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The Keys to Maker Education:
A Longitudinal Ethnographic Study of a STEM-to-STEAM Curriculum-in-the-Making

A dissertation submitted in partial satisfaction of the

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in Education

by

Levi Chandler Maaia

Committee in charge:

Professor Emeritus Judith L. Green, Co-Chair

Professor Danielle B. Harlow, Co-Chair

Professor Richard P. Durán

June 2018

The dissertation of Levi Chandler Maaia is approved.

Richard P. Durán

Danielle B. Harlow, Committee Co-Chair

Judith L. Green, Committee Co-Chair

May 2018

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For Sydney

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VITA OF LEVI CHANDLER MAAIA
May 2018

EDUCATION

In progress	**Ph.D.** in Education, University of California, Santa Barbara
2013	**M.A.** in Education, University of California, Santa Barbara
2004	**M.A.** in Journalism, Emerson College
2003	**B.S.** in Film & Television, Boston University

PUBLICATIONS & PRESENTATIONS

2015	Maaia, L. C. (2015). QSL from Cuba. *QST,* 70-72.
2013	Maaia, L. C. (2015). *The need for adapting not adopting resources for test preparation* (Unpublished master's project). University of California, Santa Barbara.
2012	Maaia, L. C. (19 May 2012). Near Space Probe Technical Overview Presented via video at Dayton Hamvention, Dayton, Ohio.
2011	Maaia, L. C. (17 Feb. 2011). Electronic Flight Bags: iPad & Foreflight in the cockpit. Presented at FAA Safety Team Seminar, Santa Barbara, Calif.
2010	Maaia, L. C. (2010, December 28). Internet rules give big business control. *The Boston Globe*, p. A10.
2010	"California STEM Summit: California STEM Network Initiative." (2010). Pasadena, Calif: Green, J., Frame, A., Maaia, L., Emerson, A., Nilsen, K., Stewart, A., Truxler, A. & Hunter, M.
2006-2007	Maaia, L. C. (2006 November-2007 May). Voices. *Multichannel News.*
2004	Maaia, L. C. (2004). *The cost of free software: An investigation into open source* (Unpublished master's project). Emerson College, Boston.

TEACHING EXPERIENCE

2008-2014	**Anacapa School** Teacher & curriculum developer: Digital Voyage media course; Anacapa Near Space Exploration Club; STEAM Lab engineering & electronics course Coordinator: 2012-2013 Synthesis Unit – Space: Where are we going?
2009-2010	**University of California, Santa Barbara** Teaching assistant – *Teaching methods in education* course
2008	**Santa Barbara Sailing Center** Sailing instructor
2001	**Edgewood Yacht Club Sailing School** Youth program director and sailing instructor
1999	**New Bedford Yacht Club Sailing School** Youth program sailing instructor

PROFESSIONAL ACTIVITIES & SERVICE

2018-Present	**Maaia Communications** Co-founder of business strategy firm focused on assisting small businesses and startups
2017-Present	**Amateur Radio on the International Space Station (ARISS)** U.S. Education Committee member for NASA-sponsored STEM outreach program connecting students with astronauts aboard the International Space Station
2012-2018	**Full Channel Labs** President and chief technologist of research and strategy initiative for internet, television, and phone service provider
2012-2015	**Anacapa School** Director of outreach and communications for independent school serving Grades 7 to 12
2004-2012	**Full Channel, Inc.** Vice President and chief technologist at internet, television, and phone service provider
1996-2015	**ComCreations, LLC** Founder of interactive design, development, and media production firm
2002	**American Experience – PBS/WGBH** Research and interactive production assistant
2000	**Context Media** Production assistant

COMMUNITY ACTIVITIES & SERVICE

2016-Present	**Angel Flight West** Volunteer pilot for a nonprofit organization that arranges free, non-emergency air transportation for children and adults with serious medical conditions and other compelling needs
2014-Present	**Santa Barbara Amateur Radio Club** Member of the board of directors for 501(c)(3) nonprofit organization
2009-2010	**University of California, Santa Barbara** **Graduate Student Association in Education** Vice president, communications
2007	**Town of Warren, R.I. Fire Department** Volunteer NFPA Level 1001 firefighter
2006-2007	**Big Brothers of Rhode Island** Advisory board member
2002-2003	**Big Brothers of Massachusetts Bay** Big brother
2001-2002	**Boston University Community Service Center** Volunteer at elementary afterschool program in Boston Public Schools
1998	**City of East Providence, R.I. Senior Center** Volunteer teacher of personal computer seminars for senior citizens

MEMBERSHIPS

2013-Present	**Amateur Radio Satellite Corporation (AMSAT)** Member
2013-Present	**The Explorers Club** Term Member
2010-Present	**Institute of Electrical and Electronics Engineers (IEEE)** Member
2008-Present	**American Education Research Association (AERA)** Member
2006-Present	**American Radio Relay League (ARRL)** Member

CERTIFICATIONS

Federal Communications Commission

Amateur Radio Operator - General Class License K6LCM

Federal Aviation Administration

Private Pilot - Airplane Single Engine Land & Sea; Instrument Airplane

Remote Pilot - Small Unmanned Aircraft Systems

RECOGNITION

2013	QST Video Award, American Radio Relay League
2009	Philip and Helen Green Research Fellowship, Gevirtz Graduate School of Education, University of California, Santa Barbara
2009	Top Ops Community Service Award, Cablefax

ABSTRACT

The Keys to Maker Education:
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This study examined how and in what ways an instructor and students defined and influenced the co-creation of a maker-based STEM culture at an independent high school. It explored opportunities for learning and engaging in a collective, goal- and problem-based activity in an elective high school course and how and in what ways this theory and style of instruction afforded certain learning opportunities for students and what types of literacies were needed in order for students to confront the challenges of the course. Although so-called maker education has become a popular theme in STEM education, there is little significant evidence from empirical studies offering guidance as to how and in what ways the processes and practices of maker culture 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 STEM studies (Connell, Halpem-Felsher, Clifford, Crichlow, & Usinger, 1995). Even highly successful students may be demonstrating skills such as test taking, but they are perhaps not learning *literate practices* (Green, Dixon, Lin, Floriani, & Bradley, 1992) in STEM fields.

The data collected for this study included video records of activity, conversations (both face-to-face and electronic), and journals and other texts, generated by students, teachers, and administrators, which were examined using ethnographic research methods. This data collection method was chosen in order to make visible what counted as meaningful interactions, what facilitated these interactions between actors that were essential to understanding how learning is conceptualized, and what counted as literate, social, and epistemic practices in a maker-based STEM program (Cunningham & Kelly, 2017).

Four important characteristics or *keys* emerged from this research and were essential in developing a definition of what counted as a maker-based education project or initiative in an academic context. The first key was that students worked both independently and collaboratively toward engineering a solution to an ill-defined problem. Secondly, the students and the instructor learned meaningful cultural practices and in turn act as practitioners in a particular STEM field. Thirdly, the teacher, rather than acting purely as an authority in problem-solving activities, acted as a facilitator by placing an emphasis on supporting student inquiry over direct instruction. Finally, and perhaps most apparent, was that the 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, the students were encouraged not only to draw on these resources passively, but also to actively engage and participate in maker communities by asking questions and contributing their own experiences when applicable.

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Chapter I: Introduction

A study in the *Journal of Engineering Education* asserted that qualitative methodologies have received little attention in engineering education research literature (Case & Light, 2011). A recent survey of literature indicates that while there is current discussion of how past learning models and pedagogies may complement or integrate with the burgeoning *maker education* movement — a term coined by technology author and publisher Dale Dougherty to describe a transformative educational movement incorporating what he calls a *maker mindset* (Dougherty, 2013) — there remain few qualitative studies that have attempted to explicitly define maker education (Benjes-Small, Bellamy, Resor-Whicker, & Vassady, 2017) and few if any that take an interactional ethnographic approach to studying the formation of a maker-based science, technology, engineering, and mathematics (STEM) learning initiative in a high school classroom context.

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 which dealt directly with defining and understanding such maker education as I sought to understand the considerations in order to build and support students engaging in such practices. By using an interactional ethnographic approach (Castanheira, Crawford, Dixon, & Green, 2000; Collins & Green, 1992) to data analysis, I addressed this problem by making visible the processes and practices that I developed as a teacher as well as those of my students, my ways of engaging with my students, and the ways students participated in the social construction of knowledge, during a multi-year STEM initiative at an independent school serving Grades 7 through 12 in Southern California.

By understanding classrooms as cultures-in-the-making, particularly where new and innovative instructional approaches are being undertaken (Collins & Green, 1992), this study focused on how I as a teacher and curriculum developer defined and took up a framework influenced by the emerging maker movement, which will be examined in depth in Chapter II, and adapted these processes and practices for use within a course called STEAM Lab at an independent school in Southern California serving Grades 7 through 12. The abbreviation STEAM (science, technology, engineering, art, and mathematics) was borrowed from the Rhode Island School of Design (RISD) STEAM educational initiative encouraging the infusion of arts into STEM studies. While an in-depth study of the STEM-to-STEAM sub-movement was not a focus of this dissertation, there is a brief discussion of the implications of STEM-to-STEAM in Chapter II of this dissertation.

Purpose of the Study

This dissertation aimed to make visible how STEAM Lab, a two-semester high school course, developed based on 3 prior years of evolving STEM initiatives, and how the course subsequently transformed over the two semesters. It also examined the practices co-constructed in the maker classroom through the everyday actions of the students and the teacher, and how these practices constituted literacy as a situated process (Castanheira et al., 2000). In doing so, I strived to make visible how both the school culture and the course itself developed through collaboration whereby the teacher and his students worked together to solve challenges through maker-based approaches.

As a teacher with a personal commitment to engaging students in problem- and project-based curricula during school and after school, the idea of incorporating maker education into my courses was intriguing. As an education researcher, the questions that arose centered on defining maker education and what was actually entailed in the development of such a maker curriculum-in-the-making. This STEM initiative was developed in order to engage students in experiences where they could be designers, developers, and builders of STEM-based projects.

Like many teachers, I was challenged to take new approaches to teaching and learning. As an avid builder and maker in my personal life, I knew that an ever-increasing number of online resources for making, building, and do-it yourself (DIY) projects made use of new high-tech, digitally-enabled devices. However, little empirical evidence existed on best practices or guidance as to how the processes and practices of this maker culture might be integrated by teachers into school settings.

Overview of the Maker Movement

The maker movement is comprised of many separate DIY movements composed of individuals with disparate areas of interest and skills. Various DIY movements have come together through maker-based activities in order to support one another through regional and local events and online and offline communities. Websites such as instructables.com, which bills itself as a resource for “How to make anything,” provides detailed descriptions and photos of DIY projects. Thingiverse, a shared and open repository of 3-D printer files and many others, offers resources to prospective makers for free. The Arduino microcontroller platform and the Raspberry Pi single-board Linux computer both offer low-cost entry into hardware and software tinkering and are the basis for many digital art, DIY, and maker community projects. As such, maker education is not a defined pedagogy, but rather the incorporation of an amalgamation of practices related to the ethos of these online and physical maker-supporting communities into educational settings.

Halverson and Sheridan (2014) provided a context for research on maker education in a Harvard Educational Review paper cautioning that the institutionalization of maker education through its take-up in formal school settings might “kill the essence of the maker movement,” an essence viewed by Blikstein (2008) as an agent of the democratization of knowledge about 21st century digital artifacts. Halverson and Sheridan (2014) stated that the maker movement’s role in education not only represents a “series of activities that can help improve K-12 students’ formal schooling knowledge,” but also a structure to support opportunities for authentic engagement. What is largely missing from the current body of maker education literature is direct evidence as to what kinds of knowledge and literate practices are necessary for teachers to incorporate maker culture into classroom curricula.

The modern maker education movement is influenced in part by the loosely associated global models of communities that gather virtually through online forums and communities and physically at makerspaces, hackerspaces, and other community workshops and expositions to collaborate and share DIY and homebrew electronics engineering and art projects. Perhaps recognizing the potential media audience within these emerging networked cultures, O'Reilly and Associates began publishing *Make: Magazine* in 2005, a publication focused on informal and hobby project building and creating in a wide range of areas, including amateur radio, amateur rocketry, 3-D printing, and solar composting. In 2006, the organization introduced the first Maker Faire, an annual exposition that bills itself as a family-friendly festival celebrating the ingenuity and creativity of the maker movement

("Maker Faire: A bit of history," 2017). In 2014, Barack Obama launched his White House's Educate to Innovate Initiative in an effort to improve the overall performance of the United States in science and math achievement. Obama hosted the first White House Maker Faire, during which he said, "today's DIY is tomorrow's Made in America" (Fried & Wetstone, 2014), emphasizing the need for an infusion of maker-based education into U.S. STEM curricula.

Make Magazine and the Maker Faire events are the brainchildren of Dale Dougherty, a publishing executive who started his career publishing books on early internet technologies at O'Reilly Media. Dougherty spun off Maker Media from O'Reilly in 2013 after his group's tremendous commercial success capitalizing on the maker movement. With two rapidly growing Flagship Maker Faires annually (one in the San Francisco Bay Area and another in New York) and nearly 200 smaller Mini Maker Faires around the world, Maker Media has fostered a unifying sub-culture of hackers, tinkerers, and hobbyists, from a wide variety of fields. By 2017, the two Flagship Maker Faires drew more than 200,000 attendees, almost half of whom had never before attended a Maker Faire ("Maker Faire: A bit of history," 2017).

In an effort to further guide policy, Make: Magazine publishers helped found the nonprofit Maker Education Initiative in 2014, with the stated goal to "create more opportunities for all young people to develop confidence, creativity, and interest in science, technology, engineering, math, art, and learning as a whole through making" (Maker Ed, 2016). Although this initiative has received major support from organizations, including the Bill and Melinda Gates Foundation and Chevron, among others, its website is focused mainly on conceptual arguments for inclusion of maker education in school programs, with few references made regarding empirical, longitudinal studies, or evidence-based practices for teachers. Furthermore, its website does not provide a clear definition of maker education, nor does it elaborate on the specific aspects of the maker movement which can support opportunities for K-12 students and teachers to engage in activities that incorporate meaningful digitally-enabled practices and processes that place collective and individual problem-solving abilities at the center.

The Emergence of Maker Education

The concepts of *makers* and *maker education* are not entirely new. While there is no generally accepted definition of maker education, in this dissertation I aimed to show how various maker approaches to education are actually adaptations or convergences of existing educational traditions, pedagogies, and cultures. An article from AdWeek referred to the term *maker* as “the umbrella term for independent inventors, designers and tinkerers…” (Voight, 2014). The article continued by explaining that “[m]akers tap into an American admiration for self-reliance and combine that with open-source learning, contemporary design and powerful personal technology like 3-D printers” (Voight, 2014).

A collection of related movements has emerged from the maker movement in recent years, and the incorporation of maker culture has gained traction and visibility, especially in museums, libraries, community centers, and other non-school-based learning environments. A variety of theoretical models are developing to guide them; however, few empirical studies trace their development across time, events, and actors. A common trait of maker culture is that it encourages some form of *tinkering*. According to Petrich, Wilksinson, & Bevan (2013, p. 53), tinkering is the “direct engagement with materials and phenomena [that] provides feedback, creates constraints, and inspires new thinking and solutions.”

Massimo Banzi, creator of the Arduino, a microcontroller designed specifically for students and makers, said:

> Tinkering is what happens when you try something you don't quite know how to do, guided by whim, imagination, and curiosity. When you tinker, there are no instructions — but there are also no failures, no right or wrong ways of doing things. It's about figuring out how things work and reworking them … Tinkering is, at its most basic, a process that marries play and inquiry. (Banzi, 2011, p. vi)

As a high school teacher, I believed that I was contributing to positive outcomes by encouraging hands-on learning, critical thinking, and problem solving through tinkering in my classroom and afterschool programs. However, I was troubled by the fact that the opportunities for learning and the processes and practices supporting maker education approaches in schools had not been adequately defined nor studied. I assumed that my students were indeed engaged in tinkering as part of an organic gravitation of the human mind toward play and inquiry, but I needed a system to make such phenomena visible. Furthermore, the lack of qualitative research studies in classrooms using maker education approaches is a problem, particularly considering that STEM courses are assumed to be preparing students for STEM careers.

For students entering STEM fields, possessing scientific and technical literacy is arguably as valuable as understanding the details of the subject matter itself. In fact, having an understanding of science and technologies is often an important indicator for career success in many fields (Wright, 1999). Literacy in this sense is not simply a cognitive skill (such as the ability to read and write a language), but rather it is understanding the literate practices and cultural nuances that are socially constructed by a group and reformulated by individuals within the group (Green et al., 1992), as well as the social achievements that the respective group considered significant. Castanheira et al. (2000, p. 353) stated the following regarding group literacy:

> What counts as literacy in any group is visible in the actions members take, what they are oriented towards, for what they hold each other accountable, what they accept or reject as preferred responses of others, and how they engage with, interpret and construct text.

While highly successful students may be demonstrating skills such as test taking, they are perhaps not learning to actually think as scientists and engineers. One of the primary ways people make sense of the physical world is through the practice of observing through developing models and theories to explain phenomenon. Good scientific models are repeatable and allow us to make accurate predictions about future phenomenon by providing a mechanism for its explanation. While complex and fully developed models such as Einstein's theory of relativity or the atomic model may be the first to come to mind, K-12 students can also make use of, and in fact should be encouraged to participate in, this most basic and authentic practice of science (Harrison & Treagust, 1998) by developing their own explanatory models for problems. However, due to a lack of familiarity with sophisticated scientific processes and the unpredictable nature of developing explanatory models, elementary and secondary teachers often shy away from educational practices that incorporate unique scientific inquiry and problem-based approaches to learning (Harlow, 2010).

In revisiting my own professional and academic teaching practices through this study, I began to see parallels between my logic and understanding of the design processes for maker education and problem-based learning pedagogy (Hmelo-Silver & Eberbach, 2012). This helped me formulate ways of understanding and researching my own approach to developing a STEM education initiative, and provided a basis for an integrative and recursive curriculum development process. In this study, my aim was to show how, as a high school teacher, I incorporated maker resources into a multi-year STEM-to-STEAM initiative that culminated in the creation of STEAM Lab, an elective course infused with elements of engineering, computer science, and art. I also uncovered the challenges I faced as a teacher and curriculum developer. Specifically, this study traced the history that supported the development of a two-semester, year-long, elective course from the first day through the final, collectively developed project. I endeavored to make visible what was entailed in developing this course and what resources and instructional processes I as the teacher relied on.

As both the researcher and the teacher, I faced a challenge encountered by many *participant-observers* (Spradley, 1980): understanding my own bias as both the teacher and the researcher in this classroom culture (Agar, 1994). One technique I employed in order to balance my emic perspective as the teacher, in contrast with that of an outsider, was to use the third person in describing my actions as the teacher and curriculum developer in the analysis chapters. 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. By keeping detailed records including 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 (Baker & Green, 2007).

Guiding Theory

While libraries and other informal community-based facilities — such as science and children’s museums, community centers, and afterschool programs — have embraced maker-based activities, maker-based courses in formal learning environments, such as K-12 schools, pose unique challenges for educators and administrators, especially when conceptualizing the core concepts and their relationship to the disciplinary practices of professionals (Cunningham & Kelly, 2017). The purpose of this study was to undertake an interactional ethnographic research approach in order to make visible how and in what ways an instructor and his students defined and influenced the co-creation of maker-based activities that constituted opportunities for learning and engaging in a collective, goal-based, and problem-based activity in an engineering elective high school course; how and in what ways this theory and style of instruction afforded certain learning opportunities; and what types of literacies were needed for students to confront the challenges of the course.

Much of the data collected for this study consisted of video records of activity, including conversations among participant students and facilitators. I then analyzed these video records (Baker, Green, & Skukauskaite, 2008; Green, Skukauskaite, Dixon, & Cordova, 2007) in order to make visible what counts as meaningful interactions and what facilitates these interactions between tinkerer and artifact, tinkerer and facilitator, and tinkerer and other tinkerers — observations essential to understanding how learning is conceptualized and what counts as evidence that the students are on a “trajectory of learning” (Petrich et al., 2013, p. 54).

Guided by an interactional ethnographic approach, including a participant observation framework and methodologies from discourse analysis (Castanheira et al., 2000), I examined how cultural, linguistic, and social presuppositions of the instruction influenced the creation of a maker-based course, and how certain opportunities were made available to the student participants, the teacher, and his faculty and staff support members, to jointly develop STEM learning environments across time, activities, actors, and events. By making visible the processes and practices of directed engagement in this learning environment, this study examined the roots and routes of the creation of a maker-based course. It endeavored to make visible the resources the instructor needed to create such a course, in what ways the participants engaged within the developing STEM initiative, and the key elements that defined how the STEM initiative was co-created.

Research Questions

The study was designed to examine this primary research question:

- What were the key process and practices of a maker-based STEM learning environment in a progressive, independent high school?

To address that question, I examined the following sub-questions:

- Who were the actors involved and how was this learning environment supported or constrained by these actors in a school context?
- What did the teacher need to know and what resources were required in order to create these developing initiatives?

- What counted as learning processes and practices in the developing STEM initiative?
- How was this maker-based course an example of a problem-based or project-based learning environment?

Methodology: Overview of Process

Using an interactional ethnographic perspective, this study uncovered how the instructor introduced students to resources created by and intended for members of maker communities, as well as in what ways the teacher and students adopted and adapted these textual, electronic, and mechanical objects and texts, to collectively design and build an original large-scale electronic piano art installation. Using an ethnographic approach allowed me (as the researcher) to make visible the layers of actions, knowledge, and processes that the teacher engaged students in and across phases of the course and the project. This approach also enabled me to identify challenges that the teacher faced in developing disciplinary knowledge, as well as knowledge of the problems and challenges that students faced in learning to adapt their personal knowledge and experience, particularly in engineering design, to work collectively with others. An interactional ethnographic perspective provided an empirical approach to developing the knowledge processes and practices of the students and the members of the class, both with the teacher and with one another.

Through a series of *telling cases* (Mitchell, 1984), each of which traced a particular actor through a particular cycle of activity (e.g., teacher, student, or group) over time throughout the phases of the project, I identified and explored the types of challenges in adapting maker culture processes and practices for educational, school-based purposes that have not been previously studied. I examined the social construction of ways of knowing, being, and doing in a maker movement-inspired classroom by analyzing the discourse and activities of the teacher and the students. I conducted this analysis with the aid of video; field notes made by the teacher before, during, and after his class sessions; the course materials; and the written records of the students themselves.

Grounding this study in an ethnographic perspective (Green & Bloome, 1997) provided a theoretical framework and logic of inquiry, enabling me as a participant observer to step back from the lived experience of the classroom and examine the records, documents (e.g., video records, student journals, and teacher curriculum notes), and decisions to systematically explore the research questions. The participant observation data collection model allowed me to assume both roles — teacher and researcher — within the context of the group, thus moving between the dual purposes of engaging in the activities with the students while also observing them (Spradley, 1980). This dual purpose provided a cultural context for the teacher-researcher as an observer of the classroom, while grounding the ethnographic fieldwork as situated inside the culture of the classroom.

With data gathered over the entire school year, I traced the telling cases across time to identify and explore the situated nature of the course's literate practices. Literacies and literate practices in this case referred to the specific socially- constructed phenomena defined by the STEAM Lab group (students and instructor). I strived to make visible in this study that the literate practices, such as the engineering practices in the course itself, were iterative and recursive and in a continual state of construction and reconstruction. Each of these cases provided a different view of learning and engagement, and a different perspective in gathering evidence of learning through making, tinkering, and co-creating several small and one large electronics construction project in the collective classroom space.

The students also took on dual roles, as they had the opportunity to participate in the research study as participant observers themselves. Briefing them before commencing the workshop in the concept of participant observation, a framework was developed for the students to view the work as both an academic study and an elective course. This concept was reinforced throughout the two semesters. During the course, students were encouraged to make notes in individual research journals in order to document moments in time that made visible the developing emic knowledge of the group that differed from the likely etic interpretations of the discourse, or as Agar (1994) called them, *rich points*. As students encountered the unexpected, they were encouraged to discuss their perceptions of the program in a metadiscourse, which was recorded in journals and addressed directly to the camera, to the instructor, or to one another.

The Site and Study

The teacher created the STEAM Lab high school elective course in response to a growing demand from parents, teachers, and students for increased access to what they saw as the unique educational opportunities emerging from maker culture and various engineering clubs and extracurricular activities at the school. Incorporating STEAM Lab into the regular school day presented an opportunity for students who might not have been able to participate in an extracurricular maker-based environment. Students received credit and an elective transcript grade for their work in STEAM Lab.

STEAM Lab was designed to promote thinking creatively and taking creative approaches to solving engineering problems. This approach, along with the freedom to explore, design, make, play, and tinker — behaviors that are typically undervalued in modern, formal educational settings (Resnick & Rosenblaum, 2013) — helped define STEAM Lab, especially the second semester, as a maker-based experience.

A key difference between many emerging maker-based forums and STEAM Lab is that the latter took place in a formal learning setting (e.g., a high school), while many other maker-based learning opportunities for children are community-based or institution-based (e.g., in libraries and museums), serving transient populations often with less at stake in the projects and activities. Prior to teaching STEAM Lab, the teacher 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. It looked more like an informal maker environment than a traditional high school course, in that the club met weekly after school, with the teacher serving as an advisor and guide. Furthermore, students were not able to earn course credit for their participation in this club. With the creation of STEAM Lab, more students had access to unique STEM opportunities similar to those afforded by the Near Space Exploration Club. STEAM Lab was a year-long (two-semester) course, with two class meetings per week, each one lasting 1 hour and 45 minutes for which students could earn course credit.

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 STEAM Lab received tuition assistance in the form of merit scholarships and financial aid. Furthermore, about 40 percent of the total student population was Hispanic or Latino. 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.

Phases of Analysis

In the first analysis, I traced the roots of STEAM Lab to the Near Space Exploration Club, following the routes of the club as it evolved from a small afterschool project into a schoolwide STEM initiative. In the second analysis, I sought to show how incorporating STEAM Lab into the regular school day presented an opportunity for different students to participate in a maker-based environment by offering access to those students who might not have been able to participate in the Near Space Exploration Club's afterschool, non-credit model. STEAM Lab students received credit and a transcript grade for their work, something which was not possible in the initial years of the Near Space Exploration Club. The STEAM Lab educational goals were similar, however, to the goals of the Near Space Exploration Club, as both were designed to promote thinking creatively and taking creative approaches to engineering problems. Although the first semester of STEAM Lab looked more like a traditional high school physics laboratory course with a textbook and lab reports, the second semester built off basic electronics and physics concepts from the first semester with a student-directed, instructor-supported approach in which the students individually and collectively proposed the projects and goals. The subsequent analyses strived to make visible how this approach — along with the provision for the freedom to explore, design, make, play, and tinker — helped define STEAM Lab, especially the second semester, as a maker-based experience that supported students in the processes of designing and tinkering (Resnick & Rosenblaum, 2013).

Part of the STEAM Lab course description, which was distributed to students in the summer preceding the school year and used to facilitate their selection of electives for the fall, stated that students would learn basic electronics and coding, and would also be asked to incorporate art and design into engineering projects and to learn to appreciate both form and function. The course description is detailed below:

> Ever wonder just how electronic gadgets actually work? STEAM Lab is a new course offering, which combines Science, Technology, Engineering, Art and Mathematics (STEAM) experiences into a discovery-learning laboratory. Students will learn basic theory and gain experience with electronic circuits and electrical engineering, microcontroller programming, computer hacking and hands-on making while creating, building and sometimes breaking gadgets and gizmos along the way. Experience with electronics and computer programming is not required but an inquisitive nature and a willingness to experiment is! This course is being offered as part of a UCSB study on innovative classroom initiatives in STEAM education.[1]

The infusion of arts into STEM curricula is a concept championed by a number of education research groups from a variety of institutions, perhaps most notably RISD, which currently focuses on a STEM-to-STEAM initiative. STEAM proponents argue that while the objective, logical, and analytical nature of the hard sciences may seem to stand in opposition

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[1] The STEAM Lab course description was created by the teacher-researcher and detailed on the course offering sheet sent to students.

to the subjective, intuitive, and sensual nature of the arts, they are actually complementary and the combination of the two can have a positive effect on learning (RISD, 2018).

In the past, STEM education has been dominated by convergent thinking practices, such as those encouraged through experiments such as frog dissection or the venerable baking soda and vinegar volcano and assured by the mandate of multiple-choice testing. Convergent thinking demands that students draw on material from various sources to solve a well-defined problem, often with a single correct answer. This type of thinking offers only expected results and merely confirms basic scientific principles and as such, it can often be boring for students. In contrast, divergent thinking and critical thinking, approaches more recently encouraged by Next Generation Science Standards (NGSS; 2018a), help learners to generate many possible solutions to a problem by gaining insights through observation, experimentation, and research, and offers a more challenging experience by requiring students to analyze information and recursively engineer solutions (Sousa & Pilecki, 2013). Such a divergent approach is broadly compatible with what I intended to assert are the keys to maker-based STEM education.

Additionally, the inclusion of arts in STEM learning through STEM-to-STEAM and maker-based initiatives encourages greater voluntary participation by girls in science and mathematics activities (“Pretty Brainy: STEAM learning,” 2017), which historically have attracted an imbalance of male students. In fact, in the United States, males and females are equally likely to identify as makers however unlike men, women who identify as makers are more likely to describe their path to making through the arts whereby technology is a means for creation not the focus. In many cases, social hindrances, such as a lack of available female mentors or cultural gender norms, continue to contribute to the lack of access to opportunities in technology fields for girls to tinker and make (“MakeHers: Engaging girls and women in technology,” 2014). While the specific notions of STEM-to-STEAM and gender bias in STEM fields were not a central focus of this study, selected literature, my experiences, and any emerging data related to this topic are discussed in the following chapters.

Dissertation Structure

In order to address the research questions, this dissertation is structured as follows:

Chapter II frames the maker movement as the continuation of an evolving creative technical culture that traces its history at least as far back as the Italian Renaissance where there existed a culture supporting the discovery of creative solutions to complex problems. Thus, concepts of participant engagement and literacy are explored as they relate to the maker movement as a culture-in-the-making by tracing its roots over 7 centuries, with a focus on the actions and orientations of practitioners, as well as how they construct meaning with their contemporary technologies.

Chapter III presents an overview of how research for this study was designed and conducted. I present here the methodological approach as well as the logic-in-use that I undertook in the macroanalysis of the developing high school STEM initiative. This makes visible what the participants needed to know and what resources were needed and how and in what ways I, as the teacher, proposed, developed, and implemented major *cycles of activity* (Green & Meyer, 1991) within the STEM initiative in collaboration with other stakeholders.

Chapter IV represents the first analysis chapter. I present a series of analytic processes used to trace the creation and development of the first afterschool STEM program, the Near Space Exploration Club, which was offered from October 2010 through May 2013 and consisted of three different student groups and project cycles. I present the demographics of these student groups and reconstruct the timeline and the *consequential progressions* (Putney, Green, Dixon, Durán, & Yeager, 2000) that were undertaken to make visible the cycles of decision making, design, and outcomes of each major, year-long cycle of the program. Through this analysis, I endeavored to make visible the roots and routes of the Near Space Exploration Club's high-altitude balloon projects and the evolution of those projects into a schoolwide STEM initiative, which eventually included the development of the STEAM Lab elective course.

