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Everyday Engineers: Supporting Youth's Critical Engagement

with Engineering Across Settings

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Abstract

Everyday Engineers: Supporting Youth's Critical Engagement
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Recent policy documents position engineering as a way to broaden participation for students in STEM fields, noting that engineering gives students the opportunity to deepen their science knowledge by engaging them in problem-solving practices around locally-relevant issues (NRC, 2012; Lead States, 2013). However, a recent literature review of engineering education journals found that less than 1% of reviewed articles focused on equity and broadening participation (Hynes et al., 2017), so there are few frameworks to build on when designing for culturally-responsive engineering instruction. This is compounded by the fact that less than 10% of youth participate in formal engineering learning in K-12 settings (NAP, 2009), particularly at early ages when youth are beginning to cultivate STEM-linked identities that guide their learning trajectories (Bairaktarova, Evangelou, Bagiati & Brophy, 2011; Cunningham & Lachapelle, 2014). The inclusion of engineering as part of the *Next Generation Science Standards* opens the

opportunity for more students to engage with engineering learning in the classroom, and invites research and design work that guide equitable approaches to engineering learning that build on students' everyday knowledge, interests, and experiences.

In this dissertation I described various disconnects between how engineering is conceptualized and taught in K-12 settings and how youth engage with engineering in their everyday lives. In Chapter 2, I identified gaps in research on engineering learning, particularly in relation to constructing equitable engineering learning environments that build on youth's everyday interests and expertise. In addition, I provided examples from the history of engineering to argue that everyday and tacit knowledge, and technical expertise are and have always been central to engineering problem solving, and can provide examples for how to broaden participation in engineering for minoritized youth. In Chapter 3, I used students' conceptions of engineering to construct a broad and inclusive definition of the discipline; and found youth's descriptions closely aligned with recent policy documents that defined engineering as "a systematic and often iterative approach to designing objects, processes and systems to meet human needs and wants" (NRC, 2012, p. 202). Through surveys, self-documentation, and interviews, I also found that youth in this study strongly identified as engineers and engaged in engineering-related activities and practices across the contexts of their lives. In Chapter 4, I argued that distributed and synthetic models of engineering instruction were more likely to produce youth learning outcomes of positive engineering-linked identity and interest, and promote student agency in science knowledge construction. I provided examples of how the practices of modeling, observation, and reflection enabled youth to synthesize distributed knowledge from across settings to support classroom science learning goals in

ways that were personally-relevant for students. Lastly, in Chapter five I asked the question: How can we design learning environments to help students critically understand the intrinsic and systemic sociotechnical relationship between people, communities, and the built environment? I propose the term *critical sociotechnical literacy* to describe the multiple realities of engineering solutions in real-world contexts, which include the power of the designed world and its designers to shape individual and community actions and agency.

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I am indebted to my research partner, Ms. Jones, for her unyielding enthusiasm, energy, creativity, and guidance throughout our shared work in the classroom. Ms. Jones has been involved in research with our group for over ten years, and her expertise in culturally-responsive instruction guided and shaped every aspect of this research. I would often bring ill-formed ideas to our meetings, and Ms. Jones would find a way to make them work with her students. In addition, Ms. Jones' profound commitment to equity, social justice, and community building was seamlessly woven into every aspect of her instruction. It has deeply impacted my own learning, as well as the students and families that have been lucky enough to have her as a teacher. I also want to acknowledge the leadership of Granite Elementary who prioritized science learning, community building, and teacher agency, and welcomed research into the school.

Lastly, I was lucky to share this path with my best friend and husband who supported and encouraged me every step of the way. Together we started and finished graduate school at the same time, and were blessed with our son along the way. This final sentence, of this last section, marks the start of our next adventure together. I can't wait to see what it is!

Chapter 1: Introduction

The *Framework for K-12 Science Education* and the adjoining *Next Generation Science Standards* promote engineering as a pathway to broadening STEM participation for students from non-dominant groups, noting that engineering gives students the opportunity to deepen their science knowledge by engaging them in problem-solving and design practices around locally-relevant issues (Lead States, 2013). However, this perspective is at odds with the fact that most elementary school teachers use commercially designed kits and curricula to support their science and engineering instruction. These designed units are intended for scale rather than context, and rarely incorporate the everyday knowledge, expertise, and practices, known as “community funds of knowledge” that each student brings with them to the classroom—which is a core equity strategy in these policy documents (NRC, 2012; Lead States, 2013). Designed elementary engineering curricula and kits overwhelmingly foreground science content and position engineering as an applied science (NAP, 2009; Roth et al., 2001). However, unlike traditional science disciplines like chemistry or physics that build on a common set of theory and approaches to inquiry, engineering is a synthetic field, and engineers draw on a wide range of knowledge across settings and disciplines to solve complex-real world problems for specific contexts, including everyday and experiential knowledge (Cross, 2011).

Recent policy documents and educational standards focus on design thinking and iterative design practices as central to the enterprise of engineering (NRC, 2012; NAP, 2009; Achieve, 2013). Research on design thinking emphasizes the inclusion of experiential knowledge in the practice of synthesis, arguing that tacit knowledge is

central to engineering design work and that scientific principles are embodied in the artifacts that we engage with on a daily basis, providing the foundation for science learning through observing our built communities (Cross, 2011; Stokes, 1997; Vincenti, 1990; Schön, 1983). The central role of tacit knowledge, which emerges from everyday experience, in the engineering design process makes engineering an ideal context for teachers to apply cross-setting learning in their classrooms in ways that leverage local knowledge and personal interests as resources for student learning. In addition, this approach is ideal for young learners who are just starting to develop their science content knowledge, as it opens up the "research" aspects of engineering design to a broader, more personally relevant, and accessible range of related information. Both synthesis and tacit knowledge imply a connected and distributed learning framework for engineering problem solving practices; suggesting that lived experiences, including everyday observations of the designed world contribute workable design solutions for professionals and students alike. This perspective of engineering teaching and learning was also taken up in the Framework for K-12 Science Education describing it as "any engagement in a systematic practice of design to achieve solutions to particular human problems" (NRC, 2012 p. 46). However, in spite of this positioning in recent policy documents, there is a dearth of research in these areas with respect to K-12 student learning and the design of educational learning environments for engineering.

There are currently few studies that focus on elementary students engineering design practices in formal and informal settings, and no studies on students' everyday engagement in engineering-related activities and practices. Further, Hynes et al. (2017) found that fewer than 1% of research articles published focused on equity issues in

engineering education, noting that "research on diversity and inclusion with respect to engineering was starkly limited." (p. 460). This dissertation, seeks to fill some of these gaps through a cross-setting ethnography of 28 fifth grade students over the course of one school year by asking the following questions:

1. When and where do students self-identify as engaging in engineering practices?
2. Where do students see engineering in their everyday lives?
3. What knowledge do students leverage when designing engineering solutions for novel problems?
4. How can learning environments be designed to foster equity, engagement, and science learning for elementary engineering learning?
5. What pedagogical strategies and connections support students' critical engagement with engineering as a socio-technical field?

Overview of the Dissertation

The purpose of this study is to understand how a set of 5th grade students engage in engineering practice in their everyday lives and across settings, and then to leverage those experiences in the classroom to cultivate models of equitable engineering instruction. This research was part of a two-year design based research (The DBR Collective, 2003; Penuel, Allen, Farrell & Coburn, 2015) project between a large research university and two urban school districts. The data and analyses used for this dissertation are from the second year of work, in partnership with a local 5th grade teacher around curriculum adaptation and development to engage students in engineering practices across settings, and to situate engineering learning within broader sociocultural contexts.

The teacher, Ms. Jones, and I used a co-design and co-teaching approach to test our curriculum models, and iteratively revised our instruction and tools based on classroom observations, student artifacts, formative assessments, and student feedback. Ms. Jones has been long-term partner with our research group, and has a history of enacting university models for culturally responsive science instruction with our university research group. Her history and expertise in this type of research helped guide curriculum designs, and enactments in the classroom.

Our overall curriculum arc was guided by a district-level scope and sequence for 5th grade science learning. We used district science kits, and adapted district lessons to include a total of eleven engineering design activities and projects over the course of the year, that ranged from one class period to three weeks in length. We grounded our adaptations in students' everyday knowledge through the use of self-documentation (Tzou & Bell, 2010), which allowed students to make connections to science and engineering learning across settings. Community and disciplinary experts and field trips were included in our instruction to broaden the scope of students' classroom experiences. All 28 students in the classroom consented to be part of this study, as did all adult participants. I collected and content logged 110 hours of video from 73 school visits. School observations focused on science class, but also included humanities classes, recess, and some afterschool and evening activities to understand engineering in multiple contexts. In addition to school visits, I engaged in an additional 60 hours of observations of students across settings, including fieldtrips and a residential outdoors camp, for a total of 170 hours of observation with this group of students. Although I selected a subset of nine focal case study students, I collected artifacts, surveys, and interviews from all 28

students. Artifacts included three self-documentation activities, all student science journals for each district science kit for a total of 84 journals, student reflections from fieldtrips and visiting experts, student surveys, and small and whole group causal-loop (systems thinking) diagrams. I conducted nineteen interviews with student design teams throughout the year, and used collected artifacts and students' engineering projects to ground interviews in students' own work and practices. Below is a table of the scope of data collected during this second year of research, and the analytical methods used.

Table 1.1. Overview of Data and Analytical Methods

Data	Description	Methods
Participants	28 culturally and linguistically diverse 5th grade students, teacher, researcher, engineering and public health experts	Research Practice Partnership Penuel et al., 2015
Settings	Urban classroom, 4 field trips, 5 class speakers, 15 engineering design projects	Applied Ethnography, Ball & Ormerod, 2000 Design-Based Research DBR Collective, 2003
Video	110 hours classroom video from 73 school observations	Interaction Analysis Jordan & Henderson, 1995
Fieldnotes	79 ethnographic fieldnotes from 170 hours of observation	Grounded Theory Strauss & Corbin, 1990
Artifacts	3 self-documentation tasks (113 coded pictures) Student reflections on engineering (142 coded excerpts) Engineering survey responses (370 responses coded)	Grounded Theory Self-Documentation (Tzou & Bell, 2010)

	Causal-loop/ connected learning diagrams	
Interviews	19 student design team interviews,15-25 min each (~600 coded excerpts)	Grounded Theory

Structure of the Dissertation

Critical design theories (Dunn & Raby, 2001) and critical perspectives of engineering education (Riley, 2008; Claris & Riley, 2012) focus on engineering learning and teaching in higher education and professional contexts. Regarding the impacts of engineering on communities and in practice, researchers argue that "engineers may have abundant logical thinking skills but no practice of thinking critically about problem framing, power relations within the profession, hegemonic epistemologies of the discipline, or reproductive practices of engineering education (Claris & Riley, 2012 p. 32). This dissertation work seeks to apply critical engineering perspectives to an elementary school classroom. Each of the chapters in this dissertation takes a critical lens of engineering teaching and learning across the settings of youth's everyday lives, including community, home, school, and professional partnership contexts. We aimed to cultivate elementary students' critical engineering practices by grounding engineering design work in the following questions posed in *Engineering for Social Justice* (Riley, 2008): (a) Who does engineering and for whom? (b) Who decides what counts as engineering? (c) Who benefits and who loses from engineering? and (d) How do social, political, cultural, and economic structure create our present?

My overarching research question for this work was, “How can we design for equitable approaches to engineering instruction?” In each of these chapters youth continually ask, “Who is an engineer?” and “what counts as engineering.” These questions are particularly salient for youth as they are forming their own personal and professional identities in relation to how they see those around them (Bell et al., 2012). Chapter two is comprehensive literature review of the history of engineering as a profession, discipline, and school subject over time, with a focus on how institutions have shaped K-16 engineering learning, and constrained what counts as engineering in formal settings. I provide a phylogenetic analysis of engineering across settings and in relationship to science and design thinking to argue for historically-rooted approaches to broadening what counts as engineering and who is considered an engineer. Chapters three through five engage youth in a broad set of practices and projects to redefine engineering on their own terms. Chapter three is an analysis of youth’s everyday engineering perceptions and practices, with the aim of eliciting a youth-centered definition and vision for engineering, and providing a foundation for our culturally-responsive curriculum design work. Chapter four is a description of our yearlong curriculum design work to develop approaches to engineering instruction that build on students’ everyday knowledge and interests, that positioned youth as knowledge creators in pursuit of classroom science learning goals. Lastly, in chapter five, I propose the idea of critical sociotechnical literacy to support youth’s critical engagement with the designed world, and engineered artifacts; and provide pedagogical approaches for how to do this in the classroom. Critical sociotechnical engineering engages youth in asking, “who benefits

and who is negatively impacted by a particular design solution" and invites participatory design solutions that build on community knowledge and needs.

Methods and Location of Study Design within a Tradition of Research

This research was situated in a linguistically and culturally diverse 5th grade classroom in a large city in the Pacific Northwest. The classroom is located within an open concept school, which became a factor in our initial research design and classroom enactments. The open concept design means that student noise had to be kept to a minimum, and teachers' pedagogy is always on display. I came to see open-concept designs as higher-risk environments for teachers because "failure" and "loss of control" become very visible to peer teachers, staff, and administrators. In particular, these factors impacted our use of technology in the classroom during the study. Mobile technologies, and even cameras became distracting to students in non-research classrooms, and Ms. Jones began limiting their use during whole group 5th grade time, including field trips, which limited the type and amount of data that students were able to collect across settings. Further, technology troubles in the classroom, such as apps crashing or login difficulties became noisy times when the class seemed less in control. Consequentially, we employed less and less technology over the course of the year and Ms. Jones shared that she felt more comfortable using non-technical scaffolds as part of the research designs. Part of our adaptation work centered around these constraints, and may actually make our research design and findings more applicable to other 5th elementary school sites, which often have limited access to classroom technology.

Design Based Research

This ethnography was a design-based research study of one classroom across multiple settings (Brown, 1992; Collins, 1992; The DBR Collective, 2003) that was nested in a larger design based implementation research study (Penuel et al, 2011) with two local school districts. My research included both micro and macrocycles of implementation (Cobb, 2001). The microcycles focused primarily on Ms. Jones' pedagogical practices and participant structures. Her classes used structured and predictable transitions from whole group introduction, small group work, whole group check-in, small group work, and whole group reflection. As part of my design work, and in partnership with Ms. Jones, we tried to diversify and increase the number of participant structures to include some found in professional design environments, such as gallery walks and peer critiques (Tasker et al., 2011). We leveraged Ms. Jones's pedagogical practices and participant structures as a starting point for all macrocycle design work; the goal was to create and adapt curriculum in ways that build on her strengths as a teacher, and blend with the instructional cadences she had already established with her students. In accordance with design-based research goals, I sought to develop models of equitable engineering learning across settings rather than guidelines for particular instructional artifacts (The Design-Based Research Collective, 2003).

Ethnography

I engaged in a form of cultural psychological DBR research (Bell, 2004) by using ethnographic methods to record and understand how students defined engineering, engaged in engineering in their everyday lives, and how they connected and leveraged these experiences during design projects. At the same time, I was also interested in how

Ms. Jones' understanding of engineering and engineering instruction changed over the course of the year in partnership with local experts and other teachers. According to Ball & Ormerod (2000) my ethnographic approaches differed from traditional ethnography in a number of ways including, intensity of observation, dependence on theory and hypothesis testing, and degree of verifiability. In each of these areas my own work was most similar to "applied ethnography" (Ball & Ormerod, 2000). I was usually in the classroom for an hour per day and therefore was not deeply situated in the community of practice itself, although I did take on the role of participant observer and sometimes co-teacher and substitute teacher. I employed a critical approach to my design and ethnographic work, as Ms. Jones and I created engineering learning opportunities with the intention of empowering youth to observe, critique, and take action in their local communities with relation to the built environment and health (Bell, 2004). Lastly, I implemented a variety of data collection methods specifically to verify and triangulate findings.

I used ethnographic fieldnotes (Emerson, Fretz & Shaw , 2011) to document my observations, and used "thick description" to recreate detailed written accounts and reflections from the field (Geertz, 1973). At the end of each week, I reviewed my fieldnotes and wrote analytic memos that included a set of theory-based guiding questions that helped me reflect on my observations, document interactive design-based research cycles, and classify possible data codes as part of "open coding" practices (Emerson et al., 2011; Strauss & Corbin, 1990). Through the process of weekly memos, I analyzed data as I collected it, which distinguishes ethnography from other forms of

qualitative research (Cresswell, 2007; Fetterman, 2010). Weekly analytic memos also became a critical part of my design-based work.

As with most teachers, Ms. Jones had limited planning time to reflect and iterate on our research designs and implementations. When I realized this early in our collaboration, I created a shared Google Doc for collaborative fieldnoting. At the end of each week, and sometimes after specific interventions, I shared a version of my own research memo with Ms. Jones for her to review, change, and reply. This practice helped build a strong researcher-practitioner bond, which is characteristic of design-based research (Design-Based Research Collective, 2004), and allowed for asynchronous meetings, which accommodated the demands of Ms. Jones's teaching schedule and other responsibilities.

Researcher Positionality

Throughout the course of designing and participating in this year-long ethnography, I took on multiple positions as a curriculum designer, project lead, participant, student, partner, friend, community member, and visitor that shaped the outcome of my research design, analysis and eventual findings. Savin-Baden and Howell Major (2013) described three ways that researchers accomplish positionality, including locating oneself in relation to the subject matter, participants, and context. My role as an insider and outsider varied depending on each of these areas and the research goals I had set for the overall study.

Subject Matter

Before attending my current degree program, my professional experience, degrees and research were in conservation biology and marine ecology, and I considered myself a biologist and a science teacher, depending on the context. In this sense, I am an outsider to the field of engineering. I do not have a degree in engineering, and have taken no formal classes in engineering at any level of my education. It was in reading the practices sections of the *Framework for K-12 Science Education* that I came to see my prior work in both conservation biology and teaching as deeply rooted in the engineering practices of defining problems, developing solutions, and optimizing solutions (NRC, 2012), and questioned the breadth and application of engineering practices across disciplines. As I reviewed and synthesized literature of the history of engineering and engineering practices from classrooms to professional settings, my interest in broadening what counts as engineering only strengthened, as the engineering practices of iteratively defining and solving problems, systems thinking, synthesis, abductive reasoning, working within criteria and constraints, and context-specific problem solving mirrored my work in ecology. Stokes (1997) described how federal funding structures have shifted the purpose of science research since World War II from an enterprise of discovery, to one of science for public use and application. Further, in The Essential Engineer (2011), Henry Petroski argued that the complex nature of contemporary science problems, including climate change, renewable energy, and disaster prevention will require scientists to approach inquiry as problem solving within complex systems. These were all experiences that I had within my own work as an ecologist, working in real-world settings, and working within the constraints of conserving endangered species habitat in the context of modern development and human activity.

There are both affordances and limitations to my etic position in engineering. I believe that being an outsider to the field allows me to synthesize literature openly and with a "beginners mind," meaning that I am not tied to one approach to engineering over another, and my literature synthesis and research design were guided by a need to understand the content, and a creative drive to both apply engineering practices to a new setting, and the flexibility to define engineering in ways that were meaningful to study participants and not just professional practitioners. Being an outsider to the field enabled me to easily adopt a critical engineering lens that critiqued historic engineering practices, and questioned the availability of engineering pathways to individuals from historically underrepresented groups in STEM. Lastly, I was aware of my limited ability to bring students into professional practices, and for this reason, included engineering experts at all stages of my research design process, from curriculum design, framework conception, classroom enactments, and teacher co-design efforts. The integration of engineering professionals allowed participants to situate themselves on the boundaries of professional engineering cultures, while our research design worked to expand those boundaries.

Participants & Context

I consider myself a cultural insider with regards to my classroom site and school context. This was my second year working in this classroom, and I had a close friendship with the Ms. Jones, the classroom teacher, as well as her colleagues. Our research group had worked with her for almost a decade by the time we started our collaboration. Ms. Jones is a teacher leader in her community, and frequently has student teachers and interns in her classroom. Students were used to interacting with multiple adults in their shared space, so my presence was not very different from overall school norms. From the

start of school, I was in the classroom on a near daily basis, and shifted my role between observer and teacher's aide as fit each activity. In addition to my background as a scientist, I was also a middle school teacher for five years, and took on multiple teacher-like roles in the classroom; sometimes these looked like co-teaching around a new curriculum design, and several times I was able to substitute teach while Ms. Jones was engaged with other professional development activities.

For most observations, I positioned research cameras at opposite corners of the classroom. Students were curious about the cameras, and many were excited about the idea of being filmed. I allowed all students to take on research roles at different times of the year- they took fieldnotes of their group work, listened to audio as it came through the camera, and helped me set up and take down my equipment. I hoped that participation would allow students to feel involved and agentic in the research work, and conversations with students suggested that this was the case for many of them. Although I used thick description in my evening fieldnotes, my classroom notetaking was a public practice, and I allowed all participants to read my notebook pages as I documented engineering and general class activities. The efforts to broaden who used and produced research artifacts in this space was in the interest of creating a transparent and open research environment to support my emic position in the space, and being a member of this community allowed for informal, mutual sharing of interests and identities that became the most valuable pieces of data for this study.

In the following chapter, I provide a comprehensive literature review of engineering education in primary, secondary, and undergraduate settings. In this review, I leverage the history of engineering and its diversity in everyday and professional settings

to lay the foundation for equitable approaches to engineering teaching and learning in K-12 settings. In addition, I also identify gaps in research on engineering learning- many of which I seek to fill in chapters three, four, and five.

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Chapter 2. Visions of Engineering for Next Generation STEM Teaching and Learning

Background

The acronym STEM emerged during the 2001 NSF Advanced Technological Education Principal Investigators Conference when Judith Ramaley, the assistant director of the Education and Human Resources Directorate, proposed the term as an updated from the prior acronym SMET stating that, “STEM works better because the science and math carry as the core their applications of technology and engineering” and was a more inviting term aimed at broadening interest and participation in STEM-related fields (Patton, 2013). Since its appearance in 2001, the term STEM has become ubiquitous for all STEM-related learning and teaching initiatives, with little attention to how each field (science, technology, engineering, and math) are related to each other in general and in specific contexts. As envisioned by Judith Ramaley, engineering and technology became the means through which science and math gained context (Patton, 2013), and proceeding policy documents took up this position, especially with regards to engineering education initiatives. For example, the NAP’s report on Engineering in K-12 Education positions engineering as a way to improve students’ interest, engagement, and learning in science and math (NRC, 2009). In addition, the Framework for K-12 Science Education positions engineering as a pathway for broadening participation in science, particularly for students from communities historically underrepresented in STEM fields (NRC, 2012).

