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No Bones About It: How Digital Fabrication Changes Student Perceptions of their Role in the Classroom

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Abstract

This study used cultural historical activity theory to make meaning of a digital fabrication project situated in the complexity of a classroom. Using an ethnographic perspective, we observed 14 students (aged 13–14) in a middle school's creative design and engineering class inspired by the Maker Movement. Working with the classroom teacher, a professional stuntman tasked students with fabricating a prosthetic bone for use as a movie prop using their understanding of science, technology, engineering, and mathematics. Teacher interviews and student focus groups revealed differences in perceptions between their science class and engineering class. Additionally, affordances and constraints of the 3D printer as the tool for construction are presented, as identified by student and teacher participants. Finally, two illustrative vignettes are presented to depict tensions that emerged due to facilitating this digital fabrication project within the traditional confines of a classroom.

Keywords: STEM education, digital fabrication, science, technology, engineering, mathematics

Introduction

The Maker Movement "represents a growing movement of hobbyists, tinkerers, engineers, hackers, and artists committed to creatively designing and building material objects for both playful and useful ends" (Martin, 2015, p. 30). Making is often associated with Maker Faires, makerspaces, and fabrication (or fab) labs, in which participants actively create physical objects to share with the world around them (Resnick & Rosenbaum, 2013), but it is increasingly becoming associated with formal K–12 schools (Wardrip & Brahms, 2016). In this work, we present an exploratory case study of a middle school teacher using digital fabrication in an engineering classroom during the traditional school day. We used cultural historical activity theory (CHAT) (Roth & Lee, 2007) to analyze and frame our findings. Following, we review existing literature related to making, as well as present our theoretical framework and research design, concluding with recommendations and implications of this work for those interested in incorporating making at school.

While the Maker Movement is relatively new to education and is often associated with new technologies, the act of making is, of course, not new. Historically, making traces back to innately human crafts such as woodworking and sewing (Martin, 2015), but the rise of personal fabrication tools such as 3D printers, laser cutters, and Arduino microcontrollers have revolutionized the act of making for the twenty-first century. Ultimately, making is the act of creating physical artifacts—using knowledge and skills from the disciplines of science, technology, engineering, mathematics, and art—for the purposes of sharing playful and useful creations with the world. With the implementation of the Next Generation Science Standards

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(NGSS Lead States, 2013) that specifically include engineering design, and the emergence of affordable technologies that enable novices to create increasingly complex designs, this is an excellent time to consider how the Maker Movement can transform K–12 education.

While the current Maker Movement has generated excitement about the possibilities for learning afforded by active construction in science, technology, engineering, and mathematics (STEM)-rich contexts, researchers are still investigating the relationship between making and learning. When students are making, learning typically looks and feels different from what is observed in traditional classrooms, with common critics of this approach asking, "It looks like fun, but are they learning?" (Petrich, Wilkinson, & Bevan, 2013). However, as argued by Blikstein and Worsley (2016), the theoretical justification for the benefits of making to learn already exists. From Dewey's (1902, 1938) focus on experience in education, to Kilpatrick's (1918) praise of the project method, or Montessori's (1912) focus on sensory learning to further students' individual inclinations, it is difficult to ignore the transformative power that student-centered, inquiry-based learning provides. Further, Piaget's (1980) learning theory of constructivism speaks to the value of students constructing their own knowledge based on experiences and interactions with the world. Papert and Harel (1991) built on Piaget's work to create a theory of constructionism—the idea that learning happens especially well in a context where the learner is positioned to actively construct a meaningful object to share with the world.

Moreover, Blikstein (2008, 2013a) argued for the transformative power inherent in making; through making, children have the power to move beyond the role of consumers and become producers—producers of their own learning experiences, knowledge, and, ultimately, futures. This thought shares sentiments with Freire's (1970) notion of critical pedagogy—the idea that education is never neutral and should challenge learners to recognize their role and ability to create critical change in the world around them. Along these lines, making can serve as a vessel to welcome and attract more diversity into the STEM disciplines, particularly among groups (e.g., women) and individuals (e.g., from ethnically diverse backgrounds) who are traditionally underrepresented in STEM. For example, research has shown that the creation of electronic textiles (or e-textiles), which combine sewing and electronics, allows girls to take on a leadership role more often than boys (Buchholz, Sively, Peppler, & Wohlwend, 2014). Further, Vossoughi, Hooper, and Escude (2016) provided documentation of their work in after-school settings introducing making to youth from predominately low-income communities, further supporting the call for this movement to reach *all* students; an important goal to uphold the value of making as an intrinsically human act, not something reserved for wealthy, tech-centric boys and men (Buechely, 2013, 2016).

Making to Learn

In her substantive literature review, Bevan (2017) distinguished between three types of making discussed in current research: making as entrepreneurship, making as STEM workforce skill development, and educative making. Here, we focus on the latter category, *educative making*, described as well suited for elementary and secondary school-age learners to accomplish the "broader goals of developing students' interests, capacities, and productive learning identities" (Bevan, 2017, p. 6). Previous research has documented a host of productive gains in outcomes associated with the goals of educative making; such as increases in: creative confidence (Barron & Martin, 2016), self-efficacy and perseverance in problem solving (Peppler & Hall, 2016), resourcefulness (Sheridan & Konopasky, 2016), and adaptive expertise (Martin & Dixon, 2013).

While developing students' interests and capacities as learners is important, educative making must also attend to disciplinary content knowledge if it is to take tenure in the academic school day. We argue that students can productively engage in educative making (to increase interests, capacities, etc.) while also learning STEM content. In fact, we posit that this type of balance is precisely what will allow making to reach all students at school. Previous research has positively connected making to the development of skills in math (Garneli, Giannakos, Chorianopoulous, & Jaccheri, 2013), art (Peppler, 2016), writing (Cantrill & Oh, 2016), computing (Papert, 1980), and spatial reasoning abilities (Leduc-Mills & Eisenberg, 2011). Further, with the release of the NGSS that specifically call for engaging students in learning engineering alongside science, we advocate that now is an ideal time to consider how making connects to learning outcomes specific to these disciplines. Following, we provide a brief overview of existing research investigating the relationship between making and learning science and engineering.

Making to learn science

While Bevan (2017) acknowledged that few studies currently demonstrate conceptual science learning gains in students while making, work is beginning to emerge. For example, Peppler (2013) described how kindergarten students who learned about electronic circuits through making developed deeper conceptual gains related to key circuitry concepts such as flow and connectivity when compared to a control group who followed traditional approaches to learning about circuits. Further, Flores (2016) described a variety of educative making activities connected to science concepts, highlighting the necessity of embedding inquiry and invention in the science classroom: something educative making is extremely poised to accomplish.

Making to learn engineering

While the emergence of engineering is relatively new in K–12 schools, the NGSS explicitly call for engaging students in the process of *engineering design* (see Table 1). Bevan (2017) concluded that the existing literature connecting making to engineering learning outcomes is sparse. Much of the existing research teases apart differences in terms associated with making; namely tinkering, design, and engineering design (e.g., Petrich et al., 2013). While there are instances that provide evidence of students developing skills in design (e.g., Berland, 2016), much of the research in this area has focused on student identity and the development of dispositions that complement engineering, such as adaptive expertise (e.g., Martin & Dixon, 2013).

Making Space for Making

A variety of spaces have emerged for individuals to create with technology—both in and out of formal schools. Commonly referred to as makerspaces, these places are described as sharing "some aspects of the shop class, home economics class, the art studio, and science lab. In effect, a makerspace is a physical mash-up of different places that allow makers and projects to integrate these different skills" (Dougherty, 2013, p. 9). Sheridan et al. (2014) conducted a comparative case study of three different makerspaces in a variety of settings, concluding that each space was "multi-disciplinary both in approach and in work produced… blended formal learning environments and informal communities of practice, and [were] focused on learning as production rather than a mastery of a composite set of skills" (p. 526). Makerspaces are places where people come together to digitally and physically make in community.

Most of the existing research investigating educative making has occurred in out-of-school or informal makerspaces, found in afterschool clubs, summer camps, and museums. However, out-of-school spaces are not necessarily equitable or accessible to all children. For example, a child might not live near a prominent science museum, such as the San Francisco Exploratorium (Petrich et al., 2013). Moreover, not all families are able to afford the potentially high costs associated with specialty summer camps that provide opportunities to make. We argue that if educative making is to truly reach all students, implementation must occur in the traditional school day. Following, we provide an overview of existing empirical research on educative making divided into two sections—making in (1) out-of-school contexts and (2) formal school contexts.

Out-of-school making

Making occurs in a large range of out-of-school environments. Events such as Maker Faires, Maker Family Nights, and robotics competitions have garnered a great deal of attention and excitement, while permanent sites offer longer-term programs through community and youth centers, libraries, churches, museums, and after-school sites. Maker activities also occur at pop-up sites, through museum outreach, or mobile maker studios (Peppler, Halverson, & Kafai, 2016).

Many of the first makerspaces studied were created in informal environments such as science museums; for example, the Tinkering Studio at the San Francisco Exploratorium (Petrich et al., 2013), NYSCI Design Lab at the New York Hall of Science (Bennett & Monahan, 2013), and Makeshop at the Children's Museum of Pittsburgh (Brahms & Werner, 2013) are all dedicated spaces for making or tinkering within museums. Community-based makerspaces have also increased in popularity and reach. A 2011 survey of 250 hackers presented the average makerspace member as college-educated, male, and in his late twenties (Moilanen, 2012); however, new makerspaces are actively drawing from community interests and intentionally broadening participation (Calabrese Barton, Tan, & Greenberg, 2017). At Mount Elliot Makerspace, the majority of participants are African American families, and community partnerships and events are central (Sheridan & Konopasky, 2016). Similarly, "youth-oriented makerspaces" developed in Boys and Girls Clubs in the Midwest offer opportunities to engage underrepresented groups in making and draw from youth and community funds of knowledge (Calabrese Barton et al., 2017).