Chapter V begins by tracing the timeline of development of the STEAM Lab course, including teacher-student as well as student-student interactions, to better understand how and in what ways the teacher-student collaborative defined how this course was supported and constrained by actors in a formal school context. Through the use of backward mapping using a timeline of events, I was able to make visible what I as the teacher needed to know and what resources I accessed in developing this course and then later how and in what ways the students took up maker-based resources in the development of creative solutions to complex problems.

Chapter VI presents a summary of this study's findings and its implications on theory and method, its limitations, suggestions for continuing research and study, and implications for STEM practitioners.

Chapter II: Conceptualizing Maker-Based Education

Introduction

The opportunities for learning and the ability for schools to integrate maker-based education approaches into courses have yet to be adequately defined and studied. In practice, it became apparent that my students were in fact engaged in and committed to the successful outcome of their STEM projects, both after school and in class, and I realized I needed a system to evaluate their progress and measure impact. As Petrich et al. (2013, p. 65) posed with regard to the concept of a maker-based education, "It looks like fun…but are they learning?"

While there is not one 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 (2015) proposed three elements that are critical in understanding the promise of making and the maker movement for education and are elements that can be traced back through history:

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

As indicated in Chapter I, although I as a teacher was able to witness the merits of a maker-based STEM program firsthand, the lack of a clear understanding of maker-based classrooms in formal learning environments is an ongoing challenge, particularly when preparing students for STEM careers. The "most predictive factor in students dropping out of STEM studies is the lack of student engagement with real-world problems in their coursework" (Bennett & Monahan, 2013). This is especially true for students who often do not consider themselves to be candidates for careers in STEM fields, particularly girls (Sousa & Pilecki, 2013). Schlechty (1994) defined student engagement as the presence of three characteristics: "(1) they are attracted to their work, (2) they persist in their work despite challenges and obstacles, and (3) they take visible delight in accomplishing their work in material as if they were practitioners." Supporting learning scenarios and classroom situations whereby students work in STEM fields as practitioners is where maker approaches to education may be able to support student engagement.

While highly successful students may demonstrate important skills, such as test taking, they are perhaps not learning to think as practitioners in the field do. It could be argued that technical literacy is as valuable as the subject matter itself, and a complete understanding of technologies is vital for a student's career success (Wright, 1999). In this sense, literacy is not only about learning cognitive skills, but also the literate practices that are socially constructed by a group — in this case STEM practitioners — and the social achievements that are considered significant to that group (Green et al., 1992).

Castanheira et al. (2000, p. 353) stated the following with regard to literacy in group settings:

> What counts as literacy in any group is visible in the actions members take, what they are oriented towards, for what they hold each other accountable, what they accept or reject as preferred responses of others, and how they engage with, interpret and construct text.

The concepts of student engagement and literacy as they relate to maker-based and STEM education will be discussed later in this chapter. To gain a more detailed understanding as to the origins of maker-based education, the next section will present a historical view of maker culture.

Historical Maker Culture

During the Italian Renaissance from the 14th to the 17th century, it was not uncommon for the lines between artists, engineers, and philosophers to be blurred. When Leonardo da Vinci studied under his mentor Verrocchio, he collaborated with other students to tackle novel artistic endeavors simultaneously with the engineering feats demanded by their artistic designs. Da Vinci himself is just as famous for his own engineering designs as he is for the aesthetics of his drawings and paintings. In collaboration, the two artists challenged themselves in ways that shed light — for the first time in centuries — on the arts and sciences, which had previously been shrouded in darkness throughout the dark ages of Europe. As a result, da Vinci emerged as one of the most influential minds in human history (Isaacson, 2017).

Following the transformation of art and culture under the light of the Italian Renaissance, developments in what would become known as modern science added to the revitalization of art, science, and letters during the Scientific Revolution beginning in the 16th century. This was a period during which revolutionary ideas laid the foundation for many modern scientific principles.

Engineering emerged as an academic discipline in the early 1800s, and thus began a shift from engineering education in design studios and hands-on shops to a more theoretical approach to education (Buchanan, 2015). As the Victorian era ushered in industrialization throughout the West, a small group of craftsmen focused their efforts on infusing a sense of humanity into handmade objects. Their Arts and Crafts style emerged in Europe and North America in the mid-19th century as a small but important resistance to industrialization; however, by the mid-20th century, the spirit of inquiry, ingenuity, and invention that had challenged the establishment, and which ultimately led Europe out of the darkness of the Middle Ages, had faded from many western academic forums, leaving a void of knowledge whereby engineers possessed theoretical knowledge, but little if any technical skills (Grinter, 1955). In place of the spirit of exploration found in Renaissance studios, are curricula driven by analysis, statistics, and more recently, Cold War politics, all of which influenced the production of a massive trained industrial workforce over the promotion of creativity, ingenuity, and personal invention.

The concept of educating well-rounded Renaissance men was replaced in the early to mid-20th century by an educational system that favored students who were focused almost mechanically on tasks and outcomes (Grinter, 1955). As a consequence of this shift, mathematics and science, once areas of immense creativity and innovation, were largely reduced to rote memorization of abstract concepts (Blikstein, 2008). This is apparent in modern schools, as less expensive, theoretical coursework, and learning materials often prevail over engineering labs and applied design work. Students who allegedly do not have the aptitude for STEM courses are often relegated to purely technical functions through *vocational education*, which often looks very different from shop classes or apprenticeships of decades and centuries past (Blikstein, 2008).

Until recently, advanced, hands-on engineering activities that are a part of technology's leading edge, including access to sophisticated software and hardware, have remained expensive and were often restricted to specialized professionals. Thus teachers were typically only able to permit students to explore documented knowledge in the form of books, and participate in predetermined demonstrations masquerading as experiments. This "culture of disengagement" that is so prevalent throughout engineering education has been described as producing engineers that are often "disconnected from 'social' and 'political' concerns" (Cech, 2013, p. 48).

One study found that the majority of students exiting college engineering programs were often less concerned about public welfare than when they entered. This shift in students' attitudes can be attributed to factors such as the lack of time and space for non-technical conversations in engineering curricula (McCaig, 2013). Some advocates of maker-based education claim that more time and space for interpersonal *and* technical exploration can be afforded through the integration of maker-based problems and projects in school settings (Petrich et al., 2013).

Model Trains and Early Computers: Constructivism and Constructionism

In the 1960s, the Massachusetts Institute of Technology (MIT) was a hotbed of geek culture. The Tech Model Railroad Club (TMRC) was the hub of a new, so-called “hacker community.” The TMRC built and maintained several large model railroads with complex logic switching mechanisms that more closely resembled an early mechanical computer than a child’s toy. TMRC hackers were not the sinister cyber-criminals often associated with the *hacker* moniker today. Instead, TMRC hackers were individuals who simply enjoyed the process of tinkering and complex, technical problem solving. At a time when the term *computer* generally meant multimillion-dollar, room-sized machines, students in the TMRC daydreamed, tinkered, and challenged themselves to come up with novel ways to repurpose the towering mainframes to serve their own needs (MIT, 2017). In stark contrast to Cech’s claims of apathetic engineers in many of today’s universities, TMRC members found unique ways to initially use the computers to control the logic of complex model trains. One group of TMRC members in particular became intensely interested in the computational power of the machines themselves. These individuals formed an offshoot of TMRC and began using early computers in ways that the mainframes’ designers never imagined they could be used (and often against the wishes of the systems’ officially-sanctioned stewards) (Levy, 2010).

It was from this pervasive spirit of tinkering and hacking — an integral part of the nascent computer science culture of MIT — that Seymour Papert, a South African-born mathematician and educational researcher, built upon the work of his colleague Jean Piaget. 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 (Papert, 1980). Piaget (1973, p. 15), famous for developing the model of how children learn best through the construction of knowledge in their minds, proposed the “use of active methods which give broad scope to the spontaneous research of the child or adolescent and requires that every new truth be learned…or at least reconstructed by the student and not simply imparted to him.” Piaget (1973) formalized this into a learning theory he called *constructivism*, which explained that knowledge is not simply conveyed by a teacher to a student, but socially constructed by the learners collaboratively.

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. For Papert, the epistemological model of the traditional instructionist classroom was coercive and in direct conflict with Piaget’s pedagogies (Blikstein, 2013).

After working with Piaget for a number of years, Papert joined the MIT 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 into the field, and effectively learn about mathematics (Papert, 1971). In his seminal book *Mindstorms*, Papert (1980) proposed the following two fundamental ideas: (a) that it is possible that learning to communicate with computers can be a natural process, and (b) that process may change the way learning takes place.

Papert adapted Piaget's constructivist theories, which suggest that knowledge is socially constructed, and added famously: "the idea 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" (Papert & Harel, 1991). 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 (Papert & Harel, 1991).

Throughout his career, Papert realized these theories with the development, implementation, and iterative refinement of his Logo computer programming language, which he created in 1967 (Abelson, Goodman, & Rudolph, 1974). At a time when computers were used primarily in scientific research, business, and by the military, Logo was revolutionary in that it exposed young students to basic concepts of geometry, allowing them to visualize complex shapes on a computer screen using mathematical inputs. Papert (1997, p. 79) said: "I thought of giving children the power to program computers as a tiny first step in a complex process whose details could not be anticipated."

Papert's ideas regarding the role of learners is similar to Lévi-Strauss' (1962) concept of a *bricoleur*. Derived from a French word with no direct English equivalent, a bricoleur is similar to a Renaissance person who is inclined to undertake challenges in pursuit of knowledge. A bricoleur draws on the materials, tools, and resources at hand — and tinkers in order to solve problems, create, and invent through trial and error — all the while learning and constructing more complex knowledge about the subject. The popular

1980s television series *MacGyver* is based on perhaps one of the most familiar bricoleur scientists in popular culture. The television character's name alone has become synonymous with quick-thinking and improvised solutions.

Building on Lévi-Strauss' notion of what a bricoleur does, both physically (with materials and tools) and mentally (with concepts and ideas) to construct his reality, Papert depicted an image of bricoleur scientists as empowered individuals who "construct theories by arranging and rearranging, by negotiating and renegotiating with a set of well-known materials" (Turkle & Papert, 1992). The terms *tinker* and *bricoleur* are key to Papert's notion of learning, as they aid in modeling the way in which both teachers and students assume risk by applying novel approaches to problem solving, guided by whims through a socially constructed framework (Martinez & Stager, 2013).

One study that provides evidence for Papert's claims is the work his team conducted in the 1980s in Boston classrooms, where students learned the topic of fractions through Logo programming (Harel & Papert, 1990). At a time when personal computers were beginning to creep into education, Papert's team worked with fourth-graders in a Boston inner-city public school using a Logo-based constructionist learning environment. The students worked on a project where they directly used Logo to design and develop educational software that could teach fractions. A subsequent evaluation of the Boston Logo program showed that students displayed a better understanding of the Logo programming language and greater mastery of the metacognitive mathematical skills, as compared to a control group which did not participate in the Logo program (Harel & Papert, 1990).

In 1999, Papert led a unique intervention in the Maine Youth Center[2] (MYC), called the Constructionist Learning Laboratory (CLL), at the request of then Maine Governor Angus King. The MYC had been described as a correctional facility for troubled teenagers, and had been accused by Amnesty International of torturing teenagers in its custody (Amnesty International, 1998). The CLL showed that it could provide positive reinforcement and educational opportunities for an otherwise subjugated youth population.

For the MYC faculty, there were a number of restrictions on what was permitted at the facility for participating CLL students. One of the main features of the CLL was that there was no segregation by age (i.e., grade levels) and the school day was not divided up into class periods. Working with troubled students presented additional challenges to a traditional model of instructional education. Having been relieved of the State of Maine's curriculum and assessment requirements, the CLL became a place where incarcerated students were, perhaps for the first time, treated as competent individuals (Stager, 2013).

Each workspace contained a personal computer, and the only rule specific to the CLL was that students had to make or create something. Activity was viewed as critical to the success of the CLL, which happened to look similar to the model of makerspaces and Fab Labs, both of which I will cover later in this chapter. It was this requirement that students be active, which set the tone for productivity, particularly with this challenging group of students. Inspired by the Reggio Emilia education model, students took ownership of their projects and worked up to 5 hours per day (Stager, 2013). These projects were based on subjects mainly of the students' choosing. Projects were guided by teachers when a new skill or concept needed introduction, and were ultimately left open-ended so that students

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[2] The Maine Youth Center was recently renamed as the Long Creek Youth Development Center (https://www1.maine.gov/corrections/juvenile/Facilities/LCYDC/index.htm)

could return to other tasks once the challenge had been addressed. Using a strength-based learning approach rather than a deficit approach, Papert believed that a model of open-ended, student-motivated activity, in which students were allowed to tinker with computers and LEGO robotics, would lead to larger questions and more complex hypotheses (Stager, 2013).

Youth at the MYC who participated in the active learning model of Papert's CLL program were largely successful, and many of them would go on to enroll in college courses. Some students left the MYC and enrolled in higher education programs, which would likely have been impossible had it not been for Papert's intervention. Overall, students who worked with the CLL program were far less likely to return to state custody. Just 14% of MYC students who participated returned within 2 years, compared to the 70% recidivism rate of the MYC's general population (Stager, 2013).

Papert is also noted for the contribution that his Logo computer language has made on the world of physical computing and robotics in education. Named after Papert's book, LEGO Mindstorms robotics kits were the technological foundation for the FIRST LEGO League competition. This competition encourages schoolchildren to participate in real-world engineering challenges by designing and building computer-programmable LEGO robots and entering their creations into competitions ("FIRST LEGO League," 2016).

The Democratization of Invention

Paulo Blikstein, an assistant professor of education at Stanford and founder of the FabLearn Labs program (formerly named FabLab@School), took the teachings of Paulo Freire and Papert and interpreted them for 21st-century education. Freire proposed a pedagogy of literacy education in which students and teachers in classroom cultures learn, participate, question, reflect, and reason about their surroundings, thus providing students an opportunity to construct meaning through contemplation and *authentic thinking* whereby a teacher imparts knowledge to student in a one-way model. According to Freire (1987), authentic thinking is “thinking that is concerned about reality, [it] does not take place in ivory tower isolation, but only in communication.” Blikstein claimed that Freire’s framework for education can in fact be successfully supported by creating “environments in which [students’] passions and interests thrive” (Blikstein, 2008, p. 4). Citing Papert’s goal of using technology in constructionist education, Blikstein proposed, through the intersection of Papert’s and Freire’s educational philosophies, that learning is not the result of being taught; the key to successful, project-based, student-centered learning can be seen in much of Papert’s work:

> Freire’s focus on humanism and Papert’s emphasis on the creation of personally meaningful artifacts are highly complementary. I conjecture that constructive, expressive technology makes it possible to further Freire’s agenda of emancipation, perhaps as powerfully as with language and literacy. (Blikstein, 2008, pp. 6–7)

Blikstein called this technology a *Trojan horse*, saying that “students appropriate the Trojan technology as authentic means to liberate themselves from the incarceration of traditional pedagogy” (2008, p. 26). However, in many instances where computers and digital technologies have been introduced into school curricula, it has largely been done using instructionist pedagogy rather than a constructivist or constructionist frame. In the early 1980s, others were contemplating the use of computers in education. Robert Taylor (1980) authored a widely cited book describing what he saw as the three major functions a computer could serve in education: a tutor, a tool, and a tutee (student). In Taylor’s model, the computer served as an instrument of instruction rather than a platform for discovery; in other words, students would be required to adapt to the technology rather than adapting the technology to suit them (Stager, 2007). In the widespread, unidirectional model that is most prevalent in today's classrooms, transformative constructionist educational experiences that are focused on humanism as well as individual and personal construction of knowledge are largely not considered (Blikstein, 2008).

Blikstein's work with constructionist pedagogy began in 2001 as a graduate student at MIT. It was while working on a project in the small *favela* ("shanty town") of Heliópolis in São Paulo, Brazil that Blikstein made a connection between constructionism pedagogy and one of Brazil's most well-known cultural practice of *jeitinho brasileiro* ("the Brazilian way out") problem solving. This cultural practice helped residents thrive in the harsh economic situation of Heliópolis, where they needed to invent creative ways to solve the problems of poor infrastructure, poverty, and lack of resources (Blikstein, 2008).

As Papert did in the MYC, Blikstein took time to understand the local culture before even attempting to implement a constructionist pedagogy into his workshops there. As a result, he was able to create authentic learning experiences using novel technologies. In his summary, Blikstein (2008, p. 22) said that "digital technology was not just a 'tool', but an agent of fundamental displacement … students could see their teachers as learners, and learn from their learning strategies." Teachers and students in Heliópolis undertook complex projects addressing the topic of energy. These projects ranged from creating information about safe versus unsafe connections to the electrical grid (a somewhat normal occurrence in this low-income community) to designing an automatic retractable roof and temperature-controlled ceiling fan using a computer-controlled robotics kit. It was the complexity of these projects, their salience to the local culture, and the empowerment that the students and teachers felt in developing solutions that led to successful outcomes.

Blikstein (2008, p. 22) went on to state the following with regard to the projects:

> Compared to conventional school materials, the projects undertook by students were generally more integrative, diverse, and complex. This complexity, in turn, opens up more possibilities for connection with traditional disciplines. For example, designing sensors or robotics' devices demands extensive research in Physics, Chemistry, and Mathematics.

At one point, students working on a project requiring LEGO motors ran out of materials, and decided to instead use salvaged parts from a broken tape recorder. Soon, salvaged parts had largely replaced the prefabricated LEGO parts in the majority of the participants' designs and prototypes. Blikstein (2008, p. 19) noted that *jeitinho brasileiro* was so powerful in the mindset of Heliópolis residents "that the prefabricated floundered, while the serendipitous prevailed."

Blikstein (2008, p. 24) claimed that if a Freirean-constructionist model of learning could be implemented under the adverse conditions in Heliópolis in a school with scarce resources, that teachers would eventually "let themselves become learners again, engaged playfully in projects together with students, and were enthusiastic leaders in subsequent implementations … Once deschooled, students shake off the dust and engage in authentic inquiry and construction."

In 2006, Neil Gershenfeld began an outreach project called Fab Labs to develop shared community workspaces at MIT. These self-contained fabrication shops provided users with access to laser cutters, 3-D printers, and other computer-controlled, rapid-prototyping machines. His initial goal was to bridge the gap at MIT between computer science and electrical engineering courses in order to give students opportunities to create real objects through hands-on experience with digital fabrication techniques (Gershenfeld, 2012). His solution, a rapid-prototyping course called *How to Make (Almost) Anything*, was an overnight success. To handle the interest from students, he expanded the workshops across the MIT campus and began branching out to other area schools as Fab Labs went viral. In a 2016 interview at MIT, Gershenfeld had this to say about how digital fabrication fit into the institute's curriculum: "What I enjoy most is how this crosses classroom boundaries, with students ranging from new undergrads to new faculty members, and with artists teaching engineers about engineering, and engineers teaching artists about art" (Chandler, 2016).

Realizing there was an opportunity to empower students through this type of constructionist collaboration, especially those from low-income families and others who had an unrealized aptitude in science, math, and engineering, Blikstein began developing the FabLearn Labs project in 2008. Using Gershenfeld's Fab Lab model, Blikstein adapted the nascent, community-based workshop framework for use in schools:

> Digital fabrication is a new chapter in this story. Especially in low-income schools, students would often tell me that they used to 'make' and build things with their parents and friends, and often had jobs in garages, construction companies, or carpentry shops. However that experience was disconnected from their school life, since they did not see a link between the intellectual work in the classroom and the manual labor in the wood shop. (Blikstein, 2013, p. 209)

Blikstein's framework has been instrumental in raising awareness of maker education in recent years. At the same time, those who came before him were influential in helping modern educators see the merits of creativity born from the Italian Renaissance and furthered by the recent online networking of subcultures of informal inquiry, such as hobbyists, hackers, and artisans. The next section will explore modern maker education in greater detail.

Modern Maker Culture in Education

A rebirth of do-it-yourself (DIY) and maker culture began in the United States with the emergence of Maker Media's *Make: Magazine*, the brainchild of publishing executive Dale Dougherty. Former *Wired* magazine chief Chris Anderson (2012, p. 17) called the maker movement "a new industrial revolution," distinguishing it from the tinkering and inventing of the past by recognizing the importance of digital tools and online collaboration among makers. TechShop cofounder and CEO Mark Hatch also agrees that the maker movement is distinct from other forms of digital tinkering. He asserted that the manifestation of ideas as physical objects through the use of digital technologies distinguishes the maker movement from coding and other virtual tinkering enabled by the internet (Hatch, 2014).

Regardless of the pedantic arguments for what constitutes the maker movement, the term remains a generic classification of a wide variety of pursuits. Most maker theorists would likely agree that the ability of humans to share knowledge rapidly by electronic means and quickly collaborate on solutions to complex problems, both locally and over distance, has enabled the rapid growth of networking communities with similar interests. Perhaps more so than any other industrial revolution, the maker movement represents, in some small way, an affirmation of democracy through an increasingly accessibility to knowledge through free communication and collaboration (Halverson & Sheridan, 2014). Many of these so-called makers are amateurs with a wide spectrum of skills and abilities linked by their shared passions. However, these collaborative communities are no longer limited to merely amateur pursuits in informal settings; educators are now incorporating the wealth of resources being generated by maker communities into their own educational settings (Halverson & Sheridan, 2014).

While there are some K-12 initiatives that involve hands-on activities with students — such as the FIRST LEGO League robotics program, an offshoot of Papert's LEGO Logo programming initiative — direct engagement through constructivist and constructionist theories is hardly a widely implemented educational practice in U.S. schools. There is more involvement from a corporate perspective, as companies such as Maker Media influence a variety of DIY and maker subcultures and has become a shepherd of collaboration across various disciplines. However, Maker Media appears not to publish a detailed stance on educational pedagogies on its website.

Over the past decade, in many communities around the country, local groups of makers have come together to open cooperative-based community workshops. These spaces are known by a variety of names, including Fab Labs, hackerspaces, makerspaces, and TechShops, among others. There is an ongoing discussion in maker communities as to the implications of each name, as each space has its own variations of theories, structures, membership models, and services. One common feature among these spaces is that membership is open to the general public (Cavalcanti, 2013). An example of one such DIY community is the Santa Barbara Hackerspace (SBHX) in California. Founded in 2009 in a

450-square-foot industrial park office unit, it grew to fill a space of more than 2,000 square in less than 5 years. The SBHX community offers its members access to professional-grade tools, test equipment, and perhaps most importantly — and similar to the TMRC at MIT — a community which supports innovation, collaboration, and learning through informal experimentation and tinkering ("About the SBHX," 2012).

While initially based on Papert's early work, it can be argued that the FIRST LEGO League, which currently focuses on collaboration through competition, has since strayed from Papert's original theories of independent and student-driven exploration and problem solving. For many students, especially those who have not fully committed to a STEM field, the structures imposed by a highly competitive robotics competition, for example, may not be as persuasive or compelling, while evidence suggests that a tinkering-based approach may be an effective way to engage learners by encouraging them to develop their own set of goals, support structures, and constraints (Petrich et al., 2013).

Many community-based maker learning environments have not emerged from explicitly educational initiatives, but rather as a result of the passion of a small group who, knowingly or unknowingly, identify with constructionist educational theories (Resnick & Rosenblaum, 2013). Looking to harness the benefits of the constructionist model, these self-directed, community-based learning models — along with museums and other public learning spaces around the world, such as the New York Hall of Science and the San Francisco Exploratorium — have enabled makers to collaborate with academics to research, gather evidence for, and implement some of the theories that are behind the conceptions of these spaces designed for making and tinkering.

One such public space is the Tinkering Studio, a dedicated makerspace located in the San Francisco Exploratorium. This space's designers conceptualized the Tinkering Studio as "Part exhibition space, part science laboratory, and part atelier…" (Petrich et al., 2013, p. 51). The Tinkering Studio is thematically organized around materials and phenomena that regularly change, as this makerspace was designed to organically engage visitors of all ages, interests, and backgrounds. Many elements of this space are reminiscent of Petrich et al.'s (2013, p. 54) model of conceptualized learning, which is:

> …based on an expansive view of learning, conceptualized as a process of being, doing, knowing, and becoming. In this way, we move beyond traditional school-like conceptions (knowing), beyond traditional constructivist conceptions (doing), and include conceptions of the socially situated developing self being in becoming as central to activities and processes of learning.

In order to recognize and document learning and also better understand which design decisions facilitate specific types of learning opportunities in the Tinkering Studio, researchers on the project's design team undertook a variety of qualitative research studies aimed at studying the efficacy of various maker education models. Much of the data collected was through video records of activity, including conversations among participants (tinkerers) and facilitators (Petrich et al., 2013). Exemplifying what Case and Light (2011) asserted about the state of engineering literature, Petrich and colleagues did not specifically reference the theories used to design the studies nor what grounded their data analysis process. While there are a number of narratives of the experience of individual participants referenced in their text, it is unclear if a comprehensive discourse analysis was performed.

Petrich et al. (2013) went on to make a number of claims about what counts as meaningful interactions and what facilitates these interactions — namely between tinkerer and artifact, tinkerer and facilitator, and tinkerer and other tinkerers — which are essential to how the authors conceptualize learning. Additionally, the development or presence of these qualities is evidence of learning, as defined by the four areas in Table 2.1 below.

Table 2.1

Four Learning Areas and Associated Descriptions

1. Engagement
a. Duration of active participation
b. Frequency of participation
c. Work inspired by prior examples
d. Expressions of joy, wonder, frustration, and curiosity
2. Intentionality
a. Variation of efforts, paths, work
b. Personalization of projects or products
c. Evidence of self-direction
3. Innovation
a. Evidence of repurposing ideas/tools
b. Evidence of redirecting efforts
c. Efficiencies gained through growing fluencies with concepts, tools, and phenomena
d. Complexification of processes and products
4. Solidarity
a. Borrowing and adapting ideas, tools, approaches
b. Sharing tools and strategies; helping others to achieve their goals
c. Contributing to the work of others

Note. Adapted from *Design, Make, Play: Growing the Next Generation of STEM Innovators* (p. 66) by M. Honey and D. E. Kanter (Eds.), 2013, New York, NY: Routledge. Copyright 2013 by Taylor & Francis.

At the heart of the concept of tinkering is the iterative and recursive process of encountering challenges and overcoming those challenges, only to encounter more challenges. This was evident in the Tinkering Studio study, as observations and subsequent interviews indicated that participant learners were initially uncomfortable with this process. However, over time, the participants became more comfortable with the tinkering process, reporting an increased confidence in their abilities to learn and understand the phenomena at hand as a result of challenging themselves in the tinkering process. Petrich et al. (2013, p. 55) referred to this process as becoming "stuck and then 'unstuck'." This natural, iterative, and recursive problem-solving process is indicative of students' increased understanding of materials and phenomena.

This observation is corroborated by recent work by Norton, Mochon, and Ariely (2011), who examined the cognitive bias that people place on artifacts that they had some part in creating (dubbed "the IKEA effect" after the Swedish furniture outlet that is famous for products which require assembly). As part of the design of the Tinkering Studio, participants are able to point to an artifact they created as part of their experience there. The presence of a community of tinkerers and facilitators, as well as a variety of other artifacts (e.g., materials which can be repurposed for creation and other participants' constructions), can reinforce participants' confidence and fuel further inquiry (Petrich et al., 2013).

The Tinkering Studio team used their research findings to assemble a framework of principles for the design of an effective tinkering learning environment, which included guidelines for activity design, environmental design, and facilitation. This team presented a case study for developing authentic engagement by designing an environment and a program that encouraged participants to take up a more powerful role in their own learning. Rather than coaching students to perform the requisite steps of a predetermined experiment (a practice they call *schooling*), through video analysis, the team developed and documented a structure that encourages scientific inquiry through learner-driven processes. Petrich and his research team pointed to the iterative process, evidence of deep engagement, and the fun itself, as evidence that this makerspace fosters learning and is fun and rewarding in the process. Thus, they claimed that students are both having fun and learning (Petrich et al., 2013).

Implications of STEM-to-STEAM

There is a growing sentiment in academia and in the tech industry that the prevalent approaches to teaching and learning in STEM are not producing the types of innovators in STEM fields required for 21st century problems because the prevalent approaches to STEM education in high school and at the college level are regarded as risk averse and do not *facilitate creativity* (Boy, 2013). The Rhode Island School of Design's STEM-to-STEAM advocacy initiative was created to address these shortcomings by supporting research on the benefits of incorporating the arts into STEM education. The Rhode Island School of Design has garnered support for STEM-to-STEAM from several prominent education organizations, including Reading is Fundamental, several K-12 schools, the producers of Sesame Street, and the New York-based Institute of Play (RISD, 2018).

While the cultural and practical ramifications of such an initiative fall outside of the scope of this study, the election to incorporate art into my course was based on research indicating that students with backgrounds in art and design are more likely to be successful in science and business careers. In particular, a 2013 study of university alumni who majored in STEM fields revealed that those graduates who owned businesses or held patents had, as children, up to eight times the involvement with crafts or photography than the general population. One explanation for this link could be that complex problem solving in both the arts and sciences fosters divergent thinking (La More et al., 2013).

Taylor (2016) 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. 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" (Boy, 2013). Boy 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" (Boy, 2013).

The increasing complexities of the modern, interconnected world through digital networking implies that engineers and scientists must think holistically. Instances of such thinking can be seen in some of the most successful consumer products. As an example, Steve Jobs famously enrolled in graphic design and typography courses in college where he first gained insight into the importance of both design and user experience in technology. His appreciation for and understanding of design carried forward into the wildly successful and innovative products at Apple that embraced both form and function equally (Isaacson, 2011).

However, there remains an important issue facing education researchers, teachers, and curriculum developers interested in the STEM-to-STEAM movement. It is similar and parallel to the challenges facing the maker education movement: There are few empirical qualitative studies specifically focused on the development, processes, and practices of STEAM curricula and arts-infused STEM initiatives in action. Given, however, that there is much anticipation surrounding STEAM education, there are a number of ongoing projects and studies that may add to this research base in the near future (P. C. Taylor, 2016).

Libraries Becoming Makerspaces

With the proliferation of communications and information technology comes fundamental changes to communities and cultures. Public libraries are an example of a type of community organization that has been undergoing a rapid metamorphosis (Bauler, Stewart, Gaspard, & Maaia, 2009). The public library was once a gathering spot for a broad spectrum of visitors, including weekend researchers, novel-readers, autodidacts, newspaper junkies, families, and students. Libraries have typically provided a variety of services in addition to the curation of their book collections, with evening learning programs and reading groups for the young and old as standard fare. With the advent of online research tools that rival those in print, the major draw for a library's book and magazine collections has diminished in relevance. Many public libraries are now also struggling with a de facto mandate to serve an increasing proportion of homeless patrons, who use libraries as a rest stop for warmth and sanitation (Bauler et al., 2009). In response, librarians have begun to consider the possibilities of repurposing their community-oriented space to include resources that potential patrons may not have regular access to. In searching for these resources, many libraries have begun collaborative relationships with local maker communities. In a 2010 report on library technology, Jason Griffey (2010, p. 32), head of Library Information Technology at the University of Tennessee at Chattanooga, stated: “Libraries have traditionally been ‘come in [and] learn stuff’ places, but there’s no necessary reason that they couldn’t also be, as another maker slogan says, ‘get excited and make stuff’ places.”

In 2013, the Australian Library and Information Association (ALIA) designed a case study for a library in Victoria Park, which served a diverse, middle class community of 32,000 residents. ALIA examined how this library successfully collaborated with a local hackerspace, known as the Perth Artifactory, to create an afterschool maker session program in a local school for students between the ages of 13 and 17 (Kelly, 2013). The library’s aim was to cultivate participants’ curiosity in a safe and fun environment, while building interest in the library’s transition into becoming a makerspace.

