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INVENTING WITH MAKER EDUCATION IN HIGH SCHOOL CLASSROOMS

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Although maker education has become a popular theme in science, technology, engineering, and math (STEM) education, there is little empirical evidence from qualitative studies offering guidance as to how the processes and practices of maker culture might be integrated into school settings. This is a problem when preparing students for careers where the lack of student engagement with real-world problems in coursework is the most predictive factor in determining which students will abandon STEM studies (1). Even highly successful students may be demonstrating skills such as test taking, but they are perhaps not learning literate practices in STEM fields (2). This interactional ethnographic study focused on the actions and discourse among teachers, students, administrators, and parents. Through an analysis of video and textual records of activity across four years, it explored opportunities for learning and engaging in collective, goal-based, and problem-based activities. It made visible how these actors influenced the co-creation of a maker-based STEM culture at an independent high school, as activities evolved from an after-school club focused on designing, building, and launching high-altitude balloons to an electronics and software coding elective lab course incorporating elements of the science, technology, engineering, art, and mathematics (STEAM) movement. The author's dual role as both teacher and researcher grounded his ethnographic fieldwork in maker education and invention.

Key words: STEM; STEAM; Maker education; Ethnography; Engineering education

THE EMERGENCE OF THE MAKER MINDSET

At the turn of the 20th century, John Dewey proposed the idea that school should be more experiential and grounded in real-world artifacts. Since that time, however, few large-scale efforts have significantly influenced or changed the decontextualized, instructionist curriculum that continues to be the status quo in the United States.

Jean Piaget, famous for developing the model of how children learn best through the construction of knowledge in their minds, proposed using active methods to allow children to learn through experience and creation and not simply have truths be "imparted" to them (3). He formalized this into a learning theory he called constructivism, which explained that knowledge is not simply conveyed by

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a teacher to a student but socially constructed by the learners collaboratively.

After working with Piaget for a number of years, Seymour Papert, a South African-born mathematician and educational researcher, joined the Massachusetts Institute of Technology faculty in the 1970s and set off to develop learning environments free from coercive education methods, including the use of grades as primary motivators. Papert's own theories of learning were evident in the title of his 1971 paper "Teaching Children to be Mathematicians Versus Teaching About Mathematics." He believed that then-emerging personal computers could be a key resource in allowing students to conceptualize complex mathematical ideas, gain firsthand experience in the field, and effectively learn about mathematics (4). In 1967, Papert developed Logo, a computer programming language that allowed children to build their own software — and, later, robotic, computer-controlled hardware — in an integrated development environment. In his seminal book *Mindstorms*, Papert proposed the following two fundamental ideas: 1) It is possible that learning to communicate with computers can be a natural process, and 2) that process may change the way learning takes place (5).

Papert adapted Piaget's constructivist theories, which suggest that knowledge is socially constructed, and added famously that "this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe" (6). Papert called his modified theory constructionism and claimed that, using its theories, science classes could resemble art classes, where students could creatively explore the field of study rather than simply be taught it (6).

Over the past two decades, a variety of self-directed, community-based, and collaborative learning environments that permit learners to explore, tinker, and play with objects while encouraging them to be creative have emerged in museums and other public learning spaces around the world, such as the New York Hall of Science and the San Francisco Exploratorium,. These organizations are often associated with the maker movement, maker education, and the maker mindset, and they have begun to work with academics to research, gather evidence of, and implement the theories behind the conceptions of these spaces designed for making and tinkering (7).

Although maker education has become a popular theme in schools, with makerspaces and tinkerlabs being built on K-12 campuses, there remains little empirical evidence offering guidance as to how the processes and practices of maker culture are aligned with constructivism and how they might be integrated by teachers into school settings. The lack of a clearer understanding of the possible roles of maker education in schools is a problem when preparing students for careers where the lack of student engagement with real-world problems in coursework is the most predictive factor in determining which students will abandon science, technology, engineering, and mathematics (STEM) studies (1). The concern is that even successful students may be demonstrating skills such as test taking, but they may not actually be learning literate practices in STEM fields (2).

At the heart of both the maker education and invention education movements is the iterative, recursive, and inquiry-based process of encountering challenges and overcoming those challenges only to encounter more challenges. Petrich and colleagues called this process becoming "stuck and then 'unstuck'" (8). According to their theory, it represents the hallmark of maker education and exemplifies students' deepening of the understanding of materials and phenomena. A common thread between makerspaces and other informal, maker-based learning spaces is that they exist to support activities in STEM (and, in some cases, science, technology, engineering, art, and mathematics (STEAM)) areas by fostering a community based on passionate work with materials and phenomena with the primary goal of gaining a deeper understanding of how they work in order to solve a personal, learner-centered problem through some form of creation.

Among the problems I faced as a high school classroom teacher in developing my own maker-based STEM learning approaches was that I could only draw on a small body of research that dealt directly with defining and understanding such maker education initiatives as I sought to understand the considerations in order to support students engaging in such practices. Halverson and Sheridan provided a context for research in this area; however, they cautioned that the institutionalization of maker education through its take-up in formal school settings might "kill the essence of the maker movement" (9). Two important questions have emerged in recent years when considering the inclusion of maker education in schools:

1) What exactly is the maker mindset in the context of formal education settings?
2) How might educators successfully integrate elements of the maker mindset into their classrooms without killing its essence?