Research at these out-of-school maker sites tends to focus on developing interest and learning dispositions. The few studies that focus on STEM tend to examine the NGSS engineering practices (Martin, 2015; Peppler, Maltese, Keune, Chang, & Regalla, 2015). From a survey of 51 youth-oriented makerspaces, Peppler et al. (2015) found that engineering practices were "the most frequently reported and seemed to resonate with more than 40% of makerspaces." Multiple times a week, youth defined problems, planned, investigated, and designed solutions (Peppler et al., 2016). Making in informal settings has also been associated with deeper understanding of science

Table 1
Engineering design, as described by the NGSS.

Define problem	Define a simple design problem reflecting a need or a want that includes specified criteria for success and constraints on materials, time, or cost.
Develop solutions	Generate and compare multiple possible solutions to a problem based on how well each is likely to meet the criteria and constraints of the problem.
Optimize solution	Plan and carry out fair tests in which variables are controlled and failure points are considered to identify aspects of a model or prototype that can be improved.

concepts and real-life applications (Vossoughi & Bevan, 2014). However, most studies within youth-oriented makerspaces examine the development of skills such as creativity, communication, critical thinking, and career skills (Peppler et al., 2016), or learning dispositions such as patience, curiosity, drive, or confidence (Sheridan et al., 2014).

Making in schools

Incorporating making at school is an especially timely endeavor considering that many students now view school as separate from their everyday lives (Barron, 2006; Dougherty, 2013). Too often, schools present science and math as abstract ideas, decontextualized from students' personal narratives (Bennet & Monahan, 2013; Eisner, 1985). Washor and Mojkowski (2013) provided three reasons that schools cause students to disengage when learning STEM content: schools (1) focus too much on assessment, rather than exploration and creativity, (2) rarely provide hands-on, authentic learning opportunities, and (3) only value learning that occurs in school, failing to provide opportunities for students to bring their personal interests into school. The Maker Movement provides unique opportunities to bridge this gap.

By integrating technology in student-centered learning environments such as makerspaces, more students are finding value in school (Martin & Dixon, 2013). When students are creating with technology they "become more engaged, spend more time investigating and/or constructing and take ownership for and build confidence in their abilities to learn and understand" (Petrich et al., 2013, p. 56). Additionally, Blikstein (2013a) argued that makerspaces are essential to the school learning environment because they (1) enhance existing practices and expertise representative of manual labor (and potentially validate students' personal experiences being raised in a low-income community where blue-collar work is more common), (2) accelerate the processes of ideation and invention, and (3) allow for long-term projects and deep collaboration. Martinez and Stager (2013) explained that projects involve "work that is substantial, sharable, and personally meaningful" (p. 57). By engaging students in meaningful projects with appropriate tools for expression, technology has a democratizing effect that places the means of expression in the hands of children.

Select K–12 schools are emerging that emphasize educative making. For example, the Brightworks School, an elementary school in San Francisco, is entirely designed around the idea of creative building (http://www.sfbrightworks.org/), yet enrollment is selective and tuition is pricey. Further, Lighthouse Community Charter (https://lighthousecharter.org/) is an example of a public school implementing making through their Creativity Lab. It is important to note that many of these schools exist in Silicon Valley—a hub of technological innovation. However, this signals concerns regarding issues of equity voiced by scholars such as Buechley (2013, 2016) and Vossoughi et al. (2016). Making is an innately human act that *all* students should have the opportunity to experience in their normal school day, regardless of parental income level or zip code.

Additionally, some research has focused on teacher preparation in regards to making. For example, Wardrip & Brahms (2014) conducted a professional development workshop for middle and high school teachers centered on creating with technology (specifically Arduinos and 3D printers). Results indicated that teachers were proud of their creations, but struggled with the use of technology and the programming required. Additionally, Wardrip and Brahms (2016) described their experiences as museum educators working to train local elementary school teachers in educative making, concluding that successful teachers *wanted* to incorporate making into their classrooms, found creative ways to connect making to other content areas, and did better when there was a designated space for making (as opposed to a mobile cart). In earlier work (O'Brien, Hansen, & Harlow, 2016; Harlow & Hansen, 2018), we described our efforts to prepare preservice elementary school teachers to facilitate educative making in a university science methods course by designing and facilitating an activity at a School Maker Faire. Further, Cohen, Jones, Smith, and Calandra (2017) surveyed and interviewed preservice and early career teachers, concluding that these teachers saw the value of educative making, frequently making connections to other instructional strategies such as inquiry and project (or problem)-based learning; teachers also discussed potential barriers to making in school, such as access to resources and unsupportive administrators.

Bridging the Gap: Bringing Making to School

Over the last ten years, the idea of making has expanded from a few hackerspaces and community groups into a thriving movement, leaving many schools and administrators eager to adopt educative making into the curriculum. However, Papert (1980) warned about the pattern of powerful ideas losing value when implemented by schools, constrained by schedules, budgets, accountability, and oversight. Additionally, other scholars have cautioned against blind adoption of making in the classroom, fearing that "attempts to institutionalize making—through schools, after-school programs, etc.—will quash the emergence, creativity, innovation, and entrepreneurial spirit that are hallmarks of the 'maker revolution'" (Halverson & Sheridan, 2014, p. 500). Similarly, Martin (2015) warned educators from becoming too fixated on the tools themselves; as Martinez (2014) stated, "Going shopping will not change education. It never has." Simply buying a 3D printer for a classroom will not transform education if the learning around the tool is superficial. Blikstein (2013a) referred to this issue as "the keychain syndrome" and cautioned educators against "the temptations of trivialization" (p. 8). Considering the history of the school system and novelty of the Maker Movement, more research is needed to explore how teachers can best engage K–12 students in educative making while at school.

In this work, we present an exploratory case study of a middle school teacher using digital fabrication in an engineering classroom during the traditional school day. We used Cultural Historical Activity Theory (CHAT) (Roth & Lee, 2007) to analyze and frame our findings. Following, we describe our theoretical framework and research questions, present our research context and methods, and share findings to guide the implementation and facilitation of educative making at school.

Theoretical Framework

In this study, we used CHAT as an analytical tool to explore the complex act of making within a classroom. CHAT, regarded as "Vygotsky's neglected legacy" (Roth & Lee, 2007, p. 186) and "the best kept secret of academia" (Engeström, 1993, p. 64), holds great analytical promise for educational settings. More than eighty years ago, Vygotsky championed the notion of studying the cultural context and setting around an individual, in opposition to behaviorist approaches (Vygotsky, 1986). Leont'ev (1978) and Engeström (1987) continued this line of research, with Engeström developing the activity system framework and popularizing the CHAT triangle (see Figure 1). More recently, Roth and Lee (2007) argued that, "an activity is realized through concrete actions, which are directed towards goals" (p. 16). Ultimately, activity can only be understood through concrete actions of individuals working to accomplish some goal in context.

While CHAT is a highly dynamic framework for studying complex systems, we focused our analysis on two specific components of CHAT—*rules* and *tools*—because they were the most salient in the classroom and project under investigation. Additionally, tensions that emerged between interacting components of CHAT are discussed as these are considered sources of change and progress within the activity system (Engeström, 1987). In the following subsections, rules and tools in the context of CHAT are discussed, followed by an overview of the larger, activity system—a middle school engineering classroom.

Rules

Rules constitute "an important resource for situated actions" (Roth & Lee, 2007, p. 199). Rules consist of the cultural norms, expectations, and practices that occur within a specific context and guide the actions of subjects within the activity system. For example, in the traditional classroom, rules might consist of staying seated in a desk and paying attention to the teacher who is primarily stationed at the front of the room. If a teacher has also created the norm that a student must raise her hand to speak, whispering to a neighbor is then viewed as breaking a rule. If children are reprimanded for talking out of turn, this then reinforces and upholds the culture of the classroom.

Tools

In general, a tool within an activity system serves "as the conductor of human influence on the object of the activity; it is externally oriented; it must lead to changes in objects" (Vygotsky, 1986, p. 55). People make and use tools to learn, communicate, and influence objects or outcomes. Tools are "crafted at a point in time and adapted over time: Their development is shaped by the needs, values, and norms of the culture(s) in which they are created and used" (Foot, 2014, p. 331). Vygotsky distinguished between two types of tools—psychological and technical. Psychological tools are "directed toward the mastery or control of behavioral processes," including tools such as language, writing, art, and algebraic symbols. In contrast, technical tools are "directed toward the control of processes of nature," and could include tools such as laser cutters and 3D printers, which are used to manipulate physical matter occurring in nature (Vygotsky, 1981, p. 137).

The Activity System: A Middle School Engineering Class

In our work, we considered students and teachers as socio-cultural actors in the activity system of a classroom. Specifically, the students were enrolled in a mandatory course required of all 8th grade students (aged 13–14) called "creative design and engineering" (herein referred to as "engineering class"). As is described later, in this engineering class, the students designed and fabricated objects using various technologies. In this study, we focused only on the curriculum unit using the 3D printer. The students were also all enrolled simultaneously in a science course that was taught by the same teacher. The science class was more traditional in that it followed a textbook and students completed labs with prescribed steps. We explored how the students' articulated conventions about their experiences in engineering class compared to their experiences in their science class, recording their perceptions of learning and coursework in these different contexts. Additionally, we investigated how the tool (the 3D printer) impacted students' participation and completion of a digital fabrication project within the engineering classroom. Finally, we identified several tensions between interacting nodes of the activity triangle shown in Figure 1. These tensions are sources of both change and progress within an activity system. Figure 2 depicts our conceptualization of the activity system under investigation in this study.