The sessions each focused on a different aspect of maker culture. Initially, they focused on basic, off-the-shelf kit building to expose participants to a variety of tools and techniques, including soldering, Arduino programming, and 3-D design and printing (Kelly, 2013). Despite the group’s inexperience and time constraints, after the first session, students were able to successfully assemble electronic components onto a circuit board. However, the group did not adhere to the prescribed time schedule to complete this project, and many students completed less than a quarter of the overall planned work. These shortcomings were attributed to the inexperience of both participants and instructors (Kelly, 2013).

While ALIA organizers anticipated a high initial interest followed by waning attendance, interest remained high for subsequent sessions, and several students quickly outpaced the rest of the group. The ALIA report did not indicate if these accelerated students were encouraged to be mentors for and collaborators with other students who were struggling with the material, a key aspect to the community-building values found in many maker communities today (Kelly, 2013).

Overall, ALIA organizers were pleased with the success of the pilot program, as it represented the first attempt to integrate electronics and desktop fabrication into a local library. Future plans included use of the Lilly Pad hardware platform, as well as the combination of textiles and electronics. In 2013, the leadership team at the Victoria Park Library in Australia reported that they were confident enough in the process that emerged over the course of the workshops to continue to work on incorporating the makerspace component into their organization (Kelly, 2013). Andrew Kelly, eServices coordinator at the Victoria park library, stated: “Libraries may [support lifelong learning] by taking an active role in their community's learning, by supporting new ideas and helping to make clients’ interactions with the library more collaborative and vibrant” (Kelly, 2013, p. 9).

Productive Failure

A common thread between various informal maker-based environments such as makerspaces is that they usually exist to support activities in STEM areas by fostering communities of individuals who are passionate and engaged. These learning spaces are designed to emphasize the process of understanding how things work in order to solve personal, learner-center problems through some form of creation. Successful learning often occurs when learners reach an impasse and become *stuck* then later solve the problem and become *unstuck*. Originally based on *impasse-driven learning* (VanLehn, Siler, Murray, Yamauchi, & Baggett, 2003), Kapur and Buelaczyc (2012) termed this phenomenon *productive failure.* Conversely, for individuals who participate in an activity in which they do not reach an impasse and their thinking is not challenged, learning is far less likely to occur without extensive direct instruction (Kapur & Bielaczyc, 2012).

Kapur (2008, p. 415) reported that a preliminary analysis suggests that certain student characteristics, such as persistence, tenacity, inventiveness, and persuasiveness, tended to be important for positive outcomes from such un-scaffolded processes, and that under certain circumstances “permitt[ed] students to struggle and possibly even fail can be a productive exercise in failure.” While there may be efficacy in problem-based learning approaches, Kapur (2008) cautioned educators against wholly embracing ill-structured, un-scaffolded practices, instead suggesting that further research was needed to determine the right conditions for productive failure practices to be successful. Kapur (2008, p. 415) suggested that educators must “first investigate conditions under which ill-structured problem-solving activities lead to productive failure as opposed to just failure.”

A study of algebra students in three schools in Singapore from a range of academic and socioeconomic backgrounds, compared the direct instruction model to the productive failure model using a model which incorporated delaying structure and problem-solving activities. The productive failure groups were given two periods to solve two complex problems collaboratively but without extra teacher instruction, support, scaffolding or homework. After students were given time to work on the problems, the teacher discussed how a new algebraic concept could be used to solve the problem, after which the students practiced using the new algebraic technique to solve similar complex problems. At each school, another group of students were involved in teacher-led, direct instruction lectures about the same algebraic concepts after which they practiced solving math problems in class and for homework using these concepts (Kapur, 2008).

A quantitative analysis of post-test results from both groups showed that students from the productive failure group outperformed those from the traditional direct instruction group in some, but not all instances. Kapur and Bielaczyc (2012, p. 75) claimed that in their observations and qualitative analysis that "compared to [direct inquiry], [productive failure] seems to engender deeper conceptual understanding without compromising performance on well-structured problems."

There is not enough evidence in Kapur and Bielaczyc's findings to support a claim that productive failure produces better outcomes overall. However, their study does invite many questions as to which types of qualitative analysis might be performed on the various outcome groups in an effort to better understand how encouraging productive failure by delaying structure in learning and problem-solving activities might lead to students gaining deeper conceptual understandings.

Problem-Based and Project-Based Learning Approaches

On some level, nearly all incarnations of maker-based education appear to focus on a project for the creation of something unique and of interest (e.g., an object, software, hardware, art, or craft) to learners. Research has shown that learners' interest levels in a topic "have been shown to positively impact autonomous motivation, self-study time, and persistence" (Loyens, 2015, p. v). Similarly, an *ill-defined* problem (i.e., a problem for which there are no defined goals or clear expected solutions) is an essential component for educators who employ a *problem-based* learning approach (Barrows, 1996). Placing a problem as the center of an educational project, this approach can be both inspirational and motivating for teachers and students, and has been in use in e.g., medical schools since the early 1970s.

Howard Barrows pioneered the theories and practices of problem-based learning while he was a professor at the McMaster University Medical School in Ontario, Canada (Barrows, 1968). Rather than present new information in a decontextualized lecture format, Barrows' teaching provided a more contextualized approach to solving ill-defined, but authentic clinical problems. He recognized that the professional practices of a doctor, particularly the process of patient diagnosis, utilized both hypothetical-deductive reasoning and expert knowledge in a variety of fields, and that instruction exclusively through a traditional lecture approach did not provide students (or *learners* in problem-based learning parlance) with a context for the material or its application in clinical settings. Barrows proposed that through the tackling of ill-defined problems that are similar to those encountered in real-world practices, learners can gain valuable experience in safe and controlled learning environments (Savery, 2015).

Barrows believed that this approach allowed learners to not only to understand their own knowledge and skill deficiencies, but to also identify the resources necessary to overcome these challenges, skills, and practices that would serve learners well in clinical applications, long after the medial boards were a distant memory (Barrows, 1996). As a result of incorporating problem-based learning into medical curricula, performance-based assessments were used in addition to strictly evaluating medical students based on written knowledge exams. Barrows left McMaster University in the 1980s and continued his work with problem-based learning at Southern Illinois University (SIU) School of Medicine. As a result of his efforts and as evidence of problem-based learning's efficacy, problem-based learning has spread from SIU to other medical schools in North America. Problem-based learning approaches are now incorporated into instructional practices and evaluation methods for all medical students in the United States (van Zanten, Boulet, McKinley, DeChamplain, & Jobe, 2007).

Savery (2015, pp. 8–9) noted that problem-based learning consists of the following characteristics:

- Students must have the responsibility for their own learning.
- The problem simulations used in problem-based learning must be ill-structured and allow for free inquiry.
- Learning should be integrated from a wide range of disciplines or subject.
- Collaboration is essential.
- What students learn during their self-directed learning must be applied back to the problem with reanalysis and resolution.
- A closing analysis of what has been learned from worked with the problem and a discussion of what concepts and principles have been learned is essential.
- Self and peer assessment should be carried out at the completion of each problem and at the end of every curricular unit.
- The activities carried out in problem-based learning must be those valued in the real world.
- Student examinations must measure progress toward the goals of problem-based learning.
- Problem-based learning must be the pedagogical base in the curriculum and not part of a didactic curriculum.

Project-based learning is very similar to and often confused with problem-based learning. The Buck Institute for Education (BIE), an advocacy institute for a particular variant of project-based learning approaches and clearing house for resources for middle school and high school teachers, defined project-based learning as “a systematic teaching method that engages students in learning knowledge and skills through an extended inquiry process structured around complex, authentic questions and carefully designed products and tasks” (Markham, Larmer, & Ravitz, 2003, p. 4). The BIE went on to state that both problem-based and project-based approaches “describe a process of using ‘ill-structured’ problems that are deliberately designed to require students to learn content-specific knowledge and problem-solving skills as they seek diverse solutions to meaningful questions” (Markham et al., 2003, p. viii). The BIE also claimed that its variation of project-based learning was not intended to replace “conventional methods of instruction”, but rather to be blended with them (Markham et al., 2003). The BIE issued its own definition of problem-based learning as designed around a *driving question* rather than an *ill-defined problem*, a subtle but important distinction between the two models.

Problem-based advocates from SIU who follow the Barrows tradition have drawn a much clearer distinction between the two models, claiming the following: “Within a project-based approach learners are usually provided with specifications for a desired end product … and the [project-based] learning process is more oriented to following correct procedures” (Savery, 2015, p. 10). While it is beyond the scope of this dissertation to discuss the individual merits of problem- and project-based learning as defined by various organizations, it can be said that these approaches appear to be closely tied to educational models in which learners focus on authentic, contextualized problems, and projects (i.e., that are not necessarily technical in nature) that emerge, to some extent organically, through the social construction of knowledge.

Mark Hatch (2014), CEO and cofounder of TechShop, a chain of member-based workshops similar to many independent hackerspaces and makerspaces, proposed nine tenets of maker culture: make, share, give, learn, tool up, play, participate, support, and change, in his book *The Maker Movement Manifesto*. Despite his claim to have written the definitive manifesto for the movement, the fact remains that the maker movement is not a traditional hierarchically-structured group, but rather a decentralized cultural phenomenon. No one person can be given the authority to speak for the entirety of the movement and those who identify as part of it. However, there is a clear overlap in and connection between Hatch's proposed characteristics of maker culture, the essential characteristics of problem-based learning as defined by SIU, the project-based approach advocated for by BIE, and the constructionist approach to technology in education described by Papert and Blikstein. These similarities include a clear departure from traditional direct instruction learning models. All of these approaches celebrate the social aspects of learning as experiential and student-directed, with an emphasis on collaboration and some form of iterative and recursive processes guided by the learners' strengths and interests in a particular project or problem.

Concluding Remarks

The rise of maker culture and the implications of maker education in formal and informal learning settings present new challenges and new opportunities. Many educators are discovering constructionism through various hands-on and DIY approaches and through the maker movement. However, maker-based education itself is not a defined educational pedagogy. In practice, educators are making use of a variety of theories and pedagogies to create successful instances of so-called maker-based education; however, the phenomena and conditions under which these learning opportunities were created are not widely coupled with the overarching rhetoric on maker education, the latter of which tends to focus on the technologies themselves (e.g., 3-D printing, microprocessor programming, and digital circuit design, and hacking).

The opportunity today for educators is that new technologies, such as Arduino micro-controllers and 3-D printers, provide inexpensive access to a wide audience that was never before possible. Teachers need the confidence and framework to support learning programs in which they feel comfortable taking on the roles of both mentor and learner in subject areas that they may not be experts themselves in.

Papert's and Blikstein's work in particular implied that a less structured but still rigorous maker-based environment can be successful in inspiring students in STEM subjects. Blikstein took this a step further and stated that STEM subjects need to be, as Illich (1971) coined, *deschooled*; in other words, they must be removed from an institutionalized educational context in order to allow students to distinguish between teaching, learning, and grades with actual achievement and education. This has been shown to be especially true for students who have been thought to not have an aptitude in STEM subject areas.

Although making, tinkering, and direct, hands-on experience are buzzwords in education today, the concepts are at least a century old (Blikstein, 2013), if not older. For much of that time, theorists have criticized the decontextualization of learning that occurs in traditional, direct-instruction-only school environments. Rather than separating skills and experience from the required knowledge base, "students' projects should be deeply connected with meaningful problems, either at a personal or community level" (Blikstein, 2013, p. 5).

The Arts and Crafts movement of the 19th century, similar to the maker movement of today, was a pushback against the stark and industrial esthetic that was emerging during that period. Artisans of the movement endeavored to create simply designed objects (e.g., furniture, utensils, decorations, and buildings) that emphasized the construction materials and the manual techniques used to create them. Similarly, I do not expect that making and tinkering will supplant the entire education industry; however, fostering a maker-based, constructionist approach to education, both in schools and in informal learning environments, could provide a well-needed reprieve from the industrialized educational status quo. Compelling evidence suggests that such constructionist educational designs can engender passion for STEM subjects in learners of all ages. Further research, especially using qualitative methods, can help establish better practices for the integration of maker-based learning and personal, learner-driven projects.

Chapter III: Methodology

This chapter presents an overview of how research for this study was designed and conducted. I present here the logic-in-use that I undertook in a macroanalysis of the developing STEM initiative across 4 years to make visible what the teacher needed to know and what resources he needed access to in order to develop a STEM initiative, and how and in what ways the teacher proposed, developed, and implemented the major *cycles of activity* (Green & Meyer, 1991) within the STEM initiative in collaboration with other stakeholders. I also present the methodological approach used in the micro-analyses that make visible the developing classroom culture specific to the STEAM Lab elective course, and what counted as a maker-based approach to STEM education in that context.

The first section of this chapter situates the purpose, site, and historical context of the study. The second section outlines the procedures for data collection and analysis. The third and final section of this chapter explicates the principles and guiding theories of the interactional ethnography approach used in this study.

Purpose, Site, and Historical Context of the Study

Upon commencing my graduate education research, I also began teaching a digital media elective course at an independent, coeducational, accredited, college preparatory day school serving Grades 7 through 12. The school is situated in the downtown area of a small, California coastal city. Over the 4 decades since its founding, the school has remained strategically small. In the 1980s and 1990s, it grew from a two-room high school with a dozen students, to serving, at its peak, more than 70 students in both middle school and high school grades. In the period during which this study explores, there were typically between 45 and 55 students enrolled in the school. Tuition at the school has remained comparable to other private schools in the area. In the years during which this program was developed, the school provided substantial scholarships to approximately 30 to 40% of its student body. The school also served roughly an even split between boys and girls, of which approximately one-third were Hispanic. Ninety percent or more of graduating seniors typically enrolled in college or university.

Since its inception, the school has focused on academic and experiential learning approaches. Its founders guided the school's program to focus on three philosophical components: technical knowledge, personal/social knowledge, and critical knowledge. Technical knowledge entails a skills-based approach to acquiring technical abilities in academic, artistic, and physical areas. Personal/social knowledge focuses on individual students' growth and self-awareness, as well as their roles in the greater communities in which they live. Critical knowledge endeavors to provide opportunities for inquiry-based learning and critical thinking. The school claimed to do this by "fostering an atmosphere that welcomes questions and dialogue between students and teachers" ([Research site school website], 2011a).

As a teacher at this school, I had developed a personal commitment to engaging students in cultivating and understanding their own learning processes through inquiry-based as well as problem- and project-based curricula. It was around the time of my entry into the world of education that the national push for maker education was taking shape. I liked the idea of incorporating maker approaches into my courses and, as an avid tinkerer and maker in my personal life, I was aware of the burgeoning plethora of online resources and communities devoted to a variety of making, building, and DIY STEM projects. In particular, I was interested in understanding the research base supporting these teaching approaches. Makers of all ages around the world were making use of new high-tech, inexpensive, digitally-enabled devices, such as microcontrollers, 3-D printers, and embedded devices and sensors. However, as an education researcher, I recognized that much of the hype surrounding maker education was too new to be grounded in or supported by direct empirical research. That is, some supporters of maker education had linked the movement to constructionism and constructivism (Martinez & Stager, 2013), but few empirical studies if any had examined actual maker approaches which had been incorporated into school environments.

This dissertation details an ethnographically-based study aimed at making visible the processes and practices of a teacher and his students, the teacher's engagement of his students, and the students' participation in the social construction of knowledge during a multi-year STEM initiative that utilized maker community resources and approaches to learning. The STEAM Lab course was designed alongside the emerging national push for incorporating maker education. Through a series of analyses, this dissertation aimed to make visible what a teacher and students needed to know and do in order to successfully utilize maker community resources in developing and evolving a STEM initiative from an afterschool club (Near Space Exploration Club) into an elective course (STEAM Lab).

Procedures for Data Collection and Analysis

In addressing the problem of the low frequency of qualitative articles in the *Journal of Engineering Education*, Case and Light (2011) proposed the exploration of seven different qualitative methodologies when developing engineering education studies: case study, grounded theory, ethnography, action research, phenomenography, discourse analysis, and narrative analysis. In this study, I as the teacher-researcher, engaged in participant observation with seven students in Grades 9 through 11. This allowed me to examine texts (e.g., email and paper communications, journal entries, field notes, and meeting minutes) as well as video and audio records in order to study the actions of this social group (culture) in an effort to understand what the group's members needed to know, understand, interpret, produce, and predict in order to participate in culturally and socially appropriate ways (Collins & Green, 1992; S. B. Heath, 1982). Following Agar's (1994) conception that the pathways are central to interactional ethnography as a way of knowing, I traced the roots and routes of the culture of the STEM initiative and how that culture evolved over time (4 years) into STEAM Lab, a for-credit, high school elective course.

The 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 (Spradley, 1980). 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 — both in a broad sense and also in the classroom — through the everyday actions of the students and the teacher, and how these practices constituted literacy as a situated process (Castanheira et al., 2000). In order to separate my dual roles as teacher and researcher, I refer to myself as the teacher in the third person in this chapter and the subsequent analysis chapters.

Initially, this study was intended to examine activity during the STEAM Lab course during the 2013-2014 academic year. However, in the analysis phase of the study, it became apparent that additional context was needed in order to understand the evolving STEM initiative at the school and how STEAM Lab fit into local and nationwide calls to further develop STEM-based and maker education-based programs. Thus, I drew upon records collected during the STEAM Lab course as well as my own archived records and the school's archive of information from the Near Space Exploration Club activities in prior years.

While more detailed records and video recordings were available for analysis of the STEAM Lab course, there was substantial documentation from the Near Space Exploration Club activities available to reconstruct an overall timeline of events, including email communications between the teacher and students at the inception of the project, faculty meeting minutes documenting the project's evolution, and limited video and audio records from the classroom workshop and special events (e.g., several local television and radio news media stories with student and teacher interviews).

In order to facilitate the recording of video and audio from multiple angles during the STEAM Lab course, two small high-definition video cameras were situated in the corners of the classroom. During the periods where students were working on hands-on projects, the cameras were moved around the classroom to record different points of view. This provided records to reference not only the instruction by the teacher, but also the subsequent student take-up. The high-quality (1080i high-definition video) capabilities of each camera and removable and reusable SD card memory made it possible to use video and audio recording as part of the data-gathering process without becoming an overwhelming or distracting task for the teacher-researcher. By overcoming the technical obstacles of older analog and linear digital videotape equipment — such as managing, logging and storing multiple hour-long tapes and struggling to view details from degraded images of computer screens — this method made it feasible to collect 128 hours of useful, high-quality video across 32 weeks for later examination and analysis.

During STEAM Lab, the students also participated in the 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, the teacher 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 engaged the teacher in questions about the study, and at a closing meeting in which the teacher, students, and primary investigator discussed the year-long course. Students were encouraged to take notes in individual research journals to document what Agar (1994) called *rich points*. 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, the teacher and student texts 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.

With more than 128 hours of video and audio recordings, it would be outside of the scope of this study to transcribe all of the footage. Instead, I reviewed classroom video records from the year-long STEAM Lab course in the data production process (Ellen, 1984). As part of this data-making process, I have produced a table (see Table 3.1) of the various types of records that I drew on in the data creation and a course event map (see Appendix A1) of the activities across which these records were gathered (Green, Dixon, & Zaharlick, 2004).

Table 3.1

STEAM Lab Record Types

	Record Type	**Description**
1	Recordings	Video and audio recordings from two strategically placed cameras
2	Still photographs	Taken at excursions and field trips
3	Student-generated content	Videos, postings, and comments on Google+ online course community
4	Online grade-book/quizzes	Using Engrade.com
5	Teacher field notes	From the creation, planning, execution, rethinking, and critique of the course, materials, and actors
6	Student notebooks	Lab reports, written assignments, classroom and lab notes as well as diagrams
7	Pre-course surveys	Self-assessment of students’ attitudes toward STEM prior to STEAM Lab course

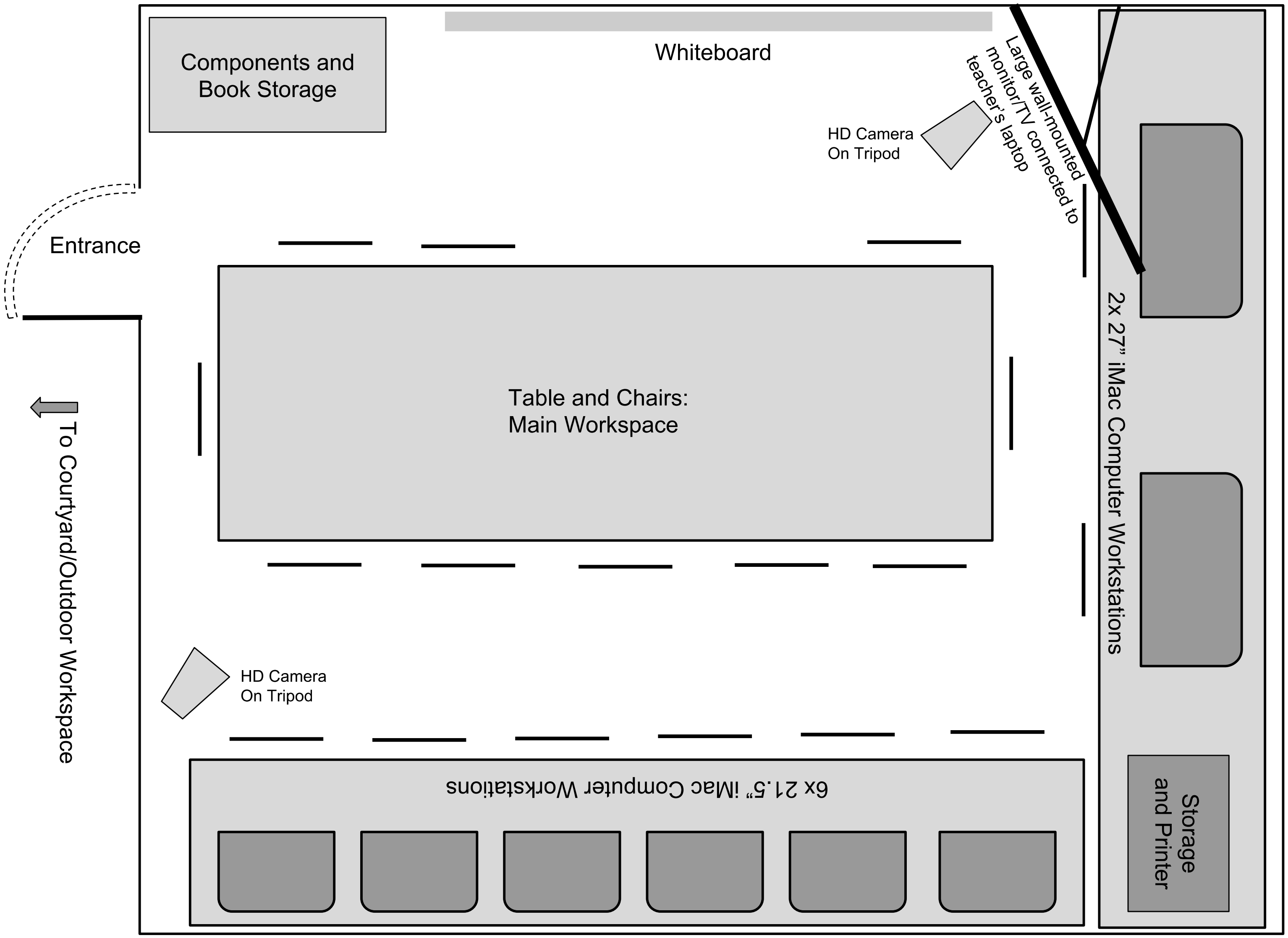
For the first four recorded class meetings, one high-definition video camera was placed in the classroom. On October 7, 2013, the fifth day of recordings, a second video camera was added under the wall-mounted television screen, as shown in Figure 3.1.

My goal was to capture student interaction and activity from one angle and teacher instruction from the second angle. In addition, when students were collaboratively conducting lab experiments, the cameras were readjusted to capture classroom activity from two angles to include more student interaction. On April 23, 2014, my advisor and a research team member visited the course and asked students about their experiences. This conversation was also recorded.

Event maps were constructed in order to establish a macro view of the chronology of the course. From the macro view of the event map, specific moments including rich points, frame clashes (Agar, 1994), and other important shifts were identified for transcription and subsequent detailed analysis using methodologies from discourse analysis, including transcription of the discourse between the STEAM Lab teacher and the students beginning with *message units* (Green & Wallat, 1982; Gumperz, 1986). Message units were marked by contextualization clues, such as eye gaze, vocal inflection, and timing. Since these subtle clues occurred in real-time, message units could only be determined after the fact. By inscribing certain events through transcripts, I was able to examine the contributions of the individual to the collective, and also analyze the dialogue based on the actors' individual points of view and the intertextuality that emerges from that which students took up as significant. Through these transcripts and analyses, anchored by event maps and the emergent rich points, I explored how students took up and used the language and literacies of STEAM Lab for learning across times and events (Green, Yeager, & Castanheira, 2008).

In order to establish the physical location of the actors, I developed a series of diagrams and maps based on what is visible to the camera in various settings. Because the classroom actually represents a series of settings, including a computer lab, an outdoor courtyard workspace, and field trip locations, more than one diagram may be necessary in order to situate the actors. An example of one such a diagram can be seen in Figure 3.1. While the two high-definition video cameras were frequently moved around the workspaces to better gather detailed video and audio, they often started in the positions shown in this figure.

Figure 3.1. Example of diagram to situate physical location of actors.



These maps, along with other contextual clues, helped situate both the verbal and non-verbal cues of the language in use (Cameron, 2001). For example, when context of use is considered, the meaning of language can vary widely. A seemingly neutral statement might be seen as a more dramatic shift if tone, eye gaze, or other *contextualization cues* (Gumperz, 1992) are considered using a sociolinguistic approach, which takes into account the "differences in language as a system, grammatical use, speech performance, and institutional language demands" (Green & Dixon, 2002; Gumperz, 1986). Gee (1999) proposed that in discourse analysis, researchers must look beyond the intricacy of language. Thus, discourse analysis is based in the theory of the social construction of everyday life. This analytical approach complemented the constructionist teaching theories employed in STEAM Lab which theorize that knowledge is socially constructed. In order to situate and discuss the patterns of action in the course, I used a taxonomy to trace the actions across the school year, the course content, the tools, and the actors. Using this taxonomy, I was able to show how and in what ways students took up the course across space and time (Spradley, 1980). From this taxonomy emerged not only how the course was constructed, but also the norms and obligations of the culture of a maker-based course.

Research Methodology

This section presents the theories guiding *Interactional Ethnography*, the approach I used to study the developing STEM culture at the school (Castanheira et al., 2000; Collins & Green, 1992). The intent in doing so was to understand, through observation, the daily life of the participants in the creation and evolution of the STEM initiative that led to the creation of the STEAM Lab course. Taking this approach grounded the conceptualization of the STEM classrooms (both after school and during regular school hours) as "culture[s] that are constructed by members in and through their discursive processes, practices and principles" (Putney et al., 2000). Thus, this study endeavored to make visible the importance of seemingly ordinary interactions between people (Dixon, Frank, & Green, 1999) and the emerging STEM *languaculture* (Agar, 1994) that developed. By taking an ethnographic perspective on discourse analysis (Gee & Green, 1998), it was possible to make visible, through analysis, the emic practices of classroom life, in an effort understand how such practices are created and the consequences for members of the classroom in knowing and understanding these practices.

Agar (1994) argued that there are in fact two types of languaculture that an ethnographer will typically encounter in a social situation. The first is the native languaculture that the ethnographer brings from his life experiences (etic), while the second languaculture is that which is native (emic) to the group. As both the teacher, researcher, and participant observer in this study, I experienced a unique circumstance whereby I encountered the second languaculture first. It was only during the analysis of the records and through reflection that I was able to step back from my role as teacher and begin to make the familiar seem strange in order to understand what was actually being produced by the teacher and his students. That is, it was necessary to step back from the role of the teacher in order to see the culture in-the-making.

Underlying this analytical ethnographic approach is the assumption that data is produced through the analysis of records. Ellen (1984) argued that data is a re-presentation of a researcher's account of history and that the process of creating data is iterative and recursive, with each new data point serving as a reference for those to follow, and as an anchor point from which to pivot to others in service of creating an understanding of the group's culture. In the examination of the records and data that were generated in the process of creating the course, I traced *telling cases* (Mitchell, 1984) which make visible new theoretical understandings of the literate practices of the STEAM Lab classroom. These cases were selected to offer a substantially different view of student learning and engagement, and to provide a different perspective in gathering evidence of student learning through making, tinkering, and co-creation of several smaller and one large electronics construction project in the collective classroom space. Discourse analysis of video transcripts from these cases make visible how "opportunities for learning are constructed within the collective space of the classroom taken up by individual participants" (Castanheira et al., 2000, p. xv).

In order to generate such detailed data, there must be detailed records from which to re-construct and re-present the classroom activity. With voluminous written, electronic, and audiovisual records archived across 4 years, this study had copious records from which to draw upon. Combining this ethnographic approach with discourse analysis allowed for both macro- and microanalyses to take place, which made visible both the overall evolution of the STEM initiative as well as how the participants engaged in daily life activities that formed the patterns of the classroom culture.

Structuration maps and transcripts were critical to the organization of the immense amount of records. A single macroscopic event map (see Appendix A2) detailing major events across the 4 years of the STEM initiative provided a useful overview and allowed for easier navigation of the records and datasets during subsequent analyses. Thus, the multi-year event map represented the first iteration of data creation. The multi-year timeline event maps were later used to reference records linked to various anchor points. This data provided a re-presentation of the group's activities over time as well as references and anchor points. The larger picture of the activity over the course of the STEM initiative needed to be developed in order to decide which subsets of the data would be analyzed more closely, thus zooming in for greater detail by creating event maps within event maps.

For example, Table 3.2 shows an example of the macroscopic level of detail incorporated into the multi-year event map. I used this scale and level of detail to inventory the actors, settings, and records available to trace the roots and routes and the iterative processes of the STEM initiative's creation. The headers detail certain key aspects of the records that were useful in referencing the resources and records available for analysis.

Table 3.2

Macroscopic Level of Detail in Multi-Year Event Map

Date	Description	Quote or Summary	Actors	Places	Topics	Actions	Followup	Source	Rationale For Choosing
Oct. 19, 2010	First email chain from teacher to founding student about formation of Near Space Exploration Club.	"It seems with a relativly small budget one can launch a weather balloon into the upper atmosphere...(it would be) very awesome to get a photo of the curvature of the earth and a black sky. I was thinking of seeing if there was any interest from students at Anacapa in putting together a group to launch an "Anacapa Space Campaign" and I immediately thought of you. Is this something you would want to help me lead? -teacher	teacher, student	virtual space	STEM, space, atmosphere, student leadership	emailing, framing as student-led	teacher and student negotiate a start "I don't know how to approach it just yet. I am worried that it is beyond the scope of a club but maybe not. Let's talk more about it in person and then we can talk to (the headmaster) and see what he thinks." -teacher	personal email archive	Seeking the original proposal of the project by the teacher to student
Oct. 26, 2010	Faculty Meeting minutes	Brief description of first discussion of near space project with faculty.	teachers, admini-strators	faculty meeting room	logistics, students, FAA regulations	planning, collaborating, developing	teacher takes list of suggested students and builds afterschool team	official faculty meeting minutes	seeking the original discusion of the initiative with the faculty and student selection
Oct. 28, 2010	Printed memo invitation to first group of students	"I am assembling a dedicated team of bright Anacapa students to spearhead The Anacapa Space Race, a special project this year at the Anacapa School. More than a club, our group will design and build a near-space probe and launch it aboard a professional-grade weather balloon. The project will require us to learn practical techniques in wireless communications, electronics, weather prediction and a host of other skills. Throughout the project we will work with NOAA and the National Weather Service, the Federal Aviation Administration as well as others with relevant authority and experience in the field. In the end we will have had the once in a lifetime experience of launching one of the few private near-space probes and hopefully returning some amazing pictures and weather data." -teacher	teacher, students	virtual space		personally delivering to students	Organizing first meeting	personal archive	Seeking to make visible the proposal to the original group of students.