However, engineering, science, math, and technology each have unique histories, epistemologies, and approaches to learning that can be lost upon integration or subordination to any one field. This is particularly salient for fields such as engineering, which has a limited history as a K-12 school subject (Carr, Bennett, & Strobel, 2012; NAP, 2009). In a review of engineering standards across 50 states, researchers found that 41 states included standards for engineering skills and knowledge, and that they were most often included as part of state science, technology, and vocational studies. Among all states, Massachusetts was identified as a leader in engineering education, as their science standards called for a quarter of science instruction to focus on engineering and technology (Carr, et al., 2012). Building on the Massachusetts model, researchers have advocated for policies that integrate engineering into existing school subjects, and have opposed stand-alone models of engineering in K-12 settings. This was primarily due to the barriers to creating standards in a new area including teacher training, school structures and schedules (Carr, et al., 2012; NAP, 2009; NRC, 2012; Rutherford, 2009). With the emergence of STEM in the past two decades, and the inclusion of engineering practices as part of the Framework for K-12 Science Education and NGSS, researchers are publishing more than ever on the nature of engineering and its role in relation to science in particular, and STEM learning more broadly. This review paper is intended to be a synthesis of work related to the history of engineering in learning contexts, with a focus on how the history of engineering can be leveraged for broadening participation in STEM through a culturally-responsive teaching and learning framework.

A systematic review of P-12 engineering education research found that researchers primarily focused on formal learning environments with 75% of the studies

taking place in school classrooms with the remaining 25% of studies situated in afterschool and other structured informal spaces (Hynes et al., 2017). Of the 256 papers reviewed, no studies explored students' everyday engineering practices across time or space, or leveraged ethnographic methods to study research participants over extended periods of time. P-12 engineering literature is primarily focused on secondary engineering learning with 57% of the papers focusing on high school students, 29% focused on middle school students, and 14% on elementary and early childhood students. Despite the awareness that engaging young learners in engineering is essential for sustained interest in the field, and positive STEM-linked identity development, there are few resources and studies focused on this age group (Hynes et al., 2017; Roth et al., 2001; Cunningham & Kelly, 2017a; Sullivan, 2006). Research questions across all articles can be summarized into 3 areas of research that show up frequently in engineering education. The first centers on students' knowledge, attitudes, beliefs, and understanding of engineering, and sense of their own abilities as potential engineers. The second major area of study tends to focus on students' problem solving processes, including engineering-related skills, and their motivation and self-efficacy in the face of design challenges and failure. Lastly, research looks at students' cognitive learning gains of disciplinary content matter (i.e., science principles) through engineering design activities. This review surfaces gaps in the literature related to broader policy goals of leveraging engineering instruction to broaden participation for all students in STEM fields. There are currently few studies that focus on elementary students engineering design practices in formal and informal settings, and no studies on students' everyday engagement in engineering-related activities and practices in out-of-school environments.

Further, researchers found that fewer than 1% of research articles published focused on equity issues in engineering education, noting that "research on diversity and inclusion with respect to engineering was starkly limited" (Hynes, et al. p. 460). However, it should be noted that this literature review did not include research from the learning sciences, science, or math education research communities. Later in this review, I provide a brief summary of that body of research to provide examples of the type of work that engineering researchers can leverage to fill this gap. There is a need for more literature on ways to support stated policy goals, particularly research that provides empirical examples of what equitable instruction looks like in a variety of contexts, as has emerged from science and math education literature over the past several decades. As later sections of this paper will address, engineering is epistemologically and historically unique from science and math. Further, engineering is often conceptualized more as a profession than a course of study, so the pedagogical and learning structures to support the development of engineering practices are less researched than in other areas, particularly in relation to elementary learners.

Problem Statement

The large number of gaps in the literature on K-12 engineering teaching and learning reflects the reality that few formal settings support sustained engineering instruction, and engineering has yet to find an academic home among traditional school disciplines. In elementary levels, engineering has been situated across disciplines, and includes programs such as Novel Engineering, and Engineering is Elementary, which integrate storytelling and literacy as foundational to the problem solving process. In secondary school settings, engineering projects tend to be situated in science classes,

particularly classes in the physical sciences. The inclusion of engineering as part of science standards by the Framework for K-12 Science Learning and the NGSS, opens that pathway for early and sustained engagement with engineering design practices and projects across all school grade levels and provides the context for further research in these areas. Below is a summary of major gaps in engineering learning literature, intended to highlight the opportunities and affordances for researchers entering this field. This list is intended only to highlight noticeable gaps for future research efforts, and is not intended to set boundaries around what is needed or valued with regards to future research.

For example, there is no consensus among the literature on a core set of engineering practices for K-12 classrooms. The Framework for K-12 education outlined eight practices including iterative problem solving, defining criteria and constraints, and synthesis. However, additional practices vary throughout the literature and there are calls for a deeper understanding of how practices fit within particular contexts (Cunningham & Kelly, 2017b; Cunningham and Lachapelle, 2014; Moore, Stohlmann, Wang, Tank, Glancy, Roehrig, 2014). For this reason, there is a need for empirical and observational research that locates engineering practices and epistemologies across diverse learning settings, including formal and everyday. Two recent studies called for "innovative" approaches to research with regards to engineering education filling these gaps (Case & Light, 2011; Douglas, Koro-Ljungberg & Borrego, 2010). Case & Light (2011) called for an increase in studies using "emergent" methodologies to engineering education, such as case study, grounded theory, ethnography, action research, discourse analysis, and narrative analysis. Douglas, Koro-Ljungberg & Borrego (2010) surfaced the long-

standing bias of engineering educational research towards positivist research paradigms, noting that few engineering and engineering education researchers have been trained in qualitative methodologies. This gap provides opportunities for ethnographic studies of youth's engineering practices across settings, including at home, after school, in community settings, and at school to highlight the heterogeneity of youth's engineering practices as they show up across settings and over time. Lastly, there is a need for research that includes critical approaches to engineering teaching and learning that surface and disrupt historical practices that continue to marginalize historically underrepresented youth in these fields, and situates engineering design solutions within community contexts. This would help shift the focus of engineering learning from neoliberal framings of economic production and assimilating diverse workers into the existing industry, to empowering youth to leverage engineering practices and ways of knowing to engage in the critique and restructuring of their designed world. Employing critical approaches to engineering means stating engineering as a socio-technical field of study. With the emerging research on the social and socio-technical nature of engineering as well as undergraduate restructuring of engineering programs to foster social engineering practice, there is a need for engineering research that leverages sociocultural approaches to learning.

Defining Engineering

Definitions of who and what count as engineering has changed dramatically over time, and still vary today. The Latin origin of the term engine, *ingenium*, translates to "clever machine" suggesting that the earliest engineers were considered inventors and creators. By the mid-14th century, the term engineer evolved across the European content

to refer to a person who builds and operates military equipment, such as a catapult. Today, the definitions of engineering vary depending on their contexts, but the subtle qualities of these definitions draw boundaries around what counts as engineering and who is considered an engineer. Whether developed by standards committees or professional societies, definitions of engineering insidiously shape the educational frameworks and broader conceptions of engineering that emerge from them.

Given the breadth and diversity of contemporary engineering disciplines, and the need for more innovative approaches to engineering teaching and learning, the National Society of Professional Engineers (NSPE) and The Engineering Accreditation Commission (EAC), the accrediting non-profit, for engineering degree granting institutions, no longer explicitly outline a unified definition of engineering (Prados et al., 2005). By the 1980s, the EAC's standard curriculum guidelines for engineering were deemed too constraining for the development of innovative approaches to teaching and learning, so in 2000 the EAC revised its accreditation process to focus on learning outcomes, assessment, and continuous improvement over strict curriculum guidelines for engineering programs in the United States (Prados et al., 2005). The EAC's, outline for specific educational outcomes and competencies for all engineering graduates are listed below and collectively describe the traits of emerging engineering professionals (ABET, 2005; pg. 3).

(a) an ability to apply knowledge of mathematics, science, and engineering

(b) an ability to design and conduct experiments, as well as to analyze and interpret data

(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability

(d) an ability to function on multidisciplinary teams

(e) an ability to identify, formulate, and solve engineering problems

(f) an understanding of professional and ethical responsibility

(g) an ability to communicate effectively

(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context

(i) a recognition of the need for, and an ability to engage in lifelong learning

(j) a knowledge of contemporary issues

(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Significant in this list of outcomes is the EAC's emphasis on the social aspects of engineering as a profession, and the positioning of engineering as a socio-technical field. In this framework for learning, engineers are expected to have deep knowledge of the economic, political, environmental and social aspects and implications of their design work—as they build on the knowledge of mathematics, science, and engineering. In addition, programs are expected to develop professional practices of collaboration and communication. These foci contrast historical models of undergraduate engineering that emphasized science and math content learning over social and professional practices, and real-world considerations for the field. While these outcomes move away from narrow conceptions of engineering as applied science, they fail to take a critical stance regarding

issues of equity and power in relation to the designed world and its impact on local communities and populations (Pawley, 2012).

While undergraduate committees recognized the need for less constraining notions of what counts as engineering, particularly with the emergence of contemporary fields of study and integration of engineering across many disciplines, many K-12 contexts still leverage old paradigms of engineering as applied science and paid work (NAP, 2009; Pawley, 2012). This phenomenon is not unique to engineering education, but found in many fields that communicate professional practice to new audiences, as Collins and Pinch (1996) wrote in *The Golem* about the use of the scientific method in science education: "It is no coincidence that those who feel most certain of their grip on scientific method have rarely worked on the frontiers of science themselves." (Collins & Pinch, 1996, p. 143). This tendency towards reductionism in education is represented by the definition of engineering in a recent review of engineering in K-12 STEM standards in the 50 US States: "*Engineering is* the iterative design and the optimization of materials and technologies to meet needs as defined by criteria under given constraints. *Engineers use* systematic processes, mathematical tools and scientific knowledge to develop, model, analyze and improve solutions to problems" (Carr, Bennett, & Strobel, 2012, p. 101). The foregrounding of science and math principles as central to engineering design solutions is not only an inaccurate representation of the role of science and math in engineering (Jonassen, et al., 2006), but is also problematic for broadening participation in engineering in K-12 settings.

However, the *Framework for K-12 Science Education* has effectively broadened and made contemporary K-12 conceptions of engineering by defining it as, "a systematic

and often iterative approach to designing objects, processes and systems to meet human needs and wants" (NRC, 2012, p. 202), and is the only policy document that defines engineering broadly enough and include the diverse types of knowledge reflective of professional engineering problem solving practices, including science, math, humanities, social applications, precedence, and tacit knowledge (Cross, 2011; Johansson et al., 2006). For this reason, it is the definition that I leverage in this dissertation work on broadening participation, equity, and critical engagement with engineering in an elementary classroom, as "instruction that builds on prior interest and identity is likely to be as important as instruction that builds on knowledge alone. …the benefits are particularly salient for those who would feel disenfranchised or disconnected from science" (NRC Framework, p. 287).

Design Thinking and Engineering

Although there are variations of how engineering is defined, design thinking and methods are integral to all contemporary definitions of engineering. The notion of design as a particular way of thinking emerged in the 1950s and design-based methodologies emerged in the 1960s to describe solution-focused, problem-solving processes that unified a diverse set of professions, such as architecture, industrial design, computer science, and engineering (Rowe, 1987; Cross, 1982; Lawson, 1980). Over time, design became a "way of knowing" that was distinct from the arts and sciences, and described the situated, iterative, creative, and technical aspects of design-based fields. (Cross, 2011. Dym, Agogino, Eris, Frey, & Leifer (2005) defined engineering design as, "a systematic, intelligent process" noting the integration of science and art in design-based solutions.

Design thinking and methods emerged from observations of professional practices across related disciplines, and not from secondary, undergraduate, or graduate formal schooling structures. Even in many engineering courses of study today, new engineers are left to discover design methods on the job, as coursework tends to focus on generalizable math and science theories over practical experience (Crismond, 2001; Dorst & Cross, 2001; Jonassen et al., 2006; Tadmor, 2006). For this reason, Adams, Daly, Mann & Dall'Alba (2011) described design thinking as "an embodied understanding of professional practice" and argued that "current educational practice [in design-based fields] typically adhere to outdated theories of learning and pedagogy evidence by a so-called "content fetish." Understanding the history and emergence of engineering as a disciplinary course of study, clarifies the disparities between professional and educational practices in engineering and other design-based fields, and calls for innovative approaches to engineering teaching and learning through cross-setting models that situate students on the boundaries of professional engineering communities of practice, and include design thinking and methodologies as central to engineering learning in and out of K-16 classrooms. Undergraduate and graduate engineering are increasingly including studio and internship models of learning as part of their degree programs, but the low instructor-student ratio of these programs makes them difficult to implement in large university settings. Further, these models of instruction have not yet filtered down to K-12 classrooms (ABET, 2005; Crismond, 2001).

History of Engineering

Historically, engineering is rooted in arts and crafts trades such as masonry and building (Crawford, 2009; Crismond, 2001; Vincenti, 1990; Stokes, 1997; Lawson, 2006;

Razzouk & Shute, 2012), and dates back to humans' earliest efforts to alter their space to meet desired aesthetic, safety, structural, and nutritional needs (Vincenti, 1990; Stokes, 1997; Lawson, 2006). The enlightenment, industrialization, and World War II all marked multiple bottlenecks, where engineering became more narrowly defined, and engineering roles became separated between the makers (laborers) and designers (disciplinary experts) for each field (Stokes, 1997; Vincenti, 1990; Schön, 1983; Riley, 2008; Pawley, 2012; Crawford, 2009). This separation of expertise was superficial at best, as laborers continued to engage in iterative cycles of designing solutions as they engaged in their everyday work, but the assumptions about these different roles became deeply embedded in how our broader culture views engineering work and formal educational pathways. These divisions are clearly described by the Accreditation Board for Engineering and Technology's guidelines for educational programs in engineering vs engineering technology: "Engineering programs often focus on theory and conceptual design, while engineering technology programs usually focus on application and implementation. Engineering programs typically require additional, higher-level mathematics, including multiple semesters of calculus and calculus-based theoretical science courses, while engineering technology programs typically focus on algebra, trigonometry, applied calculus, and other courses that are more practical than theoretical in nature." (ABET, 2005) Although these divisions exist at programmatic levels, in reality engineers and technicians work together at the intersection of theory and practice, as both spheres of work inform each other. In learning contexts, these divisions become problematic as students branch into divergent professional trajectories that correspond with power, income, and long-term job security. Research on engineering careers suggests that theory

is only relevant in some professional and/ or problem-solving contexts (Jonassen et al., 2006). This suggests that capable students are being asked to make identity-linked, short-term academic decisions that have long-term implications for professional possibilities and pathways.

Divisions between technical and disciplinary career pathways exist because of historic efforts to integrate engineering into traditional university disciplinary structures (Tadmor, 2006). The rise of western universities and modern disciplines during the Enlightenment and Scientific Revolution positioned science as a separate and superior discipline to applied design trades, and this division was wrought with embedded cultural assumptions about intelligence, class, and working with one's hands (Crawford, 2009; Stokes1997; Vincenti, 1990; Schön, 1983; Riley, 2008; Pawley, 2012). Scientists at this time were often upper class, independent, self-employed "gentlemen" while engineers were military or tradespeople who worked for wages and in the service of others. The construction of science knowledge became formalized in institutions and associated with privilege, while engineering knowledge remained situated in apprenticeship models of learning and military training schools, and became associated with the working and middle-class (Crawford, 2009; Riley, 2008; Pawley, 2012; Lewis, 2006; Razzouk & Shute, 2012).

The vision of engineering as an applied science emerged from these historical and hierarchical understandings of knowledge construction, and became further engrained with positivism in the late 19th and early 20th centuries (Stokes, 1997; Schön, 1983; Vincenti, 1990). Within the framework of positivism, disciplines became distinguished between major and minor studies. Major professions included the sciences and classics

that had stable, generalizable knowledge bases, and minor professions were flexible, changing, and situated in nature. Applied fields of study, such as engineering, education, and other social sciences fell into the minor category and became subordinate to the "facts" of science and philosophy. From this positivist perspective, technical knowledge precedes application (Schön, 1983), and early constructions of engineering and design positioned decontextualized content knowledge and science-based research before the doing of design work. Translational research-to-practice models of learning emerged from this paradigm, and still dominate applied science fields today, including engineering, medicine, and teaching (Woolf, 2008; Crawford, 2009; Schön, 1983; Tadmor, 2006).

As engineering fields were crafting disciplinary identities, the Industrial Revolution imposed further divisions on design professionals with the compartmentalization of tasks, and the separation of "thinking" jobs from "doing" jobs (Crawford, 2009). Historically, when design professions were positioned as a craft or trade, the designer was also the maker, and was responsible for the artifact throughout the production process (Crawford, 2009; Stokes1997; Vincenti, 1990; Schön, 1983; Riley, 2008; Pawley, 2012; Lewis, 2006; Razzouk & Shute, 2012; Schön, 1983; Crismond, 2001; Lawson, 2006). Agency, creativity, and problem-solving were all central to craft and vocational work. However, this changed in the industrial model in which engineers did the "thinking" work of solving problems, creating designs, and managing the embodiment of their design work, while technicians and builders did the "doing" work of constructing designs in industrial and oftentimes automated contexts. This division of labor put increased emphasis on many of design's contemporary features including

collaboration, drawing, modeling, and communication (NAP, 2009; Cross, 2008; Cross, 2011; Vincenti, 1990; Stokes, 1997). With the separation of thinking and doing, it became critical that designers could effectively communicate their designs in ways that were reproducible by others and that is when the sketch and other forms of modeling became a central design practice. (Lawson, 2006; Dorst & Cross, 2001; Purcell & Gero, 1998). A shared disciplinary discourse, as well as generalizable engineering principles and theories emerged from the need communication across design teams, projects, and project roles (Crawford, 2009).

Emphasis on theory and principle also centralized the role of science and math in engineering programs in higher education, which became magnified by the post-sputnik "science revolution," which researchers argued defined engineering education throughout the second half of the twentieth century (Lucena, 2005; Tadmor, 2006 Schön, 1992). In the May 1971 issue of Science Magazine, Joel Cohen wrote, "Physics-envy is the curse of biology." The same can be said for engineering, and the "physicsification" of engineering after World War II has had lasting impacts on approaches to engineering education, as well as public perceptions about what engineers do, and what they are required to know. The public visibility and success of government-funded physics projects during World War II and the Soviet's launch of Sputnik led to the integration of physics in a number of institutional contexts including K-12 science classrooms, undergraduate engineering instruction, and engineering professions in general (Crismond, 2001; Stokes, 1997; NAP 2009). The emphasis of math and physics in engineering instruction continues today, even though research on engineering expertise suggests that engineers do much less math in their professional work than their training would suggest

(Jonassen et al., 2006). This is particularly true in fields where computational tools and programs have automated rote mathematical practices. This suggests that there is a disconnect between engineering instruction and what engineers do in the field, as well as changes in practices over time (Dunderstadt, 2010; Council, 2009; Jonassen et al., 2006). Even most engineering faculty hold doctorates in math and science so engineering epistemologies often get positioned out of engineering classrooms in favor of math and science frameworks (Dunderstadt, 2010), and the increasing focus on generalizable theories became the focus of twentieth century engineering programs today (Tadmor, 2006). The wide recognition of disconnects between the learning of engineering and the doing of engineering were the driving forces behind the ongoing restructuring of engineering courses in higher education settings (Tadmor, 2006; Jonassen et al., 2006; Claris & Riley, 2012). In contrast, K-12 engineering education has remained largely framed and constrained post-WWII aims of instruction (Sullivan, 2006). Researchers argue that little has changed in engineering in the past thirty years, and notes that the public remains largely "unaware of the role of engineers in medical advances, in alleviating human suffering, or even in creating the iPod that puts 10,000 tunes at our fingertips" (Sullivan, 2006, p. 18).

Engineering has deep roots in military history that still impact the profession today. The historical connection of engineering and military pursuits predates the enlightenment with military training institution as the primary supporters of engineering education (Stokes, 1997; Vincenti, 1990; Schön, 1983; Riley, 2008; Pawley, 2012; Council, 2009). The division of civil engineering is a lexical symbol of the reality that most engineering is for state rather than civic purposes. Even today over 75% of

university graduates in engineering go on to work for military-affiliated agencies and corporations, and this shapes how students are prepared at the undergraduate and graduate levels (Council, 2009; Riley, 2008; Pawley, 2012). For example, in Engineering for Social Justice, Riley argued that the militaristic foundations of engineering impose hierarchical, top-down design processes that devalue creativity, intuition, and exploration during the design process, which results in conservative design processes that perpetuate the status quo and often advance the needs of those in power over the collective good (Riley, 2008; Pawley, 2012). In contrast, other design-based fields including architecture, marketing, fine arts, and technology often value innovation and creativity as drivers of successful and profitable design.

The associations between the military and engineering colleges have also had major impacts on how engineering is portrayed as a profession to the public and prospective students. Prior to World War II, engineering was still considered a trade profession and recruiting college-bound undergraduates to engineering schools proved difficult. Undergraduates were more inclined to pursue degrees in the Arts and Sciences, which were historically more prestigious. In response to this lack of interest, engineering programs constructed public narratives about engineering that appealed to young men's rugged individualism. Narratives of military service, masculinity, technical triumph over nature, and working in extreme environments successfully recruited young men to the field of engineering (Riley, 2008; Pawley, 2012; Stokes, 1997). These narratives persist in engineering today, and may be responsible for the low recruitment and retention of individuals from non-dominant groups (Riley, 2008; Pawley, 2012; Nieusma & Riley, 2010; Bardzell & Bardzell, 2013; Razzouk & Shute, 2012; Nasir, Vakil, 2017). However,

as participation in engineering has broadened, there has been a rise in socially conscious design practices, symbolized by the rise of critical design theory and humanitarian engineering (Riley, 2008; Pawley, 2012; Nieusma & Riley, 2010; Bardzell & Bardzell, 2013). Critical design theory takes on different forms depending on which discipline it is "critically" engaged with. In engineering and related fields, critical design asks designers to engage deeply with the social implications of their design work (Riley, 2008; Pawley, 2012; Nieusma & Riley, 2010; Bardzell & Bardzell, 2013; Claris & Riley, 2012). These fields challenge historic client-driven approaches to problem solving in engineering, in which the term "empathy" meant understanding a client's needs before they knew them themselves. Critical and humanitarian approaches to engineering shift empathy, agency, and social justice towards the communities affected by design solutions. Community-based models of design are now emerging from these critical frameworks, as well as the increasing emphasis in higher education on the social implications of artifact construction (ABET, 2005). Contemporary images of engineering also engage engineers in solving "wicked" global problems (Petroski, 2011). Building on this image of engineering, Sullivan (2006) argued that educators should position "engineers as problem solvers rather than creators and innovators who address the grand challenges of our time – environmental contamination, world hunger, energy dependence, and the spread of disease" (Sullivan, 2006, p. 18).