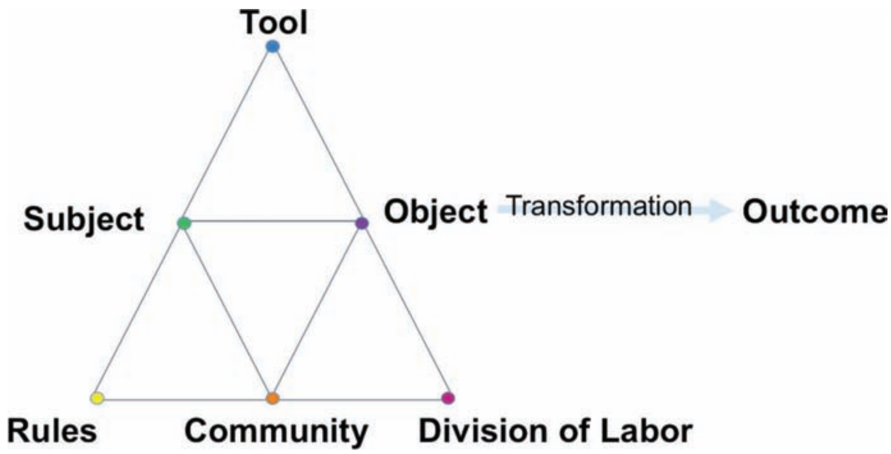

Figure 1. Cultural historical activity theory (CHAT) represented graphically.

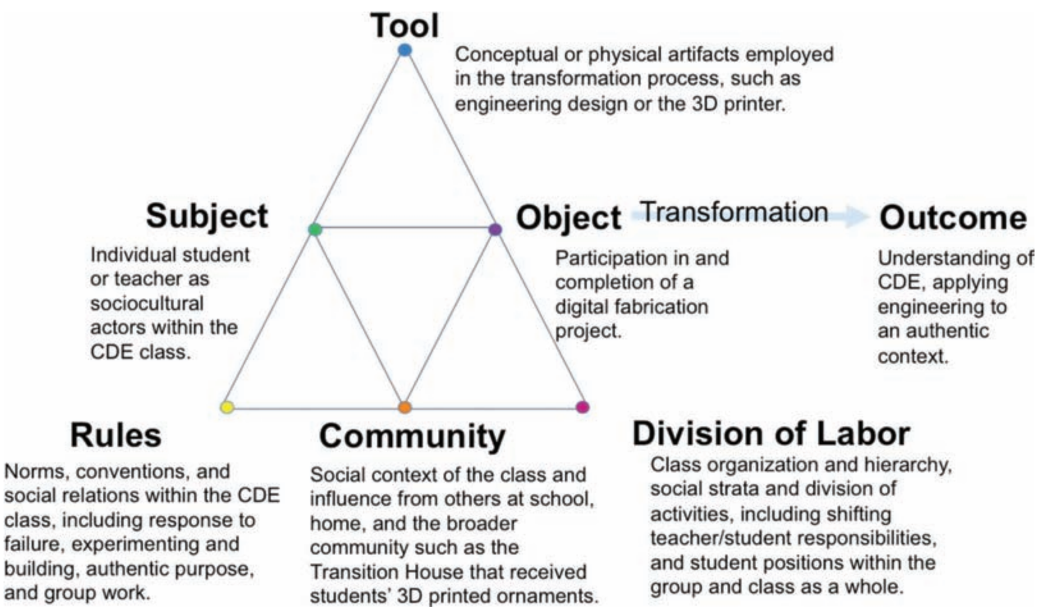

Figure 2. The creative design and engineering (CDE) classroom activity system, represented graphically.

Methods

Research Design

This research is an exploratory and qualitative case study. As defined by Merriam (1988), "a qualitative case study is an intensive, holistic description and analysis of a single instance, phenomenon, or social unit" (p. 21). At the beginning stages of this project, research on making was particularly scant, so an exploratory case study model was followed, seeking to tease out emerging themes and research questions worth pursuing. Case studies "include as many variables as possible and portray their interaction, often over a period of time" (Merriam, 1988, p. 30). A case should be a bounded system, something one can "fence in." Here, the case was bounded both by classroom walls (a single classroom) and time (a unit in a course). Specifically, this bounded case is a middle school engineering classroom where students worked in small groups to complete a digital fabrication project over the course of six months. To further focus classroom observations, we used an ethnographic perspective (Green, Skukauskaite, & Baker, 2012).

We structured our research questions around two components of the CHAT framework, rules and tools, and on tensions between all components. These areas emerged as particularly salient in the classroom under investigation and, thus, are the focus of this study.

1. *Rules*: How do students describe their experiences in their science class compared to their engineering class?
2. *Tools*: What affordances and constraints does the 3D printer provide? How do these impact the students' completion of a digital fabrication project in engineering?

3. *Tensions:* What tensions emerge within an engineering classroom situated within a traditional school system?

Research Context

This research took place at a private K–8 school located in central California with approximately 210 students enrolled. The school prides itself on being student-centered and having lower student–teacher ratios than public schools. Students apply for admission and are selected based on their previous academic record, inclusive of grades and extracurricular activities. There are select grants and funding options available for families to subsidize the tuition costs. Students can receive anywhere from $1000 to almost full tuition coverage, based on the family's need. This school was selected for research because it was one of the only local schools in the region implementing educative making connected to science and engineering at the time the study began. Further, it was the only school with a *required* engineering course for middle school students—a crucial age for sparking and sustaining engagement in STEM (Tai, Liu, Maltese, & Fan, 2006). Finally, the school was selected because the teacher was particularly motivated to learn more about how her engineering class was serving her students and approached us as partners in research. Opening one's classroom to research, especially when embarking on new models for instruction, requires enthusiastic teacher partners.

Participants

Participants included 14 (of 15 enrolled) 8th grade students, aged 13–14 at the time of the study. There were seven female students and seven male students; one male student enrolled in the class declined to participate. Fourteen of the enrolled students (or 93%) self-identified as Caucasian; the remaining student self-identified as Latino. Students worked in groups of 2–4 to complete the digital fabrication project. In addition to the classroom teacher (Ms. Taylor), an instructional aide and technology expert (Ms. Wilson) was present in the classroom to assist students. The adults were also considered participants in this study. All student and teacher names used in this report are pseudonyms.

Creative design and engineering class and curriculum

In the year prior to this study (2013–2014), the middle school science teacher (Ms. Taylor) offered an engineering *elective* class because the school was interested in STEM integration. However, when the course was offered as an elective, a greater number of boys enrolled than girls. Because the school and teacher felt that this was an essential learning experience for *all* students, the course was made *mandatory* the following academic year. In the required course, the teacher sought to provide experiences for students to design both digitally and physically. Students programmed interactive stories and games using Scratch (http://scratch.mit.edu), built robots, experimented with Makey Makey (http://makeymakey.com), and gained experience using a 3D printer—specifically a MakerBot

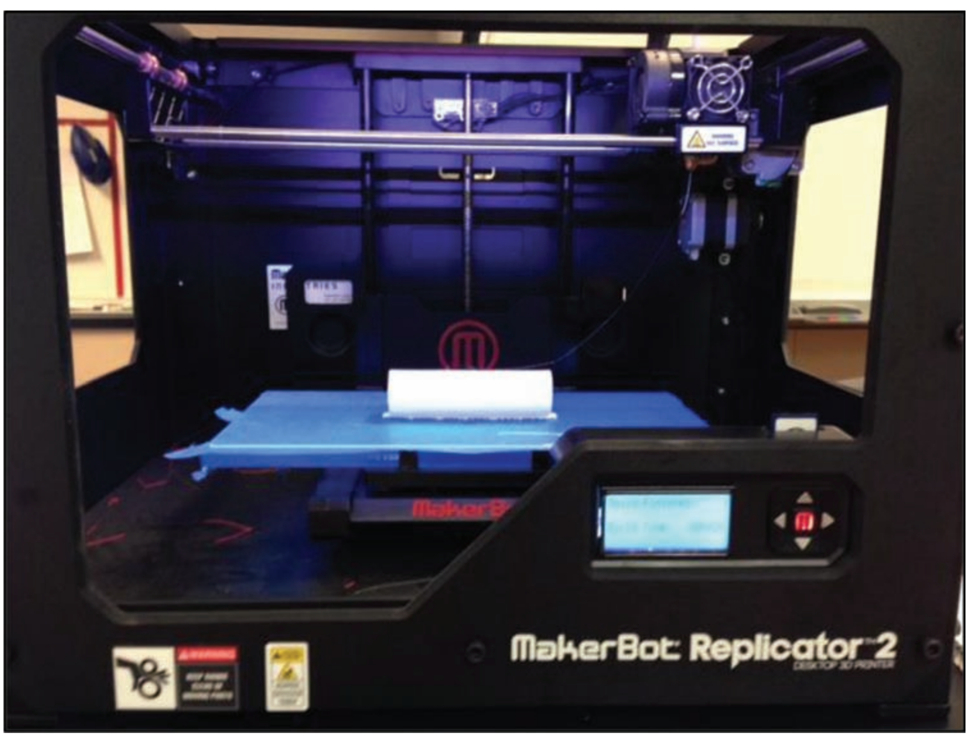

Figure 3. MakerBot Replicator 2—the 3D printer used by students in engineering class—with a prototype bone printed.

Replicator 2 (see Figure 3). Ms. Taylor also noted that she sought to teach skills and dispositions of the "maker mindset" to the students throughout the course (Dougherty, 2013). These skills included empathy, design thinking, learning from failure, focusing on process rather than product, learning to and from critique, acquiring knowledge through doing, and the importance of a growth mindset (Dweck, 2006). It is important to note that the researchers did not have control in selecting or sequencing curricular units, but rather acted as observers throughout the study, letting the teacher remain in control of her classroom and curriculum.

The digital fabrication project: Design a prosthetic bone

In the learning unit described here, students used a 3D printer and associated design software as the primary tool for construction and design of a prosthetic bone. Seeking a design challenge that had an audience outside of the school community, the teacher collaborated with a professional stuntman. The stuntman was also an enrolled student's father (herein referred to as Mr. Perez), who was missing part of his leg, an important physical characteristic for the project task. Ms. Taylor and Mr. Perez tasked students with fabricating a prosthetic bone that Mr. Perez would use as a prop in an action scene of an upcoming movie. The bone was required to look realistic, break with realistic fracturing when applied with a force, and fit within predetermined size constraints. The final bone design was required to measure 200 millimeters in length and 30 millimeters in diameter. Mr. Perez intended to use the bone covered with artificial skin and blood in the movie scene. Figure 4 shows an early prototype drawing created by one group.

Data Collection

Multiple types of qualitative data were collected: observations, teacher interviews, and focus group interviews with students. Each of these sources of data is discussed in more detail below.