Table 3.3 is an excerpt of a more detailed event map that covered a single semester of the STEAM Lab course (see Appendix A1 for the complete STEAM Lab event map). This format re-presents data constructed by scrubbing through video records and student journals of each STEAM Lab class meeting. The three columns on the left provide a clear color-coded reference depicting cycles of activity that spanned multiple days. In this subset of data, the second quarter lab experiments concluded as that cycle of activity ended, and the Arduino tutorial began with the teacher sharing segments of a video during class. In the "Themes" column, there is a brief summary of the themes explored during the individual meetings. The "Camera" and "Length" columns indicate the positions of the cameras as well as the length of footage from each camera. In the "Journals" column, I indicate if students used their engineering journals for a specific purpose, such as is the case with the "100 Questions" activity on February 3, 2014. The "Texts" and "Online Media" columns show which texts, both physical and virtual, the teachers and students referenced. Finally, the "Assignments Due" column tracks the assignments that were due during this class meeting.

Table 3.3

STEAM Lab Detailed Event Map Excerpt

										Activities	or Media	Due
	2nd quarter lab expriments	Jan. 15, 2014	First half completing crystal radio, testing them with cold water pipe grounds, intro to open source and Arduino. Bert has excellent excellent explanation of OSS around 1:18:00, continues demonstrating his fluency with computers and software	rear	1:49:10	front	1:49:34					
		SEMESTER BREAK										
Video or Film	Third quarter Arduino tutorial	Feb. 3, 2014	First day of second semester, timeline review and introduction to Leonardo DaVinci a "renaisance man" disucssion and relationship to STEAM. Discussion of STEAM as a new conceptual model. Watch G+ DaVinci mini Bio, DaVinci 100 questions book activity (preparing the brain), pass out Arduino books, Caitlin asks to read teacher's questions 1:32:00	side	1:59:25	rear	1:55:07	100 questions		How to Think Like Leonardo DaVinci, Getting Started with Arduino	G+ DaVinci mini Bio video, G+ Introduction to Arduino video,	
		Feb. 5, 2014	Second semester Arduino intro and thinking about inventing and solving problems, setting up Arduino kits and installing and exploring the IDE, blinking lights with software is easier in contrast with hardware modification to change blink rate	rear and side computers	1:46:11	front	1:48:47			Getting Started with Arduino	G+ video of Massimo Banzi, the inventor of Arduino	Homework for Wed 2/5: Read pp (preface) v.-33 in Getting Started with Arduino.
Quiz		Feb. 10, 2014	Pop quiz and Engrade password issues. Quiz review. Quiz as a motivating factor to read in advance of expiriments. "I was wrong 28:50" - teacher, discussion about metric prefixes, More work in exploring Arduino IDE and Processing language, students work in pairs to program an arduino	rear and computers	1:54:49	front and Jay & Robyn	1:50:23	Student notes on IDE		Getting Started with Arduino	Engrade: Arduino Quiz 1. G+ metric prefix chart	Homework Due Monday 2/10: Read through p. 50 in Massimo's Getting Started with Arduino Book

I created a third level of analysis in the form of a message unit (Green & Wallat, 1982) transcript of certain interactions within a class meeting period. Using the year-long STEAM Lab event map, I selected moments in time where rich points likely occurred. By watching the video recordings and using a framework of critical discourse analysis (Fairclough, 1992) and taking an interactional ethnographic approach to using video (Green et al., 2007), I was able to make visible, through a message unit-level transcript, the actions at a micro level, and also how over time, the members of this group developed their own culture or ways of knowing, being, and doing through these interactions. Because the actors' spoken words, gestures, and actions from multiple angles were captured on video recordings — as well as the tools, texts, and physical environment — I was able to trace, through these video transcripts, how students took up what was constructed throughout the course by examining the resulting *chains of interactions* among the actors (Green & Dixon, 1993).

Concluding Observations

This chapter has explicated the site and historical context of this study, the procedures used for data collection and analysis, and the guiding principles and theories employed. I have also explained how, as a teacher and researcher, I had both an emic and etic perspective on the developing STEM initiative, and how I resolved both of these perspectives through the use of interactional ethnography and discourse analysis.

Chapter IV: Tracing the Development of an Emerging STEM Initiative

Overview

A variety of self-directed, community-based, collaborative learning environments 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 that permit learners to explore, tinker, and play with objects while encouraging them to be creative. These organizations, often associated with the maker education movement, have begun to work with academics to research, gather evidence of, and implement some of the theories that behind the conceptions of these spaces designed for making and tinkering.

At the heart of tinkering is the iterative, recursive, and inquiry-based process of encountering challenges and overcoming those challenges only to encounter more challenges. Petrich et al. (2013) called this process becoming “stuck and then ‘unstuck’.” It is the hallmark of maker-education, according to their theory, and it 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 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-center problem through some form of creation.

In this chapter, I address how I as a teacher first initiated a new afterschool STEM program at a small, independent, progressive high school in Southern California. In order to separate my dual roles as teacher and researcher and as I did in the analysis in Chapter III, I refer to myself as the teacher in the third person in this analysis.

Through this analysis, I made visible the roots and routes of the program's high-altitude balloon project and the evolution thereof into a schoolwide STEM initiative, which eventually included the development of STEAM Lab elective course. I also made visible how the students and the teacher negotiated an experiential, hands-on, student-directed learning framework defined by the support and constraints of the teacher, the school, and the environment, and how the associated projects evolved into a STEM initiative that was progressively more inclusive and woven into the culture of the school. I showed how the Near Space Exploration Club, an emerging afterschool STEM program, fostered an inquiry-based, iterative, and recursive learning process similar to those described by tinkering and maker-based education advocates.

In the sections that follow, I present the steps that were undertaken to address this inquiry through a series of analytic processes used to trace the creation and development of the afterschool program, which was offered from October 2010 through May 2013 and consisted of three different student groups and project cycles. I also present the demographics of these student groups and reconstruct the timeline and the *consequential progressions* (Putney et al., 2000) that were undertaken to make visible the cycles of decision making, design, and outcomes of each major, year-long cycle of the afterschool program.

Exploring Near Space Exploration

The first major cycle of the afterschool STEM program began as a small group project to build and launch a high-altitude balloon probe into the upper atmosphere, a relatively novel project enabled by the emergence of inexpensive GPS and microcontroller technologies. While working on this project, students were committed to and engaged in their out-of-class work, as evidenced by the successful design, construction, flight, and recovery of two balloon probes across two cycles of the project over the course of 2 academic years. This was accomplished despite the fact that students could not earn academic course credit for their participation in these projects. Given the complexity and breadth of the balloon probe projects, each student was responsible for a particular system or aspect that they negotiated with their fellow students and the teacher. For example, one student chose to be responsible for path prediction and flight tracking, another student elected to design and build the atmospheric sensors, and others still were responsible for the design and build of other electronic and structural systems. While the group members collaborated at the intersections of their systems, each student took on their own set of discrete challenges. Through collaboration between students, teacher, and outside experts including members of online maker communities, each student had their own individual responsibilities within the collective.

By affording students opportunities to both collaborate on collective solutions to the overall problem while also providing space for individual inquiry and experimentation, this approach paralleled some aspects of constructionist and constructivist learning approaches, as well as models of problem-based learning and project-based learning, all of which were described earlier in this dissertation.

This analysis included several theoretical perspectives and a set of key ethnographic concepts and theories for examining records that were articulated earlier in this dissertation. The first construct central to analyzing the emergence of the afterschool STEM program was that it was not a predefined project following a linear progression, but rather a project that developed through a series of iterative, recursive, non-linear, and collaborative interactions and decisions between the teacher, his colleagues, and his students (Agar, 1994). Therefore, the development of the STEM initiative was viewed as being socially constructed across times and events and between people (Bloome & Egan-Robertson, 1993). In order to make this development visible, I used an ethnographic approach and employed multiple perspectives or *angles of vision* (Green & Meyer, 1991) to construct grounded accounts of the actions, meanings, and activities that represented the construction of opportunities for STEM learning in these particular contexts (Castanheira, Green, Dixon, & Yeager, 2007).

Central to this study was the concept of the classroom group setting as a *social situation*. Given the ethnographic approach used in this study, I drew on Spradley's (1980) conceptualization of social situations. Figure 4.1 demonstrates how, using Spradley's concept, I visualized the three dimensions that constituted the STEM initiative as a social situation.

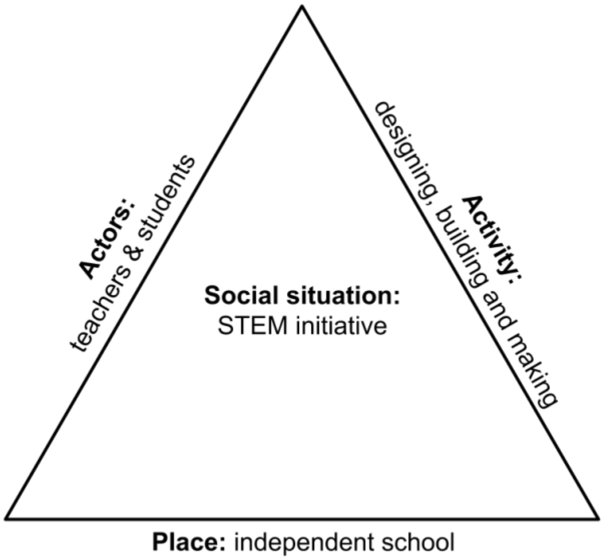


Figure 4.1. Visualization of the STEM initiative as a Spradlian social situation. Adapted from *Participant Observation,* (p. 40), by J. P. Spradley, 1980, New York, NY, Holt, Rinehart & Wilson. Copyright 1980 by Thomson Learning, Inc.

In any social situation, the actors, activities, and place are interdependent elements. The implications are that for every analysis undertaken, I explored who the actors were, the context for each activity and how it developed over time, as well as the place each activity occurred. However, Spradley not only focused on individual activities but also pointed to the need to identify clusters of interrelated activities in order to develop a more complex understanding of the activities and their relationship to the larger collection of social situations in the place.

Spradley posited that at first glance, a situation may look like a single situation in a single location. However, upon further observation and perhaps subsequent visits, one might discover that there were actually multiple clusters of closely related situations, each with its own actors and activities. He used a playground as an example to argue that various areas of the playground such as the sidewalk, swings, benches, and an embankment were different but interrelated clusters of social situations that make up what a visitor might see as *the playground.* This conceptualization implicated the need to situate, locate, and identify interrelated social situations (Spradley, 1980). While Spradley typically focused on the links that he identified during participant observations conducting during field work, this study was grounded in retrieving and reconstructing interrelated social situations from both participant observation and archived records.

I also drew on the conceptual argument of *intertextuality* as a social construct by Bloome and Egan-Robertson (1993) to guide the identification and retrieval of records from intertextually-related social situations. They contended that socially-constructed intertextuality consists of people and their actions and reactions across time. These actions can occur either as single actions or sequences of actions either in response to something that has happened or that may happen. Intertextual relationships can be identified by examining what actors propose, recognize, acknowledge, and interactionally accomplish as significant to the development of meanings, activities, and conceptual understandings in a particular social situation. Bloome and Egan-Robertson (1993) further reasoned that this makes visible what the actors view as significant to know, understand, and do. Therefore, through interdependent cycles of events, I traced references that signal intertextual ties to past and future events, in which actors experienced or constructed particular meanings and activities that serve as anchor events for analysis.

Analysis One: Representing the Boundaries of the Developing STEM Initiative

In order to systematically examine the formation of cycles of STEM activity initiated by the teacher, I created a multi-year event map which highlighted the events identified through analyses of records (e.g., raw audio and video recordings, photographs, written journals, and web and email archives). These records formed the basis for constructing data (e.g., transcripts, tables, and event maps) to analyze how the cycles of activity — both the major year-long cycles as defined by the academic year as well as the shorter dynamic cycles of student and teacher activities that make up each year — were interactionally accomplished across time and based on different types of intertextual references. I then drew on these records to reconstruct related chains of actions within the iterative and recursive cycles of STEM activity that the students were involved in developing from 2010 to 2014. The event map in Appendix A2 visually re-presents a broad timeline across the major cycles of development for the school-based STEM program leading up to STEAM Lab.

As indicated in the timeline, there were four discrete major cycles of iterative STEM initiative program development (three leading up to STEAM Lab). The first major cycle was the initial high-altitude balloon project (Balloon Probe #1), which was the first balloon probe that the students designed and launched; cycle two was the second high-altitude balloon project (Balloon Probe #2), which added live video and data downlink to Balloon Probe #1'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; 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 itself 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, perhaps just as importantly for these analyses, it was also part of an interrelated cluster of STEM initiatives at the school across a 4-year period. In Figure 4.2, 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 anchored in the STEM initiative as a virtual place.

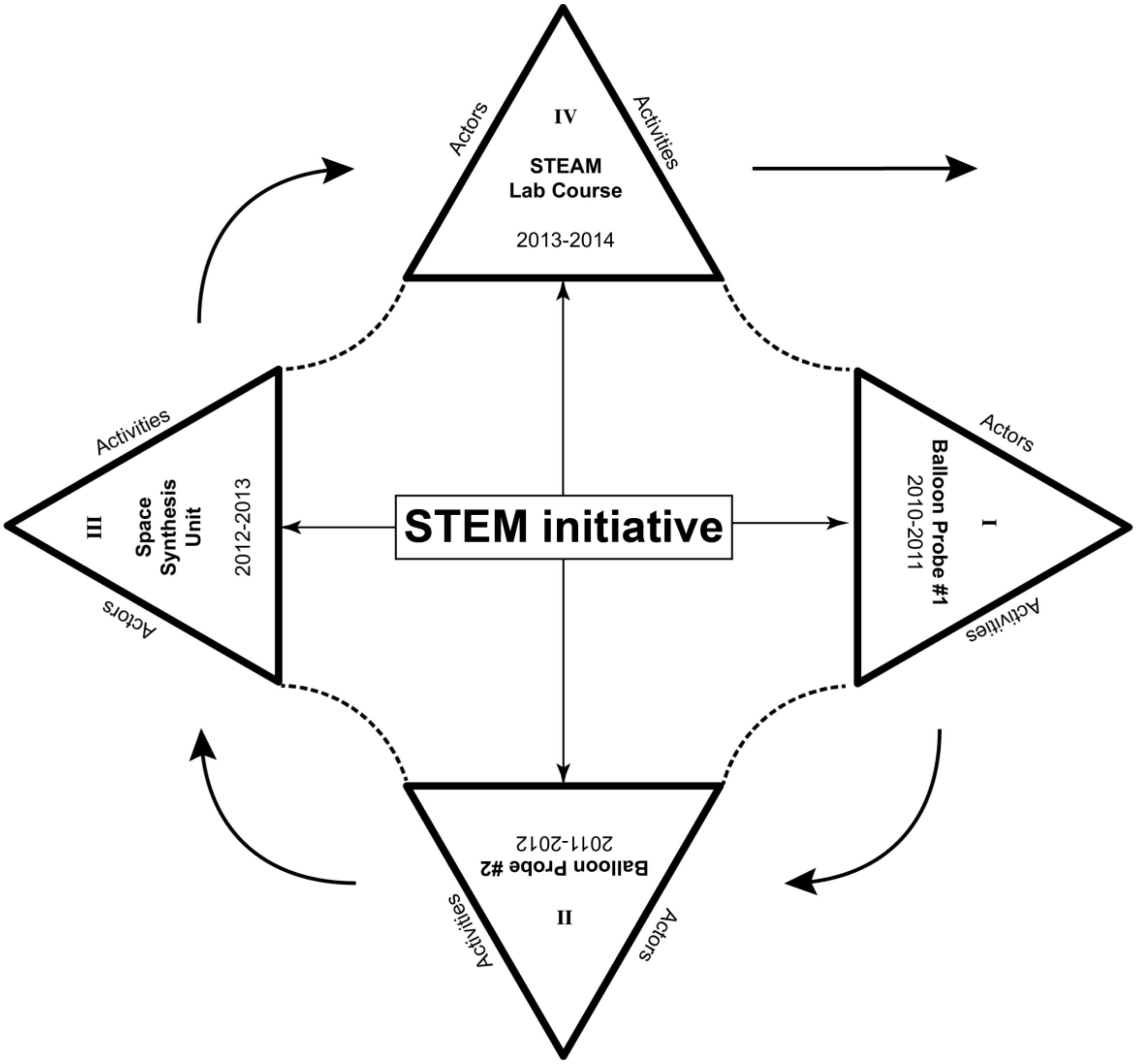


Figure 4.2. Expansion of STEM initiative as a social situation to include time. Adapted from *Participant Observation,* (p. 43), by J. P. Spradley, 1980, New York, NY, Holt, Rinehart & Wilson. Copyright 1980 by Thomson Learning, Inc.

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).

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 (tracing roots and routes) 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 (Durán & Szymanski, 1995; Putney et al., 2000).

Using a broad, 4-year event map (see Appendix A2) of the entire STEM progression as a starting point, I selected specific records of interactions, including messages from the teacher's email archive, journals and notebooks, video and audio transcripts, and other written records for further analysis. During this analysis, I identified *rich points.* Agar (1994) defined rich points are 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*. 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.

Through these analyses, I made visible the teacher's developing processes and practices, and the ways in which his ideas and those of the students were discussed and "acted into being" (Garfinkel, Lynch, & Livingston, 1981). Using a microscope *metaphor*, I present analyses through different *lenses* (Castanheira, 2000). 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 (See Chapter III). As the following analysis showed, the timeline also situates and provides 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 (Castanheira, 2000).

In the next section, I present analyses of the Near Space Exploration Club's high-altitude balloon projects, the first two major cycles of the afterschool STEM program to reconstruct the processes, practices, and ways in which the course was jointly constructed by the actors. I also explore how the teacher engaged individual students and the collective to detail what constitutes STEM learning in each iteration of the afterschool initiative and how the two cycles were interrelated.

Analysis Two: Development of The Near Space Exploration Club

Initial Contact: Searching the Email Archive for First References

The Near Space Exploration Club, as it was named by its founding student members, was a collaborative creation by the students, the teacher, faculty members and the school's administration. Figure 4.3 shows the overlapping nature of the collaborative effort that led to the creation of the project.

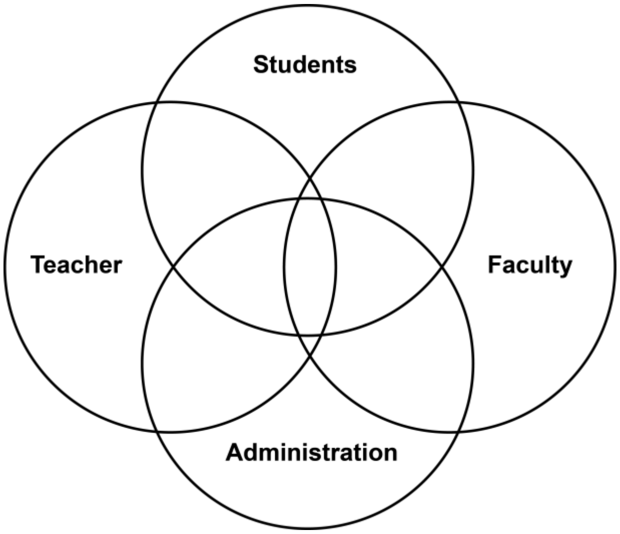


Figure 4.3. Representation of collaborative effort and overlapping stakeholder groups.

Each stakeholder group contributed to the creation of this STEM initiative and shaped its evolution over the course of its 2-year lifecycle. This analysis made visible the processes and practices through which this evolution occurred.

The teacher's archived email records were explored first in reconstructing the initial high-altitude balloon project, the formative developmental cycle of the afterschool STEM initiative in 2010. The search focused on locating the earliest reference to "balloon" in the textual content of this archive. This query led to the identification of an email exchange between the teacher and a 12th grade student on October 19, 2010. This chain of emails occurred prior to the proposal of the activity to the faculty and school administration.

Underlying the selection of this exchange is the following history of the teacher with the student. Table 4.1 makes visible the teacher's rationale for choosing this student as an early collaborator. The table also serves as anchor for the analysis of early communications in the developing stage of the STEM initiative.

Table 4.1

Reconstructed Rationale for Selecting Student

Teacher rationale
As the school's media arts teacher, I had an ongoing series of dialogues about homebrew electronics and basic electrical engineering projects with this student. Thus, when the I decided to pursue the initial Near Space Exploration Club after-school project, I made the decision to include this student in early conceptualizations to gauge his interest in participating and his perspective on student buy-in. This led to a series of early email exchanges in which he was invited to provide his feedback on my proposal as it developed.

The focus for the discourse analysis in this email exchange was on the language the teacher used to frame the idea of assembling students to participate in what was initially called a "school space campaign." The proposition for this STEM activity was an ill-defined problem unto itself, as the very form the balloon probe project would take (i.e., course, club, or afterschool activity) had yet to be determined. Table 4.2 below details the full email, broken down by each line of text.

Table 4.2

First Email from Teacher to Student on October 19, 2010

Line	Text of email by sentence	Referential proposition
1	You might have seen these stories in your [online] travels about people sending cameras into "space."	Building on prior dialogues with student and proposing a particular topic that might be of interest.
2	It seems with a relatively small budget one can launch a weather balloon into the upper atmosphere.	Pointing to the financial feasibility of such a project. Proposing parameters of a potential project.
3	While 100k ft. doesn't qualify as outer space by most standards, it is still very awesome to get a photo of the curvature of the earth and a black sky.	Further defining parameters and outcomes of a potential project.
4	I was thinking of seeing if there was any interest from students at [the school] in putting together a group to launch a "School Space Campaign" and I immediately thought of you.	Exploring potential interest of students in constructing a group focused on this goal. Recognizing student as potential co-designer and student organizer.
5	Is this something you would want to help me lead?	Requesting student's interest in leadership role.
6	Links to stories about high-altitude ballooning: http://news.cnet.com/8301-17852_3-20019825-71.html http://space.1337arts.com/	Providing background resources to formulate and contextualize the project.

The concepts of gauging student interest and seeking student collaboration are important subtexts from the email. In Table 4.2 (line 5), the teacher directly asked the student to help lead the project which he had described as having the relatively ill-defined goal of launching "a weather balloon into the upper atmosphere" (line 2). The teacher sought to have the student help gauge overall student interest in such an idea, which provides inscribed evidence as to the teacher's intention to include students in the design, development, and implementation of this proposed STEM activity and substantiates that the nature of the curriculum was not predefined but was part of phenomena-in-the-making. This was made more clearly visible when the teacher asks the student: “Is this something you would want to help me lead?” (line 5). The teacher then provided the student with links to online content for further reading.

According to electronic timestamps, the student responded to the teacher’s initial email contact less than 4 hours after the academic school day had ended. The contents of that message is represented in Table 4.3.

Table 4.3

Student’s Response to Teacher’s Initial Email Contact

	Text of email by sentence	**Referential proposition**
1	I've seen a few of these before and thought it would be really fun to do, so I would love to help you out with this!	Expressing familiarity and interest in the proposed project.
2	It doesn't seem like it would be incredibly hard, and it sure would be cool.	Presenting optimistic outlook for success of the project.
3	It would also probably be a lot of good publicity for the school.	Displaying awareness of positive potential for the school.
4	Would it be an after-school thing?	Inquiring about schedule and format.
5	Or like a club/elective next year?	Inquiring about schedule and format.
6	Either way it would be awesome.	Expressing interest regardless of formal academic context or reward, indicating high level valuing of the project and intellectual curiosity.

On the first line of his response, the student wrote that the goal of building and launching a balloon to 100,000 feet seemed attainable. This indicated the student’s positive reception to what the teacher had proposed. The student remarked that the probability for “good publicity” for such an accomplishment would be helpful in the school’s outreach efforts (line 3). This statement represents a clue as to the student’s possible awareness of this progressive school's need to recruit new students through outreach efforts that set its programs apart from the offerings of other private and public schools. The student also asked the teacher whether he thought the activity would fit into the existing structure of the school day (lines 4 to 6). Here, the student hinted that he may be interested in being involved in the initiative — regardless of the structure of the program (e.g., school day activity or afterschool program) additional time commitment, and lack of opportunity to earn an academic course credit — suggesting his early buy-in to the activity (line 6).

Overall, this exchange suggests that a nascent languaculture of this STEM initiative was developing. For example, the language the teacher used suggests that he was looking to students not only as course or project participants, but also as collaborators. His solicitation of their ideas and feedback on the design of the developing STEM program itself is evidence of this. Moreover, in this case the student had responded with language supporting the creation of an iterative and recursive metaprocess in the formation of the activity (i.e., the balloon project STEM initiative), this had the potential to benefit both the internal curriculum and the school's external recruitment efforts.

In order to further analyze this, Figure 4.4 below shows the relationship of the topics either made explicit or part of a subtext in the teacher's initial email contact with the student. Each topic intersects in some way with another, such that they can be represented as spheres of overlapping influence.

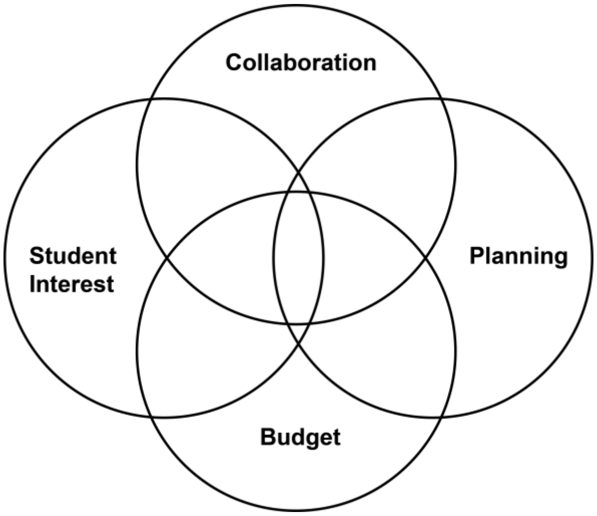


Figure 4.4. Relationship of topics based on initial email with student.

Based on the analysis of this initial exchange, it was evident that the student and the teacher had overlapping concerns and ideas, yet each proposed their own unique set of ideas for the other to respond to as part of their collaboration.

Faculty Meeting on October 26, 2010

Following the initial email exchange between the student and teacher, the teacher scheduled time during the October 26th faculty meeting in order to present a proposal for the high-altitude balloon project to his colleagues as a potential school-sponsored activity. The faculty meeting represented a weekly gathering of all teachers as well as the school's headmaster. The agenda was prepared in advance and teachers discuss all aspects of academics and school operations at these meetings. All faculty members are invited and encouraged to speak about issues pertaining to their own teaching activities, including the solicitation of assistance and support as well as individual students' needs.

The development of the high-altitude balloon project structure in the faculty meeting added an overlapping element to the collaborative nature of the course. The Near Space Exploration Club was not initially the primary focus of this study and as such, detailed written and video records were not collected; however, the teacher maintained a fairly robust archive of information from the project, including notes, purchase records, faculty meeting notes, and electronic communications. In Table 4.4 below, I focused on the brief but substantive faculty meeting minutes, which indicate that the headmaster scheduled the teacher's presentation on the STEM project as one of the first items on the meeting agenda, and allotted a total of 40 minutes for discussion of the topic. The minutes indicated that the question of how the program would fit into the school day was posed to the faculty.

Table 4.4

Excerpt of Faculty Meeting Minutes – October 26, 2010

	Text of faculty meeting minutes by sentence	**Referential proposition**
1	[Teacher] and [male student] are interested in exploring the possibility of participating in *Project Icarus,* began at MIT in 2009, with digital cameras launched into near-space to take photographs of the earth from high up–with FAA regulations being followed, of course.	Summarizing idea and referencing similar. Project conducted at the colligate level.
2	It's a fun project that could be a club, an afternoon elective, or an after-school project.	Proposing ideas for structure based on. Existing constructs of school activities.
3	The activity would best be limited to four to five students – perhaps [list of students including three boys and one girl].	Suggesting a small group to pilot the program.
4	Mentorship from [a parent and engineer]	Suggesting external mentorship be sought.

As represented in Table 4.4, the language indicated that the faculty showed a willingness to support the program in one of three forms (line 2). The minutes also indicated the faculty's willingness to support the activity in the structure of what the school defined as a club (a 30- to 40-minute meeting held once per week), an afternoon elective (offered from

1:10 PM to 2:55 PM twice per week), or an afterschool project (a flexible model with less existing structure and formalized support). These options gave the teacher the freedom to structure the project such that he could support the students involved at his discretion. The faculty stated that it would be best if the project was limited to a group of four or five students (line 3), including three boys and one girl whose names were proposed collectively by the faculty members and listed individually in the minutes.

Having only taught one elective course at the school for 2 years, the teacher was not familiar with all of the students at the school; deferring to the faculty permitted him to draw on the collective experiences of his colleagues in order to make a more informed student recruitment effort. His deferral to the collective faculty supported the claim that this initiative was collaboratively and socially constructed.

The faculty meeting minutes also made visible the concern that the additional time commitment of this activity could pose a problem for some students, and suggested that the instructor only engage students who had exceptional academic records and had proven that they could perform under additional academic pressure (line 3). Given that the students would be participating in a time-intensive afterschool extracurricular activity, the faculty had a strong desire that it not compromise students’ academic obligations or negatively affect their grades. This concern demonstrated a particularly influential aspect in developing the course, as it served as both a support and a constraint. While the instructor was able to seek support thought soliciting feedback for the recruitment of students, he had to work within the constraints based on requirements for academic evaluation and college preparation that the faculty faced, as evidenced in the meeting notes. Such concerns over students' available time to dedicate to additional projects would likely be amplified in larger, more rigidly structured school settings.

Student Invitation Memo on October 28, 2010

On October 28, 2010, two days after the faculty meeting, the teacher composed and hand-delivered an invitation memorandum to the four students who would become members of the first afterschool high-altitude balloon project group. In this four-paragraph memorandum (See Table 4.5), the teacher's discourse again signaled the open-ended, student-teacher collaborative nature of the project.

Table 4.5

Introductory Memo from Teacher to Students

	Summary of memo by paragraph	**Referential proposition**
1	Introduction to "near space" high-altitude ballooning through references to similar successful projects by MIT students.	Expressing feasibility of somewhat lofty project goals.
2	Outlines broad goals and sets parameters of local project: "… our group will design and build a near-space probe and launch it aboard a professional-grade weather balloon"; summarizes types of research and learning opportunities students can expect including interactions with meteorologists, air traffic controllers and other experts: "The project will require us to learn practical techniques…."	Showing opportunities for unique experiential learning (for both students and teacher) through a problem-based approach.
3	Brief explanation of faculty's student selection process as being exclusive and merit-based and brief summary of possible meeting times both during and outside of the normal school day.	Presenting scheduling challenges and time commitments required of students.
4	Proposes starting meetings in January 2011, immediately following winter break; tells students that it is a "tremendous opportunity" and asks students to consider if they will participate and provides personal contact info, inviting students (and their parents) to reach him if they have any questions.	Demonstrating teacher's commitment to openness and the project.

