment beyond that which the students and their families were accustomed to. When asked about the time commitment, Ms. Green described this meeting, stating:

> The InvenTeam was really unpredictable. I just told them at the very beginning, we had this parent meeting and I was like, "It's going to be hard. And there's going to be a lot of outside of school time. And I don't know how much. And I don't know when."

Below, Ms. Green discusses how students ultimately responded to the pressure to produce a working prototype during the final phase of the project:

> I really wanted everything to be done. I wanted everything to be done by the end of the school year, but that wasn't realistic. But I would keep calling kids in and I'd be like, "Okay"…And if it was a temperature sensor problem or if it was a wave shield problem, Jeff would come in. If it was an infrared sensor problem, Nora would come in. Jordan was in a lot. There were these kids that kept coming in. Just coming in, and coming in, and coming in…because I don't know what the…I wasn't sure how to fix it.

In spite of occasional lapses in student motivation, Ms. Green's report that students "just kept comping in" speaks to students' persistence, which she would later cite as an outcome she was most proud of as she reflected on the project:

> One of the things that I'm most proud of is their persistence. Just persisting. Now, I think each of them, even if they weren't the one who was doing the programming, each of them knows that you can do so much just by persisting…Which is a really huge deal. Jordan, I think he surprised himself big time with what he could accomplish. Nora, I doubt she surprised herself, because she already knows. She has this grit. This intense grit. She'll do whatever. But some kids are like, "Oh, I didn't know how to do that. And I didn't think I could do that. And I did so much."

The value of persistence was echoed by many students' survey responses. For example, Jade shared, "I've learned about being persistent. I have had to recreate the prototype for the housing of the invention multiple times when measurements and shape needed to be changed."

InvenTeam Members See Themselves as Engineers In an interview conducted at the end of the project, Khalil reflects both on his persistence and how he envisioned himself as an engineer, drawing a comparison between engineering projects he has completed "as a student" and the InvenTeam project, where he states that he was "working more like an engineer":

> Typically, as a student, there's a clear-cut answer or at least an idea of what you're expected of completing for an engineering project, versus when you are working more like an engineer, and its practical, you don't know. You're just trying to find the answer and there's so many different answers and ways to get to an answer that initially…it can be hard getting on that path and you question, "Is this right, what I'm doing?", and you might find out that what you're doing isn't going to work or you messed up along the way, so you have to start over and it can get frustrating, but you have to keep going.

In survey responses, several students drew explicit connections between the skills they learned in the course and how they envision themselves pursuing engineering. For example, Zack responded that "being a part of the InvenTeam has given me the opportunity to develop necessary skills that I will need to continue to pursue a career in engineering or technology."

Outcomes: Refining Engineering Interests

One of the ways the project helped students see themselves as engineers was by affording opportunities to refine or confirm their interests in specific engineering fields. Khalil described how his experience coding the app for the device confirmed his interest in engineering fields that involve computer science, noting that the InvenTeam experience helped him "grow from being a beginning coder to an intermediate coder." Nora also reported that the InvenTeam experience helped her further specify her interest in engineering. In contrast to Khalil, Nora shared that the project disconfirmed her interest in computer science applications or electrical engineering noting, "I learned that I really don't love coding at all." Nora goes on to reflect on how the project helped her see what it is like "being in engineering on a macro level" while she maintains her interests in chemical and environmental engineering sparked from an internship experience:

> InvenTeam was bigger, I mean it was much more like real engineering…like even though I actually don't enjoy coding or electrical, since it was a major yearlong goal, with all these other parts, it helped you see what it's like being in engineering on a macro level. So, I'm looking forward to what it's like when I can do that with the stuff I'm more into, like chemical or environmental that I did some work with in my summer internship.

Tensions Within the InvenTeam Activity System

Tension (a): Students Struggle with Technical Challenges

One of the major tensions within the activity system involved students (along with Ms. Green and project VIPs) reckoning with the technical challenges presented by the various physical and digital tools they interfaced with throughout the project (e.g., sensors, meters, breadboards, computer code). The technical challenges of testing individual sensors were compounded once students sought to integrate the various sensors (GPS, infrared, motion, thermal) comprising the device's multi-tiered alert system. With the end of the school year looming, the team became consumed with troubleshooting code and solving issues with sensor integration in order to achieve their goal of presenting a working device at the MIT InvenTeam EurekaFest event in June. Lawrence discussed this particularly challenging troubleshooting phase when interviewed by a local reporter about the project, saying, "the most challenging part of the process was every week, things kept breaking. It was really difficult to put the sensors together. We used maybe 1,000 code combinations to program it correctly." This persistent challenge of "putting sensors together" and troubleshooting their code illustrates the tension between student motivation and the difficulty inherent in the technical tools with which students were working, depicted as tension (a) in the InvenTeam activity system diagram (Figure 3). In the end, this tension proved facilitative, creating pressure that led students to persist in the face of technical challenges and ultimately achieve their object.