While there is not a single defining characteristic of the maker movement, nor does there exist a national certification or franchising body for all maker-based learning programs, the philosophies of many of those involved share a similar heritage. Martin proposed three elements that are critical to understanding the promise of making and the maker movement for education, and they are elements that can be traced back through history:

1) *digital tools*, including rapid prototyping tools and low-cost microcontroller platforms, which characterize many making projects;
2) *community infrastructure,* including online resources and in-person spaces and events; and
3) the *maker mindset*, which is based on values, beliefs, and dispositions that are commonplace within the community (10).

In the hope of providing practitioners with a clearer view of what maker education in formal settings might look like, this study added to these elements by proposing four key characteristics that embody the activities and actions of maker-based education in a classroom: Firstly, students worked both independently and collaboratively toward engineering a solution to an ill-defined problem. Secondly, my students and I learned meaningful cultural practices and, in turn, acted as practitioners in STEM fields. Thirdly, rather than acting purely as an authority in problem-solving activities, I, in the role of the teacher, acted more as a facilitator and guide by placing an emphasis on supporting student inquiry over direct instruction. Finally, and perhaps most apparent, is that students were introduced to and encouraged to draw on local and virtual maker community resources, including local makerspaces, online forums, and the plethora of multimedia documentation available online in related fields.

THE STUDY

Participants

The small independent school where this study was conducted served a socioeconomically and ethnically diverse population. Roughly half of the students enrolled at the time of the STEAM Lab course received tuition assistance in the form of merit scholarships and financial aid. Furthermore, about 40% of the total student population was Hispanic or Latino.

The Developing STEM Initiative

There were four major discrete cycles of iterative STEM initiative program development leading up to STEAM Lab. Prior to teaching STEAM Lab, I was the faculty advisor to the Near Space Exploration Club at the same high school. This club was an afterschool program for high school students who were interested in building and conducting high-altitude balloon experiments. The students were selected for participation in the club by a faculty committee and were required to have excellent academic performance. The club looked more like an informal maker environment than a traditional high school course, in that the club met once weekly after school. Furthermore, students were not required to attend and did not earn course credit for their participation in the club. As the faculty adviser to the group, I served as a guide to the students.

The first major cycle of STEM activity was the initial high-altitude balloon probe that students designed and launched as part of the after school club; cycle two was the second high-altitude balloon project, which added live video and a radio data downlink to the first probe's basic data logging sensor array; cycle three was the year-long Synthesis Unit, a schoolwide focus on space exploration, which concluded with a live International Space Station (ISS) contact via amateur radio and a visit to the school from a NASA astronaut; and cycle four was the two-semester STEAM Lab elective course during which the students designed and built a large scale electronic piano.

While it was a social situation made up of various related clusters of simultaneous activity, STEAM Lab was also a subset of the school culture at large and a part of an interrelated cluster of STEM initiatives at the school across a four-year period. In Figure 1, I show visually how, building off of Spradley's concept of interrelated social situations, I expanded the dimensions of the STEM initiative to each cycle of activity as interrelated social situations across time that share anchors in the STEM initiative as a virtual place.

Within each sub-cluster, it was possible to zoom in deeper in order to find more subsets of activity within those social situations. For example, within the first Near Space Exploration Club project (Balloon Probe #1), there was one school year of balloon probe design and construction efforts (social situations across time) as well as subgroups of students working on various efforts and systems within those projects simultaneously (social situations across space).

Methodology

Tracing the Roots and Routes of STEAM Lab

In order to identify recurrent ideas, practices, and processes, I constructed a series of contrastive analyses by examining what members proposed, recognized, acknowledged, and interactionally accomplished by analyzing records of both spoken and written discourse. Backward and forward mapping through time from a key event or anchor point permitted tracing activities and actions back to their origins, as well as following their trajectories through time to document and better understand the social construction of the developing culture and knowledge base of the STEM initiative. Through this process, I identified a series of consequential progressions in which one activity was central to the development of subsequent activities (11,12).