Engineering Epistemologies

Given the heterogeneous (Adams et al., 2011; Roth et al., 2001) and synthetic (Cross, 2011) nature of engineering, there is no shared consensus on a unified epistemology of engineering practices or philosophy of knowledge (Bucciarelli, 2003;

Figueiredo, 2008; Frezza & Nordquest, 2015). When engineers are asked to define the nature of their own work, their responses fall into three main categories: applying science, solving problems, and making things, but engineers rarely surface the situated or social nature of these practices (Pawley, 2012; Adams et al., 2011). At a workshop entitled "Toward an Epistemology of Engineering" given at the Royal Academy of Engineering in London in 2008, Mario Figueiredo shared his often-cited framework on the four dimensions of engineering knowledge (Figure 2.1).

Figure 2.1. The Four Dimensions of Engineering

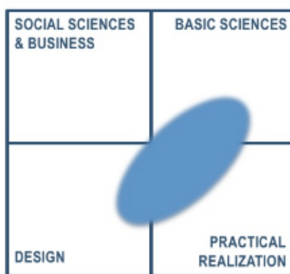
SOCIAL SCIENCES engineer as sociologist	BASIC SCIENCES engineer as scientist
engineer as designer DESIGN	engineer as doer PRACTICAL REALIZATION

Basic sciences refer to engineering as "the application of basic sciences," with an emphasis on experimentation, logic, and discovery of first principles as its predominant activities. Engineering as social sciences assumes engineering is "an integrating part of socio-economic reality" and includes fields of business as well as the social aspects of design work including user interactions. Engineering as design uses "systems thinking instead of analytical thinking," and solves problems from a holistic and contextual perspective that includes uncertainty and intuition in decision making processes. Lastly, engineering as practical realization refers to solutions-oriented nature of engineering work, and includes social aspects of engineering directed towards "changing the world" as well as engineering behaviors of perseverance through iterative design processes and

failure. This dimension is sometimes referred to as “engineering as craft” (Adams et al., 2011). The iterative nature of engineering design work is integrated into each of these four dimensions, and is considered a unifying aspect in diverse enterprises of engineering, that distinguishes it from traditional forms of science inquiry (Figueiredo, 2008).

In defining the four dimensions of engineering, Figueiredo set the foundation for his larger argument that engineering is a transdisciplinary field (Gibbons et al., 1994; Figueiredo, 2008; Adams et al., 2011; Yu & Strobel, 2011) and that design solutions always exist along a set of coordinates on the axes of theory vs. practice (y-axis) and society vs. information of matter (x-axis); noting that, “specific clustering and configurations, or knowledge [are] brought together on a temporary basis in specific contexts of application, which makes it strongly oriented to and driven by problem solving” (Figure 2.2, Figueiredo, 2008, p. 94).

Figure 2.2. The situated and transdisciplinary nature of engineering solutions



This vision of engineering as transdisciplinary contrasts the dichotomous images of engineering in K-12 settings and curricula in which engineering is positioned as either a systemic process of applying science principles to engineering problems, or as ad-hoc approaches to problem solving that rely on iterative cycles of failure and redesign for

success, with little reflection or analysis guiding design processes (NAP, 2009; Wolf et al., 2001; Boesdorfer & Greenhalgh, 2014). In an attempt to ground classroom engineering in professional practice, Kelly and Cunningham (2017b) outlined a set of epistemic practices to help situate student learning within a more authentic framework, noting that the disparity between engineering education's notion of epistemic practices and professional accounts of what engineers do, is responsible for students disidentifying with engineering (Cunningham & Kelly, 2017b). This list of epistemic practices positions engineering as an interdisciplinary field, and locates engineering knowledge as emergent from iterative problem solving practices; and are grouped into four main categories: 1) engineering in social contexts, 2) use of data and evidence to make decisions, 3) tools and strategies for problem solving, and 4) finding solutions through creativity and innovation. While these categories and the epistemic practices outlined in each section do broaden traditional accounts of engineering, they also leave out other professional practices of synthesis and the use of tacit knowledge and intuition to guide design solutions. Further, the authors don't acknowledge the importance of building on students' everyday interests and practices as foundations for engineering-related identity development and equitable instruction, although they do list students' "seeing themselves as engineers" as one of the core epistemic practices of engineers (Cunningham & Kelly, 2017).

Broadening Participation in Engineering

Early engineering curricula and educational frameworks are and have been shaped by undergraduate values and expectations for students. For this reason, I include a brief overview of undergraduate education, as a means for understanding pathways intended to

produce professional engineers, a stated goal of many engineering education policy and research documents (NAE, 2008).

While efforts to broaden participation in undergraduate engineering programs have been in effect since the 1980s, participation and graduation rates across most engineering programs has plateaued in the past decade for students from minoritized communities and women. Since the early 2000s, women have made up about 20% of engineering undergraduates and 10% of the engineering workforce. Students who self-identified as Black or Latino comprise 5% of undergraduates and 2% of the engineering workforce (Lucena, 2005; Yoder, 2012). The fields of environmental and biomedical engineering are exceptions to these larger trends for women who make up almost 50% of professional environmental engineers, and 41% of biomedical engineers, which reflects how women tend to be represented in life science more broadly, and supports research for situating engineering as a sociotechnical field as a means for broadening participation (Adams et al., 2011; Stevens, O'Connor, Garrison, Jocuns & Amos, 2008). In addition, Smith and Lucena (2016) argued that broadening participation should also be extended to include dimensions of socioeconomic class (which is not currently includes in NSF's definition for underrepresented groups) as traditional engineering career pathways include long hours of study and constricted coursework options that position out lower-income and first-generation college students who may juggle additional family and career responsibilities. This contrasts assumptions within student engineering communities that success in the field is a "meritocracy" open to anyone (Stevens et al., 2007), and highlights how first generation, low-income college students have been positioned out of engineering course of study due to the high demands and constraints around traditional

course schedules and demands on time. Smith and Lucena (2016) conducted an ethnographic study of first generation, low-income engineering undergraduates and found that their backgrounds provided them with unique funds of knowledge that allowed them to excel in professional engineering contexts, such as internships and field studies, but impacted their identities as capable engineering students in traditional course settings. While federal policy documents position K-12 engineering as a way to broaden participation in STEM fields there are few studies on formal instructional approaches or designs in support of that goal (Hynes et al., 2017; Tadmor, 2006; Lucena, 2005; NAP, 2009).

The public discourse around broadening participation and recruiting new engineers has shifted over time from private benefits for the individual (i.e. salary benefits and career options) towards economic competitiveness or a national agenda of competitiveness against other countries (i.e. patriotism and public service) (Lucena, 2005). These narratives have focused on broadening participation in engineering by assimilating individuals from underrepresented groups into existing disciplinary practices (Lucena, 2005; Riley, 2003; Claris & Riley, 2012). Diversifying participation in engineering means that we need to not just bring student into existing engineering practices and structures (as is defined by the exposure and access notions of equity), but that we take a critical look at the field of engineering education, and challenge teachers and curriculum designers to create learning opportunities that build on diverse way of knowing about engineering and being engineers in the world, with a focus on relating course materials to students' lived experiences (Riley, 2003; Claris & Riley, 2012). In professional contexts, the term '*heterogeneous engineering*' describes the integral role

that diverse types of knowledge, including tacit knowledge and lived experiences, play in designing and situating engineering design solutions in particular contexts (Adams et al., 2011; Suchman, 2000; Law, 1987). However, in K-12 settings, diverse problem solving becomes constrained by the narrow educational goals of many engineering design projects (Roth et al., 2001). Although research on culturally relevant instruction describes the social, cultural and historic aspects of STEM engagement (Nasir, Rosebery, Warren & Lee, 2006; Nasir & Hand, 2006; Barton & Tan, 2008; Bang, Warren, Rosebery & Medin, 2012; Bang, Medin, Washinawatok & Chapman, 2010), attrition in engineering is most often described as a "leaky pipeline" model of students leaving STEM fields as coursework becomes more challenging, or a "chilly climate" that is unwelcoming and unresponsive to individuals from communities historically underrepresented in STEM fields (Pawley, 2012). These models place responsibility on the individual to adapt to traditional STEM learning structures, and equate equity with access. The continued focus in the engineering education community on access as the main form of equity is disconnected from the breadth of similar research from science education that recognizes the need to ground instruction in students' everyday experiences and community knowledge as foundations for equitable learning (Aikenhead & Jegede, 1999; Brown, Collins & Duguid, 1989; Greeno, & Engeström, 2006; Zimmerman & Bell, 2012; Bell, Bricker, Tzou & Baines, 2012; Penuel, 2014). Equitable approaches to broadening participation would invite learners to build on their own funds of knowledge, interests and identities to broaden what counts as engineering, and who gets to be an engineer.

Understanding Design Thinking

Industrial and positivist narratives of engineering are only now beginning to change towards more collective and critical approaches with the emergence of research on design philosophy, history, and epistemologies and related design thinking and methods (Schön, 1983; Bucciarelli, 1994; Vincenti, 1990; Stokes, 1997; Razzouk & Shute, 2012; Suchman, 2000; Korestky et al., 2014; Cross, 2008; Cross, 2011). Research on design thinking primarily leverages qualitative methodologies including ethnography (Bucciarelli, 1994; Suchman, 2000; Hall & Stevens, 1994; Roth, 2001), case study (Crismond, 2001; Capobianco et al., 2011; Lawson, 1994; Cross, 2011; Cross, 2008; Cross & Cross, 1998; Dorst & Cross, 2001) to understand key professional engineering practices in real-world settings. This emerging research is challenging translational models of engineering as an applied science by providing thick descriptions and long-term observations of engineers' professional practices in and across contexts. It is from these studies that accounts of design thinking and methodologies have surfaced, as researchers have been able to identify and describe common design practices across professions, projects, time, and space. In a review of research on design thinking, Razzouk & Shute (2012) described design thinking as a non-linear process that used synthesis to address real-world, practical problems (as opposed to theoretical abstractions). The specific steps of design thinking vary slightly in the literature, especially with regards to how much time is spent on each step, but are summarized as follows: 1) Design thinking starts with cloudy ideas based on prior knowledge, 2) designers use sketches and models to help think through and clarify their ideas, 3) designers modify models by engaging in model-centered, collaborative discourse in what

the authors call a picture-word cycle. This phenomenon was also described by Suchman (2000) as embodied practices. Ideas take artifact form in ways that are performative, so that users can participate in design through observation, consumption, and critique. Elements of design thinking that surfaced through these studies are described below with brief connections of how these practices might look in formal K-12 classrooms, or engineering curriculum design. Broadly speaking, educational implications include engaging students in design practices such as using prototypes, experimenting with ideas, collaboration, reflection on learning, and iteratively refining design solutions. In describing the differences between instructional and professional design, Roth (2001) argued that classroom design practices should be process-focused rather than product-focused to support iterative learning through failure, and notes that even when products fail, meaningful learning can be taking place. However, some argue that instruction and curriculum have been overly focused on process to the point of conflating engineering practices as content itself (Cunningham & Kelly, 2017b). Although there is research on the use of design to mediate learning (Kolodner, 2002; Puntambekar & Kolodner, 2005). Razzouk and Shute (2012) argue that there is a need for more research in this area, as well as research that explores the domain specific and domain independent nature of design thinking.

Design is Situated: Since design solutions are oriented towards very specific problems, the nature of design is situated within time, space, and context (Crawford, 2009; Cross, 2011; Cross, 2008; Council, 2009). Efforts to summarize and communicate the design process are attempts at finding generalizable aspects of design thinking to connect design disciplines and foster greater understanding

of design processes out of specific contexts. The situated nature of design knowledge and solutions poses unique challenges for traditional classroom learning and assessment structures, especially in an era of increasing standardization of learning measures, as content-related standards bound the types of knowledge valued during synthesis. While schools are focused on individual and cognitive aspects of learning, engineering design solution knowledge is distributed across time, space, and people (Suchman, 2000), and emerges through reflective conversations with the materials used in the process of construction (Schön, 1983; Suchman, 2000; Koretsky et al., 2014; Roth, 1996). The situated nature of design means that each student design team draws on a unique set of knowledge and experiences in the construction of their design solutions, and "resulting artifacts are heterogeneous assemblages from situated activity of designers rather than as homogenous fixations of children's ideas and skills" (Roth, 1996, p. 141). In addition, the tools available to each set of students can alter learning outcomes, and therefor., learning outcomes can differ for students in the same classroom, and especially for students in diverse contexts. Reflective scaffolds that make explicit connections between students' constructed artifacts and desired learning goals can support specific learning goals, while also attending to the situated nature of engineering work (McGowan, Ventura & Bell, 2017).

Design is Synthetic: Braha and Maimon (1997) argued that synthesis is at the core of design thinking, and wrote "design is the process of putting together or relating ideas and/ or objects in order to create a whole which hopefully achieves

a certain purpose." Through synthesis, designers leverage disciplinary training, precedence and lived examples of similar design solutions, social contexts, user needs, client requests, and everyday, tacit knowledge to find workable solutions to novel engineering problems. For this reason, the nature of design connects activity across time and space (Roth, 2001; Suchman, 2000), and the artifacts of design embody the evolution of an idea, and the collective knowledge of communities (Sarlemijin, 1993; Suchman 2000). The siloed nature of school subject can place implicit boundaries around what types of knowledge get counted during the engineering design process within formal classroom context. However, engineering projects and curricula that are designed to allow solutions and knowledge to emerge from the design process itself can bridge synthetic approaches to problem solving with emergent knowledge through observation, reflection, and instructional scaffolding.

Design Leverages Tacit Knowledge: Almost universally, literature on design thinking emphasizes the inclusion of tacit and experiential knowledge in the practice of synthesis, ideation, and problem scoping. Vincenti (1990) argued that much engineering knowledge is created in the absence of science and that tacit knowledge is central to design work. Stokes (1997) used multiple case studies throughout history to disprove the popular assumption that engineered artifacts follow scientific progress and argued that "the link between scientific advance and technological innovation was in fact weak and problematic." Lastly, Sarlemijin (1993) wrote that "designs are not exclusively the results of science-based know how" and argued that engineering is grounded in "experience-based

know how." She furthered her discussion by describing the design process and its products as cultural alloys that connect everyday and disciplinary expertise in the problem-solving process (Sarlemijin, 1993). Pushing back on the "technical rationality" imposed on design by positivist frameworks that emphasize science over experience, Schön argued for an "epistemology of practice" that honors the value of intuitive and experiential learning in design (Schön, 1983). This epistemology of practice can be visualized as the backdrop of Figueiredo's four dimensions of engineering and would not be relegated to only the "design" quadrant.

The nature of tacit knowledge changes with lived experience, and therefore its role in problem solving also evolves over time. For novice engineers and youth, tacit knowledge refers to knowledge gained through everyday, non-disciplinary learning, often referred to as cultural *funds of knowledge* in literature on culturally-relevant instruction (Moll, Amanti, Neff, & Gonzalez, 1992). Research has found that play, working with family members, and prior classroom experience can all provide knowledge and experiences that students are able to transfer to novel situations (Zimmerman & Bell, 2009; Rosebery, Ogonowski, DiSchino & Warren, 2010). Individuals who pursue engineering degrees and engage in professional engineering practices gain disciplinary knowledge through their lived experiences; and over time, the gap between everyday and disciplinary knowledge narrows, as experts draw professional experience during the problem solving process.

Systems Thinking is a central practice for situating engineering within a sociotechnical framework. The scientific method was historically built on reductionist approaches to inquiry that show up in K-12 classrooms, with the notion of distilling and understanding single variables in isolation, in order to create generalizable theories that hold true across contexts. This approach to discovery leverages deductive and inductive reasoning; deductive reasoning moves from a general rule to a specific application, such as making sense of finding in light of a theory. Inductive reasoning draws generalized conclusions from limited observations, such as theory building from evidence. In each of these cases, reasoning in linear and follows a direct course between evidence and claims. In contrast, engineering is a situated and contextual field, and engineering design solutions call for a multivariate and systems-wide lens on problem solving that leverage abductive reasoning, which is the construction of best possible answers from incomplete data, inherent in the socio-technical and ill-defined nature of many design problems. (March, 1984; Rowe, 1991; Cross, 2008; Cross, 2011; Lawson, 2006). Instructional tools such as conjecture maps and causal loop models are useful approaches for engaging students in authentic forms of systems thinking that ask student to model the behaviors and make predictions about complex systems' behaviors under a set of environmental conditions.

Modeling is the Central Practice of Design: Modeling is a practice that enables engineers to visualize and test design solutions, as well as an anchor for problem solving discourses and processes (Suchman, 2000; Braha & Maimon, 1997; Purcell & Gero, 1998; Roth, 1996). Historically, engineers used two-dimensional

sketches to minimize failure and mediate communication between design professionals and technicians (Cross, 2008; Suchman, 2000). In contemporary engineering practices, virtual modeling is replacing both sketch and physical models as cost-effective and accurate ways to build, test, and optimize design solutions (Weintrop et al., 2016; Lawson, 2006). In undergraduate and graduate courses, virtual models and simulations are also used to engage learners in more authentic engineering practice than classroom walls and time constraints can allow (Koretsky et al., 2014). The performative aspects of design and construction of objects in the world allows individuals to engage in a relationship with them and the knowledge required in their construction, therefore engineering artifacts are models for disciplinary learning through precedence (Wilensky, 1991). Therefore, K-12 students can leverage the designed world as embodied knowledge and practice to ground their own engineering learning and problem solving processes. Real-world models can be integrated into classroom instruction through simulations, modeling software, such as Sketch up, and pictures of designed structures as sources of inquiry and inspiration.

Design is Solution-Focused: Although most design process diagrams start with "defining the problem" (Lead States, 2013; Council, 2009), design is actually a solution-oriented process, and the nature of the problem-definition often only emerges through engaging in the practices of design. This is called the problem-solution co-evolution (Dorst & Cross, 2001; Cross, 2008; Maher, 1996; Koretsky, et al. 2014; Lawson, 2006; Purcell & Gero, 1998; Roth, 1996) and is a central feature in literature on the nature of design (Braha & Maimon, 1997; NRC, 2009;

Crismond, 2001; Cross 2011; Cross, 2008; Bayazit, 1993; Dorst & Cross, 2001; Jonassen et al., 2006; Koretsky et al., 2014; Lawson, 2006; Lawson, 1994). The problem-solution co-evolution paradigm in design is one example of what Schön calls "reflection in action" and "reflecting in practice." These are both ways of learning by doing during the design process and align with broader sociomaterial theories that link actions and artifacts (Pickering, 1995; Fenwick & Edwards, 2013; Latour & Woolgar, 1986). Research suggests that science knowledge emerges from the "doing" of design work, and that the production of product and construction of knowledge co-evolve through an iterative process of thinking and doing during design activities (Schön, 1983; Schön, 1992; Stokes, 1997; Vincenti, 1990; Cross, 2011).

Design is Iterative: K-12 engineering curricula and supporting documents focus on iteration as the defining feature of design (NAP, 2009; NRC, 2012; Lead States, 2013; Johnson et al., 2015), and argue that productive friction (Koretsky et al., 2014) and functional failure (Vincenti, 1990) drive iteration. The iterative and emergent nature of design solutions can be a tension in a classroom that is already time-constrained, if students do not have the opportunity to engage in successful problem solving within the time frames allowed for a project. Iterative design practices without associated time for success, can lead students to feel frustrated or disempowered during engineering projects. Therefore, instructors and designers should account for this aspect of project work; scaling down engineering projects and changing expectations and criteria for success can support student learning and motivation in theses space. However, overly

scaffolding the problem-solving process can reduce the authenticity of design tasks, and limit emergent learning and the knowledge used during the problem solving process, and is not an optimal approach to working within classroom time constraints.

Designers work with Ill-Defined Problems: Since design lends itself to many possible solutions, the problem solving process is by its very nature ill defined. However, some researchers have pushed back on this argument, and note that many engineering problems and projects have been solved many times before, which allows engineers and students alike to build on precedence when designing their own solutions (Vincenti, 1990). For this reason, Vincenti (1990) proposed two types of engineering design problems: normal and radical. Normal design solutions include recurrent themes and structures that reemerge over time and contexts. Vincenti argues that both professional and student, engineers engage in normal problem solving most of the time. In contrast, radical design solutions revolutionize a field or way of operating in the world, and often represent major advances in technology that emerge in partnership with scientific discoveries. Nanotechnology and its associated products are representative of contemporary radical design solutions.

Design is Collaborative and Knowledge Construction is Distributed: Learning in professional design settings occurs in groups, and knowledge and problem solving is distributed among team members and artifacts (Hall & Stevens, 1994; Jonassen et al., 2006; Suchman, 2000; Penuel, 2014; Bell & Winn, 2000). Hall & Stevens (1994) found that in professional, but not educational settings design

processes are supported by layered activity of talk, feedback, and design revisions. Suchman (2000) found that multiple and varied artifacts mediated professional discourses, gestures, and sense making through the design process. In contrast, school-based notions of personal accountability and individual learning contrast authentic, distributed design practices. There is a need for new approaches to classroom assessment that account for the distributed nature of design work, especially examples that allow for emergent learning and multiple role-taking during the problem solving process for students.

Designers Work within Criteria and Constraints: All design is guided by criteria and constraints, but the nature of these constraints varies by setting. Engineering curricula and policy documents often try to frame criteria and constraints in terms of engineering principles, natural laws, and materials use. In contrast, research on professional design practices intentionally highlights the fact that criteria and constraints often rest outside of designers' expertise and is situated within sociotechnical systems (Adams, et al., 2011). In professional contexts, criteria and constraints include economic, political, and social aspects of design, including cost, materials, environmental regulations, customer expectations, and permitting. (Jonassen et al., 2006; Cross, 2008; Petroski, 2011; Cross, 2011; Vincenti, 1990; Lawson, 2006; Bucciarelli, 1994). Dunderstadt (2010) used this aspect of design to argue for broad-based training beyond STEM fields in engineering undergraduate education. Further, success in engineering is rarely measured by engineering standards and is instead subject to social, environmental, and performative critiques and assessments (Jonassen et al.,

2006). In classroom settings, material availability shifts the nature of natural constraints on engineering design solutions in ways that can alter student learning trajectories towards specific learning goals. For example, Roth (1996) found that glue guns enabled students to build structures that circumvented traditional engineering knowledge of using trusses to add support to a structure, as glue provided adequate support and was more accessible to students than disciplinary solutions.