Observations

In the 2014–2015 school year, we collected ethnographic field notes on 20 hours of class meetings, documenting students' design process weekly over the course of this six-month digital fabrication project. Researchers from a nearby university acted as "participant observers" in the selected classroom (Spradley, 2016). During observations, researchers were primarily stationed at a side table when the teacher was reviewing information in front of the class. When students transitioned to working in groups, researchers walked around the classroom, interacting with students. Researchers also recorded ethnographic field notes during each observation (Delamont, 2008).

Interviews

At the completion of the project, a teacher interview was conducted with Ms. Taylor, and four student focus group interviews were conducted with 13 students in total (one student was absent on the day of focus groups). All interviews were conducted on the school's campus, in a

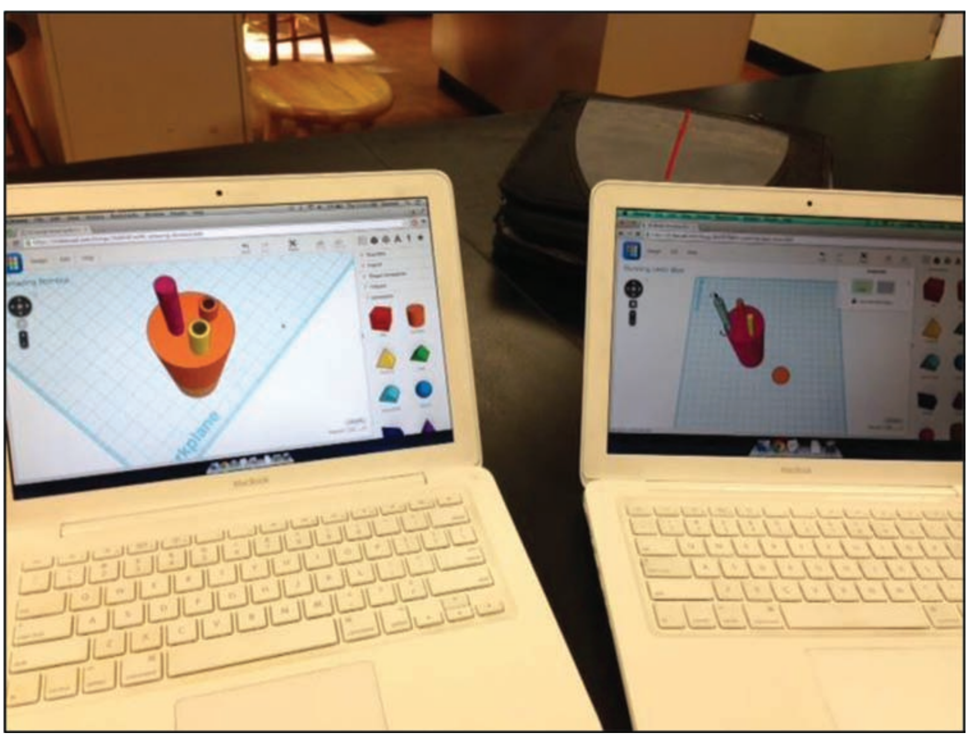

Figure 4. TinkerCAD design software, showing early prototype bone designs by one group.

quiet room free from distractions. Student focus group interviews ranged in length from 30 minutes to 70 minutes, and students were interviewed with the same students they worked with to complete the project. Questions asked during the student focus group interviews covered the 3D design experience and working with groups. Additionally, during the focus group interviews, students worked together to create a Venn diagram, comparing their traditional science class and their current engineering class. The Venn diagrams served as the starting point for discussion during the focus group interviews. Students were asked to explain their diagrams, elaborating and expanding on their ideas as a group. The teacher interview lasted approximately 60 minutes, and included questions about her motivation, planning, and instruction related to the engineering class.

For the interview and focus groups, semi-structured protocols were used (Brenner, 2006). A semi-structured interviewing protocol begins with precise questions and probes, but allows the individual researcher flexibility in conducting the interview. This type of protocol was selected to provide more freedom in following up on unanticipated questions or topics that might arise during the interviews. Both student focus groups and the teacher interview began with a grand tour question such as, "Walk me through an average, typical day in engineering class," "How does class usually start, progress, and end?" or "What type of work do you usually do?" These grand tour questions elicited the lived experiences of students and the teacher in real-world context, from their perspective, and provided detailed data worth following up on within the remainder of the interview. All questions were designed to be "open-ended, neutral, singular, and clear" (Patton, 2002, p. 353). Additionally, Spradley (1979) provided guidance in creating descriptive questions. Descriptive questions proved valuable in understanding experiences and perceptions of the participants, allowing individuals to speak broadly and discuss topics that they believed were important. Additional probes were also created for each question, in case participants needed assistance in expanding responses.

Data Analysis

First, all interviews were transcribed. Then, descriptive, emergent coding was used to pull common themes from the transcripts (Saldaña, 2012) based on each research question. Descriptive coding summarizes the data into a word or short phrase, most often a noun. Table 2 shows each research question, the corresponding code that was applied, a brief description of the code, and an illustrative example for each code from the transcripts.

The coding scheme shown in Table 2 was created and refined through discussion. Two researchers (both authors of this paper) then used the coding scheme to code all of the focus group and teacher interview data using Dedoose software (http://www.dedoose.com). These researchers then reviewed each individual code to increase inter-rater reliability. In the event that the researchers disagreed about an applied code, discussion was used to reach consensus. After this round of coding, codes were grouped into their corresponding categories and further discussed to tease out emerging themes. After emergent themes (e.g., size limitations as a constraint of the 3D printer) were identified for each research question, additional analysis was completed using the ethnographic classroom field notes; specifically, each classroom observation was reviewed to confirm or disconfirm and supplement what was stated in the teacher interview and student focus groups. Illustrative excerpts were pulled to support the emergent themes for each research question.

The second stage of analysis was to code the students' Venn diagrams. Figure 5 shows an example Venn diagram completed by one group of students during a focus group. For analysis, each descriptor for science and engineering on

Table 2
Research questions and descriptions of qualitative codes.

Research question	Code(s)	Description of code	Example
How do students describe their experiences in their science class compared to their engineering class?	Rules—engineering Rules—science	Refers to explicit mention of conventions in engineering class and/or science class.	Hannah: The second time we made (the bone) better. And, this time we made it even better. Just keep making it better.
What affordances and constraints does the 3D printer provide?	Tools—physical affordance constraint	Refers explicitly to the 3D printer. If positive, it is an affordance. If negative, it is a constraint.	Sadie: You're being reliant on the 3D printer to print our actual designs, because sometimes it will print things too far in, or too squiggly here or there. So, it's like the preciseness of the 3D printer was also a factor.
What tensions emerge within an engineering classroom situated within a traditional school system?	Tension	Refers to source of trouble or frustration, as voiced by participants.	Arianna: We don't actually know how the 3D printing process works because Ms. Taylor does it on her computer. We just email her the design…or ask Ms. Taylor if it's big enough because it might print out really, really small. But, she mainly controls all the things.

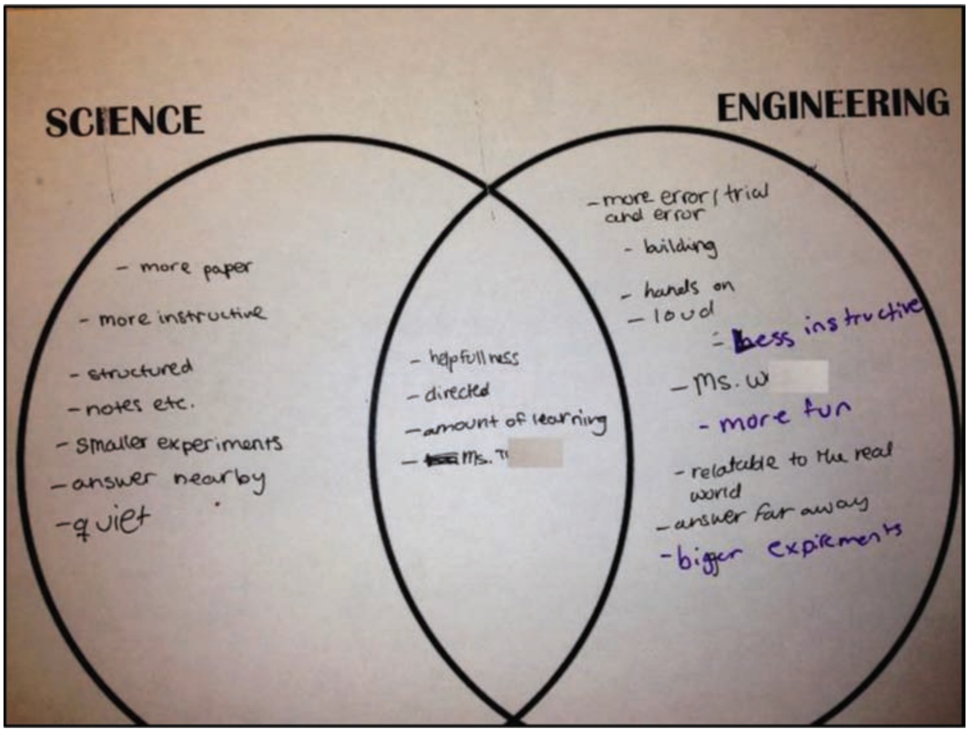

Figure 5. An example Venn diagram completed by students during the focus group.

Table 3
Summary table of student responses when asked to contrast science class and engineering class. Descriptors that appeared more often are listed at the top of the column.

Science	Science and engineering	Engineering
More paper (3) Structured (3) Chemicals (3) Take notes (2) Smaller experiments (2) Right and wrong answer (2) Answer nearby (1) Quiet, working alone (1) More educational (1) Harder (1)	Always learning (2) Helpful (2) Directed (1) Involves math (1) Involves experiments (1) Trial and error (1) Ms. Taylor (1)	Building (4) Less instructive (2) Relatable to the real world (2) Hands-on (2) More trial and error (2) Ms. Wilson (2) Answer far away (1) Loud, group work (1) Not a right or wrong answer (1) Fun (1) More modern (1) Bigger experiments (1) Measurements and units (1) Coding/programming (1)

the Venn diagrams was counted and summed to identify potential trends. Table 3 presents a summary of these trends.