Tension (b): Community Expectations versus Student Goals

Over the course of the project, students received widespread recognition for taking on the challenge of inventing a device to mitigate hot car deaths. "[STEAM Charter School] Students Work to Prevent Hot Car Deaths" reads the headline of one story featured in a local neighborhood paper. At the project's mid-grant technical review, community members lauded the invention's potential for societal impact and encouraged the students to work toward bringing the invention to market. For example, during the question and answer period following students' presentation, one community member prompted the audience to applaud the students again exclaiming, "I commend you…just think how many lives can be saved when your product hits the market." Another audience member with a background in business remarked that he was "really impressed with the presentation and the good this could do" adding that he "can see where y'all can make a lot of money" before encouraging the students to pursue a patent: "if you produce something and someone can see what you are doing, they can take it like that. How can you protect this? I hope you have that covered. Start thinking about a patent now."

As students continued work on the project, a tension between the object envisioned by community members (developing a device that would actually be brought to market in order to prevent hot car deaths) and students' object (a working device by EurekaFest) became apparent. Community members tended to foreground the invention's societal implications, often sharing their excitement about the long-term possibilities for the invention. Students appreciated the warm reception for their idea while also tempering their ambitions for the device. Occasionally, students expressed that they felt pressure to go beyond their main goal of designing a working device and that, at times, this pressure could be distracting or overwhelming. In one interview, Nora shared that she felt "all the discussion of a patent" was premature, noting "we've got so much work to do before we can even think about that." This tension between community expectations and student goals is evident in Jeff's comment during a class session following the mid-grant technical review: "they [audience] were psyched about what we can do with this. Right now, I'm not thinking about that. I just want to get this code to work."

Although the potential for societal change was not always top of mind as students worked on the device, students did describe certain circumstances in which they became reinvested in the problem of hot car deaths. First, as was the case following the mid-grant review presentation, students described how presenting their work to an audience and receiving recognition from the community affirmed the importance of their invention. Nora recounts the following episode in which her dentist shared that she had seen a local news story about the project:

> It became more meaningful when we'd tell someone what we were doing and they would be like, "Oh wow, I just saw this." And then when they would care, it made it seem relevant again…like, when I went to the dentist office, it was like

> in the springtime. I was getting an x-ray and she says that she saw me on the news, and then then she'd say, "Hey that's a really important problem and I'm glad that young students are working to fix it." Things like that made it more relevant.

Second, students became more energized about the potential societal impact after making a breakthrough or overcoming a particularly daunting challenge. For example, Nora describes her reaction when she learned that the InvenTeam had been awarded a provisional patent:

> It was one of those times when I was like, "is this a thing?" We are high school students, but, I mean, it kind of works…and they approved it. So, could this really be a thing that could do some good?

In another example, students became visibly excited during a Saturday work session after resolving a coding issue preventing the device's communication with the iOS app. When asked to comment on how the project was going, Lawrence responded half-jokingly, "it's not a project. It's a real thing to save lives."

Tension (c): STEM Applications Constrained by Specialized Roles

Although meaningful application of STEM knowledge and skills was evident across the InvenTeam, the degree to which students applied and advanced STEM knowledge or practices was not always evenly distributed. Unlike a traditional high school course driven by a set of common learning goals or standards, the level and areas of expertise students developed were somewhat constrained by their particular role and the individual interests, knowledge, and skills students brought or sought to develop over the course of the project. Certain members of the team focused the majority of their time on the more technical aspects of the invention, amassing an impressive number of hours coding or working on the invention's circuitry. Simultaneously, other students had roles that focused primarily on administrative aspects of the project (e.g., fundraising, procurement, communications). Thus, not every student developed in-depth understanding of the device's sensors and the complex code that integrated their functionality. As the project deadline approached, success depended largely on a few students' specialized expertise related to particular aspects of the invention, resulting in increased workload and pressure but also additional learning opportunities for a subset of InvenTeam members.

Potential deleterious effects of specialization were mediated by two factors: prerequisite engineering knowledge and the expectations of the Engineering Applications course. Because all students entered the course having completed foundational engineering courses, Ms. Green was able to prioritize the project's goal of invention over student mastery of a common set of engineering concepts and skills. As was evident when the project's Fundraising Lead stepped in to assist with soldering the device, students' prerequisite knowledge and experience also enabled flexibility in student roles according to the project's needs. The Engineering Applications course explicitly intends to provide engineering students an opportunity to apply STEM knowledge to develop solutions to technological problems. As such, the standards for the course are relatively broad, focusing on the engineering design process as well as applied skills including planning and time management, communication skills, and marketing. Although the InvenTeam project was not structured to systematically afford opportunities to master each course standard, the overall level of difficulty and applied nature of the project meant that students easily met the Engineering Applications standards as a matter of course.