Design is Performative: The products and processes of design are specifically created for use, and the problem solving practices of engineering become embodied in observable visual structures. In this sense engineering is a performative practice that invites user participation through observation, use, and critique (Suchman & Trigg, 1993; Pickering, 1995). Designed objects are not only measured by set criteria, but also by how users interact with the design. Fenwick & Edwards argued that socio-material learning is based on a “performative ontology” that invites more practice-based participation from learners. This aspect of designs surfaces in K-12 classrooms through public design challenges and associated failures of designs. Because of this, classroom engineering requires cultural shifts in thinking and assessment in addition to structural learning scaffolds. Formative assessments through teacher observation, and student reflection may be the best fit for engineering design projects. Additionally, successful classroom design would require a safe and supportive culture that allows space and time for functional failure and production friction to guide design-based learning activities.

Critiques of Design Thinking

As noted earlier, emerging research on the history, philosophy, and anthropology of design embraces the situated and contextual aspects of design that inhibit theory building. However, critics of this view argue that design is a young science that has yet to develop more universal methods. Kuhn argued that design was at a prescience phase and that it needed to go through several more phases before it would reach that of a mature science with associated laws and theories (Kuhn, 1969 postscript). Additionally, others note that engineering design education and practice lack an adequate base of scientific principles and are guided too much by specialized empiricism, intuition, and experiences (Dixon, 1987). These critiques are reminiscent of early 20th century divisions between major and minor disciplines. Similar to other situated fields like anthropology and sociology, design should not be positioned as subordinate to disciplines that regularly use inductive reasoning practices to construct generalizable knowledge.

Educators as Instructional Engineers

Donald Schön was the first to position education as a design-based field and educators as designers (Schön, 1983), and research on curriculum design has described the specific practices teachers engage with when adapting learning for specific classroom contexts (Davis & Krajcik, 2005). This image of teaching as design contrasts other approaches that position teaching as a science. Science-oriented views include fidelity of implementation models of instruction that assume the same materials and methods can produce the same results across diverse contexts. The notion of the educator as a social and learning engineer is powerful for repositioning teachers with agency and professional

freedoms in an age of increasing constraints around instruction, and punitive measures related to teachers' instructional practices.

Representations of Design for Education

Since a model of the design process was first published 1965, many authors have attempted to refine or reconstruct the design process as a simple, communicable, conceptual model with slight to major changes in how the authors view the design process. The vast differences among these models speak not to disagreement in the field about what design thinking is, but on the situated nature of design-based problem solving and methods. Not only will each design field have its own process, but research suggests that each designer has his or her own design process that sometimes changes depending on the context (Cross & Cross, 1998). Because of this variation, generalizable models are reduced to the most basic perceived elements of design, and therefore often misrepresent the complexities of design. For example, since 1965 most design diagrams include cyclical processes, but some researchers argue that cyclical models are not ideal, because they ignore the situated nature and systemic web-like features of design, and position design as a never-ending cycle of improvement. While this likely has negligible impact on professional practice, it can have a substantial influence on how teachers and curriculum designers perceive and communicate design to students. Further, it can affect how learning opportunities and projects are scaffolded to cultivate expertise in design. Nigel Cross (2008) described two ways of representing engineering design processes to diverse audiences- as prescriptive diagrams, or though analogy and story. Prescriptive and descriptive models of the design process are prototypes that summarize or communicate how design is done in a visual way. They are often incomplete and

reductionist, and tend to present dichotomous views of design as either convergent/ divergent or serialist/ holist, as opposed to synthetic and complex.

Researchers recognized the shortcomings and limited applications of descriptive and prescriptive diagrams and proposed instead that design could be taught through analogy, case study, and story (Cross, 2008; Braha & Maimon, 1997). For example, Nigel Cross (2008) used an analogy of soccer to emphasize the role of collaboration, strategy, and training for successful design. Analogy and story may be a powerful educative tool to teach design in the classroom. Story is less prescriptive than a diagram and is less likely to be taken up as the "right" or "only" way to do design. Further, design vignette (as video, text, or spoken story) can model productive collaboration practices, the role of creativity in the design process, the co-evolution of thinking and doing in design, and approaches to synthesizing multiple forms of information including everyday and related disciplinary knowledge. video was a useful tool to scaffold student discourse around design practices.

Situating Content in Engineering Design

Foregrounding science and math content knowledge out of the context of doing design is deeply rooted in schooling and historical notions of major disciplines (Schön, 1983). In Schön's words, "the normative idea of curriculum places general principles and methods before skills and application," and Schön argued that these content first models reflect a positivist epistemology of practice that conflicts with design-based ways of constructing knowledge through action. While universities and agencies thought they were increasing the rigor of engineering by foregrounding instruction in physics, math, and other science disciplines, by the 1970s engineering employers began to complain that

recent graduates "couldn't do anything" in professional contexts, and lacked the experience, creativity and communication skills that were necessary for successful design (Crismond, 2001; Tadmor, 2006; Razzouk & Shute, 2012). Since that time, some engineering schools have begun to reintegrate engineering practices and vocational models of instruction into their undergraduate programs through design-based pedagogies and project-based learning that diversify traditional classroom participant structures (Crismond, 2001; Litzinger, Lattuca, Hadgraft & Newstetter, 2011; Tasker et al., 2014). As engineering higher education programs are trying to integrate more authentic design practices into their instructional models, K-12 engineering education continues to perpetuate the limited, hierarchical, and analytical notions of engineering described above. The "rugged individualist" narratives used to recruit young, male engineers into engineering in the past, today excludes women and other individuals from non-dominant groups from identifying as engineers and participating in engineering learning and communities (Capobianco & French, 2014; Capobianco et al. 2011; Pawley, 2012; Riley, 2008; Nieusma & Riley, 2010). Further, the physicsification of engineering and rigid, top-down design models position engineering as subordinate to science learning, which has three implications for classroom learning. First, it devalues the intuitive and creative aspects of design thinking and positions out students drawn to more creative fields and displaces everyday knowledge in the design process. Second, it induces anxiety around teaching engineering for elementary school teachers, and teachers with weak math and physics backgrounds, which make them less likely to integrate relevant aspects of engineering into their instruction (Boesdorfer & Greenhalgh, 2014; Capobianco, 2011). And third, it restricts the degree to which students engage in authentic design until

they've completed advanced science and math courses, which is why fewer than 10% of students in the United States have been exposed to formal engineering instruction before the twelfth grade (NAP, 2009). Reframing learning through engineering as synthetic and emergent has the potential to situate engineering in diverse contexts. Further, surfacing the distributed nature of engineering design knowledge eases pressure on teachers who have less experience and confidence teaching engineering, and allows students to be positioned as emerging experts within the classroom, through the course of engineering design work.

Theoretical Perspectives of Learning in Engineering

Research on learning in engineering often focuses on engineering epistemologies (or the lack of) when navigating the tensions of applying engineering in other disciplinary contexts, particularly in relation to situating engineering in K-12 science classrooms (Figueiredo, 2008; Vincenti, 1990; Cunningham & Kelly, 2017b). However, research focused on engineering epistemologies and the nature of engineering knowledge, have had little impact on transforming engineering curriculum and instruction to date, and are often too removed from instructional frameworks to have direct application to curriculum design and pedagogy. Transformative engineering instruction for equity and inclusion will require researchers and curriculum designers to look beyond the cognitive and individual theories of learning that draw on Constructivism, Constructionism, and experiential learning that have strongly framed engineering education research to date (Dewey, 1938; Papert, 1980; Papert & Harel, 1991; Wadsworth, 1996), and to draw on situated, distributed, and socio-cultural theories of learning that situate disciplinary knowledge and student learning trajectories in heterogeneous contexts in which they

unfold. Most literature on engineering education draws on these "grand theories" and "framework of action theories" (DiSessa & Cobb, 2004), but what is needed is more work on domain-specific instructional theories – humble theories focused on the pragmatic concerns of teaching engineering in K-12 settings. Longer-term studies are needed in diverse contexts to understand the heterogeneity of engineering *in* practice (Penuel, 2014), and to provide design principles for inclusive engineering instruction that situates the technical aspects of this work in cultural, social, and historical contexts. Recent research from the informal marking and tinkering community has designed contexts that situate the informal design work of youth within larger historical and social contexts, that leverage the diversity of cultural practice and "funds of knowledge" that youth bring to these spaces as foundations for knowledge and artifact production (Vossoughi & Bevan, 2014; Bevan, Gutwill, Petrich & Wilkinson, 2015, Calabrese Baron & Tan, 2018). These studies serve as a models for similar research related to engineering and design-based learning in the classroom. Social practice theory perspectives on learning attend to how the sociomaterial arrangement of places, actions, and positions can lead to specific learning outcomes including future participation, interest, and identity (Bell, Bricker, Reeve, Zimmerman & Tzou, 2013). In the context of K-12 classroom learning, engineering instruction should be designed for social and material engagement in addition to cognitive learning gains. Socio-cultural perspectives of learning would aim to situate learners along the boundaries of engineering communities of practice through partnerships, fieldtrips, and the use of technology to extend learning beyond classroom walls, and to situate students' engineering practices within a large social context.

Learning through Engineering Design

Currently the literature on children's design and engineering in the classroom looks at two main factors: how it fosters science learning, and how it fosters collaboration and problem-solving. There are gaps in the literature regarding how to cultivate expertise in design in the classroom, the means to assess engineering practices (NAP, 2009), and there are few rich accounts of students' engineering design work. Researchers argue that this lack of guidance and example, has led to the cultivation of novice engineering practices and narrow conceptualizations of engineering among K-12 students (NAP, 2009; Boesdorfer & Greenhalgh, 2014; Capobianco et al., 2011; Cunningham & Lachapelle, 2014). For example, the majority of engineering curricula implemented in school engage student in ad-hoc design challenges that employ unsystematic trial-and-error problem-solving methods that include little to no design or planning (Council, 2009; Cunningham & Lachapelle, 2014). Research suggests that these ad-hoc approaches to engineering have led students to see engineers as laborers, builders, and technicians, but not as designers or creators (NAP, 2009; Capobianco et al., 2011). This suggests that the essence of engineering and design, design thinking, is absent for most K-12 engineering learning experiences. Literature on design expertise in professional practice sharply contrasts with how engineering education is executed in K-12 classrooms and can offer support for curriculum developers and teacher professional development, and assessment efforts around engineering and design-based learning. Expertise develops through focused and informed practice (Ericsson, 1993; Cross, 2004). The foundation of cultivating design expertise in students requires that students be engaged not just in ad-hoc design activities, or recipe-like prototyping, but in the authentic methods,

approaches, and practices that are associated with successful designs in the professional world.

Further, engineering in science classrooms takes on many forms, and most are project-based and constructionist models of learning, rather than authentic engineering through design practices. For example, design-based science learning (DBSL) is a combination of scientific inquiry and engineering design that engages students in design challenges for scientific purposes (Fortus et al., 2004; Apedoe et al., 2008; Puntambekar & Kolodner, 2005). Fortus and colleagues (2004) defined DBSL as "a pedagogy in which the goal of designing an artifact contextualizes all curricular activities. Design is viewed as a vehicle through which science knowledge and real-world problem solving skills can be constructed." Scientific discovery and understanding are the goal of DBSL. In contrast, the goal of engineering learning is to see how a scientific concept works in a particular design solution, in concert with other types of knowledge and experience (Apedoe et al., 2008; Puntambekar & Kolodner, 2005; Boesdorfer & Greenhalgh, 2014; Fortus et al, 2004). In DBSL settings, teachers often foreground related science principles and expect students to integrate them into their designs (Apedoe et al., 2008; Puntambekar & Kolodner, 2005). There is little engagement with the practices of synthesis, systems thinking or modeling (Kolodner, 2002; Council, 2009). Instead students tend to work in the epistemologically scientific framework of claims-evidence-reasoning, and explanation (Kolodner, 2002). Assessments are often in the form of pre and post-test and are oriented around the learning of science concepts, rather than the success of the design itself (Apedoe et al., 2008; Puntambekar & Kolodner, 2005; Boesdorfer & Greenhalgh, 2014; Fortus et al, 2004; Razzouk & Shute, 2012). In contrast,

an authentic engineering environment would engage students in design-first instructional models in which students would be asked to synthesize and apply a breadth of experiential, intuitive, and disciplinary knowledge to find workable solutions to their design task (Koretsky et al., 2014; Kolodner, 2002; Schön, 1983; Stokes, 1997; Crismond, 2001; Dorst & Cross, 2001; Razzouk & Shute, 2012). Emergent principles would then be used to optimize a solution during the iterative design process.

Scaffolding content-related learning is necessary to help students reach learning goals through emergent design processes. Scaffolded design learning environments have been shown to lead to greater learning gains through the synthesis of diverse knowledge and application to design, and also the cultivation of design expertise. In a two-year design-based research study, researchers found that the addition of "distributed scaffolding" including a design diary, whole group discussions, and architectural "pin up" sessions helped students integrate science principles into the design process, and also articulate how applying these principles to their design led to better solutions (Putembaker & Kolodner, 2005). Other research examples used virtual learning environments (Koretsky et al., 2014; Sherrett et al., 2013) or computer programs (Papert, 1980) to scaffold learning through design. Professional development, educative supports, and instructional tools are needed to help teachers scaffold engineering instruction at scale. Engaging teachers in authentic engineering learning, in addition to their students is essential for successful implementation in the classroom. Research suggests that teachers play a critical role as participants in student design teams. Knowledgeable teachers can encourage systematic design practices, help students synthesize knowledge across time,

space, and domains, and learn science through design (Roth et al., 2001; Council, 2009; Puntambekar & Kolodner, 2005).

The majority of research on engineering education comes out of the science education community, as most engineering instruction is integrated into larger STEM programs (NAP, 2009). For this reason, the bulk of research on engineering education looks at how design-based instruction can mediate the learning of science and math concepts. Researchers suggest that design is a gateway for student learning of science concepts because it engages students in hands-on applications of science principles (Benenson, 2001; Crismond, 2001; Kolodner, 2002; Lewis, 2006). Even in the absence of supportive scaffolding, studies using pre and post-test evaluations have shown that engineering design can increase student understanding of math and science concepts (Apedoe et al., 2008; Fortus et al., 2004; Putembaker & Kolodner, 2005). Engineering and design thinking mediates learning through four key processes, personal relevancy, application of related principles, embodiment of related principles, and by fostering discursive practices around an artifact.

Some research suggests that engaging in engineering design activities gives students the opportunities to apply math and science principles in meaningful ways and can contextualize abstract concepts (Bilkstein, 2013; Jonassen et al., 2006). In *Invent to Learn*, Martinez (2013) argued that it is this extraction of principles from direct experience that distinguishes engineering form making and tinkering. Through synthesis, engineering design activities also enable students blend experiential and disciplinary knowledge in a way that creates a hybrid-learning environment (Jonassen et al., 2006; Bevan & Vossoughi; Vossoughi et al., 2013). In this way engineering design mediates

learning in a way that is personally relevant and agentic, and can be focused on community purposes (Vossoughi et al., 2013; Quinn & Bell, 2013; Roth, 1996). The design of artifacts is a meaningful context for learning because it enables learners to represent their thinking in a physical and collaborative way (Roth, 1996; Vossoughi & Bevan, Vossoughi et al., 2013). Through collaborative discourse around physical objects, learners are able to leverage the intuitive, experiential and disciplinary knowledge embodied in the artifact to support argumentation (Roth et al., 2001; Puntambekar & Kolodner, 2005). Roth et al. used measures of science discourse during design activities as an indicator of science learning.

Domain General and Domain Specific Aspects of Engineering

The Framework K-12 Science Education intentionally defines engineering "in a very broad sense to mean any engagement in a systematic practice of design to achieve solutions to particular human problems." This definition includes all design-based fields including engineering, architecture and even graphics design. This broad definition could potentially allow for the integration of engineering into a diverse range of K-12 subject areas and everyday design pursuits. In addition, increasing student awareness of the diversity of design-related fields could broaden student participation and interest in design and cultivate more student design-linked identities. Design thinking and practices are associated with a broad range of disciplines, including fine arts, business, marketing, architecture, landscape architecture, engineering, computers, and technology, so there is the potential for engineering practices to be taken up in a wide range of classroom settings. In addition to being integrated into non-science classrooms, engineering could be a tool to frame interdisciplinary curricula to connect learning across these disciplines

and beyond. In the literature, some authors choose to distinguish between design disciplines, while most do not. For example, Braha & Maimon argue that design in the fine arts is focused on the creative process, engineering is a technical account embodied design, and architecture is a merger of the two. Cross 2011 wrote that engineers rely less on intuition and more on quantifiable data than other designers. In general, the more technical the design field is, the more disciplinary it will be. Often, what differs across design disciplines is the nature of the problem being solved (Quinn & Bell, 2013) and the expertise leveraged to solve that problem.

The existing literature on interdisciplinary curricula is largely critical of its application in schools and argues that the advocacy and assumptions around the benefits of interdisciplinary learning have outpaced research about what good interdisciplinary curriculum should look like, and whether it even leads to better and more connected learning (Burton, 2001; Wineburg et al., 2000). Studies of existing interdisciplinary curricula show that it often takes a wide and shallow approach to learning (Burton, 2001). Interdisciplinary topics are usually linked thematically, but with little to no engagement in any disciplinary practices (Burton, 2001; Wineburg et al., 2001). Researchers also claim that interdisciplinary models falsely frame disciplinary learning as stagnant (Mansilla et al., 2000; Hamel, 2000), when in fact authentic disciplinary engagement in any field requires significant boundary crossing into other domains, and collaboration among diverse professionals (Mansilla et al., 2000). Misconceptions about what a discipline is and what counts as disciplinary learning plague school-based learning (Mansilla et al., 2000; Hamel, 2000; Applebee et al., 2000), and become even more distorted in attempts to create interdisciplinary environments (Burton, 2001; Mansilla et

al., 2000; Hamel, 2000; Applebee et al., 2000). In contrast to thematic interdisciplinary approaches to learning, design has the potential to model equitable, practice-based interdisciplinary instruction, especially if it builds on students' tacit and everyday knowledge as the foundation for integrated learning. As a synthetic and situated field, design is inherently interdisciplinary (without having to use the often criticized term), and it has the potential to connect learning in more meaningful ways than traditional interdisciplinary curricula. Through STEM programs, engineering instruction is often integrated with science, math, and technology, and proponents of STEM argue that technology, engineering and science are a seamless web that can't be separated in practice (Bevan et al., 2015 Blikstein, 2013; Boesdorfer & Greenhalgh, 2014; Roth et al., 2001; Fortus et al., 2004). Informal tinkering and making spaces have also shown that connections to art, creativity, and open discovery broaden access, participation and interest in engineering and design, especially for students from non-dominant communities (Roth, 1996; Vossoughi & Bevan, Vossoughi et al., 2013). Literature on professional and college-based design and engineering learning actually call for more integration between engineering, design, and the humanities (Bardzell & Bardzell, 2013; Council, 2009; Dunderstadt, 2010; Janassen et al., 2006; Pawley, 2012; Nieusma & Riley, 2010; Riley, 2008; Riley, 2003).

The Framework and NGSS implicitly connect engineering and social science by advocating that design solutions should be oriented towards solving human problems. There are advantages and disadvantages to this framing of design. The advantage is that it invites engineering into social science classrooms, but the challenge is integrating engineering and social science in ways that critically engage students in evaluating past

and present engineering design solutions in the context of politics, power, and community (Pawley, 2012; Riley, 2008; Nieusma & Riley, 2010; Bardzell & Bardzell, 2013). The Framework notes that, "A major goal for science education should be to provide all students with the background to systematically investigate issues related to their personal and community priorities" (NRC, 2012, p. 278). Although it is implied that this approach to science learning applies across contexts to engineering as well, researchers should explicitly state the purpose of engineering learning for solving personally-consequential problems in local contexts. Research in support of integrating design and social science note that engineers and designers often design artifacts, space, and processes for public use but do not always take into consideration the greater public good or the social impacts of their design (Nieusma & Riley, 2010; Riley, 2008; Riley, 2003). Pawley wrote that client-driven design often means that designers and engineers are solving problems that benefit institutions and people in power at the cost of the broader community, and argued that when framing engineering as solving problems, students need to be taught to ask, "Solving problems for whom?" In addition to providing more supports for design thinking, next generation engineering curricula should also provide supports that help teachers employ equitable interdisciplinary approaches when engaging student in the design practices of modeling, synthesis, systems thinking that include engaging students in personally-relevant problem solving contexts. In addition, engineering instruction and curricula should invite students to continually ask "for whom" the design world was built, and "for whom" their design solutions benefit.

Engineering and design instruction have the potential to connect learning across disciplines, time, and space, and in this sense does have the potential to broaden

participation in STEM. Equitable engineering and design instruction should allow students to build on their own experiences and expertise as the foundation for integrated learning and should connect students to each other and diverse resources to help them construct knowledge as they engage in a design-first model of engineering instruction. Evident from gaps in the literature, there is a need for quality engineering curricula that engage students in the practices of engineering in real-world contexts. In addition, teachers need to be provided with more authentic tools and scaffolds to support classroom-based engineering and design.

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Chapter 3: Everyday Engineers: An analysis of youth's everyday engineering practices and identities across settings

Introduction

Recent policy documents position engineering as a way to broaden participation for students in STEM fields, noting that engineering gives students the opportunity to deepen their science knowledge by engaging them in problem-solving practices around locally-relevant issues (NRC, 2012; Lead States, 2013). However, a recent literature review of engineering education journals found that less than 1% of reviewed articles focused on equity and broadening participation (Hynes et al., 2017), so there are few frameworks to build on when designing for culturally-responsive engineering instruction. This is compounded by the fact that less than 10% of youth participate in formal engineering learning in K-12 settings (NAP, 2009), particularly at early ages when youth are beginning to cultivate STEM-linked identities that guide their learning trajectories (Bairaktarova, Evangelou, Bagiati & Brophy, 2011; Cunningham & Lachapelle, 2014). The inclusion of engineering as part of the *Next Generation Science Standards* opens the opportunity for more students to engage with engineering learning in the classroom, and invites research and design work that guide equitable approaches to engineering learning in the classroom that build on students' everyday knowledge, interests, and experiences.