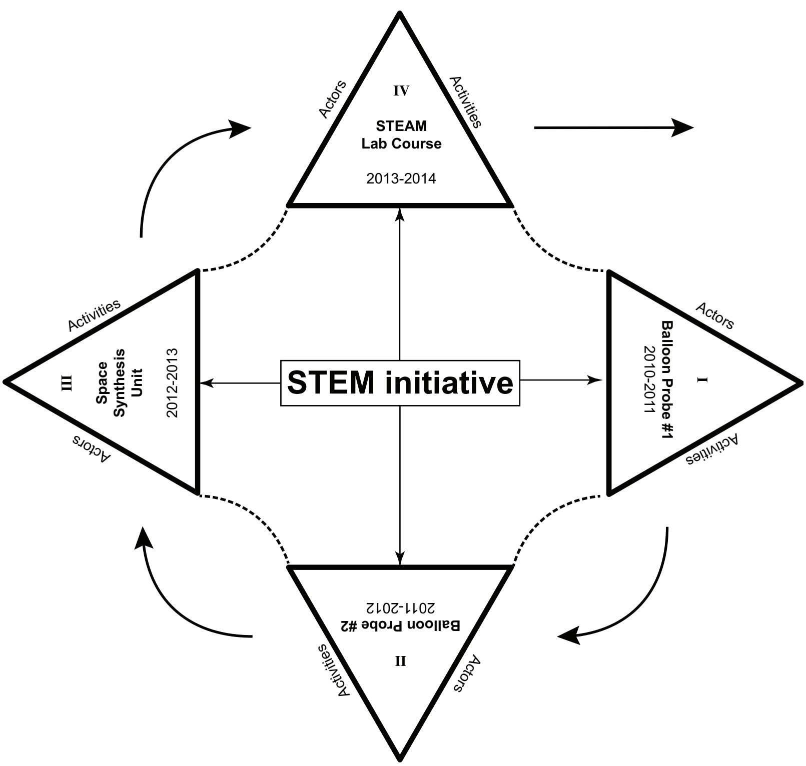

Figure 1. Expansion of STEM initiative as a social situation to include time. Adapted from *Participant Observation* by JP Spradley, New York (NY): Holt, Rinehart & Wilson; 1980. P. 43. Copyright 1980 by Thomson Learning, Inc.

Using this broad four-year and four-cycle event map of the entire STEM progression as a starting point, I selected specific records of interactions, including messages from my own email archive, journals and notebooks, video and audio transcripts, and other written records for further analysis. During this analysis, I identified rich points. Agar defined rich points as moments where there is a surprise or departure from expectations for an outside observer or an uninitiated participant who is not familiar with the language of the group or discipline or, as Agar called it, languaculture (13). Rich points can help identify where cultural knowledge, processes, and practices become visible to the participants in order to lay a foundation for tracing the cycles of development and evolution of this STEM initiative within the local school community.

Looking Through Different Lenses

Through these analyses, I made visible my developing processes and practices and the ways in which my ideas and those of my students were discussed and "acted into being" (14). Using a microscope metaphor, I present analyses through different lenses (15). For example, the event map timeline of the preparations and course activities provided a macroscopic lens that would serve as an anchor in subsequent analyses to explore cycles of recursive and iterative activity. As the following analysis showed, the timeline also situated and provided context for more microscopic analyses and a narrower focus on particular activities through discourse analysis. The timeline formed a foundation for making visible activity through a broader macroscopic lens and then zooming into microscopic interpersonal interactions and speech to construct a more complete view of the nature of this developing STEM culture (15).

The Emergence of STEAM Lab

Taylor claimed that "STEAM education is essential for producing a creative, scientifically literate, and ethically astute citizenry and workforce for the 21st century," but the issue of STEM-to-STEAM goes deeper than just the infusion of divergent thinking (16). A study conducted of 34 participants, representing academia, government, research and industry, and experts in space and education, during the International Space University Space Studies Program, sought to make visible "what Space can contribute to global STEM education" (17). The author summarized the results of this study by stating "that creativity cannot be treated separately from STEM, and Arts should be an integrating part of a novel approach called STEAM." He went on to state that "(t)he current state of risk aversion (especially prevalent in many learning institutions) does not facilitate creativity" (17).

With the creation of STEAM Lab, more students had access during the school day to earn course credit while participating in unique STEM opportunities similar to those afforded by the Near Space Exploration Club. STEAM Lab was a two-semester course, with two class meetings per week and each class meeting lasting one hour and 45 minutes. Unlike the Near Space Exploration Club, for which the faculty nominated students for participation, STEAM Lab was made available in August 2013 as an elective course for which students (often with their parents' guidance) were permitted to register. Students selected their electives by listing their first three choices on a mail-in registration form. The final STEAM Lab enrollment and placement decisions were made by a faculty committee, in which I was not a participant. Students were assessed a $200 course materials fee that covered books, materials, and electronic components kits.

Methods for Realizing the Goals of this Study

This study aimed to show how STEAM Lab, a two-semester high school course, developed and how the course subsequently transformed over its two semesters during the 2013-2014 school years. It also examined the practices co-constructed in the maker classroom through everyday actions and how these practices constituted literacy as a situated process (18). In doing so, it made visible how both the school culture and the course itself developed through collaboration, whereby my students and I worked together to solve challenges through maker-based approaches through a series of consequential progressions that made visible the cycles of decision making, design, and outcomes of the activities (6).

Using an interactional ethnographic approach to data analysis made visible the processes and practices that I, as the teacher, developed, as well as the practices of my students, our ways of engaging, and the ways in which students participated in the social construction of knowledge (18,19). The data showed how I, as the instructor, introduced students to resources created by and intended for members of maker communities. The study also made visible how and in what ways my students and I adopted and adapted these textual, electronic, and mechanical objects and texts. As part of the final project for STEAM Lab, I tasked the students with the ill-defined problem of creating a large-scale, interactive electronic art installation using Arduino microcontrollers. The students in STEAM Lab collectively chose to design and build an original large-scale electronic piano that responded to the weight of a person by illuminating its keys and playing musical notes out of a loudspeaker.