Tension (d): School Norms versus the Process of Invention

Although the project aligned well with the goals of the Engineering Applications course, the case study highlights a number of tensions and complications that occurred as high school students exercised agency as inventors. Within the InvenTeam context, the lines between what it meant to be a student, teacher, and engineer were often blurred, with students often positioned as authoritative experts and project managers. The blurring of these lines often afforded powerful learning opportunities, as in the many episodes where students taught Ms. Green or Mr. A critical content related to their area of expertise. Indeed, observation and document data detailed intense collaboration between the students, Ms. Green, and Mr. A. For instance, one post on the InvenTeam Twitter feed reports, "Ms. Green and Nora are collaborating to code and integrate the Arduino WIFI and the infrared sensor." In her role as the teacher of the Engineering Applications course, Ms. Green guided student work over the course of the project and assigned grades based on their contributions and participation, as documented in their DDJs. At the same time, it was more common for students to inform or update Ms. Green on how they planned to spend their time in class than for her to provide explicit instructions about what students should be working on. While these dynamics conveyed a level of trust and agency to students, it also meant that student engagement and participation fluctuated considerably over the course of the project and that Ms. Green was not always equipped to monitor student progress closely or to get students back on track when engagement wavered.

The culture of InvenTeam sessions violated many of the norms, rules, and procedures governing how time and space are traditionally used and allocated in high school settings, generally, and at the Senior Academy, in particular. It was not uncommon for students to not be in the classroom at all during the scheduled meeting time as they completed tasks related to the project in other areas of the school or even off campus. Unlike in many of their other courses, listening to music, using cell phones to make calls, and bringing in snacks for the group were commonplace during InvenTeam sessions. Saturday work sessions included long periods of intense focus punctuated by breaks to eat wings or enjoy an impromptu performance of the latest dance trend. Student work on the project did not conform neatly to the prescribed schedule of the school day or even the school year, as evident by the necessity of Saturday and summer work sessions and the continuation of the project as an Independent Study the following year. As the end of the school year approached, it became apparent that both Ms. Green and many of the students on the team were devoting considerably more time and energy to the project than to other courses and priorities and that the urgency of "getting the device to work" resulted in a higher level of stress than many students were accustomed to during a typical final exam season.

Finally, the project suggests a certain tension between the goals of invention and the traditional goals of high school education. In describing important outcomes of the InvenTeam experience for students, Ms. Green underscored both outcomes related to engineering practices (applying STEM knowledge/skills, persistence, collaboration) and social and economic benefits students enjoyed as a result of their work on the project. For example, Ms. Green highlights how the team's fundraising campaign afforded new experiences, discussing how the team's Boston trip for the Lemelson-MIT EurekaFest event "broadened their horizons," noting that several students had never flown on a plane and that students loved "getting to stay in this fancy hotel" and being able to eat out at restaurants. She underscores how the experience contrasted with school norms, stating that "we did ridiculous things that most schools would not be excited about," such as students renting Hubways and riding bikes around Boston. Ms. Green viewed these activities not simply as fun perks but as an opportunity for students to see that their hard work paid off, explaining "they wanted to do that and they earned it and we did it…being able to pay for stuff that they earned money for through their awesome academic work is super cool."

Once students achieved their goal of designing a working device, they were faced with the question "what's next?" Although most students were prepared to move on as they would with any class project, a subset of students could not abide the prospect of shelving what they believed to be a potentially life-saving invention (or foregoing the possibility of adding a patent to their college applications). Although the school was able to take the unusual step of creating an Independent Study for students to continue their work, it is not realistic to expect schools to add courses or adjust schedules to accommodate unpredictable and often extended timelines of invention. Members of the school community encouraged the InvenTeam to pursue a patent for their invention long before they had a working prototype; however, as invention is not typically a priority in K-12 schools, resources to assist students with the patent process were scarce.