Studies on youth conceptions of engineering emerge largely from positivist research traditions (Streveler & Smith, 2006; Case & Light, 2011), and therefore existing research tends to define equity through individualistic, cognitive, and disciplinary lenses. These lenses frame equity in terms of individual ability and access to engineering-related

resources and knowledge. The focus in the engineering education community on access as the main form of equity is disconnected from the breadth of similar research from science education that recognizes the need to ground instruction in students' everyday experiences and interests as foundations for equitable learning (Aikenhead & Jegede, 1999; Rodriquez, 2015; Brown, Collins & Duguid, 1989; Greeno, & Engeström, 2006; Zimmerman & Bell, 2012; Bell, Bricker, Tzou & Baines, 2013; Penuel, 2014). The vision of equity from the perspective of culturally-responsive pedagogies, recognizes the personal and community ways of knowing that students bring to classroom settings, and seek to design personally-consequential learning experiences that connect cultural and disciplinary knowledge (Bell et al, 2013; Barton, Tan & Rivet, 2008; Aikenhead & Jegede, 1999; Gonzalez, Moll & Amanti, 2006; Gutiérrez & Rogoff, 2003; Philip & Azevedo, 2017). As described by the *Framework for K-12 Science Education*, "Instruction that builds on prior interest and identity is likely to be as important as instruction that builds on knowledge alone" (NRC, 2012 p. 287). An engineering learning environment designed for broadening participation would ask questions about what practices are valued in the formal learning environment, and how engineering is framed to include community and everyday ways of knowing that are personally-relevant to students in that space (Penuel, 2014). This approach builds on authentic engineering design practices that include tacit and experiential knowledge as foundational to designing solutions for engineering problems (Vincentti, 1990; Schön, 1983; Suchman, 2000; Cross, 2011). Further, culturally-responsive instruction calls on educators to engage students in engineering practices in socially and politically transformative ways, that situate problems solving practices within larger socio-technical frameworks

(Rodriguez & Berryman, 2002; Adams et al., 2011; Philip & Azevedo, 2017; Bang & Vossoughi, 2016). Culturally-responsive engineering instruction invites youth to redefine engineering in ways that reflect their everyday and community forms of practice, and to leverage engineering knowledge and practices for social action and change.

Significance of the Study

Over seventy-five percent of published research on K-12 engineering teaching and learning from 2000 to 2015 focused on formal classroom settings, with the other 25% focused primarily on non-formal learning settings that have a set curriculum or program schedule (Hynes et al., 2017). However, most learning occurs outside of formal settings and school time (Dreier, 2008; Banks, Au, Ball, Bell, Gordon, Gutiérrez, Heath, Lee, Lee, Mahiri & Nasir & Valdéz, 2007), and building on these everyday, lived experiences is central for developing related engineering-linked identities for youth (Lemke, 2001; NRC, 2012; Kelly, 2014; Van Horne & Bell, 2017). However, researchers argue that there is a lack of coordination between home and school cultures, particularly for STEM-related fields (Aikenhead & Jegede, 1999), and that "achievement gaps" for minoritized youth are the result of these disconnects rather than individual learning deficits (Aikenhead & Jegede, 1999; Nasir, Rosebery, Warren & Lee, 2006; Nasir & Hand, 2006). With increased focus on engineering as a way to broaden participation for historically underrepresented youth in STEM fields, more research is needed to understand how and when youth identify as engineers across the contexts of their everyday lives.

Learning is situated within an expansive social, cultural, and historic framework and finding commonalities and bridging opportunities to connect learning across settings

is essential for students learning (Brown, Collins & Duguid, 1989; Greeno, 2006; Zimmerman & Bell, 2012). Understanding the origins and trajectories of youth engagement with engineering is necessary for connecting learning from home and community to the classroom, and long-term ethnographic studies are best able to elicit this type of information, as “everyday ways of knowing may not be explicit ways of knowing by the family, but instead may be woven into everyday ways of being in the world- science and engineering practices may be intertwined with everyday activities and problem solving” (Bell, Lewenstein, Shouse & Feder, 2009, p. 93). In other words, students may not always be able to express their everyday knowledge and practices, nor how they use them as resources for their own learning, but ethnographic work in partnership with communities can surface these patterns and ways of knowing. While there is little research on student’s everyday engineering knowledge and experiences, we can leverage related literature from math and science learning to understand the important role that understanding and incorporating students’ lived knowledge is for future disciplinary learning and identity development.

Learners are immersed in a range of situated contexts for learning, which Gutiérrez (2008) termed “horizontal learning.” Trajectories of learning extend over time and across multiple settings, and learner identities are built across these cultural pathways over time (Barron & Bell, 2015; Bell et al., 2013). As students engage in learning across contexts, they leverage and develop “repertoires of practice” (Gutiérrez & Rogoff, 2003) that incorporate everyday and cultural ways of knowing about disciplinary subjects, and can provide learning resources for school learning when incorporated into formal instruction (Moje, Ciechanowski, Kramer, Ellis, Carrillo & Collazo, 2004). Research on

learning how cultures, such as home and school, interact to produce learning outcomes, provides examples for the development of culturally-relevant instructional frameworks that can be adapted for use at scale (Nasir & Hand, 2006; Philip & Azevedo, 2017; Penuel, 2014; Gutiérrez & Penuel, 2014). Findings from this body of research suggest that overlaps between learners' everyday experiences and disciplinary practices of science can open access points for students who might not otherwise participate in STEM fields (Nasir, Rosebery, Warren & Lee, 2006), and equitable learning environments that build on youth's everyday experiences are central to culturally-responsive instruction (Barron & Bell, 2015; Riley, 2003; Claris & Riley, 2012; NRC, 2012; Bell, Bricker Tzou & Baines, 2013; Roth & Barton, 2004; Barton, Tan & Rivet, 2008; Kelly, 2014). However, researchers have argued that there is a need for more studies on youth's early and out-of-school engineering practices (Cunningham & Lachapelle, 2014 Capobianco & French, 2014), to guide instructional models and frameworks for broadening participation in K-12 classrooms.

Petroski (2003) argued that children naturally engineer when they take things apart to see how they work. This observation is foundational to many making and tinkering programs oriented towards young children in informal settings (Bell & Quinn, 2013). Research on early childhood play found that young children engage in iterative design and tinkering in ways that mirror professional practices (Bairaktarova, Evangelou, Bagiati & Brophy, 2011; Biagati & Evangelou, 2016). And, that preschool-aged children displayed intuitive knowledge of design practices when working with blocks and other construction materials. Children's everyday play includes 'reverse engineering,' or taking things apart to see how they work, as well as active construction of new objects (Brophy

& Evangelou, 2007; Biagati & Evangelou, 2016). McGowan, Ventura, and Bell (2017) observed similar play-based engineering among a diverse group of fifth grade students during a yearlong ethnography across settings. In this study, students developed solutions to novel engineering design problems by observing and 'reverse-engineering' similar solutions in their homes and communities. Youth developed expertise as they critiqued existing designs, and were able to elicit generalizable science principles by describing common elements of designed solutions across time and space.

Research shows that in spite of efforts to increase engagement with engineering in K-12 classrooms, students maintain narrow conceptions of what counts as engineering, and show a waning interest in engineering learning and professional pathways over time (Capobianco, Diefes-Dux, Mena, Weller, 2011; Dawes & Rasmussen, 2007; Cunningham & Hester, 2007). For example, through a 'draw an engineer' study, Capobianco, Diefes-Dux, Mena & Weller (2011) found that elementary students' conceptions of engineering emerged from the term "engine," and associated engineers with male laborers, builders, technicians, and rarely as designers. These findings build on a 2008 longitudinal study by the National Association of Engineering that found students envisioned engineers as white males, who worked as builders, operators, planners and maintenance workers. In this study, youth also viewed engineering as difficult to learn, and positioned themselves as "not smart enough" for the field (Brophy, Klein, Portsmore & Rogers, 2008). In a more recent study, researchers developed and tested an engineering identity development scale to measure children's conceptions of engineering and potential career aspirations, and found that the integration of engineering practices in the science classroom as early as first grade fostered children's' interest in engineering activities and careers

(Capobianco & French, 2014). However, there are tensions between this body of research on early engineering learning, with some research arguing for the natural inclination of children as engineers and their intuitive engagement with engineering practices, and the alternate framework that views formal learning as an opportunity to introduce engineering to young learners. The gap between these two perspectives reflects the need for connected learning frameworks in engineering learning, and more research on youth's engineering practices across settings, both in everyday and disciplinary contexts. In particular, there is a gap in research on youth's perspectives of the epistemological and axiological dimensions of engineering in their everyday lives, as well as their own self-described identities as engineers. Research on youth's accounts of engineering across contexts, are necessary to develop instructional models for equitable engineering instruction (NRC, 2012; Philip & Azevedo, 2017). Penuel (2014) described two types of disciplinary learning, learning *as particle*, as often occurs in more formal contexts and learning *in practice* as often occurs across the everyday contexts of our lives, and argued that everyday practices gives light to cultural practices of engineering necessary for broadening the field itself: "education research is needed that focuses on how people use science and engineering *in* social practice as part of collective efforts to transform cultural and economic production" (Penuel, 2014, p. 1). A culturally-relevant approach to engineering design learning would seek to understand youth's everyday engineering experiences and would use them as a starting point for personally-relevant and community-focused instruction in design. This study hopes to lay the foundation for such work by studying how youth to self-identify the meaning, activities, practices, and purposes of engineering across the contexts of their lives.

In an example from undergraduate learning, Smith & Lucena (2016) leveraged a funds of knowledge theoretical framework to study how everyday knowledge and experiences provided low-income first generation (LIFG) college students in engineering the expertise and experience to excel in both the disciplinary and professional aspects of engineering work. Their research found that LIFG engineering students were able to use their everyday knowledge and life skills to excel in professional contexts such as externships and interviews (compared to their undergraduate peers) in relation to their ability to use machinery, think of engineering design problems on multiple tiers of engagement (as engineers and technicians), and talk with diverse team members of their engineering design teams, including technicians. Engineering researchers need more examples of this type of work for K-12 settings, and literature from science and math education provide exemplars of the pedagogical power of recognizing student expertise and building on students' everyday practices as foundations for STEM learning. For example, youth street vendors who struggled in formal math contexts displayed expert arithmetic skills in work-related, informal contexts (Carraher & Schliemann, 2002), and high school basketball players who struggled in school math classes easily calculated free throw percentages in the midst of playing basketball (Nasir & Hand, 2006). While some researchers might argue that the concrete nature of these examples provided context for abstract skills, culturally-responsive pedagogy perspectives would argue that it was the personal and cultural relevancy of these contexts that provided the groundwork for cultivating expert practices.

Research Questions

Building on the notion that equitable learning is grounded in students' everyday experiences, this study asked research questions to surface when, where, and how students engage in engineering across the contexts of their lives. Engineering is defined as both construction of knowledge and artifacts through participation, and consumption of engineered products as inspiration and precedence for design decisions, and as a form of technical literacy for participation in contemporary life. Therefore, this research is guided by the following questions:

1. What counts as engineering to elementary students from a linguistically and culturally diverse community?
2. When do non-dominant students self-report doing engineering and self-identify as being engineers?
3. What are the epistemological arrangements of students' everyday engineering practices, and how do they compare to traditional K-12 engineering education epistemologies?

Theoretical Framework

Learning in Practice

This study views engineering learning form a social practice theory perspective, which describes people with shared practices, professions and pursuits as a community of practice (Lave & Wenger, 1991; Wenger, 2000; Holland & Lave, 1999). Learning is situated and takes place on the boundaries of communities of practice (Lave & Wenger, 1991; Wenger, 2000), and expertise develops as individuals move from boundaries to the center of a community (Lave & Wenger, 1991). While identity development occurs at the center of a community, reification and innovation occur on the boundaries, and at the

intersection of multiple communities of practice (Wenger, 2000). Youth reside along multiple communities of practice including at home, in school, and throughout other everyday contexts (Akkerman & Bakker, 2011). Bringing students into disciplinary and professional ways of knowing is best facilitated when these new environments include and build on students' existing ways of knowing (Akkerman & Bakker, 2011). Students bring multiple experiences from across settings to create hybrid spaces (Gutiérrez, Lopez and Tajeda, 1999) along community boundaries. Further, youth identities exist on multiple planes—individual, social, and cultural (Zimmerman & Bell, 2012 building on Rogoff, 2003). The Individual plane includes personal epistemologies (Hammer, Elby, Scherr & Redish, 2005), personal interests and affect (Hidi & Renninger, 2006), and students' personal sense-making practices (diSessa, 1998). Social aspects of identity recognize that an individual's activity is situated and informed by socio-material arrangements as well as community and cultural ways of knowing (Zimmerman & Bell, 2012; Cole & Engeström, 1993). Lastly, the cultural plane of youth identity describes how everyday practices are shaped by cultural tools, including language, the physical environment, and historical precedence (Wertsch, 1998; Zimmerman & Bell, 2012). However, identity is not fixed across contexts, and shifts in response to the affordances and constrains of any particular setting (Bell et al., 2013; Dreier, 2009). Given the dynamic nature of situated learning, it can be challenging to elicit consistent and reliable responses to questions related to youth's science and engineering-linked identities, interests, and practices, especially in the context of a static research study. For this reason, McDermott and Webber (1998) argued that researchers should ask questions beyond "what is math?" or "what is science?" but to broaden these questions to include

“when is math, science, or for this study engineering?” “What” questions are theological in nature and aim to elicit generalizable ways of knowing and viewing the self in relation to a field of knowledge. Asking “when” situates activities and practices in context, and allows a fluidity of engagement and identity development more reflective of the dynamic spatial and temporal nature of youth learning and development.

Practices move across boundaries and communities of practice (Star & Griesemer, 1989). Akkerman & Bakker (2011) defined three boundary domains for youth—work, school, and everyday settings, and argued that learning across these boundaries required coordination with the help of boundary objects. Learning occurs both *in* and *as* practice: “focusing on science [or engineering] in practice… foregrounds peoples’ contributions to everyday social practices and asks how science and engineering figure in and are developed through those social practices. It leads to questions about how people participate in such practices, what roles they take on, and how and when their participation helps to create better lives for themselves and others in their communities” (Penuel, 2014, p. 90). Broadening what counts as disciplinary practices to include learning as both in and as practice, allows youth to use their everyday knowledge and interests as a foundation for disciplinary learning in ways that are personally-relevant and consequential (NRC, 2012; Bell et al., 2013, Barton & Tan, 2010). Practices leveraged across contexts can become tools for supporting culturally-responsive classroom learning (González, Moll & Amanti, 2006). The goal of this work is to provide one example of the diversity and complexity of youth’s engagement with engineering-related activities and practices across the contexts of their lives.

Dimensions of Engineering Knowledge

Given the heterogeneous (Adams et al., 2011; Roth et al., 2001) and synthetic (Cross, 2011) nature of engineering, there is no shared consensus on a unified epistemology of engineering practices or philosophy of knowledge (Bucciarelli, 2003; Figueiredo, 2008; Frezza & Nordquest, 2015). When engineers are asked to define the nature of their own work, their responses fall into three main categories: applying science, solving problems, and making things; engineers rarely surface the situated or social nature of these practices (Pawley, 2012; Adams et al., 2011). At a workshop entitled "Toward an Epistemology of Engineering" Figueiredo (2008) shared his framework on the four dimensions of engineering knowledge that locate engineering knowledge in four basins: 1) engineering as basic science, 2) engineering as social science, 3) engineering as design, and 4) engineering as practical realization or craft. Figueiredo (2008) argued that engineering is a transdisciplinary field, and that engineers leveraged knowledge from each of these domains to design specific solutions in context. This vision of engineering as transdisciplinary contrasts the dichotomous images of engineering in K-12 settings and curricula in which engineering is positioned as either a systemic process of applying science principles to engineering problems, or as ad-hoc approaches to problem solving that rely on iterative cycles of failure and redesign for success, with little reflection or analysis guiding design processes (NAP, 2009; Roth, 2001; Boesdorfer & Greenhalgh, 2014).

In an attempt to ground classroom engineering in professional practice, Cunningham and Kelly (2017) outlined a set of epistemic practices to help situate student learning within a more authentic framework, arguing that the disparity between

engineering education's notion of epistemic practices and professional accounts of what engineers do, is responsible for students waning interest in engineering over time (Cunningham & Kelly, 2017). This list of epistemic practices positions engineering as an interdisciplinary field, and locates engineering knowledge as emergent from iterative problem solving practices, and are grouped into four main categories: 1) engineering in social contexts, 2) use of data and evidence to make decisions, 3) tools and strategies for problem solving, and 4) finding solutions through creativity and innovation. While these categories and the epistemic practices outlined in each section do broaden traditional K-12 accounts of engineering, they also leave out other professional practices of synthesis and the use of tacit knowledge and intuition to guide design solutions. Further, the authors don't acknowledge the importance of building on students' everyday interests and practices as foundations for engineering-related identity development and equitable instruction, although they do list students "seeing themselves as engineers" as one of the core epistemic practices of engineers (Cunningham & Kelly, 2017)

Methods

Context

This research was situated within a larger research-practice partnership project (Coburn, Penuel & Geil, 2012), that was a large-scale design based implementation research initiative (Penuel et al., 2011) called the Partnership for Science and Engineering Practices (PSEP) that included multiple tiers of participant interactions (Severence, Leary & Johnson, 2014), including school district leaders, researchers, disciplinary experts, an area non-profit research organization, and 75 3rd – 5th grade elementary school teachers from one regional school district and 25 middle school teachers from another. This larger

research initiative was focused on engaging teachers in sustained professional learning through a curriculum adaptation model focused on practice-based science teaching and learning. Through this larger research effort, teachers adapted, studied, and refined commercial science kits to support next-generation science learning. This particular research study emerged from a yearlong ethnography in one fifth grade classroom. The partner teacher, Ms. Jones, is a long-term partner in research on culturally-responsive instruction with members of our research team in ways that build on students' everyday interests and expertise in relation to science learning. She has participated in ethnographic studies and curriculum co-design with our research group for over ten years (Zimmerman, 2008; Tzou & Bell, 2010; Reeve & Bell, 2009; Zimmerman & Bell, 2012; Zimmerman & Bell, 2014). Her experience and history in this work greatly informed my research design, including pedagogical approaches and instructional tools designed to surface when, where, with whom, and how students engaged in engineering practices across the many contexts of their lives including school, home, community, online, and during fieldtrips. We used surveys, self-documentation techniques, interviews, and a student-guided multimodal inquiry app called Zydeco to gather and make sense of the student experiences. Zydeco is a multimodal mobile platform designed to support student inquiry practice across settings (Cahill, Kuhn, Schmoll, Pompe & Quintana, 2010; Quintana & Lo, 2014). Students used digital cameras to take pictures of when and where they saw engineering in their everyday lives, and I uploaded pictures from their cameras to the Zydeco cloud platform. In the classroom, students used iPads to title and tag their pictures their pictures in Zydeco, and as a class we organized, summarized, and shared these tagged pictures. The teacher and I predetermined some tags such as 'science,'

‘home,’ and ‘school.’ Students also added their own tags including ‘friends’ and ‘fun.’ Zydeco served as a ‘signature tool’ that surfaced and coordinated students’ sense making of engineering activities across contexts (Penuel, 2014).

Data Collection

As part of a larger study that employed a mixed methods approach to data collection and analysis, this particular study used design-based research and qualitative methods (Bell, 2004; Cresswell & Clark, 2007; Fetterman, 2010; Ball & Ormerod, 2000) to understand students’ everyday engineering practices across settings. Erickson (1986) described how ethnography is used to describe particular examples of general findings. While this study was situated within only one elementary school classroom, I believe the findings generally can be applied at scale, with changes only to the particulars related to each student. I used ethnographic fieldnotes (Emerson, Fretz & Shaw, 2011) to document my observations, and used “thick description” to recreate detailed written accounts and reflections from the field (Geertz, 1973). Through the process of weekly memos, I analyzed my data as I was collecting it, which distinguishes ethnography from other forms of qualitative research. In addition, I video and audio recorded classroom observations and interviews (Hall, 2000; Jordan & Henderson, 1995) and compared fieldnotes with video content logs for more thorough accounts of classroom activity, including interaction analyses of students’ talk and material engagements.

Participants included 28 consented linguistically and culturally diverse fifth grade students. Most observations focused on a 5th grade science class, during normal school hours. However, I also followed students as they participated in four off-site fieldtrips, and engaged in fifteen formal engineering projects and activities across settings including

the classroom, fieldtrips, and family engineering nights at the school. Data included the following:

- 79 ethnographic fieldnotes (~170 hours of participant / observation)
- 110 hours of classroom video (from 73 school observations)
- 30 hours of student engineering design work across settings (from 15 engineering projects)
- 3 self-documentation tasks with 113 coded representative pictures
- Student written reflections on engineering (142 coded excerpts)
- Engineering Activity Task Survey responses (370 coded responses from 27 students)
- 19 student design team interviews,15-25 min each (~600 coded excerpts)

Student Self-Documentation of Cultural Experiences

The majority of my ethnographic observations occurred during classroom science instruction, with some additional observations during other subjects, fieldtrips, recess, afterschool, and evening family programs. I used photo-elicitation interviews (PEIs) (Clark-Ibanez, 2004, and self-documentation methods (Tzou & Bell, 2010; Reeve & Bell, 2009) to elicit students' engagements with engineering practices and activities during out-of-school time. Self-documentation is a qualitative methodology by which participants (students) collect photographic data to provide a visual representation of aspects of their cultural lives outside of an observable context. Clark-Ibanez's (2004) original notion of PEI's, interviewees photos were solely used for interviewing purposes. However, later research expanded on this methodology to include open coding of photos to make sense of students out-of-school and cross-setting practices, to guide culturally-responsive curriculum design work in elementary science classrooms (Tzou & Bell, 2010; Reeve & Bell, 2009).

For this study, I gave each of the 28 5th grade students their own digital camera for home, school, and field trip use, and asked them to take up to 5 pictures at each site

[see Appendix A for example self-documentation task worksheet, and Appendix B for camera card instructions]. After each self-documentation task, I collected cameras and uploaded digital files to individual student accounts on an online application called Zydeco. In Zydeco students were able to label their pictures using both predetermined and student-generated labels, and were able to view their classmates' photos and labels [see Appendix C for Zydeco activity details]. Labels included school subjects, engineering terminology, and popular student hobbies. While viewing a classroom set of pictures, students were asked to make collective claims about how they, their peers, and their communities engage with engineering in their everyday lives. My analysis included these meaning making activities, classroom conversations around student photos and tags, and design team interviews in which I specifically asked students to share more information about their self-documentation photos in relation to engineering practices and engagement. In addition to pictures, several versions of this activity asked students to describe the similarities and differences between science and engineering, which were then asked again during each round of student interviews and reflections. These data are also included in this analysis.