In this memorandum, the teacher introduced the overall project idea to the students by outlining a similar high-altitude balloon and camera project conducted by students at MIT (paragraph 1) and provided links to the students for further reading and photos. The students were then invited to “design and build a near-space probe and launch it aboard a professional-grade weather balloon.” The teacher continued by informing the students that “the project will require us to learn practical techniques in wireless communications, electronics, weather prediction and a host of other skills.” The use of the phrase “require us to learn” suggests that the teacher himself came to the project as a co-researcher and collaborator.

This language reflects the teacher’s developing pedagogy and general outline for the project, which included several discrete skill areas in which he himself had a range of expertise and experience. This language also suggests that the teacher had invited students to learn *with* him — and not necessarily *from* him — an important distinction in this case. This nuance was most evident in the teacher’s early plan to seek opportunities to learn directly from experts at the National Weather Service (NWS) and Federal Aviation Administration (FAA), including them as collaborators in the group’s research and framing himself as a co-researcher guiding the learning process (paragraph 2). Rather than providing direct instruction, the teacher guided the construction of a pedagogical model of co-discovery that more closely aligned with a problem-based learning model.

As discussed in Chapter II of this dissertation, problem-based learning approaches can provide particularly effective learning around ill-defined, but authentic problems when students are able to combine opportunities for hypothetical-deductive reasoning along with expert knowledge in a variety of fields. In this case, the teacher used language in early communications with his students framing the problem-based approach he would take with the balloon probe project. Examination of early planning documents, including the faculty meeting minutes and early communications with students, made visible how the teacher identified an ill-defined problem (launching a high-altitude balloon) as well as some initial suggestions for resources necessary to overcome this challenge, as prescribed by Barrows' (1996) problem-based model.

Balloon Probe #1 and Balloon Probe #2

Faculty and students agreed that that project meetings would take place once per week on Tuesday afternoons at 3:30 PM following the regular school day. Throughout the 2010-2011 school year (mainly during these Tuesday meetings), the Near Space Exploration Club collaborated with professional meteorologists, researched similar high-altitude balloon projects, and corresponded with hobbyists, hardware engineers, component suppliers, and air traffic controllers as they set goals, defined parameters, designed, and built the first high-altitude balloon probe, dubbed "Balloon Probe #1."

While the group members documented their final designs, much of the work, especially the iterative failures and successes along the way, were not recorded in detail, and the day-to-day schedule of activities was not preserved. In order to trace back through these activities, I retrospectively drew upon information in the teacher's electronic archive, including project budget and purchasing documents, reconstructed headnotes and documentation created for news media, social media, and online distribution in order to reconstruct a timeline of events for the project. As part of the planning, design, and construction throughout the school year, the group visited the nearby NWS office and also independently researched atmospheric conditions and weather to make flight path predictions and hypotheses for results from the on-board atmospheric sensing equipment they were building. As construction of the probe and its electronic instrumentation concluded and the launch date drew nearer, students coordinated with air traffic controllers at the regional FAA Air Route Traffic Control Center to ensure the safety of manned aircraft in the vicinity of the balloon flight.

On May 23, 2011, less than 7 months after the club first gathered, the school issued a news release following the successful launch of the balloon probe 2 days earlier on May 21. The release and the flight summary documents were subsequently published on the school's website, including details of the payload and statistics from the flight, the specific altitude achievement (91,122 feet above sea level, which was just shy of the students' 100,000-foot goal), and a report of the successful tracking and recovery of the payload of student-built experiments. The school's website also archived the still photos and scientific data captured by the Arduino-based atmospheric sensing instrumentation. As a result of the news release, several local media outlets — including the local National Public Radio affiliate and daily newspaper — covered the project, interviewing the students and the teacher in the process and providing additional records of the events. One student who participated in the design and construction of the balloon probe found the recovery of the probe hardware after the successful flight to be especially rewarding. This student was quoted in the school's news release, stating: "We worked so hard on this project…It was such an amazing feeling to see the capsule back on the ground and to know we had done it!" ([Research site school website], 2011b).

Following the successful launch of Balloon Probe #1 probe, the headmaster encouraged the continuation of the program for a second year and acquired outside funding from donors to support the finances for a second balloon probe. Beginning in September of the following (2011-2012) school year, the three students from Balloon Probe #1 who had not yet graduated joined Balloon Probe #2, the second iteration of the balloon probe project and the second major STEM initiative cycle of this study. The three returning students, along with two additional students who were selected by the faculty, participated in designing and building a second high-altitude balloon probe. Using a larger latex weather balloon, the second probe lofted two payload packages, adding a high-definition video camera and live video and data downlinks via amateur radio, a student-built Geiger counter, as well as a modified array of scientific sensors and still imaging equipment (Near Space Exploration Club, 2011). Two students earned their FCC amateur radio licenses as part of the project, lending their federally issued call signs to the radio transmitters aboard the probe.

According to the online flight summary and news release following the May 5, 2012 launch of Balloon Probe #2, the second flight reached 111,814 feet above sea level, as recorded by the onboard altimeter, and eclipsed the first probe's altitude record by more than 20,000 feet. In those documents, one student commented: "Our initial projections showed it would touch down near Taft; we never expected it to climb so high and stay there for so long" ([Research site school website], 2012). This quote made visible certain expectations that this student had for himself and the group, particularly that the second balloon would perform similarly to the first one. The outcome challenged his thinking, creating an intellectual rich point which he revisited when asked at a later time about his experience in the program. This type of reflection upon his own work stood as evidence of the student's own intellectual curiosity, and illustrated the type of iterative and recursive thinking required by this STEM program's developing problem-based learning approach.

Collaborating with NASA on a Synthesis Unit

After two successful student-built high-altitude balloon probe flights over a 2-year period, the teacher decided to explore a divergent path with the Near Space Exploration Club in its third year. Despite the success of the two high-altitude balloon probes under the afterschool STEM program model with a small group of academically-talented students, the teacher and the school remained committed to a more inclusive STEM initiative which could engage more than just a core group of students and be included as part of the regular school day. A brief email from the teacher to the school's headmaster on May 12, 2012 marked the first archived record of the teacher's interest in participating in the Amateur Radio on the International Space Station (ARISS) program, a STEM outreach program supported by NASA's former Teaching from Space initiative, a program designed to connect schoolchildren to an astronaut aboard the ISS. The ARISS program's stated goal is to "inspire students, worldwide, to pursue interests and careers in science, technology, engineering and math through amateur radio communications opportunities with the ISS on-orbit crew" ("About ARISS," 2017).

With the blessing of the headmaster, the teacher created the proposal and applied for the school to participate in the ARISS program, stating the following in the opening of the proposal:

> The [school] faculty has collaborated to create a unified ARISS curriculum for the 2012-2013 school year. We will build off of this opportunity to integrate space exploration themes into the comprehensive curriculum plan in which the [Near Space Exploration Club] and its member Amateur Radio operators will host the ARISS contact event for the entire [school] student body and special guests in attendance. ([Research site school archive], 2013)

In late August 2013, during the weeks leading up to the first day of school, the teacher announced to the faculty that the ARISS program had selected the school to participate in its own live amateur radio contact with an astronaut aboard the ISS. The school's physics and calculus teacher responded by writing: "Let me know what I can do to help integrate, coordinate, expand, educate, amplify and whatever else we can do to maximize this opportunity for the school and for whomever else might benefit" (email archive). In the teacher's email archive, there was a brief note from the school's headmaster indicating his further support for this expansion of this initiative. On September 11, 2012, the headmaster informed the teacher that the school's annual *Synthesis Unit* theme for that year would be space exploration. The school's website describes the Synthesis Unit as follows:

> The annual three-day Synthesis Unit is [the school's] premier tool for developing critical thinking skills. Each Unit provides students with unique opportunities to explore a topic in depth. Expert speakers make individual 45-minute presentations with plenty of time for questions and answers. After three days of presentations, students create *products* designed to *synthesize* the information learned during the presentations. Individual research papers are submitted, and group presentations are made at a special assembly. Each student

earns a grade and academic credit for the unit based on participation, the quality of the research paper, and the group project. ([Research site school website], 2011c)

Subsequently, the headmaster named the teacher as the faculty coordinator of the Synthesis Unit. This appointment, along with the demonstrated support from the school's faculty and administration, represented further evidence of institutional support for the teacher's desire to expand the developing STEM initiative to include more students from the school's general population in collaboration with other faculty members and the students themselves.

The teacher and his colleagues conducted preparations for the Synthesis Unit over the course of the fall semester, assembling a roster of 18 different speakers and events, including researchers from nearby university campuses and aerospace firms (see Appendix B). On the evening of the first day of Synthesis Unit activities, the school hosted a public presentation at the local library with NASA Astronaut Richard Linnehan. In his first remarks to the room of guests, Astronaut Linnehan said: "[the school's students] ask better questions than most people ever ask, including most adults I talk to" ([Research site school video recording], 2013). This quote was in reference to his earlier interactions that day with students at the school. As evidence of student engagement in the Synthesis Unit, a high school student said the following in an interview with a reporter from a television news story covering that evening's event: "There are so few people in this world that have been to space and to have someone here that had (been to space), it was really great" (*KEYT Newschannel 3 Synthesis Unit coverage*, 2013). On the second day of the 3-day Synthesis Unit, the teacher had coordinated transportation for the entire school to visit the space launch complexes of the 30th Space Wing at Vandenberg Air Force Base (See Appendix B for entire Synthesis Unit schedule).

The culture of this particular school was in support of interdisciplinary collaboration, especially as part of the Synthesis Unit. The calculus and physics teacher later proved to be instrumental in providing resources for the further development of this iteration of the STEM initiative, while other school staff and faculty also participated with support for the space Synthesis Unit from administrative (scheduling and logistics) to instructional activities (incorporating space into classroom lessons). These actions demonstrate further willingness for cooperation and follow-up collaboration between faculty members required for the overall success of this STEM initiative. It was evident that the teacher continued to collaborate with colleagues at the school, experts in STEM fields, and students in developing an expansion of the STEM initiative, which would include students in the entire school in an exploration of space topics.

This Synthesis Unit also marked the beginning of a cycle of transformation for STEM at the school. With the expansion of the teacher’s initiative beyond the afterschool club cohort, all students in Grades 7 to 12 at the school were included in the Synthesis Unit’s space-based STEM activities. Led by the students in the Near Space Exploration Club, the ARISS contact in May 2013 was the capstone event for the Synthesis Unit.

The Near Space Exploration Club reached out to members of the local amateur radio club for support. Two local amateur radio operators agreed to provide the necessary equipment and expertise to ensure that the students had made a successful contact with the ISS. During the contact — which was held at a nearby corporate campus and included students from a nearby elementary school as well as adult members of the school community and news media — Astronaut Chris Cassidy answered questions from 16 students. Following the live contact, a local television reporter interviewed a student member of the Near Space Exploration Club who said: “I've never been a super sciency (sic) type so this has been pretty cool to do. Science hasn't always been my thing but it’s been really fun learning about this” (*KEYT Newschannel 3 ARISS coverage*, 2013). In addition, a middle school student who had not participated directly in the Near Space Exploration Club independently studied for and passed the FCC amateur radio licensing examination. These actions support the claim that students involved in the Synthesis Unit were influenced by the initiative, and that the initiative transformed students’ attitudes positively toward STEM in a manner that was in line with both the school’s and the ARISS program’s stated goals.

Seeing Sustainable STEM Models

The consequential progressions I mapped from the first high-altitude balloon probe STEM project as part of the Near Space Exploration Club up through the Space Synthesis Unit show a widening breadth of scope for STEM initiatives at the school. More students were exposed to STEM fields as a result of the widening of the initiative from a small, exclusive afterschool club into a schoolwide Synthesis Unit. There is evidence that the opportunities for learning through problem-solving associated with the high-altitude balloon project motivated students in areas they might not otherwise be interested in.

While the Synthesis Unit had become an institutionalized part of the school, the topics covered each year tended to be more ephemeral, in that there was not a sustained daily or weekly effort to focus on the topic throughout the school year. Given the Synthesis Unit’s purpose to allow students to think critically and synthesize information on particular topic, it was successful in drawing additional students’ interest into STEM fields. The success of the Synthesis Unit in broadening the scope of the STEM initiative's impact was a motivating factor for the teacher to continue to find other ways to engage more students in STEM activities that they could be directly involved with the design, creation, and success of a major, year-long project, a challenge that the teacher undertook the following school year through the development of STEAM Lab, which is the subject of the analyses in the following chapter.

Chapter V: The Emergence of STEAM Lab

Overview

The goal of this chapter is to re-present key points in time in the development of the STEAM Lab course, including teacher-student as well as student-student interactions, to better understand how and in what ways the teacher and his students defined how this course was supported and constrained by actors in a formal school context. Through the use of backward *mapping* using a timeline of events (Green, Castanheira, & Yeager, 2010), I first traced the preparations the teacher made in the prior school year leading up to the offering of the course offering to re-present what the teacher needed to know and what resources he accessed in order to create this course. Through the use of backward mapping using a timeline of events, I was able to make visible what the teacher needed to know and what resources he accessed in developing this course and how and in what ways the students took up maker-based resources in the development of creative solutions to complex problems.

Following the two near space probes and the school-wide Synthesis Unit and culminating with an amateur radio contact in 2013 between the school and the ISS via the ARISS program, several faculty members, students, teachers, and parents urged the teacher and the school administration to continue to support opportunities for all students to participate in STEM activities outside of the required core science and math courses. Larger public and private high schools in the local area had already begun developing full-scale engineering academies, including magnet engineering schools, within the public-school district. As demand for STEM programs increased locally, several national high-profile initiatives, such as the Obama White House's Nation of Makers, were also making similar pushes for STEM education nationwide with programs. In 2013, Code.org launched a project known as the Hour of Code, which was created to encourage mathematics and science teachers to make time for students to be exposed to the basics of computer programming. This project has transformed into a global initiative, reaching over ten million students in nearly 200 countries (“Hour of Code,” 2017).

In response to these local and national calls, the school’s headmaster authorized the faculty to develop core STEM courses, including new statistics and pre-calculus course offerings, a robotics elective for middle school students, and a redesigned conceptual physics course. The teacher began to research a transition toward a for-credit STEM elective to be offered during the regular school day. During the 2013 school year, the teacher had also been lobbying to create a student-driven elective course called STEAM Lab that was based on the Near Space Exploration Club. However, unlike the Near Space Exploration Club, the STEAM Lab course was open to enrollment by all high school students at the school. Moreover, it was a full-fledged, for-credit, elective course and was not limited to only a few days during the school year (*Faculty meeting notes archive*, 2013).

Analysis Three: STEAM Lab

In order to make visible how the teacher developed the STEAM Lab course curriculum, I drew upon the teacher’s journal and reconstructed headnotes. Through these analyses I was able to trace the teacher’s thinking at the inception of the course and the take-up of the evolving maker ethos’ infusion into the course. The first entry in the teacher’s course journal was dated March 27, 2013 (6 months prior to the start of the new STEAM Lab course) and consisted of the following question: “Why should students care about STEM?” This question suggests that the teacher was seeking ways to obtain a similar level of student engagement for the course that was evident in the previous high-altitude balloon probe projects. This question is also evidence of continuity in the developing theme in this STEM initiative of collaborative social construction and co-creation of opportunities for learning.

This case exemplified Schlechty's (1994) definition of student engagement. Students were committed to the project and were excited about the project's goals, they delighted in devoting time and energy to tasks for reasons other than motivation for a grade or course credit even when challenged, and they learned from practitioners and acted as practitioners in various STEM fields (e.g., weather, aeronautics, physics, electronics, and various engineering fields). It was evident from the Near Space Exploration Club afterschool programs that students worked earnestly, intensely, and often independently without the prospect of earning grades or course credit, as neither was issued in the program. Without a high level of student engagement, the club would likely not have continued beyond its first year. As discussed in Chapter IV, during the Near Space Exploration Club projects, the teacher acted more as a guide and facilitator, allowing students to research and solve the ill-defined problem of launching a balloon to the upper atmosphere to collect and return data. By the spring of 2013, the teacher was working to create a similar classroom environment, but this time in a for-credit course.

Pre-Course Preparations

Drawing largely on the wealth of DIY and maker materials available online as a research base for potential engineering projects, the construction of the course itself was a type of meta-making in its own right. Entries in the teacher's journal from that spring and summer highlighted the struggles faced in developing a course design and curriculum that would meet the challenge of bringing an informal model of teaching and learning into a more formal classroom environment, while retaining the authentic aspects of student-directed learning that were the hallmark of the Near Space Exploration Club. The teacher's purchasing requests and course budget worksheets indicated that the school administration afforded some financial freedom to design a learning environment which not only exposed students to tools and techniques typically associated with the maker movement, but also the ways in which these digital technologies could be incorporated into the teacher's pedagogy necessitated further contemplation given the experience with the Synthesis Unit.

The teacher identified the main goals of offering a for-credit opportunity during the school day in which students could work on a variety of STEM projects, rather than just high-altitude balloons, while maintaining a student-directed learning design. One mechanism that was suggested by Professor Richard Durán during a meeting discussing educational goals for the course was the concept of student journals to serve dual roles by providing both documentation for the engineering process and education research data for the study. In his own journal, the teacher noted that he intended to depart from a lab and lecture framework, and instead opted for an approach similar to studio art courses (*Teacher's journal*, 2013, pp. 15–17).

Based on his personal experience in both formal and informal learning environments, the teacher also noted that in order for students to be successful, they would need to be engaged on a deeper level. This meant regarding students as stakeholders in the project, and the teacher sought a guiding framework for this claim. His approach was in alignment with Blikstein (2008, p. 11), who said that "dialogical education, requiring the establishment of a true conversation between learner and teacher, cannot survive if discourse and practice are not compatible to the eyes of children." Blikstein's interpretation of the Freirean-constructionist model of learning implicates both teachers and students as learners, as well as students as stakeholders in their own educational journey. Put another way, when neither students nor teacher know the outcome of a problem or project, the path to a more authentic quest for learning can be created. Students are *deschooled* and afforded the freedom to embark on authentic inquiry and construction of knowledge (Illich, 1971).

In a March 2013 journal entry (*Teacher's journal*, 2013, pp. 1–2), the teacher identified common instructional threads in his prior work with students in STEM and STEM-related projects, which are summarized as follows:

- The teacher was not an expert in the area of study or with most of the materials. He had basic working knowledge of the technologies but little, if any, experience with the specific materials used in the projects.
- The teacher provided an initial framework for the project by defining parameters; however, he planned to leave many of the specific goals, technologies, and choice of materials up to the students to research, explore, design, and implement.
- The teacher and the students were co-discoverers and co-creators of the Near Space Exploration Club's culture as well as of the projects that emerged.

Additionally, in March and April of 2013, the teacher posed the following design questions in his notebook:

- How can I support classroom situations in which students can participate in the practices associated with scientific inquiry?[3]
- How can I support students with shared past experiences and also new ones?
- How can I ensure that students are not just tech dependent but tech savvy?

As the teacher considered the design questions detailed above, he noted the maker-embraced technologies and ethos that would work best as platforms for discovery in an elective course:

  - Raspberry Pi
  - Arduino
  - Amateur radio
  - Electronics kit building
  - Inventing and problem solving
  - Coding
  - Circuit-bending

Laying a Pedagogical Foundation

While the teacher had not yet discovered project-based nor problem-based learning models, he was familiar at the time with Papert's (1991) theory of constructionism and Piaget's (1980) theory of social constructivism. Both of these philosophical viewpoints continue to influence educators working with maker-based educational programs and are

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[3] Harlow examined the process of teaching students to develop their own explanatory models in the course of scientific inquiry. The teacher used that idea as a starting point for developing curriculum in this course (van Zanten et al., 2007).

cited in the nascent literature base of the maker education movement (Martinez & Stager, 2013). Based on these viewpoints, the teacher began constructing a course design with the idea that knowledge is socially constructed by making, tinkering, building, and problem solving.

The first piece of evidence of an emerging model for the teacher's version of maker education blended was recorded in his journal: "Perhaps use the [school's art teacher's] model of introducing artists throughout the semester. STEAM Lab could introduce inventors and artists" (p. 7). The teacher went on to say that his intention was to prepare students to be "part of the maker movement" and "become a creator, not merely a consumer" (*Teacher's journal*, 2013, p. 7). These quotes signify the teacher's alignment with an applied approach to learning, one that is indicative of problem-based learning and constructionism. In this case, students learned through the social construction of a classroom culture and a physical object.

By early summer, the teacher's notes indicated that he was deconstructing his prior classroom experiences in an attempt to understand what led to past teaching successes and failures in both formal and informal learning environments. Recorded in his notes from mid-June 2013, the teacher recalled a particular question from a prior year that made a lasting impression on him. One of the students working on a high-altitude balloon probe project asked: "How do you know what you know?" (*Teacher's journal*, 2013, p. 8). Directly below this in the teacher's notes was a follow-up introspective question: "How can I show students how I learn?" Questions like these posed by students as well as the teacher's own reflections provided links to the theories and themes of problem- and project-based learning, maker education, and other student-centered pedagogies (Savery, 2015).

Selecting Texts and Materials for STEAM Lab

By the end of June 2013, the teacher’s notes indicated that he had selected several engineering and electronics texts to evaluate various technologies and approaches to electronics, making, and building. The following key criteria and considerations that were used in evaluating these texts were recorded:

- Reliability: Do students find the material relatable, engaging, and eventually relevant to their project goals (challenging to answer in advance of understanding the students’ goals)?
- Practicality: Does the text make theory visible to students as well as provide a framework for some successful practical outcomes?
- Integration: Does the text integrate with modern hardware and software that students can tinker with and explore? Do students have a base and starting point for exploration and discovery after working with the text?
- Cost: Do the texts and related hardware and software fit into a reasonable budget? And what is a reasonable budget?

In this early process, the teacher’s notes indicated that he was in the early stages of reviewing texts that introduced readers to electronics and new technologies identified in popular maker culture publications, such as microcontrollers, single-board computers, and low-cost sensing devices, as a medium for construction that could afford students the opportunity to solve complex problems with hardware that was relatively new, excitingly capable, and inexpensive. The texts initially reviewed for inclusion are detailed in Table 5.1.

Table 5.1

Texts Considered for STEAM Lab

Text Title	Authors
Getting Started with Arduino	Massimo Banzi
Make: Electronics	Charles Platt
Make: More Electronics	Charles Platt
Getting Started with Raspberry Pi	Matt Richardson & Shawn Wallace
Gonzo Gizmos	Simon Field
Getting Started in Electronics	Forrest M. Mims III
The ARRL Ham Radio License Manual	H. Ward Silver

As indicated in his notes, the teacher narrowed this list down to a final group of three texts: *Make: Electronics*, *Getting Started with Raspberry Pi,* and *Getting Started with Arduino.* Below, a brief summary of each text is presented, showing what the teacher considered for each (*Teacher's journal*, 2013, p. 10).

Make: Electronics. Maker Media is the publisher of *Make: Magazine* and host of the original Maker Faire events. In 2009, the company published a volume by Charles Platt called Make: Electronics, a book which was geared toward electronics experimenters. The book cover calls this text "a hands-on primer for the new electronics enthusiast" (Platt, 2015). With 36 experiments in five sections divided by topic, Platt emphasized learning through discovery and inquiry by focusing on practical applications for electronic circuits over pure theory. In the author's statement, Platt (2015) said: "Most introductory guides begin with definitions and facts, and gradually get to the point where you can…build a simple circuit. This book works the other way around."

The teacher was attracted to Platt's practical approach through colorful printed imagery along with sidebar articles on historical figures, including inventors such as André-Marie Ampère and Alessandro Volta, while presenting background and theory in companion boxes alongside experiential activities. This somewhat non-traditional approach to an instructional text stood in stark contrast to Forest Mims' *Getting Started in Electronics*, a classic electronics text published in 1983. In his notes, the teacher wrote that Platt's text was "far less academic than [Mims'] book, but [there are] many more practical ideas" and that it was "a bit more approachable" (*Teacher's journal*, 2013, p. 10).

When Platt's text was published, Maker Media had partnered with Radio Shack stores to sell companion kits with the text, which included the electronics components needed to complete all 36 experiments. This pairing was very appealing to the teacher, primarily because students would have ready access to the tools and materials needed to participate in the labs outlined in the text. The companion kit also allowed them to move quickly through the labs with quality materials matching exactly what was described in the text.

In his notes, the teacher indicated that he had selected this text for the first semester because he felt it presented complex electrical engineering concepts using clear and colorful imagery, and that concise explanations followed with an experiential laboratory component. The book also provided non-scientific cultural and historical context, naming individuals, both men and women, throughout history who had contributed to the advancement of various STEM fields. This historical timeline was one of the bases for the timeline that the teacher maintained on the classroom wall throughout the school year. Additionally, the book publisher, Maker Media, had been a driving force behind the maker movement.

Table 5.2 shows the table of contents of *Make: Electronics*, which indicates how this text reflects the maker community's generally experiential approach toward creating useful tools for accomplishing goals. The book offers 36 different experiments as a means of showing its readers the convergence of theory and practice in electrical engineering. While the experiments themselves specify parameters and have known, expected outcomes, the text provided a grounding and background for students that would allow them to later experiment on their own. In particular, students were able to build off of the concepts, components, and circuits in these experiments in the development of their own projects, as will be examined later in this chapter.

Table 5.2

Table of Contents of Make: Electronics

1. **Chapter 1 Experiencing Electricity**
    1. Experiment 1: Taste the Power!
    2. Experiment 2: Let's Abuse a Battery!
    3. Experiment 3: Your First Circuit
    4. Experiment 4: Varying the Voltage
    5. Experiment 5: Let's Make a Battery
2. **Chapter 2 Switching Basics and More**
    1. Experiment 6: Very Simple Switching
    2. Experiment 7: Relay-Driven LEDs
    3. Experiment 8: A Relay Oscillator
    4. Experiment 9: Time and Capacitors
    5. Experiment 10: Transistor Switching
    6. Experiment 11: A Modular Project
3. **Chapter 3 Getting Somewhat More Serious**
    1. Experiment 12: Joining Two Wires Together
    2. Experiment 13: Broil an LED
    3. Experiment 14: A Pulsing Glow
    4. Experiment 15: Intrusion Alarm Revisited

4. **Chapter 4 Chips, Ahoy!**
    1. Experiment 16: Emitting a Pulse
    2. Experiment 17: Set Your Tone
    3. Experiment 18: Reaction Timer
    4. Experiment 19: Learning Logic
    5. Experiment 20: A Powerful Combination
    6. Experiment 21: Race to Place
    7. Experiment 22: Flipping and Bouncing
    8. Experiment 23: Nice Dice
    9. Experiment 24: Intrusion Alarm Completed
5. **Chapter 5 What Next?**
    1. Customizing Your Work Area
    2. Reference Sources
    3. Experiment 25: Magnetism
    4. Experiment 26: Tabletop Power Generation
    5. Experiment 27: Loudspeaker Destruction
    6. Experiment 28: Making a Coil React
    7. Experiment 29: Filtering Frequencies
    8. Experiment 30: Fuzz
    9. Experiment 31: One Radio, No Solder, No Power
    10. Experiment 32: A Little Robot Cart
    11. Experiment 33: Moving in Steps
    12. Experiment 34: Hardware Meets Software
    13. Experiment 35: Checking the Real World
    14. Experiment 36: The Lock, Revisited
    15. In Closing

Getting Started with Raspberry Pi. The Raspberry Pi was not the first single-board computer available, but it was the first to specifically target educational users with a low price point and targeted online documentation and community support for K-12 students and teachers. Both the Raspberry Pi's ease of use and low cost continue to make it very attractive to educators wishing to put computing devices in students' hands for less money than many new or used textbooks. Retailing at $35 when it was first introduced in early 2012, it quickly became out of stock due to high demand for several months after its introduction (N. Heath, 2013). Since 2013, two newer versions of the Raspberry Pi have come to market with a similar positive reception.

The Raspberry Pi series of devices were designed to run on an operating system named Raspbian, a variant of Debian Linux. Raspbian provides a nearly complete Unix-like operating system with a graphical user interface as well as general purpose input and output pins for interaction with physical sensors, instruments, switches, and other devices. None of the Raspberry Pi devices come with printed manuals or tutorials; however, Richardson and Wallace (2012) published *Getting Started with Raspberry Pi*, coincident with the release of the original Raspberry Pi in 2012. This book directs readers through the device's setup process and provides several tutorials and example projects, including running a visual programming application known as Scratch on the Raspberry Pi, programming it with Python, and using the Arduino integrated development environment (IDE) on it to program Arduino microcontrollers directly.

The Richardson and Wallace text met most of the criteria that the teacher had laid out. Having been published by Maker Media, the book's content was designed to be both relatable and engaging for a beginner audience. The book and Raspberry Pi hardware were well integrated, inexpensive, and approachable. However, the teacher decided against introducing Raspberry Pi to the students in this course, given that they would have access to eight iMac computers for running various IDEs and for other reasons described below.

Getting Started with Arduino. When comparing the Raspberry Pi to the Arduino, the teacher noted that the latter would probably have a shorter time from power-on to results given its simpler language and configuration. Massimo Banzi, an Italian software developer, entrepreneur, and educator, led the team that developed the Arduino microcontroller.

Microcontrollers are the brains behind almost all electronic devices and appliances people interact with on a daily basis. While there are many microcontroller platforms available, Banzi (2011) and his team at the Interaction Design Institute Ivrea (IDII) in Ivrea, Italy sought to develop a simple yet powerful open-source hardware and open-source software development platform targeting artists, designers, and educators who might otherwise lack the technical sophistication to work with proprietary microcontroller platforms. Banzi wrote in the book's introduction that it "was written for the 'original' Arduino users: designers and artists" (Banzi, 2011, p. 2). Banzi claimed that the Arduino affords new users a quick and rewarding path toward successful tinkering. The widespread global communities of Arduino project support, its compatibility with macOS, Windows, and Linux, and its widespread adoption by maker communities support this claim. Banzi's book provides examples for getting started, showing readers what can be done while encouraging them to experiment and tinker.

The Arduino project began in 2004 as a master's thesis project by one of Banzi's students at IDII. By 2016, there were 17 official Arduino boards and dozens of unofficial variants (Banzi, 2011). The platform has been embraced by Maker Media, as evidenced by multiple feature stories in Make: Magazine and the publication of two editions of Banzi's book through O'Reilly and Maker Media. The Arduino is not the most powerful, fastest, or most robust electronic prototyping platform, but its low-cost, open-source model was the impetus for a surge of interest in maker communities working at the intersections of art, coding, electronics, and physical computing (Banzi, 2011).

Of note in Table 5.3 is that Banzi's book assumes a similar approach to that of Platt's in Make: Electronics. The text itself takes the reader through a series of *consequential* *progressions* (Putney et al., 2000) as it unfolds the process for programming an Arduino, beginning with an introduction detailing the preparations needed to install it on a desktop computer (Mac or Windows), followed by a series of basic demonstrative programs with example software code which lays a foundation for the reader to tinker and explore on their own. The teacher selected this book, also published under O'Reilly's Make imprint, since it matched this consequentially progressive approach to tinkering and making that he planned to lead the students through in STEAM Lab (*Teacher's journal*, 2013, p. 10).