A participant observation data collection approach allowed me to take on the roles of both the teacher and the researcher within the context of the group, thus moving between the dual purposes of both engaging in the activities with the students while observing them (20). This dual role provided a cultural context for me as an observer of the classroom and allowed me to ground my ethnographic fieldwork as situated within the culture of the classroom. Using this approach, I examined my own practices as the teacher as well as those of my colleagues and my students as we co-constructed the STEM initiative. Through our everyday actions — both in a broad sense and also in the classroom — our practices constituted literacy as a situated process (18).

As both the researcher and the teacher, I faced a challenge encountered by many participant observers: understanding my own bias as both the teacher and the researcher in this classroom culture (13,20). By keeping detailed written, audio, and visual records, I was able to balance my own recollection of events with these electronic and physical records in order to make sense of this classroom as a culture-in-the-making (21).

During STEAM Lab, the students also participated in this research study as participant observers. By briefing them before the commencement of the workshop on the concept of participant observation and the goals of the study, I developed a framework for the students to view the work as both a research study and a maker-based, for-credit elective course. This concept was reinforced throughout the year as the students asked questions about the study and at a closing meeting in which the research team discussed the year-long course. Students were encouraged to take notes in individual research journals to document what Agar called rich points (13). As students encountered the unexpected, they were encouraged to discuss their perceptions of the program through a meta-discourse. One student even chose to review the recorded footage to assemble a film reel featuring highlights of the projects. Although the video records provided the primary resource for data collection and production, my journal and the students' texts (journals, online comments in the course social network, and emails) helped trace the participants' thinking and learning.

In order to step back from my role as the STEAM Lab teacher and into my role as an observer, it was necessary to review the records at a period of time when I was not actively involved in teaching, developing, or facilitating the course. My detailed course notes, including lesson plans and field notes from instruction, proved to be invaluable resources as I reconstructed the two STEAM Lab semesters. Using the records and data generated by the participants, it was possible to determine which moments across the year-long timeline were useful in further analysis to address the research questions for this study.

ANALYSIS

In the following analysis, I focused on one set of interactions in STEAM Lab between two students, Bert and Caitlin, as they explored possibilities for the electronics to control the activation of the piano keys. One technique I have employed in order to balance my emic perspective as the teacher, in contrast with that of an outsider, is to use the third person in describing my actions as the teacher and curriculum developer in the analysis section. This approach allowed me to separate my role as a teacher and curriculum developer from my role as a researcher who was responsible for analyzing and reporting on this study.

Bert was a 10th grade boy who was a self-proclaimed video game fanatic and had been in the teacher's digital media courses in the past but had not participated in any of the Near Space Exploration Club STEM cycles. He was present, however, for the Synthesis Unit on space. Bert had struggled with learning and social challenges for his entire academic career as a result of a developmental disorder. While his individual challenges were not a focus of this analysis, they are worth noting in order to provide insight into these interactions.

Caitlin was a 10th grade girl at the time of the study. According to school records, her academic achievement was typically above average, although she could be easily distracted when subjects were not challenging or interesting to her. In the days leading up to the series of interactions on April 7, 2014, Caitlin, who eagerly accepted the challenge of designing and constructing the electronics for the piano, had encountered several roadblocks and technical dead ends in searching for a mechanism to provide synthesized sound and light activation for the large piano keys.

On this particular day, in the midst of developing the piano's computer interface, Bert, who had been tinkering with Makey Makey, a self-proclaimed "invention kit for the 21st century," was sharing his discoveries with his classmate Caitlin. The Makey Makey is an Arduino-based invention tool on a circuit board resembling a video game controller. The board's layout includes a joypad and buttons and connects to most computers to provide input signals in the form of keystrokes. The teacher purchased the Makey Makey and made it available to the students in the classroom, along with the materials in the Make: Electronics components kits. Bert was drawn to the device and had been tinkering by connecting the Makey Makey's electronic leads to a variety of objects (fruit, cardboard boxes, hands, and fingers), as suggested in the product's literature. Conductive material enables interactions through the device with the connected computer over a USB port.

Analyzing Classroom Discourse

The discourse below made visible the formation of a collaborative relationship between these two students working to solve a common problem by sharing knowledge and experiences with one another. In this case, the teacher provided the students with an ill-defined problem (the assignment that led to the development of the electronic piano), and, within the scope of that project, each student work group defined further parameters for the various aspects of the project (additional sub-problems). The problem, in this case, was designed to simulate the organic rise of real-world problems and allowed for free inquiry in the search for solutions. It was visible through analyzing this interaction between Bert and Caitlin that constructionist theories of learning through collaboration on a public project with new electronic objects and tools could help get students beyond certain hurdles.

As shown in Table 1, Caitlin signaled through her initial question, "Did you just get this, or were you playing with this last time?" (lines 7-11), that she was looking to Bert for his insight into the functionality of Makey Makey. Bert initially hesitated (lines 12-17) and then went on to explain to Caitlin how the device interacts with the computer to create sound. Here, there appears to be evidence of students assuming agency and responsibility for this particular problem of interfacing the piano with the computer. It can also be seen that the students turned to one another with questions (line 20) and worked together to design mini-experiments to test theories and advance their thinking (line 22).