Engineering Activity Task Survey Design

The Engineering Activity Task (EAT) survey is an adaptation of Zimmerman and Bell's (2012) ethnographic Science Activity Task (SAT) protocol which was implemented with youth as part a conversational interview process (Zimmerman & Bell, 2012; Zimmerman, 2008). Similar to self-documentation, the SAT was created to add ecological validity to interview and survey methods which failed to account for the diversity and range of youth's engagement in scientific practices and activities across the

contexts of their lives. For the original SAT design Zimmerman & Bell (2012) leveraged science-related activities and practices identified during a multi-year, cross-setting ethnography of elementary case study students at home, school, and informal learning environments. The SAT consisted of 36 activities and practices that were grouped into four main categories- school, home, media, and community. Similarly, the EAT emerged from ethnographic data, and member checking with students, and the team of fifth grade teachers. However, since this ethnographic work was rooted in the school setting, I used self-documentation data and student interviews with all 28 5th-grade students to finalize the survey categories [see Appendix D]. The first portion of the EAT asked students "where" they see or do engineering across the contexts of their lives, and included classroom anchoring phenomena as part of our larger ethnographic work on designing for engineering in elementary school settings. The second part of the survey asked students "when" they engaged in engineering-related activities, and included specific activities such as "playing Minecraft," as well as generalizable practices, such as "fixing things" and "solving problems," as these topics emerged as cross-cutting practices that students surfaced regularly in interviews and classroom discussions.

Data Analysis

The unit of analysis for this study was students' practices, as practice is at the intersection of social, cultural, and individual expressions of self in relation to engineering in a specific context and youth identity development (Zimmerman & Bell, 2012; Lemke, 2001). Survey responses, interview transcripts, and self-documentation photos, including those tagged by students in Zydeco, were coded in excel using an open coding process (Strauss & Corbin, 1990). Photos were initially coded as visual artifacts,

and were then entered into excel with text descriptions and associated codes. Many codes co-occurred, therefore co-occurrence of codes was designed into the coding structure, and major codes such as “activity” and “practices” were divided into two categories (i.e. sub activities and sub practices) to account for co-occurrence. The division of activities and practices into two groups was not intended to subordinate some codes to others, but was a measure of convenience. In addition, I included multiple columns for the epistemic dimensions of engineering codes to allow for heterogeneous combining of dimensions in specific contexts. For example, playing an instrument is both a craft and design because of the iterative nature of developing expertise through practice. Early coding schemes emerged from related literature, and new codes iteratively emerged during the open coding process. For example, “epistemic orientation of activity” draws on Figueiredo’s 2008 Framework for the four dimensions of engineering knowledge (basic sciences, craft, design, and human sciences) with a fifth dimension of ecological engineering that emerged from student data (as described below). Tier 1 codes were more likely to draw on theory and literature, while Tier 2 codes were more likely to be emergent. One could argue that some of the activities could be practices and vice-versa. I distinguished each by grain size- activities could encompass multiple practices. For example, the activity “building things” could include the practices of designing solutions, learning from failure, defining problems, etc. (See Table 3.1)

Table 3.1. Data Codes Descriptions

Tier 1 Codes	Tier 2 Codes	Examples
Who	expert, peer, parent, teacher	"One of [the architects] talked about how astronomy and science help them." "Ana's idea was to cross chopsticks at the top of the tower to make a nest [to hold the tennis ball]." "Jacqui's mom helped us (a chaperone)." Survey responses identifying roles.
Where	home, online, school, fieldtrip, community, after school	"I usually go to my friend's house...And we build (Legos) for like two hours straight." "At my house we try to figure out ways to improve our playhouse so we have to figure out should we use blankets to make a roof or use some of the wood that we have." Survey response identifying locations.
What	art, appliances, infrastructure, instruments, natural world, tools/technology, toys, video games, crafts, furniture	Self-documentation pictures of • home washer and drier • bridge • gutter on the side of a house • computer monitor • iPhone Survey responses identifying objects.
When	art class, everyday, humanities, PE, science class	"Math. Recess. Like in rainy day recess, we make Legos." "Science. Math." "Games!" Self-documentation pictures • art class • home • fieldtrips

		Survey responses identifying where.
Activity	Building things, creating, engineering project, fixing things, gaming, playing researching, working in groups	"I always like to sketch and sometimes I would do like paint one of the furniture at my house." "I used to have this hobby, I used to make paper craft." "We made a gated fence around and made a roof and a wooden door." Self-documentation pictures: • cooking • gardening • tools Survey responses identifying activities.
Sub Activity	authentic, cooking, gardening, homework, Lego, Minecraft, music, Terraria	
Practice 1	communicating information, defining problems, designing solutions, envisioning multiple solutions, investigating materials, modeling, optimizing, planning	Many of the practices codes emerged from the Framework for K-12 Science Education (NRC, 2012). "Like on my homework I'm always brainstorming or sometimes I just use a different way like there's a math problem that has like decimals and then I just break it down by having another story for the math problems." "My group had argued at first but we decided to take the 2 ideas, and use the engineering triangle to put them together to solve and optimize our bridge!" "I think optimizing it from like where it is already because like the idea of having like a castle and then adding stuff to the castle." "I remember when we built the filter we had like, fails like 22 times in like 3 days. But, I remember that one, but then like at the last filter we made, we could put it down the drain." (pouring down the drain was the criteria for a successful filter) "I think trying, and then if it didn't work, you see what made it not work and try and make it work. That's what we did a lot."
Sub Practice	argumentation, assessing solutions, computational thinking, considering problems in context, cultural, learning from failure, sketching, making tradeoffs, synthesizing, systems thinking, using math, using science, working well with others	

		"What we did was engineering because we planned what we were going to build." Survey responses identifying practices.
Nature of Activity	constructing / consuming	Consuming: Self-documentation pictures • Infrastructure • Public transportation • Water meter Constructing: • Building things • Minecraft "Today I made a skyscraper with my group. We all started on ideas. Then we drew out the idea, and then build it, but we had some problems so we created a plan [details step by step plan for making the tower sturdy]."
Epistemic Orientation	basic sciences, craft, design, ecological, human sciences	Self-documentation pictures of natural engineers (i.e. birds and plants) "If we can have clean water for toilets then it might help Ebola. Also, if we have clean water, people could wash their hand and maybe stop the spread of the disease."
Model of Instruction	applied science, coevolution, model for inquiry, reverse engineering, distributed/synthetic	"It's kind of like we made our own laws." "I think it did because since we already had the scientific principle down, we could actually just think of it in our own way and try to recreate it, but try to make it better." "I feel like engineering maybe builds off of science, maybe. Because there are multiple different types of science and engineering is a part of it in like seeing if you need this, you have to build this… it uses science."
Outcomes	agency, identity, nature of engineering, fulfilling a need, aesthetic, fun, solving design challenge, disciplinary knowledge	"When I grow up I want to be an architect or engineer."

		"How we did engineering today is that we built something that was fun." "Being an architect is cool because you can create different things." "I learned more about engineering by teaching me that building and making things is hard and it takes a long time." "[engineers] make computer models for their ideas."

I analyzed coded data, and used basic descriptive statistics for my findings. The differing nature of the data produced different sets of results, therefore my results are organized by research instrument. Self-documentation pictures were by nature of the instrument more open ended and showed a greater breadth of findings. For this paper, I aggregated all coded data by class to elicit more generalizable findings regarding the research questions, "What [*generally*] counts as engineering to elementary students from a linguistically and culturally diverse community? And, when [*generally*] do non-dominant students self-report doing engineering and self-identify as being engineers? Lastly, I contextualized the coded data with related students' excerpts from classroom video and interview data. For example, the response "Playing Minecraft" on the EAT

received the following codes with a brief explanation of their application when appropriate:

- Home: students self-reported playing Minecraft at home or in a friend's home.
- Videogames
- Everyday: playing Minecraft was a regular out-of-school, unstructured practice for students in which there was no formal learning curriculum or framework.
- Gaming: gaming received a separate tag from playing because students engage with each other through the gaming media rather than directly.
- Minecraft: Minecraft emerged as its own code because students distinguished it as being more like engineering than other types of videogames.
- Constructing: Minecraft is a game where students actively construct virtual worlds and scenarios, as opposed to passively consuming a pre-designed virtual template.
- Design: Minecraft is epistemologically oriented with design, as students self-identified with the iterative design practices when talking about Minecraft.
- Co-evolution: the learning model for Minecraft best fits with a co-evolution model of design in which new design challenges emerge during the process of iteratively developing solutions.
- Fun: the self-described purpose and outcome of playing Minecraft for the students was universally about having fun.

Ecological Validation of Instruments

I conducted three rounds of focal group interviews with student engineering design teams, and my interview questions emerged from student self-documentation

pictures, survey responses, engineered artifacts, and video data. I found that talking about objects and data were a way to triangulate student responses with ethnographic observations and fieldnotes for the purposes of ecological validation (Cole, Hood & McDermott, 1994). I also framed questions in ways that were more likely to elicit answers from young students (Glesne & Peshkin, 1992). For example, I would ask: “How would you describe engineering to your first grade reading buddy?” rather than asking them, “What is engineering?” I regularly shared preliminary analyses and findings with students as a form of member checking the data, and many student interview quotes are examples of their reflections about coded artifacts and research findings.

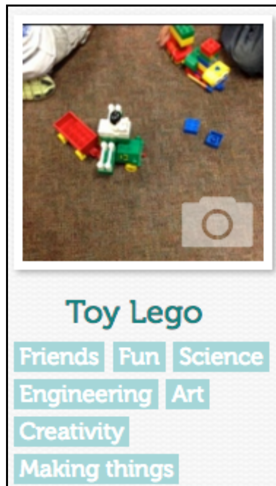
Results

Finding 1: Students’ definitions of engineering: fun, creative, and precise

Throughout the course of my year-long observations, I regularly asked students to describe, define, and redefine “engineering.” In our first activity, students chose 2-3 of their self-documentation photos to share with the class through the Zydeco App. Zydeco allowed me to upload student pictures to a shared, virtual platform through which students were able to code their own, and their classmates’ photos (Figure 3.1). I uploaded 68 student photos to Zydeco. The most common codes that co-occurred with the term “engineering” were, fun (11), science (9), creativity (7), making things (6), friends (5), and art (5). Early in our study, engineering was frequently used interchangeably with “building” and “making things,” as one case study student, Aidan, shared, “Engineering is a way of making things.” For this reason, I would sometimes use the term “making things” in conjunction with “engineering” in interviews and student

artifacts to elicit students' reasoning about the relationship between making and engineering [see Appendix C].

Figure 3.1. Students Self-Coded Data in Zydeco



For many students, material affiliations grounded their language and conceptions of making and engineering, as reflected in Chase's description of engineering, "Legos are similar to engineering." However, interviews and informal conversations unfolded in ways that enabled students to identify specific socio-material practices related to Legos or other artifacts and tools that helped us collectively define making and engineering in ways that were personally-relevant to students, in relation to scale, process, purpose, and examples in context. The term "making" took on the meaning of small-scale endeavors. As one student, Clara, shared, "Engineering…takes longer, and needs more people than making." In addition, making included the practice of building, but not designing. One student Mia shared that "makers follow engineers plans." Another student, Paige, added

that "when you make things you already know how to do it." These and related responses defined making in ways that included reproduction, but not creation. Students also distinguished their own practices as either engineering or making. Students *made* Lego models when they followed kit directions, but they *engineered* Lego structures when they added pieces, changed designs, or created their own artifacts through iterative design. One student Josh described this difference as, "I really feel like that when you do it on your own, when you can make anything that you want, it's better. There's more engineering in that, and there's more fun because you get to create your own." When students translated this to their classroom engineering work, one student, Hannah, shared how building a go-kart according to the district's 5th grade science kit guidelines were like, "someone else did the engineering triangle for us."

Almost universally, students associated both making and engineering with fun, however engineering included more creativity, agency, precision, and purpose than making. As one student Josh shared, "I feel like a big part of engineering is fun. Doing your own thing." In contrast to making, students situated engineering beyond just the creation of a project, but also its use in larger social contexts. As one student, Hannah, shared, "Both [making and engineering] are creative, but engineering is for the greater good." In addition, students had a sense that engineering included planning and iterative design cycles for improvement. One design team's conversation below reflects this perspective:

> Mia: "Engineering requires plans before building. Engineers redesign to make something perfect."
>
> Nick: "Engineering is like art, but you don't really draw your plan…"

Paige: "…you just do it."

Nick: "You do it, and then when it looks bad, you make it better."

Students descriptions of engineering from this study align closely with the Framework for K-12 Science Education definition of engineering as "a systematic and often iterative approach to designing objects, processes and systems to meet human needs and wants" (NRC, 2012, p. 202). This broad framing of engineering invites diverse perspectives of engineering practices across contexts, that include art, creating, and fun, as well as science and math knowledge. Student definitions were focused entirely on in-the-moment practices and affect, as well as past experiences as foundations for engineering design decisions. Students rarely, if ever, surfaced connections to formal knowledge, indicating that tacit understandings of math and science principles were more relevant to students' engineering practices than formal theories.

Finding 2: Engineering is a social endeavor, and students learn with more knowledgeable others.

Student responses on the EAT and through interviews revealed that engineering was a deeply social endeavor by all students, and one in which students learned through distributed expertise (Brown, Ash, Rutherford, Nakagawa, Gordon, & Campione, 1993) and legitimate peripheral participation (Lave & Wenger, 1991). Self-documentation data is not included in Table 3.2 as self-doc descriptions specifically asked student to take pictures of "things not people" for privacy and consent concerns [see Appendix A]. All students who took the EAT identified as "doing engineering" with experts, which reflects our larger research design efforts to connect youth to diverse community and disciplinary

engineering experts. These experts included informal educators on fieldtrips, speakers from a fieldtrip to a local architectural and engineering company, and classroom speakers from the same engineering firm, a local aeronautical industry, and volunteers from Doctors without Borders. For this reason, I do not argue that students regularly do engineering with experts in their everyday lives, but that youth locate engineering expertise and knowledge with disciplinary experts. Further, students' self-identified as learning authentic engineering practices and knowledge through partnerships with experts during this study.

Table 3.2. With Whom Youth Engineer

Who do you engineering with?	Student Responses
expert	29
peer	10
parent	7
teacher	6

In addition to locating engineering knowledge in experts, students regularly reported and discussed "doing engineering" during out of school time with friends- particularly through the activities of gaming (such as Minecraft and Terraria), play (such as sports and music), and building things (such as forts and Legos). Learning from friends included engaging in joint activity, but also learning through observation of peer designs (both successes and failure). For example, Mateo shared that he liked engineering with friends "because they have the best ideas!" Nick and Sam laughed about the sustained focus of their engineering practice when playing Legos. Nick said, "I usually go to my friend's house… and we build for like two hours straight." Sam added, "No bathroom breaks!" and both nodded and laughed. I asked how we could cultivate that type of focus

in school activities, and they suggested, “maybe put Minecraft on the iPads.” In addition to learning with peers, many students identified activities with their parents as engineering when they engaged in chores, home projects, play, and observation. Paige shared that she engineers “with her mom” when they play Legos and Minecraft together, and she emphasized her point that “girls play Minecraft too!” Nick recalled building a chicken coop with his dad to keep out neighborhood cats and rats, and Hannah shared that trying to design more efficient ways to wash the dishes with her mom was a lot like engineering. Many of these students’ stories about engineering with parents showed up in their self-documentation photos as well. Pictures of gardens, cooking, using computers and related technology, and building home projects were among the most common pictures shared by students (see Table 3.2). One student Elias, recounted many instances of engineering with his dad, and when I asked him, “When do you feel like an engineer?” he replied, “Whenever my dad is around.” In class conversations, Elias described his dad as a construction foreman, and told stories of reviewing video data of construction projects with his dad in the evening to prepare for his next day. Elias and I compared those experiences to the type of research I was doing in the classroom (i.e. recording video, making design decisions, and reviewing data to share with the class on a regular basis). In an interview I asked Elias, if there were experiences from his everyday life related to engineering that he used during classroom activities., and he related helping fix his Dad’s car to building a go-kart that could make a turn: “I seen like sometimes my Dad's like little car breaks down, so we like fix it, and see if it like turns or not. I see when it turns, like one wheel is closer to the other. Like make a turn (the classroom engineering design challenge), like these wheels is like (gestures on a piece of paper)

really close to each other, and these wheels are like farther, and then it would like turn." Elias was able to recreate the wheel arrangement during his go-cart design (see Figure 3.2) by adding more tension to a rubber band on the left side of the go-kart and allowing slack in the rubber band on the right side of the go-kart, which shifted the front axle and front wheels to the left. Learning with adults most often modeled historic images of engineering as a craft and trade learned through lived experience and apprenticeship into socio-material practice. These models of learning located engineering practices within specific communities, times, and contexts, and also provide general competencies and practices that could be applied across setting, as Elias was able to do with a classroom go-kart project.

Figure 3.2. Elias Make-A-Turn Go-Kart

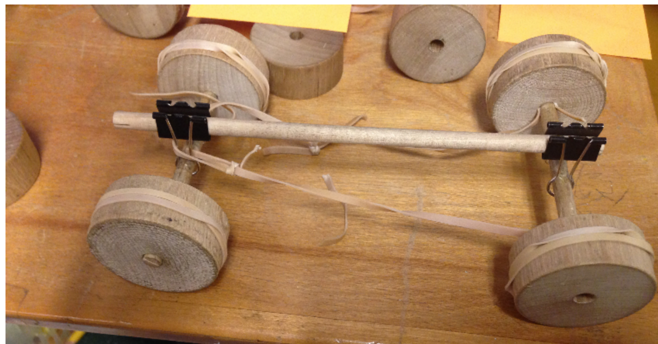


Figure 3.2: Note the tension in the lower rubber band and slack in upper rubber band. When the rubber band was wound around the rear axle, the front axle shifted to the left. This design was in response to a series of design

Lastly, students also self-reported learning through online media, such as YouTube videos, and game tutorials. Although this category was not in the initial EAT design, it is one that I would add in future versions as it emerged as a regular and shared experience among many of the students, particularly in relation to gaming. For example, Paige, Nick, Chris, Josh, and Aidan all recounted the same YouTube channel as a source of their Minecraft learning and expertise development. Students shared that it was

difficult to intuitively engineer in Minecraft because the game doesn’t obey tradition laws of physics, and the laws of the game aren’t always predictable, as represented by the exchange between Nick and Paige below:

> Nick: “Minecraft...Minecraft there's not much physics in Minecraft. You can make a block float without it falling down except for gravel and sand. [When I] make creations in Minecraft, I don't, like, make them stable and stuff. It doesn't have to look stable because blocks float.”
>
> Paige: “But you have to be sure! The game has, like, it has like no constraints.”
>
> Nick: “Oh yeah, there are also worlds that are not flat and there are worlds that are flat.”

In a later conversation Josh and Parker engaged in a similar exchange, and described Minecraft as having “Redstone mechanics” that differed from “Newton’s Laws of Motion.” For Minecraft players, the online community, which Nick noted, “has over 20 million players,” and was a source of knowledge and a way of learning through legitimate peripheral participation for youth (Lave & Wenger, 1991). Students started on the boundaries, watching more knowledgeable players rehearse plays and reveal game mechanics through online videos, and then became more knowledgeable others through practicing and learning in their own local contexts with friends. This finding revealed how digital tools and virtual communities have shifted how knowledge and practices can be situated, without being situation bound (Nussbaum-Beach & Hall, 2011; Dreier, 2008).

Finding 3: Students locate engineering and participate in engineering-related activities across the contexts of their lives.

Answers to where and when students did engineering were remarkably similar for both the EAT and Self-Doc data, in spite of major differences between the two research tools [Table 3.4]. For example, students took the EAT survey in school, and it was focused on engineering across settings, including many school examples. The Self-Doc was a home-based activity and had fewer constraints for what students could include. For both of these research tools, students reported doing engineering at home most often. School and fieldtrips ranked second and third for the EAT, but were not options for the self-doc. Community-related engineering responses were similar for both the EAT and self-doc. Videogames, especially Minecraft ranked highest on the EAT for "when students felt like they were doing engineering." The same was true for the self-doc, however student pictures were more general and the tools and technology label included gaming devices, smart phones, computers, as well as calculators and other devices. Interviews helped distinguish gaming from other technology-related activities for self-doc pictures. On the self-doc instrument, students also identified material infrastructure—toys, crafts, the natural world, and art—as being associated with when they do engineering across settings. The intersection of survey and self-doc responses provided nuance and context to student's responses. For example, most students reported engineering at home, and the self-doc gave concrete examples how youth defined engineering in their home context.

When we summarized combined EAT and self-documentation data by student (N=24 students who responded to both research instruments), we found that students self-

reported engaging in engineering practices and activities across the contexts of their lives (Table 3.3). Significant is the fact that 96% of students reported doing engineering in their homes and 54% in their communities, as these contexts are largely left out of research on engineering learning. A recent literature review of articles from 2000 – 2015 found that 75% of engineering education research took place in classrooms, and 25% was in informal spaces, meaning that are large part of youth's engineering work is not covered in existing research. Most youth associated play, gaming (especially sandbox games), building and making things, drawing, fixing things and trying new things as being engineering. Practices overlapped considerable with the Framework and NGSS, but also surfaced how youth consume engineering as part of living in a sociotechnical world.

Table 3.3. Combined Self-Doc and EAT responses by student (N=24)

Where	Activities	Examples	Practices
Home (96%)	Playing (98%)	Lego (58%)	Cultural Practices (71%)
Community (54%)	Gaming (83%)	Minecraft (71%)	Optimizing Models (67%)
Afterschool (13%)	Building & Making (71%)	Cooking (50%)	Designing Solutions (58%)
Natural World (30%)	Drawing (71%)	Gardening (46%)	Learning from Failure (56%)
School (96%)	Fixing Things (58%)	Music (46%)	
Fieldtrip (92%)	Trying New Things (46%)	Sports (33%)	

Lastly, youth's everyday engineering practices were closely aligned with the dimensions of design and craft, and no students reported doing engineering in relation to science knowledge nor to produce science knowledge.