Table 5.3

Table of Contents of Getting Started with Arduino

1. **Chapter 1 Introduction**
    1. Intended Audience
    2. What Is Physical Computing?
2. **Chapter 2 The Arduino Way**
    1. Prototyping
    2. Tinkering
    3. Patching
    4. Circuit Bending
    5. Keyboard Hacks
    6. We Love Junk!
    7. Hacking Toys
    8. Collaboration
3. **Chapter 3 The Arduino Platform**
    1. The Arduino Hardware
    2. The Software (IDE)
    3. Installing Arduino on Your Computer
    4. Installing Drivers: Macintosh
    5. Installing Drivers: Windows
    6. Port Identification: Macintosh
    7. Port Identification: Windows
4. **Chapter 4 Really Getting Started with Arduino**
    1. Anatomy of an Interactive Device
    2. Sensors and Actuators
    3. Blinking an LED
    4. Pass Me the Parmesan
    5. Arduino Is Not for Quitters
    6. Real Tinkerers Write Comments
    7. The Code, Step by Step
    8. What We Will Be Building
    9. What Is Electricity?
    10. Using a Pushbutton to Control the LED
    11. How Does This Work?
    12. One Circuit, A Thousand Behaviours

5. **Chapter 5 Advanced Input and Output**
    1. Trying Out Other On/Off Sensors
    2. Controlling Light with PWM
    3. Use a Light Sensor Instead of the Pushbutton
    4. Analog Input
    5. Try Other Analogue Sensors
    6. Serial Communication
    7. Driving Bigger Loads (Motors, Lamps, and the Like)
    8. Complex Sensors
6. **Chapter 6 Talking to the Cloud**
    1. Planning
    2. Coding
    3. Assembling the Circuit
    4. Here's How to Assemble It
7. **Chapter 7 Troubleshooting**
    1. Testing the Board
    2. Testing Your Breadboarded Circuit
    3. Isolating Problems
    4. Problems with the IDE
    5. How to Get Help Online

Developing the STEAM Lab Syllabus

Having spent the majority of the spring of 2013 reading the candidates for course textbooks, the teacher had chosen the final publications for the course before the end of the prior school year (2012 to 2013) and was beginning to formulate a course design that would incorporate the instructional plan of the selected texts along with his goal that students gain exposure to the material quickly enough to begin student-driven learning. In a July journal entry, the teacher documented an interest in developing a constructionist approach to learning in which students would create an electronics project for public display at an art show. This type of thinking aligns with Papert and Harel's (1991, p. 1) theory that people learn "especially felicitously in a context where the learner is consciously engaged in constructing a public entity." In addition to being purely technical and scientific, this project had the potential to deliver some artistic value.

Given the open-enrollment nature of the course and the students who had already expressed interest, the teacher expected that many enrollees would come with little, if any, physics or electronics background. One challenge he faced was to find ways to take a constructionist approach to learning, in which the students would be able to use their diverse individual strengths to contribute in the construction of an engineering design project (Parker, 2013). Determining what those students' strengths might be prior to the start of the course was difficult; as a result, creating a tightly framed approach to the project's development would be nearly impossible. While the teacher did not know it at the time, his course design was beginning to take the form of a problem-based learning instructional approach.

By the start of the school year, the teacher had identified the general format of the course and had indicated in his notes a desire to set up the first semester curriculum as a more traditional science and engineering lab course. According to his journal, the first semester of STEAM Lab tracked the experiments in *Make: Electronics* in an attempt to lay a foundation for electronics theory (e.g., understanding Ohm's law and current versus voltage) and basic skills (e.g., soldering, basic circuit troubleshooting, and circuit schematic literacy). The second semester focused on the applied use of the students' experience with the tools and objects presented in the first semester in order to create a large-scale electronic art installation (*Teacher's journal*, 2013, p. 21).

Digital and Physical Inventory

Throughout the course, the students and the teacher interacted both face-to-face and through digital and analog media. Although many artifacts were purposefully preselected for inclusion in STEAM Lab, such as the texts and tools mentioned above, many other artifacts were the product of the collaborative and social construction of the classroom culture over the course of the school year. In an effort to re-present the interrelationships between all of these artifacts, Figure 5.1 represents a (*Teacher's journal*, 2013, p. 22) chart of the various course artifacts that were used throughout the learning process. This analysis assisted in creating a logic for understanding as well as cataloging many of the objects that may have seemed ordinary to the participants but had significance when viewing this course as an outsider.

is a kind of course artifact	engineering tools	iMac computers
		electronics component packs
		soldering irons
		Google
		Arduino example code libraries
		student generated code
		Arduinos
	recording devices	multimeters
		Makey-Makey
		markers, pens and pencils
		HD video cameras
	texts	Engineering notebooks
		Make: Electronics
	virtual communication spaces	Getting Started with Arduino
		Google Plus community
		Engrade virtual gradebook and test platform
		engineering journals

Figure 5.1. STEAM Lab course artifacts.

The First Day of STEAM Lab

In this section I examine how the teacher transitioned from his role as course designer and developer to course framer, scaffolding the creation of the STEAM Lab course collaboratively with his students though the introduction of maker artifacts. Through video analysis, I endeavored to make visible actions the teacher took in framing the course goals with his students, the ways in which the teacher introduced students to resources and artifacts created by and intended for members of maker communities, and how the teacher and students then took up, adapted, and transformed these textual, electronic, and mechanical objects and texts. I also aimed to make visible and provide a context for the teacher's creation of a course influenced by maker themes and his individual students' journeys throughout the course.

The first day of any course is instrumental in setting the norms and expectations for the entire school year (Baker & Green, 2007; Spradley, 1980). It is the first time that the students and the teacher come together as a group and the teacher begins to set norms for the classroom. Although the teacher and the students may be familiar with one another, the early actions of the course participants, particularly on the first day, defines how they are going to develop, creating norms for functioning within the individual roles and as individuals within this group (Green, 1983). Based on the teacher's notes, during the months leading up to the first day of school, the teacher had been engrossed in research in a range of areas, from maker culture to practices for learning basic electronics and coding. The first STEAM Lab class took place on September 23, 2013 and marked the beginning of a transition from the teacher's preparations for the course, which were driven by his own individual efforts over the past several months along with early collaboration with faculty, to a fully collaborative effort between the teacher and his students and the inclusion of his students as participant observers and researchers in this study.

Understanding that the first day was vital in framing the entire course, the teacher, acted as both teacher and researcher, explained the study and the purpose of the cameras to the students and began recording shortly after the class began. After this introductory discussion, the first video recording began about 20 minutes into the first class. All of the students were in attendance on the first day.

The teacher supplied each student with a bound composition book for the recording consisting not only of notes in preparation for tests and exams, but more importantly, personal reflections and records for iterative growth through experimentation using the engineering design process (Green & Wallat, 1982). The first order of business following the explanation of the cameras and the study aspects was to introduce the students to the engineering journals that they would be using to record their notes throughout the course and to communicate with the teacher who periodically read the students' journals.

Using the video and audio recordings of the first day, both the verbal and non-verbal cues of this inclusion of the students in the creation and documentation, processes became visible during a series of events in the first few minutes of the course, as the teacher presented each of the artifacts or tools that he had selected in advance to frame the course. An examination of the single-angle video from the introductory portion of the first class revealed three distinct events that the teacher used to frame the course and explain to the students how they could take up roles as learners and makers as well as participant observers. Table 5.4 below makes visible the complete transcript of the events that transpired on the first day. Overall, the introductory meeting was structured as more of an informal dialog than a lecture or lab. The students asked questions about what they could expect from the course as well as what the teacher expected from them.

Table 5.4

Transcript Excerpt from Day One

	speaker	***teacher discourse***	***students discourse***	***students discourse***	***students discourse***	***artifact***	***Developing references & actions***
1.	Teacher	so, this is the book we're going to be using				Make: Electronics	
2.		and this is the person that were gonna to talk about today					
3.	Caitlin		wait				
4.			are we going to start with electronics?				
5.	T	yes					
6.		we're going to start with electronics					
7.		[actually, um]					
8.	Shaun			[are we going to actually start doing stuff today?]			
9.	T	yes					
10.		we are actually going to start doing stuff					
11.	Jay				actually?		
12.	T	so					
13.		why don't we open to page one of the book					
14.	Jay				woo hoo		
15.					page one!		
16.					yeah		
17.	Shaun				boo do		
18.					yeeaassss		
19.	T	so					
20.		normally we're not gonna be reading the whole book out loud					
21.		but since you guys had					
22.		this is the first day					
23.		you've got the book					
24.		got the book in your hands					
25.	Caitlin		oh!				*raises hand in advance;* Caitlin is predicting teacher will ask for volunteer reader
26.	T	I'm gonna have Caitlin read the first page					
27.	Shaun			wait			
28.				what page is this?			
29.	T	page one					
30.	Caitlin						*Caitlin reads page 1 about acquiring components and materials*
31.	T						*Teacher unpacks multimeters as Caitlin reads*
32.	T	so you guys won't have to worry about that (buying components)				component packs	*brings component packs down from shelf*
33.		because					
34.	Caitlin		thank you				
35.			Levi!				

As indicated in Table 5.4, the first major tool or course artifact that the teacher introduced was the *Make: Electronics* textbook. In line 1 of the video transcript from the first day, the teacher framed the textbook as a tool the students could use to learn about electronics and eventually build their own creations. By showing how this text provided the basic building blocks for engineering concepts and how it was linked to actual scientists and engineers, the teacher provided his students with context for scientific inquiry. Caitlin, one of the students, asked if the class would start right away with electronics, to which the teacher replied, “yes, we are actually going to start doing stuff.” This suggests that Caitlin may have expected the course would be front-loaded with theory prior to experimentation. The teacher then asked for a volunteer to read from the textbook about getting started on the first experiment and Caitlin raised her hand. Having Caitlin read the instructions aloud from the textbook gave her an opportunity to participate in the teaching process immediately. The teacher later invited all students to read aloud and discuss the ideas presented in the text.

In addition to the textbook, the teacher provided each student with a STEAM Lab engineering journal. These were identical, wide ruled, stitch-bound, composition books. In his introduction of these journals, the teacher outlined his own journaling practices to model his expectations for students, explaining how the engineering journal could be both similar and different to a typical course notebook. The teacher encouraged students to document their own discoveries and engage in a textual dialog with him through their writings in the engineering journals (see Appendix C). The teacher enabled this dialog later in the course by assigning lab reports and other assignments to be completed within the journals, creating a bound and collective written record for each student.

In his introduction, the teacher described the engineering journals as semi-private spaces that only the teacher and students were permitted to review. The teacher further explained that he made notes of interesting things that happened and resources he might want to return to. He invited students to directly engage with him through the notebooks by writing down questions for which they wanted answers to, emphasizing that the notebooks were a channel for private communication with the teacher and that the Google Plus community he had setup for the course was a more public (available to all STEAM Lab students and the teacher but not the general public), social media space for interaction and dialog between all group members.

On line 9 of the transcript in Appendix C, Shaun asked the teacher if they should also write their names on the front cover of the journal, while Bobby, another student, followed up with a suggestion to write only his initials rather than his full name. A conversation about this aspect emerged when a third student, Jay, suggested that “engineers don’t use initials.” This may have been a reference to Jay’s awareness that the group would be taking on the roles of engineers. His delivery, tone, and facial expressions served to indicate that the remark may have been intended to be humorous but also implied that Jay had a sense that engineers were precise and descriptive in their work and thus use complete names rather than initials. While it cannot be fully known exactly what Jay was thinking in this moment, this interaction suggests that Jay was developing an early awareness of what it meant to be an engineer.

In analyzing the teacher’s notes, records, and video recordings in the months leading up to the beginning of the STEAM Lab course, there is evidence of a concerted effort by members of the faculty and school administration to support his endeavors to expand STEM offerings. The teacher was given fiscal support and the freedom to create a new elective course by the school administration. On the first day, he presented resources to his students that were trusted by leaders in maker communities, such as Maker Media. He also employed engineering best practices, such as encouraging documentation (e.g., engineering journals) and collaboration (e.g., Google Plus community). These practices set the tone and provided structure for the course, establishing expectations for his students from the beginning.

Throughout the first few course meetings, the teacher and his students began to set norms for the class and collectively negotiated terms by discussing expectations and answering each other's questions. In the subsequent analysis, I explored in what ways students negotiated terms and interacted among themselves while working to solve a technical problem with a microcontroller as part of the final project in the second semester.

Making Keys

Following the first semester (September through January) of working through most of the experiments in *Make: Electronics* and the Massimo Arduino book, visiting local art museums and hackerspaces, as well as discussing inventors, inventions, and using technology to solve problems, the class turned its attention toward a final project which would mark the culmination of their work with electronics (this can be traced by following the year-long course event map detailed in Appendix A). This final project, known as the Electronic Art Installation, was defined in the assignment sheet drafted by the teacher and is depicted below in Figure 5.2.

Assignment Sheet

The installation should be a large scale, modular piece consisting of multiple integrated systems. Using the theories and practices we have begun to explore in STEAM Lab, these systems should consist of electronic visual and optionally audible elements (lights and/or video and possibly sound) which relate with spectators as they move through the environment. Observers should become participants in the art as specifically designed circuits control functions of the system, which allow for human-machine interaction through electronic sensing. Possible sensors include those that measure proximity, light, contact, weight, temperature/heat, sound, radio signals, etc.

Students will be expected to design an overall system as a class of seven, however individuals or smaller groups will tackle the design and construction of various sub-systems. Evaluation and assessment (i.e., grading) of the project will be based on the following areas:

Adherence to engineering method

* Do students follow methodical steps?

Individual and group critique of the final product and process

* How do students self-evaluate the project?

Technical sophistication of design

* Does the project design demonstrate that students have challenged themselves by expanding on the experiments done in class?

Implementation of stated design

* Does the final outcome demonstrate a realization of the original design plan? If not, do the deviations add to or detract from the final outcome?

Originality and novelty

* Does the engineering and aesthetic design demonstrate original creative thinking?

Thoroughness of lab notes

* Have students all thoroughly documented their progress in their lab notebooks?

Self-assessment

* How do students honestly critique the project themselves based on this criteria?

Figure 5.2. Electronic Art Installation assignment sheet.

During a class meeting on March 10, 2014, the students brainstormed several ideas and quickly reached a consensus around one student's concept for a giant electronic piano. According to sketches and journal notes, the design would support a full-sized adult and synthesize musical notes. Additionally, the keys would light up when stepped on. Soon after developing a rough plan, the students began drafting dimensions and a bill of materials for the construction of the piano. The teacher suggested that the students divide up the work and assign themselves to teams to tackle various aspects of the project, such as design and construction, electronics, and coding. The students divided the responsibilities among themselves, with several student groups forming to begin their self-directed research.

Analysis Four: Student Interactions in STEAM Lab

In the following analysis, I focus on one set of interactions mainly between two students, Bert and Caitlin, as they explored possibilities for the electronics to control the activation of the piano keys. Bert, a 10th grade boy and self-proclaimed video game fanatic, 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, it is worth noting in order to provide insight into these interactions.

Caitlin, a 10th grade girl, joined the STEAM Lab course following a year with the Near Space Exploration Club afterschool team that organized the ARISS contact during the prior spring. 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 keys.

In Caitlin's absence, Bert had been tinkering with Makey Makey, a self-proclaimed "invention kit for the 21st century" that was designed by Jay Silver and Eric Rosenbaum, both students at MIT under the guidance of Seymour Papert's former advisee Mitchel Resnick (Makey Makey LLC, 2012). This USB device 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 had purchased a 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 literature. Conductive material causes the interactions with the computer over the connected USB port.

This discourse made visible the formation of a collaborative relationship between these two students working to solve a common problem by sharing knowledge and experience with one another. In this case, the teacher provided the students with an ill-defined problem (the Electronic Art Installation assignment) and within the scope of that project, each student workgroup defined further parameters for the various aspects of the project (additional sub-problems), which was designed to simulate the organic rise of real-world problems and allows for free inquiry in the search for solutions. It was visible through analyzing this interaction between Bert and Caitlin (see Appendix D for the complete transcript) that Papert's concepts of constructionist learning through collaboration on a public project with new electronic objects and tools could help get students beyond certain hurdles.

Table 5.5

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 the 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

As shown in Table 5.5, 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).

Table 5.6

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-
79		don’t know
80		actually
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 explain it
90		in a minute
91		to you guys
92	C:	(continues to fiddle with board and wires)
93		so cool

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 5.6). 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 object that is not a traditional computer input device (e.g., mouse or keyboard), 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 students (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 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, and represents an essential characteristic of problem-based learning as they continued to tinker with the material.

Table 5.7

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

As can be seen in Table 5.7, 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 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 (e.g., cardboard box, oranges, and their own skin), 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 with Makey Makey as a substitute for the computer keyboard using Apple's GarageBand software on the iMac (Line 249). GarageBand is a program which 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.

Table 5.8

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 holding 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	J:	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

Later, the teacher acknowledged Bert and Caitlin's developing understanding with an approving chuckle (Line 310). Bert and Caitlin had made an important discovery on their own — using Makey Makey, they furthered their understanding of electronics and circuits through tinkering. In this brief collaboration, the students also discovered a way to interact with a computer laying the groundwork for their later use of iMac as the synthesizer for the life-sized piano. The two appeared to enjoy the learning journey together, as evidenced by smiling and laughing and general excitement upon making discoveries throughout the process, and the advancements they made by tinkering and experimenting together ultimately led to a deeper understanding of electronics and circuit design. As a result of this intellectual journey, they were able to construct a working, life-sized, electronic piano with minimal teacher intervention. There is evidence here that suggests the two students were both having fun and learning.

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, 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 (270-295). 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 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.

Table 5.9

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
349		(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

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 5.9). 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 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 can 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 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.

Table 5.10

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

380	Caitlin:	we don’t know where to start
381		because
382		(unintelligible)
383		the computer actually thinks that when you press it
384		you’re pressing the arrows and the space keys
385	Teacher:	ok
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 an Arduino and its
411		and someone just programmed it and they picked those
412		those keys

From Table 5.10, it is clear Bert and Caitlin delved deeper into the workings of the Makey Makey and GarageBand, only to find out that it would not be so simple to remap the keys (Lines 380-384). The Makey Makey was designed for basic exploration, and it became apparent that the students had already intellectually outgrown the limitations of the device. At this point, the teacher again stepped in as a cultural guide. In this case, the teacher possessed some knowledge about how the Makey Makey was designed when he responds that “it is an Arduino-based device” (Line 410). The teacher asked a series of questions (Lines 390, 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 teacher may not have known the precise answers to his queries, but he listened to the students’ questions, likely 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. 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 might 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 answer 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 (Science Buddies, 2012).

Additionally, the group (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 matrix did not work due to compilation errors in her 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.

STEAM Lab and Making

STEAM Lab provided a space for students to learn in a traditional, directed way, 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 (e.g., learning challenges or disciplinary issues) 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, who was part of the Near Space Club student team that helped organized the ARISS contact, 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, of which were similar to the events analyzed in this chapter. 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 working, giant-sized, electronic piano at the spring art show despite a major setback unintentionally caused by the teacher's (my) interference during circuit construction.

Chapter VI: Conclusion

This study examined how and in what ways my students and I defined and influenced the co-creation of a maker-based STEM initiative at an independent high school. Informed by interactional ethnography (Castanheira et al., 2000; Collins & Green, 1992), I made visible the processes and practices over time of this curriculum-in-the-making. I traced the root and routes of opportunities for learning and engaging in a collective, goal-based, and problem-based activity in an elective high school course; how and in what ways this theory and style of instruction afforded certain learning opportunities for students; and what types of literacies were needed for students to confront the challenges of the course. This final chapter presents the reader with a summary of the findings of this longitudinal study, including the analysis of the onset of the STEM initiative through the Near Space Exploration Club and continuing across 4 years with findings and conclusions from the analysis of the STEAM Lab course. Additionally, included are the limitations of this study and its implications for education researchers and suggestions for continuing research and study, as well as implications for teachers and other STEM education practitioners.

Introduction

Upon commencing my graduate education research, I began teaching an elective course at a small, independent school serving students in Grades 7 through 12. Although I did not hold a state K-12 teaching credential, the headmaster of this private school had the flexibility to hire teachers at his discretion. At the time of my hire at the school, I had no prior experience teaching in a K-12 classroom; I did, however, have extensive experience working with children in less formal learning environments as a sailing instructor and a mentor at afterschool programs in inner city public schools. Additionally, my education and business experience in media and television production were in alignment with the media arts course I was first hired to teach at the school. After several years of developing curricula and teaching practices in a media arts course and later in the STEM initiative, it became clear that the work I was doing with students could form the basis for further research in STEM education, with the aim of informing the qualitative research base in STEM education and the nascent maker education movement. My students had been engaged in and committed to the successful outcome of their STEM projects, both after school and in class; however, understanding the educational implications of these less formal opportunities for learning through tinkering and making, as well as how a school might integrate maker-based education approaches into courses, had not been adequately defined nor studied. Qualitative methodologies in particular have received little attention in engineering education research literature overall (Case & Light, 2011).

Another contributing factor was the importance of exploring literacy demands of these developing areas of education. Wright (1999) argued that technical literacy and a complete understanding of technologies is vital for career success in STEM fields. Thus, literacy, under this view, does not only entail learning cognitive skills, but also understanding the *literate practices* (Green et al., 1992) and significant social achievements of STEM practitioners. This study made visible, through discourse analysis (Gee & Green, 1998), the literate practices of one particular STEM-to-STEAM initiative and how students learned to think and act as practitioners by collaborating to solve problems as they designed and made things.

Design of the Study

Initially, this dissertation was to be a longitudinal study across one academic year designed to look at how and in what ways my students and I, as the teacher, defined and influenced the co-creation of the STEAM Lab course. However, in the process of analyzing the activity during STEAM Lab, it became apparent that there was an important historical context and a culture of experimentation that had evolved over the course of several years which led to the formation of this course. This necessitated a further look back into my history as a teacher and curriculum developer at the school to ground the work that had been done in STEAM Lab. I determined that I would need to analyze my own historical teaching records to find evidence of the supports and constraints within this historical context to best understand the impetus for STEAM Lab's creation. Thus, the focus of this study shifted from solely the STEAM Lab elective course in the 2013-2014 academic year to what I coined the school's *STEM initiative*. The STEM initiative traced its roots back to 2010 with the first high-altitude balloon project that I organized as an extracurricular, afterschool activity with several students. With this shift, I widened the scope of my analysis and added the additional analysis chapter, "Tracing the Development of an Emerging STEM Initiative," to this dissertation.

Grounding my inquiry in an ethnographic perspective (Green & Bloome, 1997) provided a theoretical framework and logic of inquiry. As a participant observer (Spradley, 1980), I stepped back from the lived experience of the classroom to examine the records, documents (e.g., video records, student journals, and teacher curriculum notes), and decisions and systematically explored the key processes and practices that defined how this maker-based STEM learning environment was constructed. As such, I separated my role as the researcher from my role as the teacher, often referring to myself as “the teacher” in the third person throughout the analysis chapters. By reaching back into my personal history in STEM at the school, I was able to explore and analyze the socially-constructed discourse and literate practices of the STEM initiative’s evolution, tracing the roots from which STEAM Lab emerged and the routes taken in the process of its iterative evolution and development. The longitudinal nature of this ethnographic study made visible how my students and I developed a situated perspective of disciplinary knowledge. Situated perspectives acknowledge that people know and understand things differently in different social settings (Green & Bloome, 1997). Furthermore, I viewed disciplinary knowledge as co-constructed by the individuals and something that remains fluid throughout the iterative and recursive process of its ongoing development (Heap, 1991). What counted as maker-based STEM education in this context was situated in the interactions of the class over time and was made visible through ethnographic approaches to analysis, primarily discourse, and textual analyses.

Research Questions

The overarching research question that guided this study was:

- What were the key process and practices of a maker-based STEM learning environment in a progressive, independent high school?

To address that question, I examined the following sub-questions that emerged:

- Who were the actors involved and how was this learning environment supported or constrained by these actors in a school context?
- What did the teacher need to know and what resources were required in order to create these developing initiatives?

- What counted as learning processes and practices in the developing STEM initiative?
- How was this maker-based course an example of a problem-based or project-based learning environment?

In order to address each of these questions, I traced the development of the STEM initiative from its inception as a near space, high-altitude balloon probe project across 4 years to the two-semester STEAM Lab elective course. During the course of this study, four discrete major cycles of iterative STEM initiative program development were developed across 4 years. The first cycle was the initial high-altitude balloon project (Balloon Probe #1). This was the first balloon probe that the students designed and launched. The second cycle was the second high-altitude balloon project (Balloon Probe #2), which added live video and data downlink to Balloon Probe #1's basic data logging sensor array. The third cycle was a year-long, schoolwide focus on space exploration, which concluded with a live space station contact via amateur radio and a visit by a NASA astronaut. The two-semester STEAM Lab elective course marked the fourth cycle, during which the students designed and built a large-scale electronic piano. The following sections present discussions of the key findings from each of these cycles.

Near Space Exploration Club: Summary and Findings

The first major cycle of STEM activity was the designing and building of the Near Space Exploration Club's first balloon project (Balloon Probe #1). During this cycle, as the teacher, I scaffolded student learning in important ways. The Near Space Exploration Club's founding goal of building a relatively low-cost electronics package and launching it into the upper atmosphere was made possible in a high school context due in large part to the growing online maker communities, including amateur radio and electronics hobbyists, and the collaborative nature of makers who often document and share their projects online. Early on in my search for information about high-altitude balloon projects by students, I located a collegiate group that had successfully launched a high-altitude balloon and drew on their experiences in my proposal of the project to students and school administration. The combination of the rapid growth of online maker communities, rapidly falling costs, and miniaturizing of sophisticated electronics (e.g., integrated GPS circuits and microcontroller technologies) supported the opportunity for such a project, one that would have once only been possible with a large institution, government, or corporate-sized budget. In this case, the budget for each of the two balloon probe projects was less than $2,000. The school's small size, independent status, and my own history of developing successful curricula may have contributed to the expeditious approval and funding of the initiative. I lobbied for support from my fellow teachers and the school's administration. The students who participated in Balloon Probe #1 all stayed with the project from beginning through to the end, and everyone who remained at the school for the following academic year rejoined the Near Space Exploration Club, despite the lack of ability to earn an academic course credit for their participation, showing early and continued student engagement (Schlecty, 1994) with the Near Space Exploration Club activities.

Following 2 years of iterative development of balloon probes, the Near Space Exploration Club shifted its focus in 2012 from design and construction to supporting the schoolwide Synthesis Unit focused on space exploration. During that school year's iteration of the STEM initiative, more students than just the core group of club members participated in STEM initiative activities related to space exploration. A live radio contact with NASA

Astronaut Chris Cassidy aboard the ISS through the ARISS program and an in-person visit to campus by Astronaut Richard Linnehan were both examples of opportunities afforded by the STEM initiative for students to speak directly with professional practitioners in STEM fields. This type of collaboration between students and teachers (in this case the *makers*) and actual STEM practitioners (the astronauts) is indicative of the nature of maker communities that are not necessarily school-based. In the example of the ARISS program in particular, there is evidence that such collaborations between NASA astronauts, educators, and students have been key in “sparking an interest in science and mathematics for many students around the world” (Evans et al., 2009, p. 161).

Actors’ Supports and Constraints

The administration and faculty of the small, independent school strongly supported me in creating the Near Space Exploration Club. The school was not subject to the same state standards as public schools, meaning that it had more flexibility to support innovative projects. Moreover, while the school was not particularly well funded (it had no endowment nor significant surplus funds), the headmaster was also the organization’s chief executive and had the ability to direct funds in support of such projects at his discretion.

In the cycles of Near Space Exploration Club activity, I drew upon my own knowledge and experiences as a private pilot and amateur radio operator to formulate an initial concept for the balloon probe. However, my students and I subsequently drew upon a collection of resources available to us through communities of makers and practitioners — both online (e.g., maker forums and YouTube videos) and local (e.g., National Weather Service office and local amateur radio club members) — as well as resources through NASA, the FAA, and other organizations and agencies that supported the group’s activities.

Additionally, the STEM initiative was substantially supported by the school's faculty and administration early on as discussed in the analysis chapters. This undoubtedly contributed to the initiative's success and sustainability across 4 school years.

There were several examples in my email exchanges with the Near Space Exploration Club's founding student that emerged through the analysis of the discourse that hint at the eventual collaborative, problem-based learning approach that developed within the STEM initiative. When asking students if they would be interested in helping me lead the project, I suggested that we might launch a high-altitude balloon, but I left specific requirements of the project out. From the beginning, I framed this as an ill-defined problem or as Simon (1973) called it, an *ill structured* problem. I offered no specifics as to how to construct the probe, and there was no kit to assemble nor a prescribed method to follow in order to build the balloon probes. Furthermore, I myself had never taken on the challenge I was presenting to my students.

The evidence in the records and discourse from the Near Space Exploration Club activities suggests that I presented myself to stakeholders (faculty, staff, parents, and students) as both a co-researcher and collaborator, reflecting my developing constructionist and constructivist pedagogy. The evidence also suggests that these actions were in alignment with Piaget's and Papert's theories in regard to the social construction of knowledge through a problem-based approach to the creation of the emerging STEM initiative.

Evidence of Problem-Based Learning

In the cases of the two balloon probes, evidence of learning can be inferred through the successful collaborative design of the projects. The balloon design and construction was the overall ill-defined problem and basis for the endeavor. I had some notions of potential resources, possible paths to explore for solutions, and a vague idea of a starting point. Each student was responsible for a particular aspect of the construction, launch, tracking, and recovery of the balloon probe.

As is the case with a problem-based learning model, the students' level of commitment and participation had a direct impact on the degree of the successful outcome of the projects. Throughout the 2 school years, each student was faced with a number of challenges and problems and I often guided them toward potential resources for solutions. However, unlike demonstrative science projects and experiments used in direct instruction curricula where there are finite resources and an expected outcome, the outcome of these two balloon probe projects were unknowable at the start.

Given that students in the Near Space Exploration Club were not tested in STEM knowledge areas prior to and following their participation, it might be asked, as Petrich et al. (2013, p. 65) posed, "it looks like fun … but are they learning?" The successful launch, recovery, and analysis of data from the student-designed balloon probes served as evidence that the students, who had no prior direct experience in launching high-altitude balloons, learned how to design, build, and launch these probes. However, the purpose of the Near Space Exploration Club — and this maker-based STEM initiative in general — was not solely about skills acquisition, but also learning how to learn.

Throughout the cycles of activity in the STEM initiative, I showed students how to research complex problems, break down a large ill-defined problem into a smaller one, and other aspects of the iterative and recursive engineering design process. One Near Space Exploration Club student member asked me: “How do you know what you know?” The goal of maker education is to expose students to the processes and practices of how to know what they need to know in order to solve problems. While this is often useful in STEM, these problem-solving skills are broadly transferrable to other fields as well. In the case of the Near Space Exploration Club, students successfully engaging with the project and iteratively working toward solving the problems by building off of their prior knowledge both counted as learning. In the cases of the two balloon probes, all of the students were engaged with their own aspects of the projects but also worked collaboratively in order to see the two missions through to completion.

Limitations of the Near Space Exploration Club Analysis

The analysis in Chapter IV supported the notion that the attitudes of the students involved in the STEM initiative had an impact on their perception of STEM career fields overall, and their own achievement in these areas changed positively following their participation in STEM initiative activities. However, this analysis repurposed my archived teaching records, including email correspondence, meeting notes, purchase records, video recordings, and journal entries, in order to make visible the formation of a STEM initiative and my iterative practices as a teacher and curriculum developer throughout its evolution. This analysis was not specifically designed to capture changes in student attitudes following their participation in this cycle of the STEM initiative. Unlike the STEAM Lab course, the Near Space Exploration Club and the related space Synthesis Unit were not initially foci of this study and thus the record gathering practices employed during STEAM Lab were not employed during club activities. As such, further investigation would be needed to collect and correlate outcomes from the activities in which the students participated.