Later, Bert showed Caitlin how holding the electronic leads on the Makey Makey could activate various tasks on the computer screen by simulating keystrokes on a USB keyboard (see Table 2). Caitlin expressed initial excitement, "Oh my god! Wait. Is the electricity going through me?" (lines 74-76), in seeing firsthand how the Makey Makey, an external USB device that is not a traditional computer input, interacted with the computer and her own body as a circuit. She then asked the teacher for an explanation; however, he was unable to give her a detailed response since he had been engaged with another student (lines 82-91). Undaunted, Caitlin continued to tinker and experiment.

This interaction led to further inquiry together with Bert, specifically in regard to a solution to the problem of interfacing the piano. Caitlin attempted

Table 1. Transcript Excerpt from STEAM Lab on April 7, 2014 – Part One

1		***17:53:00***
2		Bert and Caitlin sit at Mac computer side-by-side
3	Bert:	(opens Makey-Makey box and removes wires and board)
4		those are just stickers
5		(points to stickers in bottom of box)
6	Caitlin	(lifts box and looks inside)
7		did you just get this?
8	B:	did I just get this?
9		no
10		[I]
11	C:	[or were you playing with this last time?]
12	B:	I was playing with this last time
13	C:	This is awesome
14	B:	I
15		um
16		let me get this out for a second
17		(reaches for and opens small plastic bag and begins assembling the board)
18	C:	these are so cute (as she looks at stickers)
19		I like stickers (looks at camera and quickly looks away)
20		but where does the sound come from?
21	B:	the sound?
22		well the sound doesn't necessarily come from this
23		there is a program on site that allows you to play music but
24		I mean
25		this'll just be the controller we'll be using
26		the sensor kinda thing

Table 2. Transcript Excerpt from STEAM Lab on April 7, 2014 – Part Two

71	Caitlin:	oh
72		I have to hold this?
73		(pause)
74		ohmygod
75		wait
76		is electricity going through me?
77	Bert:	um
78		I-
		don't know
79		actually
80		[I]
81	C:	um
82		Levi
83	Teacher:	yeah?
84	C:	is it going through me?

85	T:	uh
86		well
87		(continues to talk to the other student he was previously engaged with off camera)
88		so that happens to be a very sensitive switch
89		I'll come and explain
90		in a minute
91		to you guys
92	C:	(continues to fiddle with board and wires)
93		so cool

to obtain the teacher's attention following the revelation about the Makey Makey. Caitlin asked the teacher (who was off camera but could be heard working with another group of students) if electricity was going through her as she touched the Makey Makey. The teacher gave an incomplete response, explaining that he would "come explain it in a minute to you guys" (lines 89-91). The teacher's inability to provide immediate feedback may have functioned to provide the students space to continue to take responsibility for their own learning though free inquiry. This represents an essential characteristic of problem-based learning, as the students continued to tinker with the material.

As can be seen in Table 3, in the absence of a complete explanation from the teacher, the students responded by connecting the Makey Makey leads to other objects, such as a cardboard box (line 112). In

Table 3. Transcript Excerpt from STEAM Lab on April 7, 2014 – Part Three

111	Bert:	well it works if-
112	Caitlin:	(attaches wire to cardboard Makey-Makey box)
113	B:	I mean it has to be conductive enough
114		or else it won't work
115	C:	so where does this go?
116	B:	this go-
117		um-
118	C:	to the ground
119		should I just hold it?
120		I can just keep holding [it]
121	B:	[yeah]
122		you can just hold onto it for right now
123		and
124		then we need
125		something conductive
126		um
127		Levi?
128	T:	yes sir?
129	B:	do you have anything
130		kinda like the oranges we used last time
131	C:	the box won't work?
132	T:	there might be oranges out there

doing this, Bert explained to Caitlin that he believed the connected objects must be conductive (lines 124-125), demonstrating his understanding based on prior free inquiry with the device and showing how, through guidance rather than direct instruction, the students were able to make inferences about science and test those hypotheses with the right tools. In this case, Bert was correct in predicting that objects connected to the Makey Makey leads must be conductive in order to receive a response from the circuit. Here again, however, the teacher provided minimal feedback, allowing the students to seek conductive objects to experiment with themselves. He then offered that there may be oranges on campus (line 132) that the students could use to experiment with (provides scaffolding for learning) but left the students to tinker and problem solve with minimal intervention. This interaction exemplifies the student-teacher dynamic during the experimentation in STEAM Lab. As in other interactions, the teacher did not provide answers to questions but, instead, made suggestions for further experimentation.

After the two students had experimented with a variety of conductive and nonconductive objects, they used a piano simulation website suggested by the Makey Makey documentation to play keyboard notes using a "keyboard" made of oranges connected to the leads of the Makey Makey device. From their corner of the room, the two students looked over to see if the teacher has noticed that they were making piano noises.

After allowing the students nearly 30 minutes of independent exploration, the teacher checked back in with Bert and Caitlin. Here, there is evidence of the teacher acting as a cultural guide by offering hands-off suggestions based on his students' needs in response to their actions. Seeing that they were using a small on-screen demonstration keyboard web application referenced in the Makey Makey documentation and tutorial, the teacher suggested that Bert and Caitlin try using Makey Makey as a substitute for the computer keyboard using Apple's GarageBand software on the iMac. GarageBand is a program that offers access to a larger virtual keyboard and more instrument sounds than the basic Makey Makey software.