However, the nature of engineering-related activities varied significantly between the EAT and self-docs. Due to the design of the EAT, student responses were oriented towards hands-on activities, as the EAT specifically asked students, "When do you use engineering or the engineering triangle?" References to the NGSS engineering triangle emerged from the teacher's involvement in the district implementation project, and also oriented students towards specific practices of engagement such as "defining problems," "testing solutions," and "optimizing solutions." In contrast, the self-doc simply asked student to share pictures of where they saw or participated in "engineering in their everyday lives." Our results reflect these differences in the research tools, and also paint a more holistic view of where students see engineering across contexts, and these differences are show in Table 3.4 results, which summarizes students' survey and self-documentation data by individual pieces of data collected, rather than by student as in Table 3.3. above.

One student Alana described feeling like an engineer when she constructed playhouses with her four siblings. She noted that the act of building out of everyday objects meant that she had to be creative and improvise with what was available. Another student, Josh, shared that he felt like he was engineering when he did origami, and shared, "I have this little set, like it's like a box and it says *Geogami*, so it's like geometric shapes made with origami. I actually made a little pinwheel. At first, I was like I don't know how to make this pinwheel, but then I figured it out." For many students the act of

working through problems and figuring things out felt like engineering. Lastly, many students located engineering in their sports activities. One student, Jarron, shared that sports were when he most felt like an engineer because he was "making a plan, and trying to make it work." Sierra agreed and felt that sports included practicing and trying new things.

Table 3.4. When and Where Youth See Engineering

Where (EAT)		Where (Self-doc)		What (EAT)		What (Self-doc)	
Home	195 (56%)	Home	76 (77%)	Videogames (16 Minecraft)	35 (38%)	Tools/ Technology	34 (35%)
Community	14 (4%)	Community	22 (22%)	Crafts	15 (16%)	Infrastructure	18 (19%)
School	85 (26%)	School	1 (1%)	Toys (Legos 14)	14 (15%)	Toys (Lego 10)	15 (41%)
Fieldtrip	36 (11%)			Natural world	11 (12%)	Art	9 (9%)
Afterschool	3 (<1%)			Instruments	10 (11%)	Appliances	6 (6%)
				Tools/technology	7 (8%)	Natural world	5 (5%)
						Crafts	4 (4%)
						Instruments	4 (4%)
						Furniture	2 (2%)

Design thinking research and models emphasize the non-linear and iterative nature of design (Cross, 2008). This emerged as a central focus for youth in this study. In addition to associating engineering with creating, having fun, and being precise, students often talked about learning from failure through the process of engineering over time.

Engineering education research also includes “learning from failure” as a central design practice (Cunningham & Kelly, 2017; NRC, 2012), however youth in this study also noted that engineering happened when they figured out “what worked.” Surfacing the “what worked” in design solutions became a central focus in instructional frameworks related to this study (McGowan, Ventura & Bell, 2017).

Students also associated engineering with “trying new things” and “making things work,” and there was a sense that engineering was a learning-by-doing process. This perception of engineering fits with literature that describes engineering as a problem-solution co-evolution model of engagement. The problem-solution cycle of engineering suggests that new knowledge and solutions emerge iteratively through the course of solving a problem in context (Dorst & Cross, 2001; Schön, 1992; Cross, 2008; Purcell & Gero, 1998). These types of activities were coded as “constructing” in addition to their primary codes, which conferred active engagement in the creation of an artifact, process, or strategy [Table 3.5]. Minecraft was coded as ‘constructing’ because youth actively build and manipulate objects within the virtual space. Other constructing examples included making crafts, playing sports or an instrument, and playing with friends through joint engagement in activities. In interviews, students described being active participants in these pursuits. The exchange below surfaces how students saw Minecraft and other “sandbox games” as related to engineering in their everyday lives:

> Researcher: Do you do activities related to engineering outside of school?
>
> Josh: Gaming, there's a lot of sandbox games where engineering is very vital. Like…
>
> Parker: …For example Minecraft.

Hannah: A sandbox game is one that goes on forever. Sometimes, like the physics in the game don't work, so you have to think of designing new ways of, 'how can we get this to work?'

Lela: Minecraft is definitely engineering

Chase: Because you can build buildings and stuff in Minecraft.

In contrast, I used the code 'consuming' to describe moments when students saw engineering in their everyday lives, but were not actually engaged in the activity itself. The consuming code occurred most often with self-documentation photos, as students were able to take pictures of objects in their homes and communities that counted as engineering. Further, self-documentation directions asked students to share pictures of "how they and their families *use* engineering in their everyday lives" in addition to when they were engineers. Codes such as infrastructure, the natural world, appliances, technology (including calculators and computers), and furniture were codes that commonly co-occurred with consuming. I interpret the role of students as consumers of technology, as related to the development of technical and socio-technical literacy of youth as knowledgeable community members and citizens. The importance of observing and understanding engineering is described by Sierra who related engineering to history because "we need to look back on what other people have done." In related work from our larger research project, students were able to relate the role of engineering through history to larger social phenomena related to public and environmental health of their communities (McGowan, Ventra & Bell, 2017b).

Table 3.5. Nature of Youth Engineering Activities

Nature of Activity (EAT)		Nature of Activity (Self-Doc)	
Constructing	187 (83%)	Constructing	35 (41%)
Consuming	39 (17%)	Consuming	50 (59%)

While students saw engineering across the contexts of their lives, the opposite was true for science. When I asked students, “When do you feel like a scientists in your life?”, one student, Parker, responded, “Not often. Sometimes in science class.” In a separate interview Elias shared a similar perspective when he said, “Mostly at school.” In the same interview Ana agreed, “Yeah, I think mostly at school. Sometimes there's a program with my tutor.” Overall, students viewed science as more structured and formal, and students self-report being a scientist at school more often than in their everyday lives compared to engineering. They synthetic nature of engineering possibly explains why youth locate engineering more readily in their everyday lives than science, and provides insight into how to construct culturally-responsive engineering instruction for youth. In this study, youth associated science with formal knowledge that they usually located in formal settings, such as school. In contrast, engineering was associated with material experiences that were readily available across context. The framing of engineering as fun, ‘trying new things,’ and ‘figuring out what works from failure’ were closely related to youth’s everyday experiences, and opened opportunities for youth to engineering in new spaces and contexts without having to have a foundation in formal engineering first. Given these findings, it is particularly problematic that most commercial engineering kits and curricula position engineering as an applied science, and foreground a narrow set of

science-related knowledge intended for youth to apply to a particular classroom engineering project (NAP, 2009).

Finding 4: Students engage with authentic engineering practices in their everyday lives

Students reported doing very similar engineering-related practices and activities across settings for both the EAT survey and self-documentation tools. I included both activities and practices in this portion of the analysis because students identified activities as being related to associated practices. For example, students would often talk about building things, creating, and optimizing designs in the context of playing with Legos. This perspective is respresented in Chris's response when asked when he does engineering-related practices outside of school, "When I'm building Legos. Like trying to figure out how to rebuild it to make it perfect. So, you take things apart and try to make them better. You try to optimize them."

The table below reports student responses to the self-doc and survey. Activity rates appear lower than were reported per students because of the high number or responses. For example, all students reported play as being related to engineering, and more than half of 28 students reported that Minecraft was related to engineering.

Table 3.6. Student-Idnetified Engineering-related Activities and Practices

Activity & Practices (Self-Doc) N=113		Activity & Practices (EAT) N=369	
Creating	22 (24%)	Playing	48 (15%)
Playing	19 (21%)	Gaming (16 Minecraft)	35 (11%)
Building things (Legos 10)	17 (18%)	Designing solutions	28 (9%)
Cultural Practices	8 (9%)	Systems Thinking Activities (Cultural Practices)	18 (6%)
Designing solutions	8 (9%)	Defining problems	18 (6%)
Gardening	4 (4%)	Drawing, etc.	17 (5%)
Optimizing	3 (3%)	Building things (Legos 14)	17 (5%)
Learning from failure	3 (3%)	Gardening	14 (4%)
Gaming	2 (2%)	Fixing things	14 (4%)
Using math	2 (2%)	Solving problems with people	14 (4%)
Communicating information	1 (1%)	Cooking	12 (4%)
Designing solutions	1 (1%)	Playing board games	12 (4%)
Making trade offs	1 (1%)	Fishing, etc.	11 (4%)
Fixing things	1 (1%)	Trying new things	11 (4%)
		Fixing things	11 (4%)
		Playing an instrument	10 (3%)
		Using tools	8 (3%)
		Playing sports	8 (3%)
		Learning from failure	8 (3%)

The activities that students most often associated with engineering were playing, gaming, building things, drawing, and fixing things. Elias described how he felt like an engineering when he fixed his little brother's toys, "Sometimes, like, my little brother has stuff that is broken and like, he wants to throw it away 'cause it's like broken, but I then get it and I try to fix it, and I give it back to him." In addition, students regularly reported feeling like an engineer when they were building and making things. This was reflected

in Alana’s description of building for her dolls during one of our interviews, “[I’m doing engineering when] …I play with my dolls and they don't have a house, so me and my little sister we have to like try and build a house like we take folders and make walls and three ring binders so they can have doors.” Lastly, during interviews, students frequently reported engaging in engineering practices when they were doing their homework, due to the iterative nature of homework, and because students felt homework was an opportunity to learn from failure. During interviews, six students surfaced homework on various occasions as a time when they felt like an engineer at home. Homework emerged as a unique example that very explicitly crossed home and school boundaries, and may be representative our larger research focus on where and when engineering shows up across settings. In addition, homework was a practice that they engaged in on a daily basis and was likely in their recent memories at the time of each interview, and excerpts are below:

> Researcher: When do you feel like an engineer?
>
> Mia: “Like on my homework I'm always brainstorming or sometimes I just use a different way like there's a math problem that has like decimals and then I just break it down by having another story for the math problem.”
>
> Isabella: Homework. I get a lot of questions wrong, and then a lot right sometimes.

The engineering practices that surfaced most often during this research were creating, designing solutions, systems thinking, defining problems, optimizing, and learning from failure. Cultural practices were also among the most referenced by students, and included cooking family recipes, building artifacts for worship, and systems thinking as a practice for connecting socio-technical aspects of engineering to students’ everyday lives. These

connections are highlighted by two examples later in this section. For example, Chase described how learning from failure and trying to get things to work were his favorite aspects of engineering, “It's fun to make your own design, because you can test it to like failure and stuff. Then until you get it right because that's a great part for me, to test it to see if it will work or not.” Nick also shared how the process of failure helped with his own learning, “Like every time you fail, you can see the problem and actually fix it, and make it better so when you fail you'd start over intelligently.” The focus on learning from failure similarly emerged during students’ reflections on homework as noted above.

Surprisingly what surfaced often in my data and interactions with students throughout the year, was the degree to which engineering practices defined students’ cultural and personal identities. In classroom conversations, students often talked about designs within their communities, including their temples and churches. When we walked to fieldtrip sites, students would point out aspects of these cultural icons and describe how specific design features had historical and cultural meaning. Two students who self-identified as being Buddhist shared the importance of the color red used in their local temple design. In addition, students shared pictures of cultural practices from home through the self-doc activity. Mia shared a picture of an artifact for worship that she helped build with her parents [see Figure 3.3]. In the space provided on the self-doc she wrote, “[This is] my grotto, a homebuilt statue of the Virgin Mary for worship, part of catholic worship.” Mia uploaded her picture to the Zydeco app during our whole class sharing activity and talked to her classmates about the process of building a grotto, and its purpose and meaning in her family’s life. Hannah also shared a picture of a Buddhist alter that she helped her family build and maintain in their home [see picture 3.4]. In the space

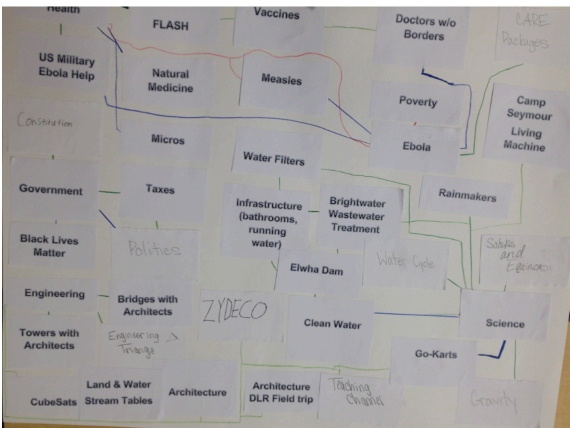
next to the picture, Hannah wrote, "[this is an] alter- I am a Buddhist so this is my alter to respect the spirits." Hannah also shared images of her mother's way of cooking traditional Vietnamese dishes, in Figure 3.5, Hannah described how her mother prepared salmon for a special soup. Lastly, we found that systems thinking activities, including causal-loop modeling was an engineering practice that helped students connect their own experiences to larger cultural, political, and health phenomena [see Figure 3.6]. During this activity, students made connections between public health, clean water, and infrastructure across contexts, including their classroom, science kits, local fieldtrips to a watershed and wastewater treatment facility, and personal and public health. Within these connections students explored how issues of race and power were related to who gets to be healthy and who is more likely to be sick (McGowan, Ventura & Bell, 2017b). Systems thinking activities also helped students locate engineering across global contexts, in addition to connecting them to their everyday experiences.

Figure 3.3. Mia's Grotto

Figure 3.4. Hannah's Alter

Figure 3.5. Hannah Cooking Soup

Figure 3.6. Systems Thinking for Connected Engineering



In addition to coding student responses for activities and practices, I also coded for the epistemic dimensions of these practices, and the purpose of the activities. As described by Figueiredo (2008) engineering practices and activities are located on distinct

coordinates along a Cartesian plane with coordinates residing in areas of social science, basic sciences, design, and construction/ craft. For this set of data, students' everyday practices were coded most often as being related to the engineering dimensions of craft (89) and design (29). Further, students reported engaging in engineering for the purpose of fulfilling a need (63), fun (23), cultural mediation (9), and aesthetics and artistic creation (8). Several students reported boredom as being a driving force behind starting an engineering challenge, as described by Sierra and Hannah below:

> Researcher: Why do you do activities like engineering at home?
>
> Sierra: For me… for engineering, sometimes I get really bored and try to make my own little mobile (means automobile) (gestures both hands to show a wheel moving forward) that can move. I use like batteries, and I use red and black wires, and stuff moves.
>
> Hannah: At home? Maybe. Because I'm an only child, yeah I have to tend to entertain myself somehow. Because I have to find different ways to entertain myself without breaking anything.

For the youth in this study everyday life provided the context and need to engage in engineering, suggesting that engineering can be a self-directed endeavor for youth, rather than a top-down structured activity. This contrasts with the way that engineering is often taught in class and through pre-designed curricula and kits. In traditional engineering instruction, a need and engineering problem are provided for students, which contrasts with the emergent and open-ended nature of engineering pursuits in their everyday lives.

Finding 5: Students extended engineering to ecological processes and non-human actors

National policy documents align engineering pursuits with human needs and wants, and position humans as the only actors in technology creation (NRC, 2012). However, several students in this study assigned natural processes, such as wetland water filtration, [Figure 3.7], the carbon cycle (photosynthesis and respiration), and non-human actors, such as birds building nests [Figure 3.8] to engineering. For these students, the natural world is defined by intention rather than instinct and inertia. This image of engineering reflects those held by ecologists who recognize the social aspects of learning for wildlife, and indigenous understandings of the natural world (Medin & Bang, 2014). For example, Alana shared that plants are like engineering because "they make air." Students also drew inspiration from natural design during classroom engineering work through biomimicry. One student, Mateo, shared how he was inspired by a bird's nest in a tree for an in-class "tower of power" design challenge—an activity in which students were asked to design a tall tower that could hold a tennis ball in the face of strong winds from a fan. These types of responses are often coded as student misconceptions of scientific knowledge. However, these findings could also suggest that students hold broad views of who and what counts as an agentic actor in the world (Latour, 2005), and the ecological reality of interdependence of all material and living elements on Earth. In this sense "Ecological Engineering" can be viewed as a 5th dimension to add to Figueiredo's (2008) four dimensions of engineering.

Figure 3.7. Natural wetland filters water (Self-Doc)

Figure 3.8. Bird's nest (Self-Doc)

Discussion

Youth identify with engineering practices, if not engineering

The results of this study differ significantly from those in existing literature on youth's conceptions of engineering and engineers (Capobianco & French, 2014; Capobianco et al., 2011; Lachapelle & Cunningham, 2014; Boesdorfer & Greenhalgh, 2014; Sullivan, 2006). These prior studies have argued that youth do not identify with engineering, rarely engage in engineering-related activities, and have waning interest in pursuing engineering endeavors as professionals. In contrast, this study suggests that youth strongly identify as engineers across the contexts of their lives, when they are

allowed to define and relate to engineering according to their own definitions. For this study, youth defined engineering as fun, creative, precise, iterative, building on existing knowledge, social, and learning from failure. This definition is similar to definitions found in the literature on professional design practices (Vincenti, 1990, Petroski, 2003; NRC, 2012), but differs from definitions that position science and math as foundations to engineering design solutions, which surface often in classroom contexts (Carr, Bennett, & Strobel, 2012, p. 101).

In addition, I attribute these differences to this study's focus on engineering practices instead of positioning engineering as a profession or a discipline. Practices span across multiple settings including home, school, and everyday contexts (Akkerman & Bakker, 2011), and students were able to easily communicate how engineering practices from the classroom and with experts also showed up in other areas of their lives. In addition, asking students "when, where, and with whom" they did engineering broadened our research questions to include concrete and dynamic experiences across contexts, rather than framing engineering as a fixed, and abstract body of knowledge.

Existing studies tend to frame engineering as a discipline—emblematic of how a STEM based learning trajectory ends in a professional engineering job. However, professional communities of practice are by nature bounded and rooted in historical patterns and ways of knowing (Wenger, 2000), and are not within the traditional scope of youth settings (Akkerman & Bakker, 2011). For this reason, framing engineering as a discipline or a profession to youth may be too removed from their known contexts to be relatable. Further, engineering-related activities and curriculum that are distilled from professional and disciplinary contexts are less likely to resonate with youth than learning

environments that invite and build on how students engage with engineering *in* practice as part of their everyday individual, social, and cultural lived experiences. This is particularly true for youth from communities historically underrepresented in STEM who may have less access to professional engineering communities than youth from dominant cultures who have historically been served by the field.

Dimensions of Engineering Across the Settings of Youth's Lives

Cunningham and Kelly (2017) described a mismatch between school and professional engineering practices, and argued that this mismatch was why youth were not interested or familiar with pursuing engineering learning pathways and professions. My research supports these findings, and found that that there is an epistemic mismatch between school and professional engineering practices and approaches in the classroom. Professional engineers tend to work as designers through evolutionary cycles of iterative problem solving (Cross, 2008; Vincenti, 1990; Razzouk & Shute, 2012; Schön, 1992), while school-based engineering tends to be overly structured in comparison to youth's everyday engineering activities, and takes on a linear applied-science model of solving problems or designing solutions (NAP, 2009). In addition to a disconnect between school and professional practices, I also found a mismatch between the epistemic dimensions of school engineering and youth's everyday engineering. Analysis of this data set revealed that students identified with the epistemic dimensions of engineering as craft and design work, while traditional K-12 curriculum tends to position engineering as basic science (NAP, 2009; Tadmor, 2006), and increasingly as design with the adoption of NGSS. I argue that this (rather than the professional-school mismatch) is why studies find youth lose interest in engineering over time, even with increased access to engineering

curriculum at higher grade levels. Analyses from student data across contexts for this study suggests that the narrow framing of engineering by traditional school curriculum materials and frameworks simply leaves out students' everyday practices. The Framework for K-12 Science Education has provided a policy foundation for constructing engineering learning environments that build on youth's everyday identities. However, future engineering curricula and assessment models will likely determine how Framework recommendations are taken up at scale.

Research on the diversity and transdisciplinary nature of engineering practices and disciplines, and their iterative reconfiguration in context suggests that authentic engineering learning that puts students on professional engineering design trajectories can in fact look many ways, and does look like students' everyday conceptions and engagements (Figueiredo, 2008). Young people come to school with diverse and authentic experiences related to engineering, and expertise through engagement with a broad set of engineering-related practices. Contrary to research claims that youth disidentify with engineering, I would argue that youth disidentify with the narrow portraits of engineering found in existing l K-12 learning settings. These include engineering as applied science, overly-scripted design work, and using prototyped engineering models for scientific inquiry. Figueiredo and others have painted an image of engineering as heterogeneous, transdisciplinary, and defined by context. NGSS and the Framework broadly define engineering in a way that encompasses these professional notions of the field, and paves the way for the development of more inclusive types of instruction, diverse participant structures, and science-based learning through design that is emergent rather than prescriptive. Designing engineering learning environments that

invite and build on students' everyday engineering activities and practices, is essential for creating culturally-responsive instruction that broadens what counts as engineering, and therefore who gets to be an engineer. The way that students learn engineering *in* practice and how those experiences are framed in the classroom shape emerging STEM-linked identities in youth. Therefore, broadening participation in STEM is not about providing students access to disciplinary knowledge and professional images of engineering, but rather about broadening what counts as engineering in the classroom and allowing youth to define those boundaries as the foundation for their life-long learning trajectories.

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Appendices

Appendix A: Self-Documentation Example

Name ____

Date___________

Keep a Journal for 2 Days

Please help me learn about how you, your family, and your community use Engineering in your everyday lives. This can include objects, ideas, actions, and more. Can you find examples of how engineering or "making things" helps people solve problems?

Take a picture or write down anything that represents how you use engineering in your life.

You can collect printed materials, draw pictures, or add things like charts in your journal too!

You can take more pictures than what you write down.

Take pictures of things, not people

Questions:

1. What are similarities between engineering and making things?

2. What are differences between engineering and making things?

What is the picture of?	Where did you see it?	When did you see it?	Why was it made?	Was it ever redesigned to get it just right? How?

Space to draw or paste pictures related to engineering in your life

Appendix B: Camera Cards for Cross Setting Data Collection

Name ___________________________

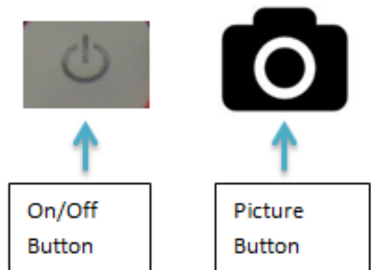
Let's Collect Data!

Can you take pictures of how you see engineering in your everyday life?

Can you find examples of how engineering solves problems?

*Take pictures of things not people!