While there is a convincing case for continued support of such a model whereby students with prior experience act as cultural guides and experts in a schoolwide STEM program, further research is needed with regard to this study to examine how students learned to act as STEM practitioners during the construction of the balloon probes and then how they shared those experiences during the Synthesis Unit. In order to answer questions about the students' participation in the Near Space Exploration Club, it would have been necessary to capture more systematic and regular video data in the ways that were done during the STEAM Lab course. However, the positive feedback from broadening student participation was a factor in my consideration for the further development of the STEM initiative with the STEAM Lab course. This is an important implication, as it represents a pivotal point in the evolution of the STEM initiative from an activity that was limited to a small group of students to one that was integrated into the school day throughout an entire academic year.

STEAM Lab: Summary and Findings

The records available from STEAM Lab in the form of video and audio recordings, online interactions, and written journals gathered during the 2013-2014 school year proved to be a double-edged sword when it came time for analysis of the activity during the course. The sheer volume of data meant that for every area examined, there was a tremendous amount of data that would have to be set aside. By creating event maps, timelines, and tables of the records and data, it was possible to parse the information and identify areas for deeper examination and analysis. Using the video recordings of each class meeting, I was able to trace the activity during STEAM Lab at a level of detail that was not possible during the Near Space Exploration Club. In tracing this activity over time, I was able to make visible a development model that enabled the STEM initiative to evolve in this school setting, first from an informal, afterschool program into an all-school Synthesis Unit, and finally a for-credit, year-long elective course (STEAM Lab) offered during the regular school day. It was during the STEAM Lab course that the analysis showed how a student-centered, problem-based approach to learning could be successfully adopted by permitting students to design and build a working, large-scale electronic piano.

Actors' Supports and Constraints

In creating the STEAM Lab course following the success of the Near Space Exploration Club and the space Synthesis Unit activities, the faculty and administration of the school was again supportive of the STEM-to-STEAM notion and the offering of a for-credit elective course. I was afforded access to a classroom, computers, materials, and funding in excess of what the students' lab fees covered as far as course costs.

While I had a basic working knowledge of aviation, electronics, electrical engineering, radio communications, and computer programming as an amateur radio operator, electronics hobbyist, and private pilot myself, I was not an expert in nor did I claim to have extensive experience with the specific applications in the various cycles of the STEM initiative: launching high-altitude balloons, establishing radio links with astronauts in space, and building a large-scale, electronic musical instrument from scratch. Instead, I provided an initial framework for my students based on the collectively-created goals that we negotiated. Together, with the support of the school, my students and I were co-discoverers and co-creators throughout the four major cycles of activity in this STEM initiative.

Throughout the STEM initiative and into STEAM Lab, the school provided physical space and financial and administrative support. However, the small campus did not have a dedicated workshop or lab facility. My students and I met in the computer room where we had access to the internet and were afforded storage space for their materials and tools. As the initiative gained traction, the headmaster commissioned a custom storage cabinet to be built for the STEM initiative to ensure that there would be ample storage as the need for on-site materials increased.

Evidence of Problem-Based Learning

Throughout STEAM Lab, particularly in the second semester after the students completed their work in the *Make: Electronics* book, I challenged them to solve a series of smaller ill-defined problems in service of the overall goal of creating a large-scale, electronic piano. During STEAM Lab, my approach to the design and construction of the piano was relatively hands-off. I introduced the students to ideas, literate practices, tools, materials, and community resources, but I placed a greater emphasis on encouraging students to tinker and explore, both collaboratively and independently. The analysis in Chapter V made visible my practice of getting students started on a path and then later circling back to observe the students' progress and guide their inquiry by providing some scaffolding. In most cases, however, I stopped short of providing direct instruction, straightforward answers, or concrete solutions to the challenges the students faced.

The evidence suggests that STEAM Lab was centered around a problem-based approach to learning and that the teacher was not focused on teaching particular STEM skills or academic disciplines, such as coding or physics, but rather the students were learning the literate STEM practices of software and hardware engineers, craftsmen, and other applicable professions by gaining firsthand experience in technical research and problem solving in those areas. Throughout the duration of the STEAM Lab course, there was evidence of collaborative social construction of knowledge whereby students drew from and made contributions to the developing knowledge base of online maker communities through free inquiry (tinkering) supported by the teacher acting as a cultural guide. I as the teacher offered hands-off suggestions based on my students' needs in response to their actions. That is, I specifically refrained, when possible, from directly assisting them with their experiments and instead favored offering my students possibilities for next steps in the form of questions rather than direct answers or instruction.

Limitations of the STEAM Lab Analysis

An unanticipated outcome of this approach to teaching and learning was that at least two academically-talented students in the course found the uncertainty of a problem-based approach to the project to be unnerving. These students expressed to the teacher a desire to know exactly what was expected to earn certain letter grades (e.g., "What do I need to do to get an A?"). In traditional, direct instruction courses, these students may have known how to identify the steps for academic success. They may have equated a positive outcome with following a prescribed method outlined by the teacher. In most problem-based, constructionist, and constructivist learning approaches, teachers act as facilitators by encouraging open-ended, student-motivated activity. As such, teachers often may not have the correct answer or a detailed conceptualization of a single anticipated outcome. Instead, their role is to help students develop hypotheses, explore tools and resources to test those hypotheses, and ultimately look to students' engagement, commitment, and individual growth when evaluating their performance. This unfamiliar learning model was, in the case of some STEAM Lab students, more difficult to accept. Conversely, those students who were challenged by traditional academics appeared more comfortable with the trials of open-ended learning and the unknowns of the STEAM Lab course's problem-based, constructionist learning approach.

These experiences in STEAM Lab were in alignment with the reported outcomes from Papert's constructionist approach at the MYC. In Papert's case, students with troubled academic and social histories excelled in an environment where they were treated as independent and competent individuals and given autonomy in an open-ended learning environment to tinker and explore, knowing that they would be expected to create something of their own imagining (Stager, 2013). However, additional research would be needed to further explain any possible link in the STEAM Lab course between student achievement and confidence in various learning models in order to make any claims about such an approach and its effect on student motivation. Of particular interest may be the correlation of student achievement in traditional classroom settings with student achievement and comfort level in a problem-based and maker education-based curriculum such as STEAM Lab.

Impact and Sustainability of the STEM Initiative

The Near Space Exploration Club, the space Synthesis Unit, and the STEAM Lab elective course were part of an evolving schoolwide push for increased STEM awareness and activity. Coincident with the offering of STEAM Lab for students in Grades 9 through 12, the school also offered a LEGO robotics elective for seventh and eighth grade students as an additional means of answering the local and national calls to action for educators to address issues of equity and access to STEM education. While this study did not specifically address the school's overall effectiveness in addressing STEM education, there was evidence that some of what began with the Near Space Exploration Club and STEAM Lab sustained after my departure in 2015.

Beginning in 2016, the school hired a new STEM teacher who began offering a coding elective in which students could learn computer programming. The school's longtime math teacher worked with students in the robotics elective, which was expanded to include all grades, to construct a remotely operated underwater vehicle (ROV) in support of a subsequent Synthesis Unit on ocean health. In collaboration with a non-profit organization focused on protecting the local marine ecosystem, the class launched the student-built ROV from aboard a marine research vessel to get a firsthand view of the underwater ecosystem of a nearby reef ([Research site school website], 2017).

Overall, the success of the Near Space Exploration Club can be traced across the initial four cycles of this STEM initiative and into the school's overall STEM programs, implying that the STEM initiative had built some elements of sustainability that survived the departure of a single teacher.

Implications for Practitioners

As the teacher and researcher for this STEM-to-STEAM initiative, I owe much of the program's success to the tremendous administrative, student, parent, and faculty support afforded to me at this particular small, independent school. K-12 teachers in more restrictive environments with less institutional support may find my particular approach to building a STEM initiative challenging. However, in school environments where resources are scarce and budgets are small, maker-based initiatives that employ a constructionist, problem-based approach to providing learning opportunities could also be successful through teacher preparation and the dedication of adequate time and resources. One need not launch a balloon into near space nor connect with an astronaut on orbit in order to achieve success with maker education. There are virtually unlimited maker 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.

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 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 (NGSS, 2018b). A better understanding is necessary as to how these directives might be supported by maker education advocates and virtual and local maker communities. Proper 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 in that regard and made visible the processes and practices of a maker-based STEM learning environment in progressive independent high school. Further study in other settings such as a large public or inner city would make visible other considerations and variables in a different context. However, Papert’s work at the MYC suggested that even students from a severely disadvantaged population are able to adopt a constructionist approach when afforded the appropriate supports and opportunities.

Implications for Future Research on Maker Education

Based on this study's findings, I demonstrated how a STEM initiative, using maker community resources, can have a sustained impact on a school community across multiple years. In the course of documenting, analyzing, and reporting on this study, I proposed four *keys* as to what counts as maker education outlined previously, and have presented these keys to the maker education community for further discussion. While this study focused only on one example of a multi-year STEM initiative, there may be other keys that have not been considered here. This implication suggests that further ethnographic studies of actual maker-based classrooms and learning spaces would help make visible what counts as maker education.

Four important characteristics or 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, 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. In fact, students actively engaged and participated in online maker communities by asking questions and contributing their own experiences when applicable.

An important outcome of this study was the recognition that teachers and students can have multiple roles as co-creators, facilitators, and learners and how, over time, these roles evolve. Future researchers might consider the four keys of maker education presented here and how and in what ways, using these keys as a guide, other types of maker-based STEM approaches could be incorporated into a school day, particularly in public school environments where there may be more institutional constraints (e.g., testing and curriculum approval requirements, time and scheduling, and funding) that would need to be overcome.

Champions of maker education have promoted it as an educational method to meet the changing career landscape in STEM fields. However, the definition of what counts as maker-based education will continue to evolve with sociotechnical and school cultures. The Maker Education Initiative (Maker Ed) strives to provide educators with resources and support when adopting maker education and offers the following as its core beliefs:

If:

- Youth are physically and emotionally well and are motivated to learn;
- Educators have the training, resources, frame of mind, and support they need;
- Youth have a supportive community that values and promotes learning; and
- Learning environments are safe, sound, and responsive to learners' different needs;

Then:

- Educators will facilitate engaging learning experiences;
- Youth will participate in learning experiences that excite and motivate them;
- Learning experiences will celebrate and develop learners' unique qualities; and

- Youth will have fun, build confidence, and become passionate about learning.

(Maker Ed, 2018)

This language offers a positive vision of the impacts of maker communities on education. In fact, it would likely be hard to find educators who disagree with much of this approach; however, Maker Ed does not provide specific guidance as to how to undertake such an initiative, nor does it make visible what is needed for teachers and administrators to know, understand, and do in order to create a successful maker education-based STEM initiative. 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. However, such qualitative analyses of maker approaches in schools remain limited.

There appears to be value in incorporating problem-based learning approaches with the plethora of maker community resources into STEM classrooms 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 maker-based education models 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 Near Space Exploration Club, its emergence into a schoolwide initiative with a corresponding influence on the Synthesis Unit, and ultimately the initiative’s evolution into the STEAM Lab elective course. Additional ethnographic inquiries using discourse analysis into the areas of further inquiry raised in this chapter may help proponents of maker education further legitimize efforts to make inroads into both public and private school curricula.

Through maker education, students may have opportunities to learn not only specific skills in STEM (and possibly STEAM) fields, but they also can learn to think as though they were professional practitioners (e.g., engineers or scientists). Through maker-based approaches, students can learn how to know 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 for further research.

Conclusion

This study made visible the emergence of one particular STEM-to-STEAM initiative and four major cycles of activity that transpired across 4 school years. These analyses made visible the links between this STEM initiative and learning models embraced by thought leaders in maker-based STEM education who are advocating for less structured, direct instruction, and more opportunities for students to participate inquiry-based and problem-based learning models. The four important characteristics or keys to defining maker education that emerged from this research were essential in developing a definition of what counts as a maker-based education initiative, both for this study and perhaps beyond.

There is evidence that the learning models embraced by the maker education movement (constructionism, constructivism, and problem-based approaches) may have profoundly positive effects, particularly for at-risk and minority students. As independent validation of my efforts in STEM education, following our participation in the ARISS program, I was nominated to the ARISS-U.S. Education Committee in 2017 in order to inform the NASA-sponsored educational initiative as they strive to best serve a diverse population of students.

The curriculum design challenge that teachers and curriculum developers face entails finding problems that both challenge and excite students as well as those that encourage student engagement. Through these constructionist processes, students can gain authentic, firsthand experience with the tools and practices of STEM. However, in order for there to be a shift toward widespread embracement of maker theories and models in schools, policymakers and stakeholders will likely require more empirical evidence tied directly to successful maker-based education initiatives, as well as more case studies of effective models with elements that can be reproduced in a variety of school settings.

Researchers and practitioners need to further document and analyze maker-based classrooms so that educators can continue to better understand what counts as school-based maker education and how and in what ways evolving maker communities might effectively support K-12 students.

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Appendix A

Table A1

Complete STEAM Lab Course Timeline

		Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
	First quarter lab expriments	September 23, 2013	Framing course. Opening Materials, Student Journals explained, Google+ explained, Chris Hadfield cartoon, kits, books, discussion of first and second semesters, arduino, learn to solder kits, review of Connor's work with ANSEC. Playing with multi-meters, charge, conductivity, resistance.	rear wide	1:36:28	none		T, S	Ch. 1 Experiencing Electricity		
Academics expectations		September 25, 2013	Google+ and survey, Engrade intro, discussion of expectations about reading, intro to wall timeline, grading, quizzes. discussion of volts, amps, magnets. Largely lecture	rear wide (two files)	1:47:42	none			Experiment 2	G+, Prelim Student Survey	Read Make: Electronics pp. 9-17
Quiz		September 30, 2013	Students take quiz, then review answers together with teacher, review of scientific method and engineering method, review of Maker Faire projects for context, dimming LED and simple circuit construction with components	rear wide and closeup on computers (three files)	1:36:32	none			Experiments 3 and 4	Engrade: reading quiz	Read Make: Electronics pp. 18-31.
		October 2, 2013	James Watt, Ohm's Law, discussion of Lab Reports, Lemon Battery Experiment	rear wide and closeup of experiments	1:39:47	none		S	Experiment 5		Read Make Electronics pp. 31-38. Go back and re-read green box on James Watt.
Video or Film		October 7, 2013	Switches! Shift Happens video,	rear wide	1:52:16	front bench	1:47:57		Experiment 6	G+	Finish Lab Summary for Experiment 5 and read Make pp. 39-49.
Quiz		October 9, 2013	Reading quiz, further discussion on journals and lab report expectations, relays	rear wide	1:16:27	front bench	1:43:03		Experiment 7	Engrade: reading quiz	Lab Summary for Exp. 6; Read pp. 50-64 in Make Electronics
		October 14, 2013	Relay Oscilator discussion brief, first schematic intro, PSAT-some students missing. Tesla film	none		none			Tesla film	Interesting comment from teacher on G+, animated schematic	Read Make pp 60-67

		Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
Video or Film	First quarter lab expriments	October 21, 2013	Discussion on Nicola Tesla, Yougoslavia money, Finish Tesla film, intro to breadboards, capacitor basics	rear wide	1:53:17	front wide	1:08:12		Tesla film, Experiment 8		
		October 23, 2013	Relay Oscilator breadboarding	rear	2:02:05	front (closeup, bench)	1:58:44 S		Experiment 8		Read and/or reread pp. 60-72.
Quiz		October 28, 2013	Teacher gives students materials from PAM, Microwave as a Faraday cage. "This is science" 2013-10-28 14_08_11 (id) 25:55, Time and capacitors, Kickerstarter intro and discussion of	rear	1:50:52	front wide	1:49:34		Students' Relay Oscillator Quiz20131028.pdf, Experiment 9		Read Make: Electronics pp 68-72 and pp 236-238.
		October 30, 2013	Wireless power! Sending electrcity through the air from radio to LED. Oscillator quiz return (teacher explains something that wasn't clear in one of his test questions), oscillator circuit discussion with animation, Caitlin notices second camera for first time, review student's G+ pitch videos, redo for those who didn't do it	rear and OTS of comp screen	1:45:39	front and OTS of comp screen	1:34:06			Student video pitches on G+ (issues with watching them after time has passed on G+).	Review for test on Nov 4th on pp. .1-72 (Exp. 1-9) in Make: Electronics book. Pick a Kickstarter and make a 1-min long pitch for it on G+. Read pp 239-241 in Make: Electronics
Midterm test		November 4, 2013	Midterm Test, begins with discussion to Bobby. When teacher tells him something is not on the test his engement with the conversation changes. Look for cues that students are most concerned about the test and not necessarily the actual process of learning, at 4:05 Bobby asks if a test can be practical (who can make the strongest magnet). Students play with Leap Motion, Santa Monica STEAM Show invitation.	front	1:47:49	none			Midterm Test, Leap Motion, OK Go Music video w/ Rube Goldberg machine, Shaun's childhood videos about Rube Goldberg machines, review student pitch videos		Review for test
Field trip		November 6, 2013	SB Hackerspace Field Trip! decompress after Hackerspace fieldtrip, Review Leap Motion pitch videos	front	28:18:00					Leap Motion pitch videos on G+ (issues with watching them after time has passed on G+). Sill photos and GIF animation on G+	Homework due Wed 11/6: Read Make Electronics pp. 73-82 (Experiment 10); One-minute video blog on "What would you design for the Leap Motion controller?

	Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
Second quarter lab expiriments	November 11, 2013	Bert talks to camera at beginning by himself. Discussion of Dos Pueblos Maker Faire and Rube Goldberg machine project there. Exp. 11 with LED and loudspeaker, discussion of how transistors work	front	1:55:07	rear	1:51:14		Experiment 10: Transistor Switching	Transistor Switching Circuit	
	November 13, 2013	Teacher works with Shaun to help him build breadboard, discussion of amplifiers and semiconductors. Students build breadboards and buzzing circuits	closeup of students working at bench	1:41:04	closeup of Shaun working at bench (2 files)	1:32:03		Expiriment 10-11: A Modular Project		Homework Due Wed 11/13: Read Exp 11 on pp 82-93. Jay is going to like this one! There could be a quiz on 11/13 so please read carefully.
	November 14, 2013	Discussion with Levi and Kimberly at Levi's office about the course.	facing L and K at desk	1:09:42						
	November 18, 2014	Turn back Midterm tests and opportuniuty for grade improvement, finish Expiriment 11	rear and closeup of Caitlin, Ashley, Jay	1:57:01	front and closeup of Shaun over the shoulder	1:56:24		Expirment 11: A Modular Project (cont'd)		Homework Due Mon 11/18: Read Make pp 104-109 on soldering.
Quiz	November 20, 2013	Soldering quiz (technical issues for some logging in), Students get hands-on with Learn to Solder Kits for first time. Basic solder technique	rear	1:42:24	front	1:40:45		Learn to Solder Kit materials	Engrade: soldering quiz	
	November 25, 2013	Students continue soldering kit and begin circuit conctruction	rear	1:48:19	front	1:46:43		Learn to Solder Kit materials		Homework due Mon. 11/25: Read the "Learn to Solder Kit" manual.
	December 2, 2013	Continue circuit soldering	rear	1:46:24	front	1:46:40				
	December 9, 2013	Different classroom! discussion of osciallating circuit, students begin laying out their own soldering breadboard	rear	1:48:54	front	1:49:34		Expiriment 14: A Pulsing Glow		Homework Due Monday 12/9: Read pp. 117-124 in Make: Electronics; Lab Summary of Learn to Solder Kit due.
	December 11, 2013	Students continue working on Expiriment 14 soldering. Circuits begin taking shape, much student narration of work and productive failure	rear and closeups	1:49:32	front and closeups	1:51:58		Expiriment 14: A Pulsing Glow		
	December 16, 2013	Students finish pulsing glow Shaun and teacher discuss his circuit and fixing it at CU 52:43. Teacher: "Do you want my help?" Shaun: "No thanks."	rear and shaun CU	1:42:20	front and closeups	1:46:38				

	Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
Second quarter lab expiriments	December 16, 2013	Students finish pulsing glow Shaun and teacher discuss his circuit and fixing it at CU 52:43. Teacher: "Do you want my help?" Shaun: "No thanks."	rear and shaun CU	1:42:20	front and closeups	1:46:38				
	December 18, 2013	Last day before Winter Break. Trouble shooting, students work on art project. Jay helps Shaun and Bert. Ashley explores how solder sucker works at 42:00	front and left half CU	0:52:35	none		Instructor has good notes on this class			Pulsing Glow Art Projects
	January 6, 2014	Grade updates for students, Chirstmas stories and winter break discussion, Ashley pulsing glow project discussion, prelude to Arduino 27:00, Renasaince video	rear	1:57:46	front	1:48:21				Pulsing Glow Art Projects
	January 8, 2014	Discussion on crystal radio and resonant circuits, end of semester housekeeping, Renasaince video	rear	1:44:00	front	1:45:49				Homework due Wed 1/8: Read Make: Electronics pp 262-267 on building a Crystal Radio.
	January 13, 2014	Continued disucssion on crystal radio and begin construction, some use different materials	rear, courtyard	1:46:41	front	1:48:28		Expiriment 31: One Radio, No Solder, No Power		
	January 15, 2014	First half completing crystal radio, testing them with cold water pipe grounds, intro to open source and Arduino. Bert has excellent excellent explanation of OSS around 1:18:00, continues demonstrating his fluency with computers and software	rear	1:49:10	front	1:49:34				
	SEMESTER BREAK									

		Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
Video or Film	Third quarter Arduino tutorial	February 3, 2014	First day of second semester, timeline review and introduction to Leonardo DaVinci a "renaisance man" disucssion and relationship to STEAM. Discussion of STEAM as a new conceptual model. Watch G+ DaVinci mini Bio, DaVinci 100 questions book activity (preparing the brain), pass out Arduino books, Caitlin asks to read teacher's questions 1:32:00	side	1:59:25	rear	1:55:07	100 questions	How to Think Like Leonardo DaVinci, Getting Started with Arduino	G+ DaVinci mini Bio video, G+ Introduction to Arduino video,	
		February 5, 2014	Second semester Arduino intro and thinking about inventing and solving problems, setting up Arduino kits and installing and exploring the IDE, blinking lights with software is easier in contrast with hardware modification to change blink rate	rear and side computers	1:46:11	front	1:48:47		Getting Started with Arduino	G+ video of Massimo Banzi, the inventor of Arduino□	Homework for Wed 2/5: Read pp (preface) v.-33 in Getting Started with Arduino.
Quiz		February 10, 2014	Pop quiz and Engrade password issues. Quiz review. Quiz as a motivating factor to read in advance of expiriments. "I was wrong 28:50" - teacher, discussion about metric prefixes, More work in exploring Arduino IDE and Processing language, students work in pairs to program an arduino	rear and computers	1:54:49	front and Jay & Robyn	1:50:23	Student notes on IDE	Getting Started with Arduino	Engrade: Arduino Quiz 1. G+ metric prefix chart	Homework Due Monday 2/10: Read through p. 50 in Massimo's Getting Started with Arduino Book
		February 12, 2014	Timeline: Elon musk, Massimo, Limor Fried. Students work more in pairs on arduino projects from Massimo book. Jay & Robyn made most progress. Introduction of the large scale art project	rear and computers	1:50:28	front and Jay & Robyn	1:51:42	Lab summary for ch 4.	Getting Started with Arduino		Homework for Wed 2/12: Read through p. 70 in Arduino book; write lab summary for chapter 4.
		February 26, 2014	Back from February break. Discussion of Steve Jobs, Steve Wozniak and the PC revolution as a homegrown movement. Elegence of Woz's simplicity. Teacher talks about trip to Cuba. Discussion about open source, ownership of hardware, software and IP as a consumer. More brainstorming and discussion about art installation. Students research online in class.	rear	1:49:14	front and Jay computer for online research	1:47:04	Instructor notes	Steve Wozniak TED Talk	Student blog posts, Instructor URL resources for other DIY projects	Homework: Finish reading Massimo Arduino book. Blog G+ post one idea for an art installation based on Arduino (see 2/12/14 rear at 1:41:00 and STEAM Lab Group Project Elec. Art Installation.doc)

		Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
	Project design, planning and tinkering	March 3, 2014	Instructor shows students "Edison" art from scrap. Introduction of MCA visit. Revisit assignment and fit into engineering model (rear 8:00:00). Homework for March 10 assigned. Hacker Principles discussed. Students talk about ideas. Robyn reveals her piano idea! (front 00:35:27) Students read Make magazine and look for ideas. Make notes in notebooks	rear	1:48:57	front	1:51:49	Notes			Homework for Monday 3/3: Keep thinking about your ideas and how you might accomplish an interactive art installation to meet the requirements of the project. You will have time Monday in class to do some additional "background research" and "brainstorm" your idea. Be ready to defend your plan to the group by the end of the class meeting. Be ready with resources (ie other projects with a code base we can draw from) that give us a headstart. Our goal will be to evaluate all of the ideas brought to the table and choose a solution(s) by the end of the class period on Monday.
Field trip		March 5, 2014	Museum of Contemporary Art visit	Stills on Google Photo							
		March 10, 2014	Discussion on board of student ideas, grid with different students. Students and instructor debate merits of different projects and negotiate final selection. Doug is scared at rear 1:26:50. Caitlin: "Can we all just agree we are going to do the piano?" at rear 1:29:30. All agree. Delegation of duties follows. Instructor talks about "iterative and recursive process" Rear 1:32:05. Framing of project by instructor. Students seem to agree on Robyn's idea despite her absence. Students begin research online. Caitlin finds relevant Arduino code rear 1:34:40. Discussion on design of piano and specifications. Caitlin finds video on interfacing Arduino with Garage Band rear 1:38:00. Great dialog between students! Caitlin's suggestion becomes the homework for the class at rear 1:55:00.	Rear	2:00:25	Front	1:58:41			Photo of whiteboard grid in Google photos	Homework due 3/10: Complete your background research and using your research notes, create a Project Proposal in your notebook based on what you have discovered. Your Project Proposal should include: 1. A small sketch or map of the site location 2. Materials list 3. Comparable or similar projects to draw on (web links or references) 4. Outline/explanation of construction process 5. Arduino source code to hack

	Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
Project design, planning and tinkering	March 12, 2014	Intent was to break out students into groups. Jay asks about the UCSB research project at 00:00:22. Jay discusses the materials research he has done at 00:03:30. Instructor explains structure 00:06:00. Robyn explains her idea to group at 00:07:00. Instructor and students develop plan for materials. Discussion about goal of group project followed by individual project 00:23:00. This ultimatly doesn't happen as time runs out at end of year. "What's our budget?" 00:30:50. Jay draws designs on whiteboard 00:52:00. Groups begin to self-form as students begin self-directed research.	Front	1:40:19					Instructables piano project for musical	Come up with a solution to building the piano's electronic sensors
	March 19, 2014	Intrsuctor shares his research into plexiglass and frames discussion. He lays out plans and presents challenges to design, demesnions and materials. Students discuss. Instructor makes mistake in sample plexi size. Students use graph paper to draw design for glass cutter. Caitlin begins work on interfaces: "That looks really scary! I'm excited, though, actually." Bert does Makey-Makey research, buttons, lights. Students explore materials. Caitlin shares her research with instructor 01:10:00 (Cam 1). Jay is missing	East Front	1:45:54	West Front	1:14:52	Graph paper drawing of piano			
	March 31, 2014	Front 00:02:00 Ashley explains drawing to Jay. El Wire introduced. Robyn absent due to suspension. Ashley, Robyn and Jay work together on design and materials list. Present detailed materials list. Shaun was persistent and patient developing button prototype but worked very slowly and encountered challenges. Bobby, at intructor's suggestion, assisted Shaun and they were successful in building button prototypes with Arduino together Rear 01:38:00. Bert sucessfully built a working circuit to test LED strips. Group discovered that power supply was not powerful to provide the amperage required for all three colors in the RGB LED strip. **Much collaboration working across groups.	Front	1:47:49	Rear	1:50:01	Instructor has detailed class summary in his notebook			

	Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
Construction	April 7, 2014	Idea from Makey-Makey research by Bert, shifts focus from MIDI to USB keyboard design. Caitlin and Bert work together on Makey-Makey Front/Outside 00:16:17 and 01:03:00. Caitlin and instructor talk through concept for USB keyboard 01:07:00. Instructor shops for materials before next class.	Rear	1:59:14	Front/Outside	1:54:08				HOMEWORK: Don't forget to leave your Lab Notebook in my box by tomorrow, Tues. April 8 so that I can have grades in on time.
	April 9, 2014	Strategy for funding acquision at front 00:02:50. Jay, Robyn and Ashley quickly built a full-size key in the courtyard. Safety issues! Application of contact paper to keys. Bobby worked on sensors and Arduino IDE coding with Bert and Shaun. Some soldering by Bert. Caitlin and instructor discuss the Uno vs Leonardo 00:35:00 (sound only). Caitlin is excited to see LEDs on 00:50:45 Bobby is on the hunt for sensors to activate the keys. ANSEC Student says she feels ripped off at Rear 01:16:10	Rear/Outside	1:45:56	Front/ Classroom Rover	1:45:50	Instructor has detailed class summary in his notebook			
	April 14, 2014	Many students were an hour late due to a conflict. Instrcutor spent first half of class working with Bert, Shaun, Bobby and Ashley. Bobby and Instructor look at switching mechanism. Remaining students join and pick up from there with design challenges and materials. Caitlin works on Arduino code. Instructor advises her.	Rear	1:49:23	Front	1:47:25	Instructor has some notes and summary in his notebook			
	April 16, 2014	Key construction continues led by Jay. Cailin works dilligently on code. Bert and Ashley work on LEDs. Shaun solders headers onto Matrix. Much excitement for two major breakthroughs: key prototype working and USB keyboard code coming together.	Rear	1:39:01	Front, Cailin, Table	1:41:35	Instructor has some notes and summary in his notebook			
	April 23, 2014	Construction. Bobby and instructor look at matrix. Jay completes key. Judith and Kimberly visit. Q&A with students Rear 1:16:00	Rear	1:48:56	Front	1:41:29				
	April 28, 2014	Integration day! Bobby and Caitlin collaborate for one of the first times to interface hardware switching with software USB keyboard code. Shaun, Bert and Jay integrate lights and key. Front 1:12:00 So close but so far away disucssion with instructor, Caitlin and Bobby.	Rear & Key Const	1:52:38	Front & Computer	1:51:10				

	Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
Construction	April 30, 2014	Final assembly of first key and electronics. Success! Students get key working with lights and sound. Overcoming floating pins on Arduino (Caitlin). Headmaster comes in for presentation.	Rear	1:55:30	Front	1:52:34	Instructor has some notes and summary in his notebook			
	May 5, 2014	One working unit, need to make more! Finish work discussion and details of assembly. Assembly line in courtyard. Caitlin works on soldering matrix and transistor bus. Yields to Francis 1:28:00, then they work together.	Rear & Caitlin	1:48:59	Front & Outside	1:49:26				
	May 7, 2014	Bert starts looking at video footage, Caitlin continues her work on the matrix and soldering the bus. Instructor and Caitlin troubleshoot code. Remaining students work on assembly line.	2014-05-07 14_13_28 (id) Rear, Bert & Caitlin	1:53:36	Front & Outside 2014-05-07 14_09_45 (id)	1:55:31				
	May 7, 2014	After school work party assembly line. Caitlin shows her brother her work, explains it and gets him involved in helping.	2014-05-07 16_07_06 (id) Caitlin	2:47:57	2014-05-07 16_05_18 (id) Outside	2:46:51				
	May 12, 2014	Key assembly continues. Caitlin and instructor troubleshoot matrix and bus where some keys are not working. Hardware and software debugging.	Outside	2:14:06	Inside	1:45:53				
	May 14, 2014	Ashley and Robyn lay down contact paper on glass. Shaun solders LEDs. Caitlin and instructor continue to troubleshoot and debug together.	Inside	2:51:29						
	May 14, 2014	After school work party assembly line building frames. Bobby and Jay do most of the work. Others don't stay. Bert solders connectors.	Outside	1:54:55	Inside	0:33:59				

		Date	Themes	Camera 1	Length	Camera 2	Length	Notebooks	Book and Activities	Online Data or Media	Assignments Due
		May 19, 2014	Caitlin continues working dilligently. Assembly continues with painting	Caitlin Inside	1:38:31	Outside	2:07:00				
After hours		May 19, 2014	After school work party. Slow progress. No Caitlin. Shaun's mother stops in.	Inside	0:48:51	Outside	0:56:46				
		May 20, 2014	After school work party. Mostly LED assembly with Shaun showing his friend what he is working on.	Inside	1:27:50						
		May 21, 2014	Indoor work. LED array assembly. Caitlin continues work with some assistance from Bert.	Inside	1:42:30						
After hours		May 24, 2014	Saturday work party. Instructor smokes Caitlin's board with overvoltage! Jay and Shaun construct keys.	Inside	2:42:58						
		May 28, 2016	Last Day! Students complete end-of-course surveys. Discussion of modidied plan for art show 00:12:13. Will display three kets. Lara recovers from damage done by instructor around same time and thanks instructor. Team continues constructing keys. Continues recording through to be additional angle to after school recording.	Rear	0:57:42	Front/ Caitlin	2:18:36				
				(two files)	1:23:45						
After hours			after school work to prep, Caitlin can't get bus working after instrcutors "repairs"	2014-05-28 15_00_56 (id)	1:19:16						
	Art show		Art show, visitors explore piano	2014-05-28 18_06_31 (id)							
				2014-05-28 18_40_03 (id)							

Table A2

Timeline Across Four Major Cycles of Development for School-Based STEM Program

Date	Description	Quote/Summary	Actors	Places	Topics	Actions	Followup	Source	Rationale For Choosing
Oct. 19, 2010	First email chain from teacher to founding student about formation of Near Space Exploration Club.	"It seems with a relativly small budget one can launch a weather balloon into the upper atmosphere...(it would be) very awesome to get a photo of the curvature of the earth and a black sky. I was thinking of seeing if there was any interest from students at Anacapa in putting together a group to launch an "Anacapa Space Campaign" and I immediately thought of you. Is this something you would want to help me lead? -teacher	teacher, student	virtual space	STEM, space, atmosphere, student leadership	emailing, framing as student-led	teacher and student negotiate a start "I don't know how to approach it just yet. I am worried that it is beyond the scope of a club but maybe not. Let's talk more about it in person and then we can talk to (the headmaster) and see what he thinks." -teacher	personal email archive	Seeking the original proposal of the project by the teacher to student
Oct. 26., 2010	Faculty Meeting minutes	Brief description of first discussion of near space project with faculty.	teachers, administrators	faculty meeting room	logistics, students, FAA regulations	planning, collaborating, developing	teacher takes list of suggested students and builds afterschool team	official faculty meeting minutes	seeking the original discusion of the initiative with the faculty and student
Oct. 28, 2010	Printed memo invitation to first group of students	"I am assembling a dedicated team of bright Anacapa students to spearhead The Anacapa Space Race, a special project this year at the Anacapa School. More than a club, our group will design and build a near-space probe and launch it aboard a professional-grade weather balloon. The project will require us to learn practical techniques in wireless communications, electronics, weather prediction and a host of other skills. Throughout the project we will work with NOAA and the National Weather Service, the Federal Aviation Administration as well as others with relevant authority and experience in the field. In the end we will have had the once in a lifetime experience of launching one of the few private near-space probes and hopefully returning some amazing pictures and weather data." -teacher	teacher, students	virtual space		personally delivering to students	Organizing first meeting	personal archive	Seeking to make visible the proposal to the original group of students.