Results

We present three sets of findings corresponding directly to our three research questions. Findings Set 1 highlights the differences in student perceptions between a traditional science class and an engineering class inspired by the Maker Movement. Findings Set 2 presents the affordances and constraints of the 3D printer as a tool for construction, as identified by student and teacher participants. Findings Set 3 provides two illustrative vignettes that depict tensions that emerged in the engineering classroom between interacting nodes of the activity triangle shown in Figure 2. All quotations are taken from focus groups and interviews.

Findings Set 1: Rules of Science Class versus Engineering Class

When drawing and discussing their Venn diagram comparing their science class with their engineering class, students articulated their perception that engineering class differed considerably from science class, despite being taught by the same teacher. A summary of all written responses from the Venn diagrams is shown in Table 3. The table lists the number of times a descriptor was recorded on a Venn diagram. Because students worked in groups to complete the Venn diagram, only four Venn diagrams were collected; thus, the maximum amount of times a descriptor was counted is four.

As shown in Table 3, all four groups of students mentioned that engineering class included building, which is not surprising given the focus of the course. However, other common engineering descriptors were less about the content and more about the pedagogical approach. Three of the student focus groups described the engineering class as less instructive, more relatable to the real world, more hands-on, and involving more trial and error. In contrast, when describing science class, three of the four groups stated that it included more paper, note taking, and structure than their engineering class. Beyond what was recorded on the Venn diagrams, the analysis of student discussion about the diagrams revealed other patterns. We found that students tended to: (1) refer to "experiment" as a noun when talking about activities in their science class, and a verb when talking about activities in engineering class; (2) discuss science class as short-term and structured as opposed to engineering as long-term and multifaceted; (3) consider the learning in engineering as memorable (as opposed to having to memorize in science class); and (4) have different reactions to failure in each context. These findings are discussed in more detail below.

Experiments with pre-determined answers versus experimenting without pre-determined results

Students talked about "experiments," a primary activity in their science class, as a *noun* or a thing that they completed. In contrast, when discussing engineering class, they talked about "experimenting," a more flexible activity that was built into their engineering design process. When describing science class, students described experiments as specified procedures resulting in known answers ("Things that been proven" and "Stuff that our parents probably learned"). For these students, it seemed like experiments in science class were artificial repetitions of experiments that were already conducted, with the answer already documented. Additionally, students positioned the teacher as the primary knowledge holder in the science classroom; she already knew the results for experiments conducted. The following transcript from a student focus group captures this observation (emphasis added).

> Arianna: Science [class] is more things that are already there, things that have been proven. And, engineering was more like trying to make new things, and **experimenting**. It was all just **experimental**, I feel like. Science is more like, you have to have the control variable, like the amount of weight you got on, the independent variable.
> Elaine: We used some of that [controlling variables]. A little bit of that, maybe. But, not as much as you usually would in science class.
> Arianna: Usually, with the **experiments** in science, Ms. Taylor knows what's going to happen. And, she's like, "You didn't get that right." And, we're just like, "Okay."

In the above transcript, Arianna described the process of fabricating a prosthetic bone in the engineering class and contrasts that to the work she did in her science class. She described that the bone project in engineering class involved "trying to make new things, and experimenting," whereas science experiments tended to be more structured, involving predetermined predictor and outcome variables and known results. Rather than reaching a singular solution through prescribed, methodical means, in the engineering class, students were encouraged to tinker and experiment to find multiple entry points and reach varied solutions. Additionally, because students believed there was no singularly correct answer, the teacher was not viewed as the primary knowledge holder as she was in the science classroom.

Short-term and structured versus long-term and multifaceted

When comparing science and engineering, the students used distance and movement to discuss process over product. In science class, there were "small steps to get from one thing to the next," a clear pathway with a single destination. The teacher was positioned as the direct guide rather than an expert explorer. If lost in science class, the teacher provided the answer (or scaffolds) to help students reach the predetermined destination. Comparatively, their descriptions of engineering class were more like a winding path, where students must "figure out how to get from one place to the next." For example, Hannah explained how Ms. Taylor "puts up the hints [in engineering] but then steps back, and [they] have to figure out how to get from one place to the next." In engineering class, the answer was described as "very far away, and you had to go find it in the distance," as opposed to relying on the teacher to convey or evaluate results for correctness. As Bailey described, the engineering class allowed her to "see how things work and how [she] can change things that aren't just on paper with a right or wrong answer. There's a gray area." Even when a destination was reached, it was not truly the end. For example, Bailey stated that the bone project had finished, but they could still refine their design and rethink the same project or apply it to new contexts; in this way, "it's never over." The following transcript from a student focus group further illustrates this finding.

> Sadie: For science, you move on every time. It's like something new.
> Bailey: It's not like long term.
> Sadie: With engineering, it's the same basically. It's the same project that you just keep enhancing and changing.
> Hannah: Yeah, cause the first time you do it…well, ours, the bone, was kind of a fail. The second time we made it better. And, this time we made it even better. Just keep making it better.
> Bailey: Within that same project, there's like variations. So, it never becomes boring. If we had, like, a science-writing

project that we had to do for a month that would probably get old after a while. But, this is something that's just not the same every time you come in.
Hannah: When you finish, you're not really finished. You're still building on.

Bailey, Sadie, and Hannah presented the view of science class as small and self-contained, while engineering class was viewed as branching and expansive. This view of science as short-term and structured versus engineering as long-term and multifaceted also fits into the conception of experiment versus experimenting. In their science class, students worked on one experiment at a time, then moved onto the next. An experiment was a "thing" to prove or "stuff" to learn. In contrast, in engineering class, students never finished because "experiment" was viewed as an action rather than a singular activity.

Memorizing versus memorable

Students described science class as consisting of paper, worksheets, notes, and memorizing. Returning to the student responses shown in Table 3, three focus groups reported that science class involved more paper and was more structured than engineering; two focus groups referred to taking more notes in science than in engineering and mentioned that, unlike engineering class, answers in science are either correct or incorrect. According to one student, Sadie, science was viewed as "more educational, than for a purpose," and as "just work and grades, like school work." In contrast, Sophie described engineering as "relatable to the real world. Not something that is small and in a beaker." Students mentioned they were actually able to remember what happened when working on longer projects in engineering, as captured in the following transcript.

Sadie: I definitely like the [engineering] class because we do like projects with it. And, I think, that in a way, it's more learning.
Bailey: Yeah.
Sadie: Because we do so many different projects that you remember how to do them in the future. Like, what worked, what didn't work. And, how to do it again.
Hannah: Yeah. And, you remember them because like they're memorable and fun.
Sadie: You can only retain so much knowledge from a lecture. And, like, you don't even remember the notes you take the next day. And so, from this, you can actually remember what happened.
Bailey: In school, we take a lot of notes. And, we generally do like handouts and they give us papers. And, it's on like paper or typing. But, when you have this kind of engineering class you get to really…build. That's what it is. Building, right?
Derek: Yeah.
Bailey: So, you get to really see how things work and how you can change things that aren't just on paper with a right or wrong answer. It's kind of a gray area, which I like.

In engineering class, students were building things and using them, with multiple opportunities to share their creations with the outside community, possibly contributing to their view of engineering class as memorable. For example, prior to the prosthetic bone project, students fabricated nametags for the incoming class of students, designed and printed ornaments for a White House competition (which were later donated to a local transition house for needy families), and showcased their work at a Creative Design Fair for the school and their families. Having outside, authentic audiences made Bailey realize, "It's bigger than this. Engineering is everywhere." The format of the engineering class was often juxtaposed with traditional schoolwork completed in science, and was even described as "a new form of learning" by Bailey. Another student, Tyler, shared that engineering class involved, "less worrying about grades, and learning stuff. It's more thinking about engineering and building things, working with your hands. I think it's more fun."

Messing up versus building on

Another interesting juxtaposition articulated by students while contrasting their science class with their engineering class was around the idea of failure. The Maker Movement extols failure as a productive force, guiding future designs. The students in the engineering class routinely encountered failure in their work and were in the habit of revising designs. However, not all students viewed this as productive. In fact, reactions and interpretations of failure in engineering class varied considerably among students.

Most students in this study described that failure within engineering class was not a bad thing, but instead resulted in meaningful learning, allowing them to further refine their designs. Three of the focus groups indicated that they viewed failure in engineering as positive and productive. Following is an illustrative transcript depicting students' description of engineering class and the connection to failure (emphasis added).

Bailey: [Ms. Taylor] puts up the hints but then steps back. And, we have to figure out how to get from one place to the next.
Hannah: Sometimes it's helpful, but sometimes we really want to know. Like, we were doing the robots together and we were trying to program it to hit the wall.
Bailey: And one wheel was going the opposite way [laughter].
Hannah: So, [Ms. Taylor]'s backing up. Giving us a couple hints, but then backing up.
Bailey: But I think that it's helpful because then you learn that **failure is not a bad thing**. **You learn from it.**

Bailey and Hannah described how failure provided guidance and a learning opportunity. When the robot did not hit the wall as expected, it challenged their assumptions and motivated them to solve the issue. The idea that failure was "not a bad thing" seemed to only apply in engineering class. As Arianna shared, "If you don't know how to calculate velocity in science, you get reprimanded for that, but if you build something really wrong, in engineering, it's like okay. Just start over."

However, in contrast to the above transcript, one focus group conducted with three boys revealed that these specific students viewed failure as "messing up" in the context of engineering, expressing confusion and frustration. Following is an excerpt from the focus group depicting this finding.

> Cody: We messed up a lot.
> Interviewer: You messed up a lot? What did you mess up?
> Cody: The bone.
> Alejandro: I think we just got frustrated.
> Cody: Yeah, and we got confused. We tried like a million times, and we just didn't know what to do.