This type of teaching cannot be fully predetermined. In this case, the teacher assumed a problem-based approach to learning, whereby he helped students identify resources that may be useful in overcoming challenges rather than simply correcting them or providing direct answers.

Later, the teacher acknowledged Bert and Caitlin's developing understanding with an approving chuckle. Bert and Caitlin had made an important discovery on their own; using Makey Makey, they furthered their understanding of electronics and circuits through tinkering. They had discovered first-hand how conductive materials can close circuits and, in doing so, also revealed a way to use physical objects to interact with a computer. This was an important first step in laying the groundwork for their later use of the iMac as the synthesizer for the life-sized piano.

The two appeared to enjoy the learning journey together, as evidenced by smiling, laughing, and general excitement upon making discoveries throughout the process. The fun that Bert and Caitlin had while experimenting with the Makey Makey piano and electrical conductivity attracted the attention of Bobby and Jay, two students working on other aspects of the piano construction. Seeing an opportunity to give a demonstration, Caitlin reopened the piano web application and challenged Jay to play music with the oranges. Jay touched the oranges but was not connected to the circuit, and music did not play. Caitlin playfully challenged Jay by saying, "I'm sorry, it doesn't work for you" (lines 297-310). Recognizing the possibility to further the experiment, Jay touched Caitlin's arm, thus completing the circuit and playing a note. "Wait, if you just touch me, it works?" she questioned out loud as Jay walked away confidently. "That's why if you hold someone and you touch a powerline, you'll get shocked," he explained (lines 323-325). Here, again, there is evidence of both a connection to prior knowledge (that electrical shocks are transferable through conductive bodies) and a collaborative social construction of knowledge, whereby members of the group, both the immediate working group of Caitlin and Bert as well as other members of the class at large, made contributions to the developing knowledge base through free inquiry and association. The students each had different experiences from outside of the classroom that helped them understand a part of problem. For example, Jay knew that not only would a person's

Table 4. Transcript Excerpt from STEAM Lab on April 7, 2014 – Part Four

297	Caitlin:	look
298		I can play oranges
299		and I bet you if you try to play them
300		it won't work (because he would not be holding the grounding lead)
301		try playing
302	Jay:	one sec
303		(walks over to Caitlin and Bert)
304		(unintelligible)
305	C:	this
306		try one
307		oh
308		I'm sorry
309		it doesn't work for you
310		(chuckles)
311	J:	(unintelligible)
312	C:	because I was hold the wire
313	J:	oh
314		let me do it
315		(touches Caitlin and plays note)
316		oh yeah (smiles)
317		(walks away)
318	C:	wait
319		if you just touch me
320		it works?
321		yeah
322		'cause you grabbed it
323		that's why if you hold someone
324		and you touch a power line
325		you'll get shocked too

body conduct electricity but that multiple bodies could also touch to allow the small current flow across each to complete the circuit. Each student's personal knowledge base and life experiences collaboratively shaped the outcomes when they were permitted to collaboratively tinker in furthering the piano project.

The next challenge the students faced was how this new discovery of controlling a computer-based piano with an input device such as the Makey Makey would translate to their life-sized piano project (see Table 5). The Makey Makey tutorial piano only permitted the students to work with six whole-note piano keys mapped to specific, hard-coded keyboard keys, including four arrow keys, the spacebar, and the mouse click. The group's design called for 14 keys, including whole notes (white keys) as well as sharp and flat (black keys) notes. However, Bert and Caitlin had encountered another problem: There were not enough switch positions on the Makey Makey to map one note to each of the 14 notes that the large-scale piano design called for. In talking through this issue, Bert suggested the idea that they explore the possibility of "remapping" the keys and notes so that they could expand beyond the limitations of the Makey Makey (lines 352-353). Caitlin built off of Bert's idea by suggesting that they might try multiple Makey Makey boards mapped to different keys (lines 360-364).

Here, again, the two students worked collaboratively toward solving the problem in a way that

Table 5. Transcript Excerpt from STEAM Lab on April 7, 2014 – Part Five

341	Caitlin:	ohhh-
342		here's the deal
343		if we could find a way
344		(pause)
345		if Garage Band can play with arrow keys
346		(pause)
347	Bert:	ok
348	C:	and space keys
359		(plays notes)
350		then
351		we can play with these
352	B:	or if we can remap these keys
353		like "A" equals "S"
354	C:	exactly
355		to be what we need them
356		but it's still not enough keys
357		(pause)
358		if we buy a whole-
359		(snaps fingers)
360		if we know how to remap them
361		it's easy
362		we just get another one and have two sets
363	B:	yeah
364	C:	one two three four five six
365		(unintelligible)
366		but still
367		the trick is how to remap them
368	B:	yeah

resembles how practitioners would do so on a professional team. They coined their own terms — such as "remap" (line 352) — and began using these terms (line 360) in a developing language to describe the problem and iterative trials for solutions.