Date	Description	Quote/Summary	Actors	Places	Topics	Actions	Followup	Source	Rationale For Choosing
May 21, 2001	First high-altitude balloon launch	We worked so hard on this project," said one female student participant. "It was such an amazing feeling to see the capsule back on the ground and to know that we had done it!"	students, teacher, headmaster, parents	Shandon, Calif.		setup, launching, tracking, recovering	students analyized scientific data and photos	online news release on school web site of the development of STEM program	Seeking textual/electronic evidence and documents inscribing the origins of the "Near Space Exlporation Club"
May 2, 2012	First email from teacher to headmaster about possible ARISS participation	This could be a really cool opportunity. I would like to apply to have Anacapa be the host of a real-time radio contact with the International Space Station. Included forwarded annoucnement of proposal acceptance from NASA/ARRL	teacher, headmaster	virtual space	education, promotion of school, collaboration among independent schools	planning	tecaher applied for participation in the ARISS program	personal email archive	first records of teacher's shift away from balloon program toward full-school and interschool inclusion.
May 5, 2012	Second high-altitude balloon launch	"Our initial projections showed that it would touch down near Taft," said a male student participant. "We never expected it to climb so high and stay there for so long!"	students, teacher, headmaster, parents, amateur radio operators	New Cuyama, Calif.		setup, launching, tracking, video and data live downlinking, recovering	students analyized scientific data (temp. pressure and humidity) and photos, teacher compiled video	online news release, compliation video	creating timeline and documenting student experiences
June 11, 2012	YouTube video summary published	A 4:35 video created by the teacher summarizing the ANSEC initiative with particular focuson on AAHAB-2.	Teacher, students	virtual space		compliation of video and photos from thoughout the project	Sent to QST magazine and awarded amaetur radio video of the year	https://youtu.be/snD6ydf5jTA	summarizes project in teacher's own words
July, 2 2012	ARISS proposal sent to NASA	"The [school] faculty has collaborated to create a unified ARISS curriculum for the 2012-2013 school year. We will build off of this opportunity to integrate space exploration themes into the comprehensive curriculum plan in which the [Near Space Club] and its member Amateur Radio operators will host the ARISS contact event for the entire [school] student body and special guests in attendance"	NASA, ARISS, teacher, students, faculty, school admininstration, parents, astronauts	virtual space	logistics and planning, educational goals, curriculum	proposing, planning	school was selected in August to participate in ARISS program	personal email archive	proposal document was authored by the teacher and shows teachers planning and rationale at the time

Date	Description	Quote/Summary	Actors	Places	Topics	Actions	Followup	Source	Rationale For Choosing
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Aug 22, 2012	Teacher announced to faculty NASA's selection of the school for participation in the Amateur Radio on the International Space Station/Teaching From Space program	Response from a fellow teacher by email "Let me know what I can do to help integrate, coordinate, expand, educate, amplify and whatever else we can do to maximize this opportunity for the school and for whomever else might benefit. "	students, teachers, headmaster, administrators, parents, community members, NASA, ARRL	virtual space		preparing, presenting, supporting	teachers followed up with congratulatory messages and offers to help	email chain	documenting outside recognition by US space agency
Jan 28, 2013	Visit by astronaut Rick Linnehan to Anacapa School and public presentation	"You (the students) ask better questions than most people ever ask, including most adults I talk to." - Astronaut Rick Linnehan	students, teachers, headmaster, administrators, parents, community	school campus and public library		presenting / Q&A sharing, collaborting, talking		news release, video https://youtu.be/yyidUl-YIKc	Showing expansion of STEM initiative to reach entire school and into community
Mar 27, 2013	first teacher's journal entry	"Why should students care about STEM?; Develop a course that gives students the tools to create, ask questions … build. Not to be afraid to make mistakes.; The next 30 years will be as distruptive as the past 200.; Consumer products vs "maker" products.; Brainstorm ways to get student "buy-in" to the work. Motivation to learn so that knowledge can be applied to attain goals. (first balloon launcg) is an alegory to life ... an idea realized."	teacher		STEM, maker culture, reflexive reference to personal history	developing ideas, writing, analyzing		p.1 of journal	Tracing roots of reconceptulization of STEM program from after school to school day.

Date	Description	Quote/Summary	Actors	Places	Topics	Actions	Followup	Source	Rationale For Choosing
Mar 30, 2017	second teacher's journal entry	"common thread in my projects: teachers do not have to be experts/have (direct) experience with the materials used in technology expiriments, only a basic working knowledge and framework for exploration with which to scaffold student learning/hands-on work. It may be possible to apply the model of (the balloon projects) where students and teachers are co-dioscoverers."	teacher		teacher knowledge			p.2	Showing teacher's conceptualization of course structure
Apr 17, 2013	teacher's journal entry	"one day of class, one day of lab"	teacher		struggling to form course structure	writing and thinking	met with research advisor	p.2	situate a starting point for conceptualization of course and early challenges
Apr 23, 2017	teacher's journal entry	STEAMLab name appears for first time. Teacher and his research advisor discuss possibilities for a reconceptualization of the STEM/Near Space program as a course. Advisor recommended reading first line of Harlow's dissertation.	teacher, advisor	lunch table	naming STEAM Lab		Teacher looked up Harlow's dissertation: "As educational researchers and teacher educators, we have the responsibility to help teachers gain the skills and knowledge necessary to provide meaningful learning activities for their students. For elementary school science, this means helping teachers create situations in which children can participate in the practices associated with scientific inquiry." -Harlow	p.2	Key moment for early conceptualization; naming of course
Apr 24, 2017	teacher's journal entry and notes from Near Space meeting	Students seem interested in branching out from balloon for next year. Ideas: weather buoy, webcam, tv transmitter, submarine, uav. Idea for demonstrating concepts as expiriments as a tool for teaching. "Artists can be engineers too!"	current STEM students, teacher	classroom	science, exploration	discussing, documenting	meet with headmaster to understand his considerations	p.3	shows teacher soliciting collaboration once again

Date	Description	Quote/Summary	Actors	Places	Topics	Actions	Followup	Source	Rationale For Choosing
May 7, 2013	teachers journal entry	note about adopting the art teachers timeline in STEAMLab	art teacher, teacher	classroom	art and historical figures	adopting and adapting	6/3/13 on p.7 shows further development of this idea	p.4	showing adaption and adoption of other teachers practices
May 10, 2017	teacher's journal entry and notes from meeting with headmaster	considerations: UC course approval, expeditionary learing, creating a "bucket" of resources, involve guest instructors	teacher, headmaster	school campus	resources and supports	discussing, documenting		p.4	shows teacher's efforts to understand supports and constraints from admin
May 14, 2017	notes from faculty meeting and input from other teachers	Physics teacher suggested expeditionary learning course	teacher, other teachers, admini-strators	faculty meeting	approaches to course development	discussing, documenting		p.6	shows teacher soliciting collaboration and suggestions for sucessful deployment
May 22, 2017	Amateur radio contact with the International Space Station	"I've never been a super sciency type so this has been pretty cool to do. Science hasn't always been my thing but its been really fun learning about this." -student participant	high school and middle school students, elementary school students from another school, teachers, headmaster, journalists, host company employees, administrators, parents, community members, NASA, ARRL, amateur radio operator volunteers		different ways of engaging with science not just becoming a scientist but seeing science in new ways	preparing questions,	TV new coverage, feedback on the experience and evaluations from faculty and students was sent to NASA	video https://youtu.be/3XiLrwmoKmM	

Date	Description	Quote/Summary	Actors	Places	Topics	Actions	Followup	Source	Rationale For Choosing
June 3, 2017	notes from meeting with head of faculty	students becoming part of the maker movement; become a creator, not merely a consumer; STEAM Lab as a way to introduce students to inventors and artists	teacher, head of faculty	school campus	grading, structure, curriculum	discussing, documenting		p.7	
June 13, 2017	teacher's journal entry from faculty meeting	questions about how to financially support the course arose; the need to understand in advance which materials will be needed and structuring a lab fee were proposed	teachers, administrators	school campus	finances	discussing, documenting	teacher would later explore Make Magazine's maker kits through Radio Shack as a way to ensure costs were defined and managed for labs. See p.10 on 6/18/13	p.9	
June 13, 2017	teacher's journal entry from call with CalPoly prof. Dennis	Dennis Derickson Ph.D. used amateur radio exam as his intro to EE final exam. Giving students the ability to expiriment with radio under this license has led to student-led activities and a campus club	teacher, professor	Call took place at school campus	amateur radio, testing/exams, curriculum				

Appendix B

Synthesis Unit Schedule

2012-2013 Synthesis Unit

Space: Where Are We Going?

Monday, January 28, 2013

8:00 a.m. Levi Maaia, Teacher and Synthesis Unit Coordinator
Space: Where Have We Been?
9:00 a.m. Matteo Cantiello, Ph.D., Research Fellow, Kavli Institute for Theoretical Physics, UCSB
Stars: Life, Death, and the Origin of Elements
10:00 a.m. Danica Marsden, Ph.D., Postdoctoral Researcher, Department of Physics and Astronomy, UCSB / Keck Institute for Space Studies, California Institute of Technology and Jet Propulsion Laborato
Telescopes and the Universe
11:00 a.m. Philip Lubin, Ph.D., Professor, Department of Physics, UCSB
Origin, Evolution, and Fate of our Universe - Current Status
1:00 p.m. FILM: When We Left Earth
Episode 5: The Shuttle
2:00 p.m. Richard Linnehan, D.V.M., Astronaut, NASA
Life as an Astronaut
7:00 p.m. **PUBLIC PRESENTATION**, Faulkner Gallery, Santa Barbara Public Library
Richard Linnehan, D.V.M., Astronaut, NASA
The Future of Human Spaceflight

Tuesday, January 29, 2013

8:00 a.m. Kristy Johnson, Astronomy Instructor, Department of Earth and Planetary Sciences, SBCC
Ancient Astronomy: The Intersection of Heaven and Earth
9:00 a.m. Michael Johnson, Graduate Student, Department of Physics, UCSB
Pulsars and the Search for Little Green Men
10:00 a.m. Nathan Walker, Design Engineer, ATK Space
How to Power Your Spaceship
11:00 a.m. **FIELD TRIP:** Vandenberg Air Force Base
Larry Hill, Chief, Community Relations, 30th Space Wing, Vandenberg Air Force Base

Wednesday, January 30, 2013

8:00 a.m. Jack Stuster, Ph.D., Principal Scientist, Anacapa Sciences
Getting Along in Space: Results of the Journals Flight Experiment
9:00 a.m. Members of the Near Space Exploration Club
Contacting the International Space Station (ISS) with Ham Radio
10:00 a.m. Michael McGee, Surveying Engineer and Consultant, McGee Surveying Consulting
Mapping the Earth from Space
11:00 a.m. Derek Dunn-Rankin, Ph.D., Professor and Chair, Department of Mechanical and Aerospace Engineering, University of California, Irvine
Flames in Space: Microgravity Combustion Science
1:00 p.m. Warren Rogers, Ph.D., Professor, Physics Department, Westmont College
Creation of the Elements in Stars
2:00 p.m. Eric Belle, Systems Engineer, Raytheon Company / International Council on Systems Engineering
Space-Based Remote Sensing Systems
7:00 p.m. **STARGAZING PARTY!** on campus
Chuck McPartlin, Outreach Officer, Santa Barbara Astronomical Unit

Appendix C

Example of Teacher Dialogue

	speaker	*teacher discourse*	*students discourse*	*students discourse*	*students discourse*	*artifact*	*Developing references/actions*
1.	Teacher	the other thing I have for you guys are your journals				engineering journals	introducing journals that he will give them
2.		where are they					
3.		oh here they are					*looking for journals*
4.							*reaching for journals*
5.		so remember I talked about the journals					*Holds up bundle of blank journals for students to see*
6.		our engineering journals					HN--referring to previous mention during informal 10-minute meeting that happened before class (1 week earlier) naming type of journal referenced as "Engineering Journal"
7.		So again					
8.		part of this					
9.	Shaun		can we write our names on here *points to cover*				recognizing process but requesting clarification
10.	T	Yeah, you can write first					
11.		and last names on this					
12.	Bobby			Are you allowed to write your initials?			recognizing process but requesting clarification
13.	T	No					
14.		You should write					
15.		at least "Bobby"					
16.		or-					
17.	Jay				engineers don't use initials		
18.	Shaun		can we use um– would a Sharpie be useful?			marker	recognizing process but requesting clarification

	speaker	***teacher discourse***	***students discourse***	***students discourse***	***students discourse***	***artifact***	***Developing references/actions***
20.	Shaun		would it smear?				
21.	T	It shouldn't					
22.		after it dries.					
23.		mine's not smearing.					
24.		*pause*					
25.		So					
26.		what goes in the journals?				engineering journals	
27.		*pause*					
28.							
29.		what goes in the journals?					
30.	Jay				notes		
31.					everything		
32.	T	notes					
33.		notes from class					
34.		what I would encourage you to do					
35.		is every day					
36.	Bobby to student			can I borrow your pen			
37.	T	write a date					
38.		that's what I do with my journal.					
39.		this is the journal that I keep					*holding up his own journal*
40.		for my research.					
41.		and I write the date					
42.							
43.		and then I just start writing stuff					
44.		and then					
45.		the next day I'll write the date					
46.		even if it's mid page					
47.							
48.		I'll use back and front					*showing pages from his journal*
49.		I'll draw diagrams					

	speaker	*teacher discourse*	*students discourse*	*students discourse*	*students discourse*	*artifact*	*Developing references/actions*
50.		I'll make note of anything that hap-					
51.		anything interesting that happens that day.					
52.		I put my course notes in here					
53.		so I know what I am going to talk about with you guys					
54.		so I would do the same thing					
55.		if I were you					
56.		is write your date on the top of the first page					
57.	Shaun		your date?				
58.	T	*the* date					*smiling*
59.		on the top of *your* first page					
60.		and then					
61.		um					
62.		use it to keep track of some of the things we talk about					
63.		if, uh, we					
64.		show a web site					
65.		or a video you want					
66.		to remember to look at later					
67.		you could write that down on here					
68.		um, anything that you think might be important					
69.		for					
70.		a quiz or a test that we might have in the class					
71.		um					
72.		as you're doing research about some things					
73.		you might want to take notes about that					

	speaker	teacher discourse	students discourse	students discourse	students discourse	artifact	Developing references/actions
74.		or if you look things up online so use it for everything					
75.		just use it for everything					
76.		if you have questions for me					
77.		you can write them in here					
78.		you might even write like: "question for Levi"					
79.		and then write, write the question					
80.		and I'm gonna look through these					
81.		every week or so and I'll write back to you					
82.		so if you have a question for me					
83.		leave a little space for me to answer					
84.		and then					
85.		I can write					
86.		an answer					
87.		for you in there too					
88.		um					
89.		I might give you assignments					
90.		I might say "hey for homework					
91.		you're gonna write in your journal					
92.		and respond to this"					
93.		or I might say				Google Plus Community	
94.		that					
95.		you should write					
96.		on					
97.		the					

Appendix D

Transcript: Makey Makey with Bert and Caitlin

17:53:00
Bert and Caitlin sit at Mac computer side-by-side
Bert: (opens Makey-Makey box and removes wires and board)
those are just stickers
(points to stickers in bottom of box)
Caitlin (lifts box and looks inside)
did you just get this?
B: did I just get this?
no
[I]
C: [or were you playing with this last time?]
B: I was playing with this last time
C: This is awesome
B: I
um
let me get this out for a second
(reaches for and opens small plastic bag and begins assembling the board)
C: these are so cute (as she looks at stickers)
I like stickers (looks at camera and quickly looks away)
but where does the sound come from?
B: the sound?
well the sound doesn't necessarily come from this
there is a program on the site that allows you to play music but
I mean
this'll just be the controller we'll be using
the sensor kinda thing
(reaches behind computer to plug in USB cable for Makey-Makey)
C: sorry (raises eyebrows)
B: no (smiles)
it's alright (not clear what happened)
C: do you want me to help you with anything
B: (stands up to plug in USB cable)
I've-
got it for right now
C: this is a really good idea
B: oh
really?
C: oh yeah
(continues to explore the pieces from the box)
B: (loads online software for Makey-Makey)
(clips wires to board)
C: (inches closer to Bert)
so you hooked this up once already?
(moves mouse away from edge of desk)
B: well [yes]
(computer screen jumps as Bert attaches wires to connected Makey-Makey)

C: [woah]
was that me?
I’m sorry
B: no
C: oh
that’s good
B: so if you hold this
I mean if this is plugged in there
and you hold onto this
you press
you press
you know
whatever
(controls screen with Makey-Makey)
C: oh
you’re controlling it?
whoah!
can I try?
B: yeah
C: (reaches over to touch board)
wait
oh
you have to go up
B: (hands Caitlin the ground wire)
C: oh
I have to hold this?
(pause)
ohmygod
wait
is electricity going through me?
B: um
I-
don’t know
actually
C: um
Levi
Teacher: yeah?
C: is it going through me?
Teacher: uh
well
(continues to talk to other student he was previously engaged with off camera)
so that happens to be a very sensitive switch
I’ll come explain it
in a minute
to you guys
C: (continues to fiddle with board and wires)

so cool
(pause)
I’m trying to click “bongo”
but it’s really hard
B: reaches for mouse to click
C: no
I don’t actually want to see it
I just want to see if I can click it
B: oh
C: (pause)
this is really cool
B: (unintelligible)
C: wait
wait
if I hook up this up
to like
this box
does it work with the box?
B: well it works if-
C: (attaches wire to cardboard Makey-Makey box)
B: I mean it has to be conductive enough
or else it won’t work
C: so where does this go?
B: this go-
um-
C: to the ground
should I just hold it?
I can just keep holding [it]
B: [yeah]
you can just hold onto it for right now
and
then we need
something conductive
um
Levi?
T: yes sir?
B: do you have anything
kinda like the oranges we used last time
C: the box won’t work?
T: there might be oranges out there
B: oh
C: oh yeah
there are
do you want me to grab one?
B: oh
I mean

if you want to
C: wait
but I still don’t understand how they make sound
(leaves room to retrieve oranges)
22:10;00

22:46;00
C: (returns juggling several oranges)
(unintelligible)
B: (plays notes on computer piano application using Makey-Makey)
C: is it being played from the-?
B: oh
yeah
Jay: (walks in from outside)
if all goes bad
Caitlin, if all goes bad
you know what we should do?
Caitlin: what?
J: is just have you sit in the corner
with a keypad
and every time someone touches it
or something
you just hit a button
so it looks like their playing
C: (nods and smiles)
why does it have to be me?
J: (unintelligible)
C: (sits back down next to Bert at computer)
B: see you can connect things to it
C: but we only have
we only have here
one two three four five six
B: yeah that’s the main problem with the Makey Makey
(the two continue to play with wires and explore)
B: oh
I see (unintelligible)
see that’s
connected to space (spacebar key)
(long pause)
now connect this
orange (reaches for orange)
(continue to play with oranges as keys)
C: That doesn’t work
does it?
(long pause as they continue to tinker)
Levi?

(takes lead and orange from Bert)
wait
B: wait
doesn’t that (unintelligible)
no
C: I don’t know
should we just stick it all the way in though?
B: um
if you want
C: (sets up new configuration)
ohh
yes
I could do this all day
so cool
you get that one
(hands one orange back to Bert)
we can hook up more?
B: yeah
it’s possible
C: ok
so
what do we do?
(unintelligible)
do we just go straight into the orange?
B: yes
exactly the way you did it
(hands Caitlin the lead)
C: do I have to hold it?
or can we-
where can we put this?
so that it’ll always be-
B: like
I don’t know
actually
C: (puts lead on another object)
doesn’t work here
(pause)
let me try
(pause)
I have to hold it for it to play
(hands lead to Bert)
and if you hold it
it works for you
(tinkering)
B: (unintelligible)
C: yeah

ok
play away
(both laugh and continue to tinker, playing notes on computer piano synth
(looks back toward teacher)
no (reaction)?
Levi
do you have any ideas about how we could start working
to get this to have more keys?
Teacher: (chuckles)
C: this is so cool
T: [so]
C: [but even still]
it's not loud
but we could also have [speakers]
T: [try op-]
yeah
you could always have speakers
um
try opening Garage Band and seeing if you can get it to do the same thing
C: ok
B: oh
ok
C: have you done this on Monday already?
B: well
yeah
I did (unintelligible)
C: but you didn't try to do it again
B: I don't think I've used Garage band period
C: ever
oh my god
I don't think I've ever used it to do something I've actually wanted to do
B: oh really?
C: I don't understand how it works
(Caitlin touches lead to Bert's leg while both touch oranges)
(piano sounds)
oh my god
we can both play now
(laughs)
so cool
(opens garage band)
B: but how do we set it to certain keys?
C: oh sorry (drops lead)
B: sorry
(pause)
(raises hand and looks back toward teacher)
Levi?

(drops hand)
C: whoa
where did the keyboard go?
(tinkers in Garage Band)
oh
it’s gone from this (the sound is no longer playing in the web application)
(long pause as they tinker quietly in Garage Band)
31:00;00

32:15;00
Bobby: (has come over from his workspace to see what Bert and Caitlin are doing)
Caitlin: this is cool
(unintelligible)
watch this
(opens up original Makey-Makey piano so show how it works with oranges)
Bobby: that’s so cool
(returns to his workspace)
Caitlin: (looks back toward teacher)
hey Jay
Jay: (off camera) wuddup?
Caitlin: look
I can play oranges
and I bet you if you try to play them
it won’t work (because he would not be holding the grounding lead)
try playing
Jay: one sec
(walks over to Caitlin and Bert)
(unintelligible)
Caitlin: this
try one
oh
I’m sorry
it doesn’t work for you
(chuckles)
Jay: (unintelligible)
Caitlin: because I was holding the wire
Jay: oh
let me do it
(touches Caitlin and plays note)
oh yeah (smiles)
(walks away)
Caitlin: wait
if you just touch me
it works?
Jay: yeah
‘cause you grabbed it

that's why if you hold someone
and you touch a power line
you'll get shocked too
Caitlin: (hands Bert lead)
you hold it
and I can still-
(plays notes on oranges while touching Bert's hand)
Bert: (simultaneously plays notes)
Caitlin ahhh
(looks back toward teacher then looks away)
ok
we don't need any help
(unintelligible)
33:52;00

(both tinker for a couple of minutes)

34:27;00
C: ohhh-
here's the deal
if we could find a way
(pause)
if Garage Band can play with arrow keys
(pause)
B: ok
C: and space keys
(plays notes)
then
we can play with these
B: or if we can remap these keys
like "A" equals "S"
C: exactly
to be what we need them
but its still not enough keys
(pause)
if we buy a whole-
(snaps fingers)
if we know how to remap them
its easy
we just get another one and have two sets
B: yeah
C: one two three four five six
(unintelligible)
but still
the trick is how to remap them
B: yeah

C: do you think it would work?
B: and if we could re-
C: (reaches for instruction sheet, unfolds and reads)
and if we could
link it to
how would it
would they both be on the same controller?
would Garage Band even recognize two controllers?
35:25;00

40:15;00
C: we don't know where to start
because
(unintelligible)
the computer actually thinks that when you press it
you're pressing the arrows and the space keys
T: ok
C: and so if you could like
change that
T: ok
C: [because]
T: [have you gone into Garage Band]
C: [yeah]
and if in Garage Band you just like press and "A"
T: yeah
C: on the keyboard
then it'll play a note
but
they're just arrows and
the instructions doesn't say anything
T: it doesn't say that you can change them?
and the arrows aren't they keys you can use in Garage Band?
C: [yeah]
T: [ok]
so
C: and I'll probably need two more sets of this
to get them to work
T: right
so
is there a way to make an Arduino
do exactly the same thing?
'cause this is an Arduino and its
and someone just programmed it and they picked those
those keys
so
you want to create an Arduino

that all it does is
instead of like what these guys are doing
is they're building
they're building buttons that make lights come on
can you press-
can you make it so that when you press a button on the Arduno
or you link in a button to the Arduino
that it sends that key
to the keyboard?
and then you can assign that key?
(long pause)
C: (whining unintelligibly)
T: 'casue you're what?
C: 'cause I'm like
giving up that
T: oh
the MIDI project?//
C: //yeah
T: well//
C: //you don't think that'll work
huh?
T: I think you're free to do it either way you want
C: ok
so we should hook both of ours up together?
I don't know what to do
C: we should
we should try this
T: I know what you mean
the MIDI is probably
I think MIDI is one way to do it
and then this is another way to do it
I don't know which one is easier
C: wait
so what do we look up?
T: so you're really trying to create an Arduino keyboard
make your own Arduino keyboard
someone must have done this
you know?
in fact
I know that people took old
(is distracted by another student and a key construction problem
42:05;00

45:50;00
C: do you have any suggestions?
B: those were pretty much

were all the suggestions I made
C: but I mean this is such a good start
I feel like you've done everything
(unintelligible)
(opens web page on computer)
46:50;00

01:04:33;00
B: (looking at Makey-Makey sheet)
C: (looking at Garage Band)
Levi
could we do anything with outputs?
Teacher: no
they have to be inputs.
(long pause)
so my-
thinking
guys
is that
this
let's see
yeah
this thing is basically a m-
highly modified Arduno
and that there's got to be code out there that exists
that you can make your own Arduino-
C: but nothing that makes noise
yeah
a bunch of them that have keyboards
T: yeah?
C: where you press it and it makes something from a little mini speaker
but nothing that-
T: no no no
um
I'm sorry
B: you could hook it up to Garage Band maybe
T: a keyboard
a computer keyboard
an Arduino that makes a computer keyboard
does that make-
I should have said that
yeah
there's probably a bunch of Arduno
keyboards that like
musical keyboards
(is distracted by another student and a key construction problem)

C: (goes to Google)
hey this is probably really easy
(reads aloud a description of Arduino code)
wait is-
this is what I want?

T: let's see
what does it say?
(reads aloud a description of Arduino code)
why would you want that

C: I don't know
so that's not what we want?

T: well
it's kind of
(reads aloud a description of Arduino code)

C: the Arduino takes over your keyboard

T: yeah
(reads aloud a description of Arduino code)

C: what's that mean

T: (reads aloud a description of Arduino code)
well
you could just unplug the Arduino if it starts taking over your computer
so essentially when the Ar-
when the Arduino is plugged in
it becomes a keyboard

C: perfect
that's what we want

T: that is what you want

C: is that all we have to do then?

T: I think so
but you'll have to figure out [how]

C: [wait]
but is that the only example

T: mm hmm

C: that's it
but its not really that long

T: (looks at computer screen)
keyboard print

C: that can't be right

T: I think its just that simple
see if you can mock something up-

C: why would it
why would it say like
keyboard print hello

T: ‘cause its gonna type out the word hello
but what you really want is
keyboard

print
"a"
keyboard
print
"b"
so that it does the correct key
in Garage Band
so what I would
C: that's it?
T: yeah
I think you-
C: oh my god
ok
T: so use the LED
um
code
C: can I keep all this
T: um yeah
C: wait
why do I need the LED code?
T: well use the LED code as an example
but instead of turning on an LED
the result should be
keyboard print and then the letters that you want
does that make sense?
C: oh
but I still need the LED code?
T: well you'll use it
but you'll substitute in
instead
you'll change the action
so instead of
you remember on like
on yours
what does it
how does it work [to make]
C: [can you get an Arduino]
B: oh
ok
T: when you press
let's take a look at Jack's code
and see what you would change in order to make it work
with
um
what you're trying to do
C: I'm opening it right now

STEAM Lab shared
why isn’t anything under here?
oh
there it is
T: it takes a second to come on
C: example code
right?
T: yeah
C: which one was it?