In the transcript above, these students described failure in the conventional sense, similar to Arianna's comment about getting reprimanded for not calculating velocity correctly in science. Rather than viewing failure as a motivational or instructional force, these students expressed confusion and frustration. As captured in the classroom observations, the teacher did provide guidance when this group of students was unsure of how to proceed, but this might also have been viewed as a response to their "messing up" rather than helpful guidance, reinforcing the sense of failure.

Findings Set 2: Affordances and Constraints of the Tool

In this project, the disciplinary content and engineering design process were motivated by the use of a particular technology, the 3D printer and associated design software. In the following subsections, both the affordances and constraints of the 3D printer and design software are shared from the perspective of student and teacher participants in the engineering class. First coined by Gibson (1979), and later appropriated by Norman (1988) for research in the field of human–computer interaction, an affordance is a "design aspect of an object which suggests how the object should be used" (McGrenere & Ho, 2000, p. 1). In contrast, a constraint is a design aspect of an object that limits or controls how the object is used.

Affordances

The primary affordances of the 3D printer that students identified were: (1) the ability to work with "new" technology, (2) the personalization and ownership of realistic products, and (3) future preparation for schools, jobs, and situations that might require the use of a 3D printer. Each of these affordances is discussed below with examples provided.

"New" technology

While 3D printers have been publicly available for some time, there was a sense of novelty surrounding the use of this tool within the school and larger community. Many students were initially incredulous, describing the tool as something from a science fiction film; as Mariah stated, "When I heard the word 3D printer, I literally thought they didn't exist…I didn't know what it was." Bailey recounted, "I remember when I was younger, people would be like, oh, they have 3D printers in offices. And, I thought 3D printers were like, you print out something on paper and it comes out like real life." The opportunity to interact with such a tool prompted student reactions such as, "That's impossible! That's amazing! And…we actually get to use it, in middle school! How crazy is that?" Most students expressed some sense of awe about using such a device in school.

After the initial enthusiasm, the 3D printer and engineering class were still associated with innovation and interest. The sense of novelty seemed connected to the idea that the students in engineering class were in a unique position—"I don't think a lot of other schools are doing the same stuff." Bailey added, "I really like it because it's something that you don't really get to experience in other schools. It's something that's specifically for us." These students viewed themselves as distinct and in a privileged situation because of the novelty they felt the tool provided. This novelty seemed to frame how they conceived the project, and in turn motivated their desire to engage with the tool.

The 3D printer allowed students to explore and contribute in engineering class in new and engaging ways, especially when compared to the traditional methods of learning used in science class, as illustrated by the following transcript.

> Tyler: [In science class] we're learning stuff our parents probably learned.
> Interviewer: Oh, okay. So, science doesn't change?
> Tyler: Yeah, science doesn't really change.
> Travis: Well, it does when there are new things found.
> Mariah: Yeah.
> Travis: But, that doesn't happen very much anymore, all the main things were already found.
> Tyler: I agree with that…with the basic things like physics, my parents learned physics.
> Travis: I can actually ask my parents, and they can completely do my work if they wanted to cause they know it.
> Mariah: Also, [in engineering class], we like being creative. That's new…I don't know.

Tyler: Like 3D printers. I don't think our parents had 3D printers.

Students again expressed their opinions regarding differences in science and engineering. Science was associated with "stuff our parents probably learned," and something that was stable—"all the main things were already found." In contrast, engineering class, and in particular the 3D printer, provided an opportunity to learn technical skills the older generation did not, while fulfilling their desire to be creative.

Personalization and ownership

Another affordance of the tool was the quality of the products it produced. From the students' perspectives, 3D-printed objects seemed realistic, close to an object that one could purchase in a store. Perhaps more important to these students, they were able to design, personalize, and print objects for themselves. The following exchange between two students captures the sense of ownership that the 3D printer provided.

Mariah: [Designing] is hard, then once your thing is printed, it's fun. It's like, oh, my gosh! I made something.
Travis: Yeah, I made it myself. I didn't buy it.

For these students, not buying the object from a store was both meaningful and motivating. It created a sense of ownership because the products were closer to professional quality. Despite the difficulty of the design process at times, students enjoyed the finished products created by the 3D printer. As Bailey shared, "It pays off in the end, right? You get something that you made." The other students in her focus group eagerly agreed with her.

In addition to expressing pride over the creation of realistic objects with the 3D printer, students appreciated the sense of personalization that the 3D printer provided, as illustrated in the following excerpt by Bailey who described an earlier project with the 3D printer.

Bailey: Since it was Christmas time…I made like a little wreath with my name. And, stuff around it. But, just like the idea of having your name on something.
Sophie: Yeah!
Bailey: It's like we get to 3D-print things, and now it's ours [laughter]. It's not for you, but me. Just the idea of personalizing something that you made. It's so forward with technology. It's crazy.

The above excerpt illustrates that there is something beyond the accomplishment of spending time designing and seeing the final product. There is ownership in the design process, but also ownership in the more traditional sense, as the students printed their names on the designs and were able to take their created objects home.

Future preparation

Several students expressed appreciation over this learning experience providing preparation for future schools, careers, and situations that might require the use of a 3D printer. The following excerpt from a focus group illustrates this finding.

Sadie: I remember when it was time for us to decide where to go to high schools, and definitely one thing I was looking into was something with a strong science department. And, I went out to [a high school] and I was touring their engineering academy. And, they were like so proud of their 3D printer. But, theirs is better than ours. It can print like three colors at one time. It's still like the same technology that we're using. And, I think it's nice that we already know how to use it. We won't struggle with it as much. Work hard, and then you can play hard.

For Sadie, using a 3D printer provided a degree of expertise in a field she was interested in pursuing. She was already aware of her affinity for science and engineering, and experimenting with this new tool relevant to STEM careers made her feel accomplished. Seeing the specialized 3D printer in the high school she might attend validated her current skillset and encouraged related pursuits in the future. She understood the relevance of her knowledge and familiarity with the 3D printer, and consequently it was not difficult to visualize herself as a high school student in a competitive engineering academy. Sadie went on to add:

I think that engineering is a huge part of all the new technologies, inventions in the world. Look at the car; look how far it's come since like the first day. And, how it's been going faster, gas mileage, using more efficient ways to do it…I think that whatever career we choose to go into, it will definitely revolve around some type of technology. Engineering teaches us those skills that we'll use later in life.

Sadie saw the use of technology in conjunction with engineering as particularly motivating for future preparation. Similarly, when asked if other schools should use 3D printers with their students, Tyler enthusiastically responded, "Yeah, so a lot of kids can learn it and it can become a more common career in the future, if all schools had them." Students seemed to understand the utility of the 3D printer and to connect the possibilities of this tool to future careers and goals.

Constraints

Despite the 3D printer providing many affordances for participating students, the students also identified constraints. It is important to note that constraints in engineering can be productive; engineers in the field are often required to work within pre-determined constraints to design a solution. However, the students and the teacher still discussed certain printer functions as frustrating. Students expressed concerns over the following physical limitations of the printer and corresponding design software: (1) the length of time objects took to print, (2) the small size of printed objects, (3) the two-dimensional nature of the design software, and (4) the less-than-perfect aesthetics of some printed objects. Each of these constraints is discussed below with evidence from student focus groups and the teacher interview.

Length of printing time

One constraint identified by both students and the teacher was the length of time required to produce designs within the typical school day. Almost all students made comments about the surprisingly long length of time it took to print. For example, when asked why they revised a design, Alejandro explained: "[Ms. Taylor] said, 'Your original bone would have taken 5 hours to print.'" Their design change was based on the inability to monitor such lengthy prints within the school day. This concern was also captured in the teacher interview, as shared below.

> Ms. Taylor: I don't think I accounted for the bones really taking like two and a half hours to print. And that, with one printer, is a lot. It just, there's only six to eight hours that I'm here. Okay, so I can get two or four [printed each day]. I left a couple [printing overnight] and [the filament] just like…enclosed the whole extruder.

Beyond the overall print time, another limitation was that the teacher needed to be physically present to monitor and troubleshoot during print time. Leaving prints unattended proved problematic for the teacher, resulting in fewer designs being printed for the students. Both parties seemed frustrated by this limitation.

Size

Many students expressed surprise at the small size of objects the printer produced. The printer used in the classroom was capable of printing items no larger than 25 centimeters (cm) in length, 20 cm in width, and 15 cm high. However, as discussed earlier, students were also limited in the size of printed objects due to the lengthy print time. As one group of female students agreed upon during the focus group, "I feel like most of the things we've done with the 3D printer have been trial and error. We didn't know it was going to come out so small." Similarly, when students could free-print one object of their choosing before the bone project, Arianna shared, "I made a box that had a lid, and it was really cool. But, then it was like the size of my pinkie." In both instances, the students were surprised at how small the printed objects were.