Discussion

By following a group of high school inventors as they took on a technically challenging project, this case study highlights new possibilities for PBL. The InvenTeam's experience suggests invention as a potentially powerful approach to facilitating projects in which students identify, research, and potentially even solve problems in their lives and communities. Further, the project provides an example of what can be achieved by harnessing the experience and diverse forms of knowledge of a class of students rather than channeling student effort into shorter-term, individual, or small-group projects. Finally, the case study adds to the literature base documenting student outcomes of PBL (Bransford & Donovan, 2005; Kolodner et al., 2003; Krajcik et al., 1998). As they researched, designed, and built the device, the members of the InvenTeam had numerous opportunities to hone their STEM knowledge while also engaging in key epistemic practices of engineering (Cunningham & Kelly, 2017). Specifically, the scale and scope of the project and students' defined roles within the project's division of labor created a context for students to continually engage in intensive collaboration and develop an appreciation for the social context of engineering design.

The varied and dynamic nature of students' purposes for engaging in the project signal a need for facilitators of such projects to attend to how students conceptualize engineering projects over time. Shifts in students' motivations and interests over the course of the project indicate that one cannot assume that youth maintain the same motivation or interest in the problem over the lifespan of a project. In the case of the InvenTeam, students' genuine concern about the issue of hot car deaths in their community was ultimately eclipsed by the imperative of presenting a working device at EurekaFest. Thus, the study serves as a reminder that, even when students take the lead in identifying a meaningful problem, the aspects of a problem that intrigue students in August may be completely different from those that motivate them to see a project through to completion in May. Additionally, that Ms. Green and her students were primarily concerned with overcoming the technical challenges presented by the project suggests the importance of explicitly facilitating what McGowan and Bell (2020) term critical sociotechnical literacy. Although students were mission-driven in the sense that they were invested in achieving their object of designing and building a device to mitigate hot car deaths, they did not continually engage in the type of critical reflection that would situate their device as part of a complex sociotechnical system. For instance, beyond occasional discussions about sustainability and whether the device would be designed to be installed by car companies or as an after-market consumer product, there was little discussion of the societal or ethical implications of the invention. Students were not asked, for example, to reflect on exactly *who* would benefit from the invention or to consider *whose* babies would be saved.

The study also raises interesting questions about the role schools can play in the process of invention. In engineering education, we emphasize the importance of engaging students in the process of identifying and solving authentic, meaningful problems. This case study raises the question, “what happens when they do?” The work of teachers and students has traditionally centered on the acquisition of certain knowledge and skills, but what would it mean for students and teachers to refocus their work to become agents of innovation? In what ways might engineering classrooms be reimagined to resemble incubators or start-ups? What resources are required and what responsibilities do schools assume when they invite students to tackle important societal problems? It might well be argued that engaging students in the process of invention and innovation should be valued over the product of students’ efforts, that whether students are able to design a working invention matters much less than the lessons learned through the design process. At the same time, there were students on the InvenTeam who cared deeply about their product and its potential as a technological innovation, if not a lifesaving invention. This case study demonstrated that the timelines of schooling and invention tend not to align. Thus, educators engaging students in ambitious design projects for which students are likely to become invested in their products would be well served to consider how they can support students over the entire lifespan of their projects, whether that means supporting the patent or production process or simply providing meaningful opportunities for students to showcase their work.

Limitations

Although this case study is likely to be instructive for the engineering education community, it is not without limitations. The study sought to follow the evolution of the InvenTeam project; however, as data collection was most intensive during the spring semester of the project year, observation data were not collected during key phases of the project’s initial development (problem identification, proposal development) or at the project’s culminating presentation. Additionally, although all students participated in multiple, short-design discussions, the breadth of student perspectives included in the study is somewhat limited by relying on full semi-structured interviews with only two students, Nora and Khalil. These limitations on student data and the focus on the InvenTeam’s work as a collaborative group meant that the case study was not able to fully explore implications for complex student-level constructs, such as individual students’ engineering identity development. Thus, in-depth, ethnographic work exploring the effects of participating in such projects on individual students would be a fruitful avenue for future research. Finally, trustworthiness of the case study was heightened by enlisting a colleague as an independent coder and through member-checking with Ms. Green; however, due to the timeline of the research, it was not possible to engage student participants in member-checking in order to get their perspective and confirmation of the case study findings.

Conclusions

Findings of this case study begin to illustrate both the possibilities and challenges of attempting engineering in practice (Penuel, 2014) in the context of a high school engineering course. By describing the level of engineering the InvenTeam was able to achieve and the degree to which the project afforded opportunities for students to apply and develop STEM knowledge and skills while engaging in epistemic practices of engineering, the case study suggests this type of time-intensive, invention-focused, PBL as a potentially powerful approach to high school engineering. Additionally, this case study demonstrates the utility of CHAT and activity systems analysis as a method for analyzing complex engineering education activity over time. By describing the elements of and tensions within the InvenTeam activity system, the study illustrates how sustained study of activity systems can yield insight into both the promise and the complexities of applied engineering projects where students are positioned not merely as students completing a class project but also, at various points, as engineers, teachers, and inventors.

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