From Table 6, it is clear that Bert and Caitlin delved deeper into the workings of the Makey Makey and GarageBand. They discovered that the Makey Makey behaves just like an external USB keyboard but can be attached to conductive materials rather than simple switches or letter keys. They soon discovered, however, that it would not be so simple to remap the Makey Makey for their purposes (lines 380-384). The Makey Makey was designed for basic exploration. The students quickly discovered that they had already intellectually outgrown the limitations of the device. At this point, the teacher again stepped in as a guide. In this case, the teacher possessed some knowledge about how the Makey Makey was designed when he responded by revealing that "it is an Arduino-based device" (line 410). The teacher asked a series of questions (lines 390 and 399-400). In response, he redirected the students with his final question, asking if there was a way to make an Arduino solve the remapping problem (lines 408-409).

The Role of the Teacher in Creating a Common Language

The teacher may not have known the precise answers to his queries, but he listened to the students'

Table 6. Transcript Excerpt from STEAM Lab on April 7, 2014 – Part Six

380	Caitlin:	we don’t know where to start
381		because
882		(unintelligible)
383		the computer actually thinks that when you press it
384		you’re pressing the arrows and the space keys
385	Teacher:	oh
386	C:	and so if you could like
387		change that
388	T:	ok
389	C:	[because]
390	T:	[have you gone into Garage Band]
391	C:	[yeah]
392		and if in Garage Band you just like press an “A”
393	T:	yeah
394	C:	on the keyboard
395		then it’ll play a note
396		but
397		they’re just arrows and
398		the instructions doesn’t say anything
399	T:	it doesn’t say that you can change them?
400		and the arrows aren’t they keys you can use in Garage Band?
401	C:	[yeah]
402	T:	[ok]
403		so
404	C:	and I’ll probably need two more sets of this
405		to get them to work
406	T:	right
407		so
408		is there a way to make an Arduino
409		do exactly the same thing?
410		‘cause this is Arduino and its
411		and someone just programmed it and they picked those
412		those keys

questions, evaluating their position and responding in a way that refocused them on a new challenge in a direction where there was a greater possibility of a successful outcome. The teacher’s responses were often subtle nudges toward directions for further inquiry and resources that might yield more productive tinkering. While he usually did not give students answers to their questions directly, he often guided them toward inquiry that could expand their thinking, as exemplified in the analysis. In this case, as a result, the advancements the students made through tinkering and experimenting together ultimately led to a deeper understanding of electronics and circuit design. Caitlin, with minimal teacher intervention, was ultimately able to design and construct a custom USB interface for the working life-size electronic piano.

This type of teaching required preparation by the teacher, including having some background knowledge about the capabilities of the tools (in this case, the Arduino) but not necessarily firsthand experience with the specifics of the respective task. Knowing that Makey Makey was based in Arduino, the teacher appeared to suggest that the students needed to refocus their attention on how it was built and how it could be modified through software and programming to accomplish what they wanted it to do.

This series of interactions surrounding the Makey Makey and keyboard note inputs may have helped shape how the students viewed their responsibility for their own learning. The teacher was not telling them what to learn but providing clues as to where to look. This represented an authentic problem-based setting where the answers to the developing problems are not necessarily known previously to any party (neither students nor teacher), thus making collaboration an essential component. In this case, there is also evidence that the students applied newly acquired knowledge resulting from these discoveries back to the overall problem through reanalysis and resolution. This is a hallmark of problem-based learning models (22).

Additionally, the teacher and students had developed a common language to talk about the problem and potential solutions. Terms such as remap, which made reference to pairing keyboard inputs to outcomes on the screen (musical notes), had emerged as part of the developing solutions. The students were on a path toward designing an external controller for GarageBand as a possible solution to one aspect of the problem.

Productive Failure

In STEAM Lab, the learning processes were not entirely un-scaffolded, as the teacher provided guidance in many instances. However, the methods he employed throughout the second semester construction phase of the course in particular were largely less structured than a typical STEM course. In the case of Caitlin, she demonstrated these traits and naturally gravitated toward work in the course that challenged her intellectually (microcontroller programming) and physically (soldering) in order to invent solutions to problems. On May 7, 2014, while working on a complex electronic matrix for the piano, Caitlin was asked by another student, "What will you do if this doesn't work?" In response, she said simply, "I'll cry." In reality, however, this statement did not match her actions. Later that same day, the electronic circuit matrix did not work due to compilation errors in her Arduino programming code. In analyzing her interactions with the teacher, her persistent nature became visible. Again, in this instance, it is evident that the teacher provided some scaffolding but stopped short of providing specific answers. The teacher did not offer direct solutions to the ill-defined problems being addressed but, instead, challenged Caitlin to continue her inquiry in order to develop a solution. Today, as a result of the explosion of inexpensive modern electronics, digital fabrication (3D printing), and computer and microcontroller programming technologies, teachers can afford students opportunities to try various solutions to problems, learn from mistakes, and take part in authentic iterations of designing, building, and testing solutions at minimal costs. Learning opportunities through invention, problem-based learning, and maker education offer similar if not often identical approaches to developing high-tech solutions to everyday problems. By challenging students with such real-world situations, teachers now have opportunities to provide the tools and support to developing prototype inventions to solve these problems with relatively modest financial investments.