The size constraints also impacted the final bone designs that students created. Two of the four student groups printed their bone in multiple pieces so the printer could better accommodate their design. Figure 6 depicts two groups' designs as drawn on the classroom whiteboard. In both designs, the bone is separated into two pieces, and the students are attempting to figure out how to best connect the pieces. The group shown on the left in Figure 6 attempted to create two interlocking pieces (drawn in blue and purple) of the bone that slid into place. Alternatively, the group's design on the right relied on the use of connecting "keys" that extruded from each side of the

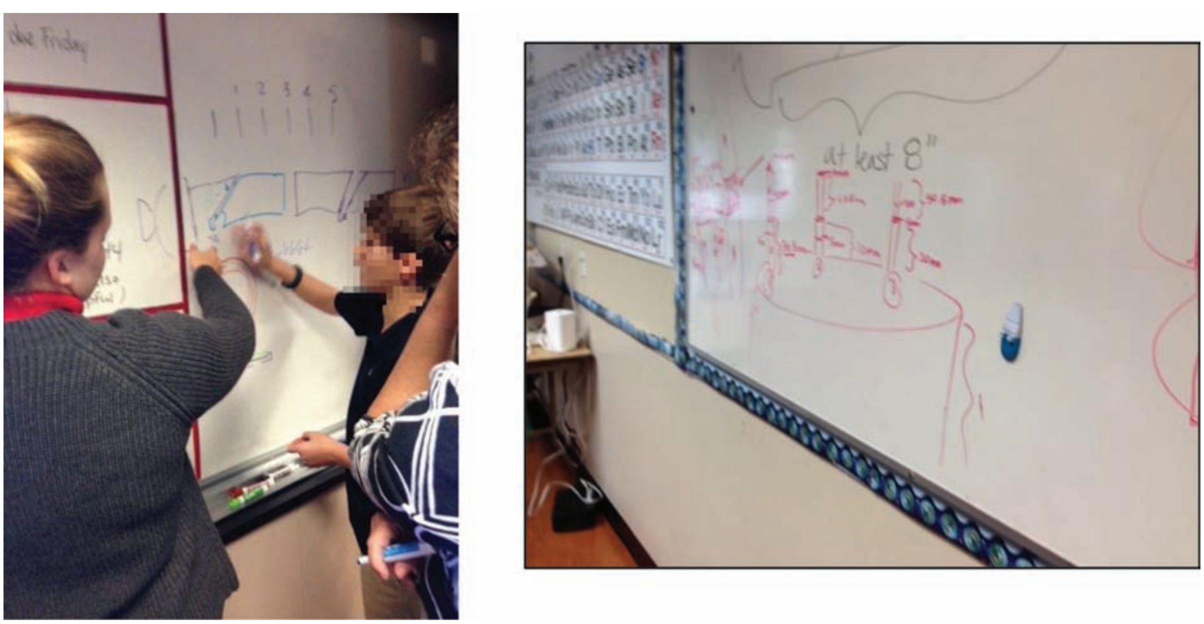

Figure 6. Bone designs that used more than one piece due to size limitations of the 3D printer.

bone; the keys interlocked, creating the illusion of one, complete bone. These multi-piece bone designs were influenced partly by the goal of breakability, but also due to the printer limitations. Since the printer was unable to produce a complete bone of the size they desired in a reasonable amount of time, groups resorted to printing multiple separate pieces.

Two-dimensional nature of design software

The size constraint of the printer was coupled with the constraints of the design software—TinkerCAD. The students designed their projects in a program that is displayed on a two-dimensional screen. The computer-generated model can be manipulated and rotated and is drawn in perspective that provides cues to the dimensionality, but is still flat. Students must interpret the flat visualization as three-dimensional, which requires spatial thinking. As Sadie shared, "It's kind of…disorienting. You can't visualize it, like, what's the 3D version of it. And, sometimes you have to click and you have to reposition it. But, then it's too far back [laughter]. So you have to find a way to push it back forward. And, so…there's a trick to it." Both the design software and the physical limitations were constraints for what the students viewed as possible of producing with the 3D printer. In one student group, Bailey shared the following about her experiences using the design software.

> Bailey: We sent [our design to Ms. Taylor], and then one [side] was like a little bit off. And, when we finally got [the print] the pegs were too big. And, one was like smaller. So, it was all just very…ugh…really frustrating at that point.

Bailey's group used interlocking keys to connect the two pieces of the bone. However, to ensure that the keys interlocked, it required a great amount of manipulation in TinkerCAD, which proved frustrating for Bailey and her group.

Aesthetics

Similar to the problem that Ms. Taylor described above, 3D printers do not work perfectly all the time. Prints may come out too stringy, not fully formed, or different from the digital design. An example of these problematic prints is shared below from a student focus group.

> Alejandro: I don't know. We sent many designs, and they came out like what we didn't do. Like, one time, we put a cut here, and there was like two holes, and two little things.
> Cody: Yeah, like a demented seashell.
> Alejandro: Another one was all melted.

Similarly, Sadie experienced a problematic print—"Different parts didn't come out very well. It was like loose 3D printing, instead of being nice and tight." Students seemed surprised that the 3D printer was not error-proof and required consistent upkeep and monitoring.

Findings Set 3: Tensions within the Engineering Classroom

Using CHAT as a theoretical tool facilitated the identification of tensions between interacting nodes of the activity triangle (shown in Figure 2). These tensions provide insights into sources of change and progress. Where there is a tension, there is an opportunity for improvement within the activity system (Engeström, 1987). At the very least, tensions are worth further investigation to gain a more complete and nuanced understanding of the activity system. In this section, two illustrative vignettes are discussed to highlight areas of tension within this engineering class situated within a traditional school setting.

We wish to emphasize that our goal in presenting these vignettes is not to criticize the teacher. Rather, our goal is to highlight challenges that might arise when incorporating educative making in a traditional school setting. The learning process looks and feels different. Typical classroom norms and practices may be antagonistic to the constructionist aims of making for STEM learning. It is crucial that we investigate STEM-rich construction using new technologies in context to create models for other educators interested in engaging their students in similar work.

Vignette 1: Tension between tool and division of labor

As was discussed, 3D printers can take a long time to print objects. Because of this, teachers using this technology in the classroom must create a system to manage printing. While Ms. Taylor desired to have her students participate in all facets of engineering and would have preferred students to remain in control of their own printing, this was impossible within the constraints of the classroom. In this engineering class, prints were limited to the assigned project. As one student shared, "Ms. Taylor won't free-for-all print." Before beginning the bone project, Ms. Taylor allowed students to print one object of their choosing; as she shared, "Their first build would be something for themselves." However, some students still expressed mild frustration over not being able to choose the item of their printing after this point in time. Additionally, another student expressed concern during the focus group over not fully understanding how the printer functioned, as shown below.

> Arianna: We don't actually know how the 3D printing process works because Ms. Taylor does it on her computer. We just email her the design, so there's not much we can do, except make sure it's big enough, or ask Ms. Taylor if it's big enough because it might print out really, really small. But, she mainly controls all the things.

In this event, the teacher was attempting to simplify and expedite the printing process by only requiring students to email digital designs. However, the way in which labor was divided (in this instance, who was in control of the 3D printer) was at the expense of a student not understanding how the tool functioned. Within a classroom setting, teachers are most often in control of the classroom space and contents; for example, middle school students rotate classrooms for each subject, moving to the teacher's individual room as opposed to the teacher moving to the students. The same applies to materials and tools within the classroom. The stakes seem higher the more expensive equipment becomes, as was the case with the 3D printer. Further, the lengthy print time required did not align with the structure of the traditional school day. In this case, the teacher controlled the tool, as is the norm in a typical classroom, but at the expense of students conducting their own printing.

Vignette 2: Tension between classroom rules and the maker mindset

An interesting behavioral situation was discussed in one focus group that highlighted the tension between typical school rules and key tenets of the maker mindset (Dougherty, 2013). This group shared a story about a student accidentally, but immediately, breaking a bone prototype after it finished printing.

> Tyler: I thought we broke it…
> Travis: Oh yeah, it was fresh out of the 3D printer. He was like, "Oh look at this bone!" and then he snapped it in half [laughter].
> Tyler: That was an accident. I wasn't paying attention. I don't know.
> Interviewer: Did it break and splinter like it was supposed to?
> Tyler: Yeah, one half. Well that's how we knew it would work.
> Yeah, but I got in trouble for it. We didn't want to use 3D material, but that's how we figured out that it worked.
> Travis: Then he spent the rest of the…period trying to glue it back together.

In the situation described above, this accident proved fruitful for the design process; the students knew that their design would splinter in a realistic manner because they accidentally broke their bone and observed the splintering. However, within the typical classroom, students are rarely celebrated for breaking things. In fact, Tyler shared that he "got in trouble" for this incident. Even if the "trouble" was nonexistent or relatively minor, Tyler still perceived it as trouble. If this incident occurred in an individual's personal workshop, there would be no trouble to get into. But, because this occurred in a classroom, with rules for behavior and participation, Tyler did not feel that he received positive recognition for his actions. Facilitating digital fabrication within the constraints of a classroom presents unique considerations and situations that do not always occur in the traditional classroom. In this instance, there was clear tension between the rules of the classroom and key tenants of the Maker Movement, particularly around ideas of experimentation and learning from failure.

Both vignettes presented in this section revealed how tensions within the classroom were tied to constraints of the physical tool. The long time required for prints, for example, led to the teacher controlling the prints and limiting who prints what and when. This also created different expectations for prototypes, such as that prototypes should be handled carefully and not broken unless during a specific test time. This led to the clashing of roles and rules, and potentially impacted understanding and experimentation due to limitations of the printer. Ironically, when this fabrication tool was introduced in the context of a classroom, norms counter to the maker mindset (Dougherty, 2013) were imposed.

Discussion

In this study, we presented a qualitative case study of a teacher engaging her students in educative making in an engineering course designed with the same spirit as the Maker Movement (Dougherty, 2013). Despite the fact this classroom was situated within a traditional school setting, this teacher incorporated emergent technology that motivated her students to engage in a digital fabrication project for an authentic purpose using a variety of knowledge and skills from the STEM disciplines. This learning experience resonates with recommendations made by Dewey (1938), Freire (1970), and Papert and Harel (1991)—students should take ownership of their learning to create change. This change was observed as an increase in interest and capacities to pursue STEM in the future (consider Sadie's recognition of how this experience prepared her for high school), but, further, allowed students to create a novel product using technology and STEM content knowledge in an authentic manner (no bones about it—the prosthetic bone was used in an actual movie scene).

Though only one example of successful integration of educative making and engineering design in a middle school classroom, our study highlights the affordances and constraints of making in this context. Case studies like ours are important at a time when proponents of the Maker Movement worry that making in schools could be the downfall of the "maker revolution," destroying the spirit of creativity, playfulness, and entrepreneurialism that are hallmarks of this movement (Halverson & Sheridan, 2014, p. 500). Peppler et al. (2016, p. 6) asked, "Is making fundamentally at odds with schooling?" considering the "emergent, messy, whimsical, engaging process of making" in relation to the standards and assessments. We argue that making does have a place in the classroom. Our results indicate that using an educative making approach with emergent technology (the 3D printer) proved more motivating to students than traditional teaching methods: as all students shared, engineering class was more memorable, enjoyable, and creative than their traditional science class. Incorporating educative making allowed these students to view themselves as active contributors to a field of study, as opposed to passive recipients of previously documented facts, as was their perception of traditional science class.

This study also highlighted tensions that emerged due to facilitating this activity in a classroom, specifically tensions connected to tool usage, division of labor, and the maker mindset (Dougherty, 2013). Tensions are important points to consider because they lead to expansion or contraction of the activity system, where new forms of learning and development occur (Engeström, 1987). For example, our study provided insights into how students gained access to and understood 3D printing given time and material constraints of the printer itself. The teacher implemented various solutions such as group rather than individual prints, leaving the printer running overnight, and having a long-term project to allow enough time for printing and re-design. These adjustments helped students demonstrate ownership of the design process and final products created by the 3D printer, despite still expressing some constraints of the tool, such as lengthy printing time and imperfect prints. This tension signals a need to focus attention on better preparing teachers to navigate the complexities of using emergent technology connected to STEM learning in a classroom setting, both in pre-service teacher education and in-service professional development.

Further, another tension emerged when the norms of the classroom and school conflicted with the norms of the Maker Movement (consider Tyler's perception of getting in trouble when he broke the bone prototype at an unspecified time). While experimentation and productive failure are important learning tools in making outside the classroom, in-school behaviors such as destroying projects are counter to school norms. The conflict between class and maker norms is troubling to some researchers (Halverson & Sheridan, 2014; Peppler et al., 2016); however, according to the CHAT framework, it offers an opportunity to push making and learning in new directions, leading to new artifacts, social patterns, and individual development (Engeström, 1987). For example, our finding that most student groups in this case study considered failure as a learning opportunity while one group considered it "messing up" suggests the importance of how educative making activities are framed in the classroom and how students are supported. Again, this signals a need to focus on how best to prepare teachers to facilitate meaningful and educative making at school; from explicit questioning strategies, to classroom management systems, and approaches for supporting diverse groups of students in experiencing success at making to learn STEM.

Implications

This work demonstrates that it is possible to engage students in an educative making project at school. While this teacher had more freedom in selecting course curriculum than may be typical in public schools and the school funds to purchase a 3D printer, this work still serves as evidence that educative making can find its place in a classroom (despite being confined by schedules, structures, and accountability). In this section, we provide recommendations to schools and teachers interested in incorporating educative making connected to STEM learning based on the tensions that emerged during this case study. Specifically, we provide recommendations for shifting school culture to better align with the maker ethos, as well as recommendations to better prepare teachers to facilitate educative making at school.

Shifting school culture

This case study demonstrated that typical school policies and norms are sometimes antagonistic to the constructionist aims of the Maker Movement. Moving forward, it is important to consider how to best support schools and teachers in implementing educative making projects that capitalize on the Maker Movement ethos of creativity, experimentation, and collaboration while still learning disciplinary content. Making is gaining traction in schools and could soon be "playing a key role in K–12 education" (Wardrip & Brahms, 2016, p. 97). Like other innovations and school-based reforms, thoughtfully introducing educative making requires significant changes in class structure, materials, learning/teaching strategies, and professional development (Wardrip & Brahms, 2016). In other words, "the Maker Movement is pushing educators, policy makers, and researchers to reexamine the relationship between schooling and learning in fundamental ways" (Peppler et al., 2016, p. 6).

Implementing changes to school curriculum, instruction, and assessment requires shifts in culture, policy, management, and training and development for teachers and administrators (Wardrip & Brahms, 2016). One major area of concern when implementing educative making at schools is around assessment: administrators and policy makers want proof that learning is occurring. However, this type of learning looks and feels different from traditional methods, and is often outside the scope of a multiple-choice test. Thus, schools must begin to broaden their perspectives about what counts as an assessment. Schools might consider assessing students using portfolios (or digital portfolios; see http://web.seesaw.me). Or, perhaps students showcase their work at a School Maker Faire (see http://makerfaire.com/global/school/) for their local communities. In fact, the artifact that students create can be used as assessment, if students can accurately explain its function and the design process they took. Leading universities, such as Massachusetts Institute of Technology (MIT), are beginning to accept alternative forms of assessments, such as portfolios, for college admission, signaling that the tides are shifting.

Moreover, schools can also benefit from broadening their perspectives of what counts as a lesson and classroom. Confining students to single classrooms for short periods of time is often antagonistic to long-term projects. For example, the students in this case study continually revisited the bone project weekly over the course of six months, working in block periods of ninety minutes each time. It is important to note that even with so much time dedicated to this project, many of the students still did not feel finished, highlighting the complexity and authenticity of the design challenge. Schools might consider having designated spaces for making (e.g., makerspaces, design centers) that are open to students before school, at lunch, or after school. Providing time and space for students to engage in the design process is crucial, and expecting students to complete an authentic and complex design challenge in a series of 45-minute segmented lessons is unrealistic. Further, changing the format of classes might also signal a need to expand beyond the classroom walls. Community members are valuable resources that schools can capitalize on to benefit their students. Engineers, scientists, artists, mechanics, and woodworkers are just several types of community members that can offer resources and expertise in the classroom. Perhaps students take fieldtrips to learn about these crafts onsite from professionals, or schools can invite community members to give talks or help students on projects-in-process. Bringing in a variety of community members allows teachers to capitalize on external resources, as well as potentially validates students' community members and families.

Supporting teachers

This case study also demonstrates the critical role of the teacher in the classroom. Teachers have a great deal of power and responsibility in enacting projects and integrating technology into the curriculum, but they need adequate time to learn about new technological tools as well as ongoing professional development opportunities. Wardrip and Brahms (2016) noted that it is reasonable for teachers to require professional development to better understand tools, materials, and project designs. Further, with the implementation of NGSS and introduction of engineering—in the form of disciplinary core ideas and practices—teachers may lack confidence in both subject knowledge and implementation strategies. As Quinn and Bell (2013) noted, "Teachers who have never experienced these practices in their own science education will have difficulty implementing them in their classrooms" (p. 26).

One option for schools to best support in-service teachers in implementing educative making connected to STEM learning is through communities of practice (Lave, 1991). Providing the space for educators to brainstorm and plan together is crucial; learning is social and teachers cannot be expected to create rich projects working in isolation. Moreover, teachers need exemplar projects that they can begin to model and adapt for their own students (e.g., Blikstein, Martinez, & Pang, 2015). This recommendation resonates with conclusions made by Wardrip and Brahms (2016), who found that teachers reported needing more time for planning and collaboration to implement making in their curriculum. In addition to other educators, community members can also serve as resources for teachers. As mentioned earlier, professionals such as scientists, artists, and mechanics are not only valuable resources for students, but can also collaborate with teachers to plan novel and authentic projects. For example, in this work, the teacher collaborated with a professional stuntman to design and facilitate the bone project, capitalizing on resources outside of the classroom to add complexity and authenticity to the design challenge.

Finally, another opportunity to introduce K–12 teachers to educative making in the context of STEM education is through teacher education programs. Preservice teachers can learn about the theoretical pioneers of the Maker Movement (Blikstein & Worsley, 2016), and explore this pedagogical approach with teacher educators and other developing teachers. This provides time and space to "establish personal connections for teachers between classroom content and routines and the practices, perspectives, and processes of making" (Wardrip & Brahms, 2016, p. 103). Engaging in the act of making also allows teachers to better understand the maker mindset. Teachers can experience productive failure in a safe space, potentially allowing them to better support their future students in a similar process. Work on supporting preservice teachers in incorporating educative making is beginning to emerge (Cohen et al., 2017; O'Brien et al., 2016), but is an area of need. If teachers are expected to teach in constructionist ways, this should start in their teacher preparation coursework, and continue into their teaching professions.

Conclusion

In an era when schools are becoming increasingly culturally and linguistically diverse, administrators and educators must embrace and experiment in their role as "curriculum architects" (Munby, 1983). Just as we encourage students to redesign the future, schools must redesign what learning and curriculum look like in a digital world, considering the needs, interests, and past experiences of their current students. Students in K–12 classrooms today have never lived in a world without technology, without screens, without fast-paced swiping on tablets, or browsing the Internet with multiple windows open. Students today are "digital natives" (Prensky, 2001) and it is essential that teaching pedagogy evolves along with our students. The theoretical justification for this type of learning is there (Blikstein & Worsley, 2016). It is now the responsibility of schools to acknowledge this type of learning as beneficial, and to begin providing the necessary space and supports for teachers to engage in this type of work with their students, free from consequences such as pay cuts or pink slips.

This study's main limitation is its focus on only one classroom, with one teacher, at one school. Further, this private school was selective and expensive. If this movement is to truly reach all students, not just those in elite private schools, a commitment to critical pedagogy is necessary. In line with Freire (1970), this movement will simply serve to reproduce the status quo, unless there is a fundamental commitment to engage *all* students in this type of learning. Research needs to investigate educative making in all types of communities, with students of different demographics and interests, if it is to avoid being a "Trojan horse" of hope (Blikstein, 2008). Research traditions in culturally relevant pedagogy (Ladson-Billings, 1995) and funds of knowledge (Moll, Amanti, Neff, & Gonzalez, 1992) can also help ensure teachers are prepared to facilitate educative making with diverse groups of students in the typical classroom.

While the goal of this case study was not generalizability, more work is needed to investigate similar courses at other schools with varying student demographics to establish best practices for creating authentic and productive educative making projects using technological tools, such as the 3D printer, while at school. As Blikstein (2013b) stated:

> Education needs a collection of models demonstrating the impact of implementing Seymour's [constructionist] ideas in school. Maybe then they will not anymore be painfully hard to implement, but a lot easier. And it is our job to build those models. So go forth and construct.

In line with Blikstein, we must construct the reality of educative making in schools for ourselves. Schools need a collection of models from which to draw; proof that meaningful learning can occur when students engage with active construction in STEM-rich contexts. Our work provides an example of educative making situated in the complexity of an existing social structure—the classroom. As the Maker Movement and related learning activities are more frequently integrated into schools, more research is needed on how to do this effectively, while still supporting critical tenets of the maker mindset, such as creativity, experimentation, collaboration, and viewing failure as a positive (Dougherty, 2013). It is through rich, descriptive accounts of making that we can document best practices and ensure that the Maker Movement is implemented with the same ethos of the maker mindset (Dougherty, 2013) within the traditional school system.

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