CONCLUSION AND IMPLICATIONS

Affordances

STEAM Lab provided a space for students to learn in a traditional, directed way and provided them with many opportunities to tinker with the concepts being explored. The entire second semester of the course was devoted to designing and building a student-initiated project idea. In this particular study, students who struggled fitting into traditional classrooms found success in solving challenges presented in a problem-based or tinkering approach.

Bert's academic file revealed a history of challenges, both socially and academically, related to diagnosed learning disabilities. Caitlin had a serious disciplinary issue in the middle of this particular school year and did not return to the school the following year. Despite these challenges, these two students were thought leaders during the STEAM

Lab course. Bert was the impetus for the approach to the sophisticated electronic circuitry, and Caitlin remained undaunted in her quest to build the complex logic and control circuits for the piano controller matrix. This played out in a series of interactions throughout the semester, which were similar to the events analyzed in this article. Despite having no prior experience with electronics, soldering, or computer programming, Caitlin designed and built the circuitry in time for the class to exhibit a giant working electronic piano at the spring art show despite a major setback unintentionally caused by the teacher's interference during circuit construction.

Implications for Practitioners

Maker-based initiatives that employ a constructionist, problem-based approach to providing learning opportunities may be successful through teacher preparation and the dedication of adequate time and resources. Students and teachers today have access to comparatively inexpensive prototyping tools. More than at any other time in history, sophisticated electronics and invention tools are available at a fraction of the cost as compared to the recent past. There are virtually unlimited opportunities for providing students with agency to ensure engagement and success as well as a growing number of online maker communities to turn to for support. However, in order for teachers and students to be successful with maker education, they need to be supported financially, institutionally, and educationally (through teacher education). The predominant approach to teaching for at least the past 50 years has been the delivery of information through a direct form of instruction. More recently, the Next Generation Science Standards (NGSS) have supported different approaches to learning, including encouraging teachers to afford students opportunities for finding solutions to problems through authentic science and engineering practices (23). A better understanding is necessary as to how these directives might be supported by maker education advocates and virtual and local maker communities. Ongoing support for teachers and students in these endeavors is key in ensuring that opportunities for authentic student participation in engineering and science practices are successful and in alignment with NGSS mandates where required.

This study showed some of the considerations that were required in developing and supporting a maker-based school environment for invention and creation. It made visible the processes and practices of a maker-based STEM learning initiative in a progressive independent high school. Further study in other settings, such as in larger public or inner city schools, would uncover other considerations and variables in different contexts.

Four important keys emerged from this research and were essential in developing a working definition of what counted as a maker-based education project or initiative in an academic context. Firstly, students worked both independently and collaboratively toward engineering a solution to an ill-defined problem. Secondly, my students and I learned meaningful cultural practices and, in turn, acted as practitioners in STEM fields. Thirdly, rather than acting purely as an authority in problem-solving activities, I, in the role of the teacher, acted more as a facilitator and guide by placing an emphasis on supporting student inquiry over direct instruction. Finally, and perhaps most apparent, students were introduced to and encouraged to draw on local and virtual maker community resources, including local makerspaces, online forums, and the plethora of multimedia documentation available online in related fields. In fact, students actively engaged and participated in online maker communities by asking questions and contributing their own experiences when applicable. I have proposed these keys as to what counted as maker education in this context.

Implications for Future Research on Intersection of Maker Education and Invention

There is evidence in this study that suggests the two students were in fact both having fun and learning. In the case of STEAM Lab, I, as the teacher, provided the ill-defined problem of creating a large-scale interactive electronic art project. In the process of invention, students are tasked with the broader challenge of addressing any number of real-world issues facing humanity through design and creation. In that sense, this version of maker education and invention education are both constructionist learning approaches. Further ethnographic studies of actual constructionist classrooms and learning spaces would help make visible what counts as maker education in different settings, as maker-based education will continue to evolve over time with changes in both sociotechnical and school cultures. An important outcome of this study was the recognition that teachers and students can have multiple roles as co-creators, facilitators, and learners. While it traced how, over time, these roles evolved, future researchers might consider how other types of maker-based STEM approaches could be incorporated into the invention process using the four keys of maker education presented here as a guide. In various settings there will be unique institutional constraints that need to be overcome, such as requirements for testing and curriculum approval, time management, scheduling, and funding.

This study provided greater detail and insight into what an actual initiative looks like and what this teacher did to first define and then develop his own maker education-based STEM initiative. There is value in incorporating problem-based learning approaches, along with the plethora of maker community resources, into approaches to invention at all levels. Additional ethnographic inquiries into maker education efforts could assist educators in gaining a better understanding of the implications of maker education as well as what various models of maker-based education look like in practice. The strength of the institutional support and freedom afforded by this particular independent school may have influenced the success of the STEAM Lab elective course. Additional ethnographic inquiries, using discourse analysis, into the areas of further inquiry raised in this study may help proponents of maker and invention education further legitimize efforts to make inroads into both public and private school curricula.

Through constructionist learning approaches, students may have opportunities to learn not only specific skills in STEM and STEAM fields, but they also can learn to think as though they were professional practitioners. Through maker-based approaches, students can learn how to determine precisely what they need to know in order to address a problem. Understanding how these processes and practices are transferable across STEM fields might also be an area of further research.

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