Using the Camera:

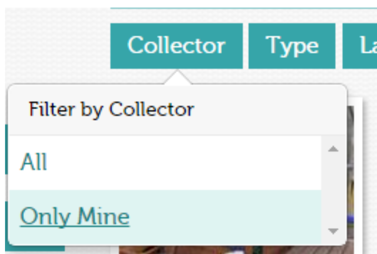


Appendix C: Zydeco Directions

Directions:

Click on the “Review Button that looks like a green circle:

Under the “Collector” button, select “Only Mine.”



Add a Title to your pictures.

Add as many labels to your picture as you can. No need to add a description. Use as many labels per picture as you can.

The labels you can use are:

- Solution, Optimize, Iterate
- Tools, Cultural, Nature, Human structures
- Engineering, Science, Technology, Making Things, Using Nature, Creativity, Art, Social Studies, Math,
- Fun, Friends, Community

Writing a Claim

Click the "Review" icon

- Tap "Add New Claim" to add a claim that answers your overarching question.
- Tap save once you have typed a claim that you are happy with.
- Tap the "Add Evidence" box to attach picture evidence to your claim. You can select as many pictures as you would like, but too many might be difficult to organize.
- Tap "Reasoning" and describe how your evidence supports your claim.

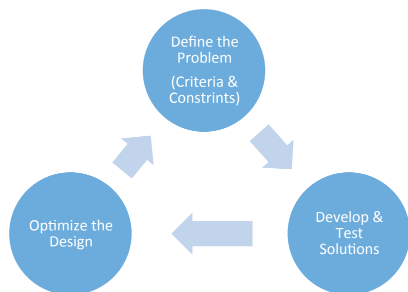
Appendix D: Engineering Activity Task Survey

Where do you use Engineering or the Engineering Triangle? Circle   as many answers as you want.

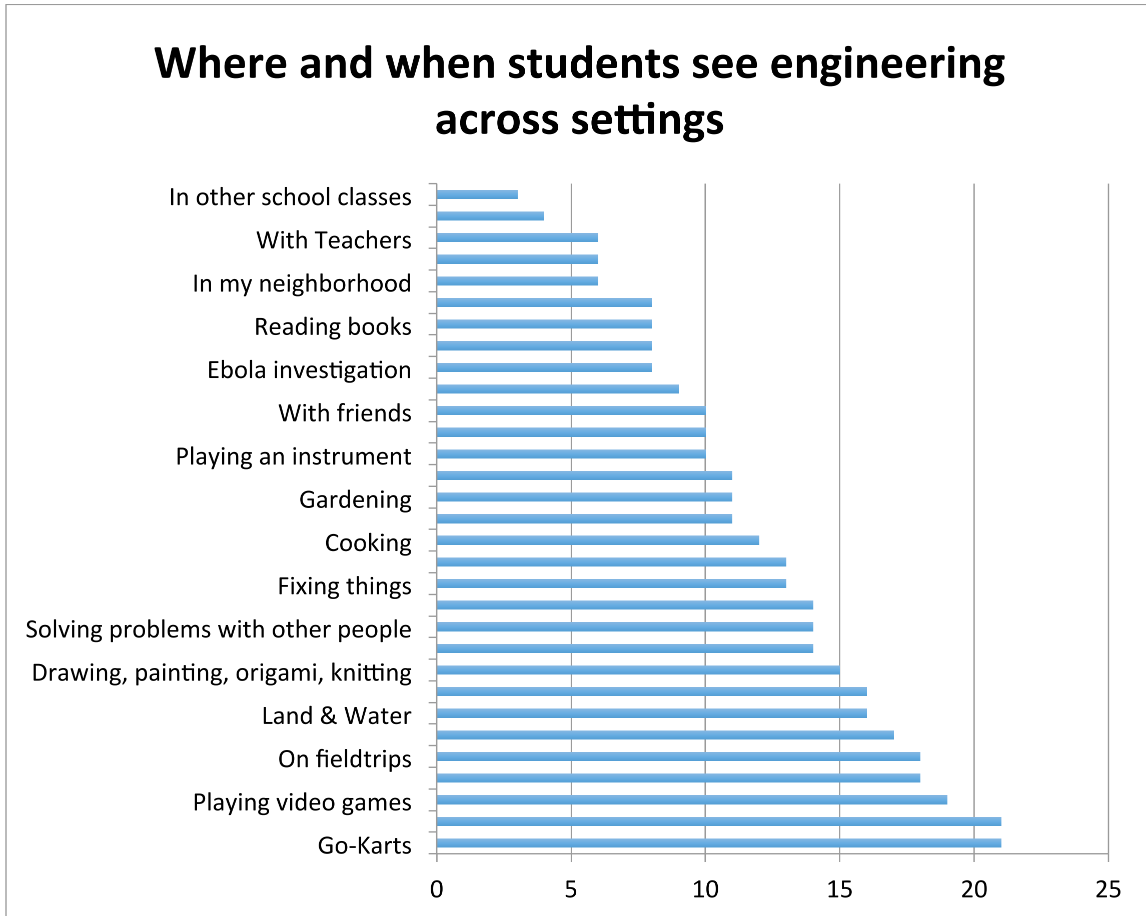
In Science Class	At Home	Go Carts
In other school classes	In my neighborhood	Land & Water
After school	With Adults	Measles Topics
On Field trips	With Friends	Ebola Topics
When we have class speakers	With Teachers or Coaches	Architecture & Design lessons (Graham Cracker Houses)

When do you use Engineering or the Engineering Triangle? Circle   as many answers as you want.

Using Legos or K'NEX	Cooking	Gardening	Fishing, Hiking, Skiing, Camping
Playing Minecraft	Drawing, Painting, Origami, Knitting	Fixing things that break	Playing Sports
Playing video games	Reading Books	Building/ making forts and other things	Solving problems with other people
Playing card or board games	Playing a musical instrument	Using Tools	Trying new things



Appendix E: Engineering Activity Task Raw Data



Chapter 4: Equity and Engagement in Science Learning through a Distributed Knowledge Model of Engineering Instruction

Introduction

Recent policy initiatives include engineering as integral to science learning in K-12 classrooms (NRC, 2012; Lead States, 2013), and represent a major shift in how engineering is situated in formal learning environments. A 2009 NRC report entitled, Engineering in K-12 Classrooms, found that fewer than 10% of youth had opportunities to engage in engineering during regular school times; therefore, the inclusion of engineering as part of the next generation science standards means that many more youth will have access to engineering instruction. However, the Framework calls on educators, researchers and curriculum designers to do more than broaden access to engineering, and challenges us to create equitable engineering learning environments that build on youth's everyday interests and experiences as foundations for culturally-responsive instruction in science classrooms stating that, "Instruction that builds on prior interest and identity is likely to be as important as instruction that builds on knowledge alone. …the benefits are particularly salient for those who would feel disenfranchised or disconnected from science" (NRC, 2012, p. 287).

The Framework defines engineering as "a systematic and often iterative approach to designing objects, processes and systems to meet human needs and wants," and notes that engineering is "more than an applied science" (NRC, 2012 p. 202). This broadens prior conceptions of engineering that focused on the application of science and math principles as central to the problem solving process (Carr, Bennett & Strobel, 2012; Clark

& Andrews, 2010), and lays the foundation for emerging approaches to engineering instruction and science learning through engineering design. However, there is a dearth of research in this area, and few models that embody expansive views of engineering design work in formal settings. A recent review of the literature on engineering education found that fewer than 1% of reviewed articles focused on broadening participation, noting that "starkly limited was research on diversity and inclusion with respect to engineering" (Hynes, Mathis, Purzer, Rynearson & Siverlink, 201,7 p. 460). Existing engineering curricula tend to engage youth in highly structured, recipe-like building activities, that often foreground science content knowledge as a way to connect engineering design tasks to classroom learning goals (NRC, 2009; Roth, Tobin & Ritchie, 2001). This approach to engineering draws narrow boundaries around the types of knowledge and practices students can use during engineering activities, and is out of sync with the transdisciplinary and synthetic nature of professional engineering design practices (Dunderstadt, 2007; Sheppard, Macatangay, Colby, & Sullivan, 2008; Cunningham & Kelly, 2017; Adams, et al., 2011).

Restrictive models of learning that limit 'what counts' as engineering knowledge position out youth that have been historically underrepresented in STEM disciplines, and tends to reify cultural assumptions about engineering as a field (Claris & Riley, 2012). For example, while research on equitable approaches to K-12 engineering is limited, similar research from the learning sciences, and math and science education offer insights for what these models of instruction should look in a classroom setting. Equitable learning builds on youth's everyday and lived experiences. As youth move through a variety of contexts throughout their lives, they bring diverse practices, knowledge, and

experiences to the classroom that serve as foundation for personally- consequential learning (Nasir, Rosebery, Warren & Lee, 2006; Roth, Tobin & Ritchie, 2001; Vossoughi & Bevan, 2014; Riley, 2008). Formal instruction designed to empower youth places experiential knowledge at the center of learning (Yosso, 2005). This expansive view of knowledge creates horizontal learning opportunities for students to bring diverse ways of knowing to the classroom (Gutiérrez, 2008), and also engages youth in critical conversations and reflections about the role that engineering, technology, and science have played in their own communities and lives.

Engineering has historically taken a deficit stance towards minoritized youth (Smith & Lucena, 2016), and neoliberal discourses in favor of broadening STEM participation advocate for assimilation models of instruction that bring learners into existing, and inequitable visions of engineering, rather than supporting youth agency and action in their own communities (Philip & Azevedo, 2017; Lucena, 2005; Riley, 2003; Claris & Riley, 2012). Neoliberal arguments for recruiting new engineers from diverse backgrounds tend to focus on individual benefits (i.e. salary benefits and career options) and national economic growth and security (i.e. patriotism and public service) (Lucena, 2005), and therefore privilege the owners and operators of STEM enterprises, rather than empowering individuals and communities historically underrepresented in these fields (Basile & Lopez, 2015). Diversifying participation in engineering means that we need to not just bring youth into existing engineering practices and structures (as is defined by the exposure and access notions of equity), but that we take a critical look at the field of engineering education, and challenge teachers and curriculum designers to create learning opportunities that build on diverse ways of knowing about engineering and being

engineers in the world, with a focus on relating course materials to students' lived experiences (Riley, 2003; Claris & Riley, 2012).

This paper leverages distributed notions of knowledge and intelligence as located in the sociomaterial world, as opposed to existing in a narrow set of texts or disciplinary knowledge, to open diverse and personally-consequential ways of knowing as foundations for problem solving in formal engineering contexts. Reflective scaffolds are layered into this distributed framework to support youth learning of related science content as emerging from the distributed design process. In this way, science learning is grounded in youth's everyday experiences and emerges as *knowledge in action* through engineering problem solving processes (Schön, 1992).

Learning by Doing in Engineering

Personal trajectories of learning emerge from historic contexts and positioning (Lave & Wenger, 1991; Holland & Lave, 2001). Foregrounding content is rooted in the history of schooling. Donald Schön (1983) termed these content first models "technical rationality" because they imply that intelligent practice is the application of knowledge in action. Technical rationality models of engineering emerged from distinctions between major and minor disciplines (Glazer, 1974; Tadmor, 2006; Schön, 1983; Lucena, 2005). Major disciplines were those with generalizable knowledge and principles, such as science and philosophy, and minor disciplines were situated and rooted in context. This hierarchical view of knowledge led to the creation of translational research models in which stable, generalizable knowledge was prioritized and used to inform practice. However, this image of engineering is problematic for broadening participation for several reasons. First, it assumes that students need to reach a certain level of proficiency

in science and math learning before being able to apply knowledge to an engineering design project. This immediately positions out young learners who have yet to receive extensive formal science and math instruction, and perpetuates current assumptions that excelling in math and science is a prerequisite for being an engineering. Secondly, research suggests that applied science models of engineering might position out learners who self-identify as creative problem solvers (Root-Bernstein, 2015). Lastly, this image of engineering conflicts with historic, informal, and professional accounts of engineering design work, in which diverse types of knowledge and experiences, including everyday and tacit knowledge, are considered central to the engineering problem solving process (Dunderstadt, 2007; Cross, 2008; Vincenti, 1990).

Almost universally, literature on design thinking emphasizes the inclusion of tacit and experiential knowledge in the practice of synthesis. Michael Polanyi defined tacit knowledge as “the intuitive sense of what to do in research based on experience with natural phenomena.” He contrasts this to disciplinary knowledge, which is developed with the support of explicit claims and evidence. Schön (1992) described tacit knowledge as the emergent learning that comes from the doing of design work, which he termed “knowledge in action.” In Schön’s framework, tacit knowledge becomes explicit through interchanging moments of material engagement and reflection, or “reflection in action.” The nature of tacit knowledge changes with lived experience, and therefore its role in problem solving evolves over time. For novice engineers and youth, tacit knowledge refers to knowledge gained through everyday, non-disciplinary learning that resides in families and communities, often referred to as *funds of knowledge* in literature on culturally-relevant instruction (Moll, Amanti, Neff, & Gonzalez, 1992). Professional

engineers gain lived experience through professional engagements, therefore the gap between everyday and disciplinary knowledge narrows over time and through the development of expertise (Cross, 2008). While the nature of tacit knowledge changes over time for engineers, it remains a central component to problem solving across contexts (Jonassen, Strobel & Lee, 2006; Lawson, 2006; Razzouk & Shute, 2012). For this reason, Yu and Strobel (2011) argued that “first-hand experience is the best way of knowing something in engineering,” and Donald Schön (1983) defined the nature of design knowledge as an “epistemology of practice” that honors the value of intuitive and experiential learning.

Translational views of knowledge assume scientific discovery precedes technological invention. However, historians argue that engineering predates science, and laid the foundation for future science exploration- not just in creating tools for discovery, but in providing artifacts for inquiry that embody cultural math and science knowledge in material rather than abstract forms. Researchers note that early experimentalism borrowed methods from arts and crafts trades to develop methods for reproducible knowledge and machine production at scale; and note that most early scientific investigations focused on figuring out the math and science principles underlying human-made structures (Vincenti, 1990; Stokes 1997; Schön, 1983; Petroski, 2011; Pickering, 1995). For example, Johannes Kepler contributed to our understanding of calculus by trying to maximize the volume of wine barrels. And Nobel prize-winning physicist, Richard Feynman, conceptualized quantum electrodynamics by observing the wobble and rotation of a spinning plate. As Feynman recalled, “I was in the cafeteria and some guy, fooling around, throws a plate in the air. As the plate went up in the air I saw it wobble,

and I noticed the red medallion of Cornell on the plate going around. It was pretty obvious to me that the medallion went around faster than the wobbling… the whole business that I got the Nobel Prize for came from that piddling around with the wobbling plate" (Feynman, 1987, p. 157). These cases provide examples of science emerging from the study of a designed artifact through both careful measurement (inquiry) and observation (emergence). However, science and engineering intersect in a variety of ways, and knowledge emerges through engagement with the sociomaterial practices of these fields, and not the transfer of abstract knowledge detached from experience (Schön, 1983). Within classroom contexts, researchers have found that knowledge emerges from the construction of physical artifacts (Papert & Harel, 1991; Wilensky, 1991), and that constructed artifacts mediate peer conversations and became "tools [for students] to think with" (Roth, 1996). In a related study, researchers found that "experience gained while constructing an artifact helped to improve the product and also gave students the opportunity to develop canonical scientific knowledge through design" (Roth, Tobin & Ritchie, 2001 p. 137).

The emergence of knowledge through design is often referred to as the problem-solution co-evolution cycle (Dorst & Cross, 2001; Cross, 2008; Lawson, 2006; Braha & Maimon, 1997). The problem-solution co-evolution cycle is a central feature in literature on design thinking and emphasizes the nature of learning-by-doing during the design process. Research suggests that science knowledge emerges from the *doing* of design work, and that the production of product and construction of knowledge co-evolve as a "mangle" of thinking and doing during design activities (Pickering, 1996; Schön, 1983; Schön, 1992; Stokes, 1997; Vincenti, 1990). This phenomenon is described by Koretsky

(2014) who wrote of the affordances of engineering in a virtual space, which allowed students the freedom to engage in multiple iterations of design work, not usually afforded in undergraduate learning environments: “Students learn to think like engineers by doing engineering. In standard learning task design, one might expect co-construction (developing a joint understanding of the task or system) to proceed before coproduction; understanding before doing. That was not the pattern we saw in the teams engaged in this project. Rather, attempting to engage in doing before fully understating led to hanging questions that were then addressed by co-construction activities and reflexively building understanding led to more productive doing.”

In addition to knowledge emerging through iterative design practices, disciplinary knowledge can also emerge from the study of the built environment. Through the reflexive study of designed artifacts, the designed world provides us with a template and context for studying engineering and design in context (Schön, 1992). Braha and Maimon (1997) defined engineering as the “concise record of embodiment of appropriate concepts and experiences,” and Suchman & Trigg (1993) argued that because engineering knowledge is embodied, it can be observed. Purcell and Gero (1998) found that looking at other people’s designs were important precedents in the design process for professionals, and researchers argue that designed artifacts embody the disciplinary knowledge related to their construction, as well as the history of their ontology (Suchman, 2000; Roth, 1996). Reverse engineering is one instructional approach that leverages the embodied knowledge of the designed world to foster disciplinary learning in formal settings. In a study on e-textiles, students created their own designs by reinterpreting e-textile creations from an online community, or by “remixing” everyday

objects for new purposes (Kafai, Fields & Searle, 2011). Also, in an undergraduate engineering course, researchers used the process of “mechanical dissection” so students could experience the mechanics of a working system (Wood, Jensen, Bunting, 2015). Wood and colleagues argued that mechanical dissection is at the heart of reverse engineering, and that it provides an artifactual modeling base for students to work from- noting that novice engineers struggled with creating new designs from a blank slate. In addition, reverse engineering “allows the engineering student to witness a physical creation that is the result of a design process they are being asked to learn” (Woods et al., 2015, p. 264). In addition to manipulating engineered artifacts, reverse engineering can also include structured observations and critiques of the built environment. Lave and Wenger (1991) used the term “learning curriculum” to describe the field of learning resources available to a learner in everyday settings. For engineering students and designers, the learning curriculum includes material artifacts, the tools for their creation, and the sociomaterial interactions in the designed world; these disparate pieces of embodied knowledge can be synthesized and oriented to support specific engineering learning goals.

Designing for Science Learning through Engineering Design

There are epistemological tensions with leveraging engineering for science learning, as science and engineering ultimately have different purposes, goals, and approaches to problem-solving. Scientists uses inductive and deductive reasoning to create generalizable claims that maintain validity across contexts. In contrast, engineers use abductive reasoning to synthesize diverse types of knowledge across disciplines to solve specific problems in context. However, design is often considered a gateway for

learning science concepts, and there are many examples of how engineering practices and projects can be used to support learning in science classrooms (Lewis, 2006; Benenson, 2001; Crismond, 2001; Kolodner, 2002), as well as improve students' perceptions of STEM learning (Adams et la., 2011). There are multiple design-based science curricula described in the literature including Learning by Design (Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, & Ryan, 2003), Design-Based Science (Fortus, Dershimer, Krajcik, Marx & Mamlok-Naaman, 2004, 2005), and Stuff that Works (Benson, 2001). Researchers have shown that engineering models and artifacts are useful for cultivating inquiry practices through manipulation and iterative redesign (Schauble, Klopfer & Raghavan, 1991; Lachapelle & Cunningham, 2014; Quinn & Bell, 2013). In addition, engineering design problems provide context for knowledge application, particularly when coupled with additional learning scaffolds (Fortus et al., 2004; Kolodner et al., 2003; Lachapelle, Cunningham, Jocz, Kay, Phadnis, Wertheimer & Arteaga, 2011; Wendell & Lee, 2010; Cunningham & Carlsen, 2014; Kolodner, Crismond, Gray, Holbrook & Putambekear, 1998; Silk, Schunn & Cary, 2009; Hmelo-Silver, Liu, Gray & Jordan, 2015). The local, synthetic, and contextual nature of engineering problems provide opportunities to integrate humanities, arts and storytelling into STEM learning environments (Cunningham, 2018; Milto, Wendell, Watkins, Hammer, Spencer, Portsmore & Rogers, 2016; Quinn & Bell, 2013; Vossoughi & Bevan, 2014; Adams et al., 2011), and supports students' understanding of systems thinking in relation to complex scientific phenomena (Penner, Giles, Lehrer, Schauble, 1997; Hmelo, Holton, Kolodner, 2000). Lastly, collaborative problem solving of engineering design problems allows students to share diverse viewpoints (Cunningham & Lachapelle, 2014) and

engages youth in meaningful group discourses of related content knowledge (Roth, Tobin & Ritchie, 2001). Researchers working in an elementary school classroom described how iterative design work allowed for emergent science learning through group problem solving practices and discourses: "experience gained while constructing the artifact helped to improve the product, and also gave students the opportunity to develop canonical scientific knowledge through design" (Roth, et al., 2001, p. 137). While there is a breadth of literature related to science learning through engineering design, recent articles have cited a need for long-term and in-depth qualitative studies to describe the particulars of learning science through engineering design to add depth and nuance to existing studies that focus mostly on science content learning gains (Case & Light, 2011; Douglas, Koro-Ljungberg & Borrego, 2010). In addition, there is a need for research that connects the design of formal K-12 engineering learning environments to a broad set of student outcomes, including agency, identity, and interest in engineering and its application in the world.

Research Questions

This research seeks to fill some of these gaps by asking:

1. What types and sources of knowledge do youth leverage when solving engineering design problems across settings?
2. How does the practice of synthesis connect knowledge across settings?
3. How is the design of engineering learning environments connected to particular youth outcomes and perceptions of engineering?
4. How can we design engineering learning environments that connect youth's everyday knowledge and experiences to classroom science learning goals?

Theoretical Framework

Distributed views of learning including distributed cognition (Hutchins, 1995), distributed intelligences (Pea, 1993), and grounded cognition (Barsalou, 2008), argue that 'knowing' can exist in a unit of analysis that is larger than the individual. Activity systems are the primary unit of analysis, and knowledge is located within a larger socio-technical framework, in which analysis is focused on interactions between individuals and their environment. Research on distributed views of knowledge argue that intelligence is not a property of the mind of individuals but is "distributed across minds, persons, and the symbolic and physical environments both natural and artificial" (Pea, 1993, p. 47). Functional subsystems are smaller units within an activity system that can be described as a 'working cognitive unit,' as these subsystems connect and bound functional knowledge, and affect the flow of information between the learner and distributed knowledge pieces (Hutchins, 1995). Distributed knowledge theories challenge the basic assumptions of social learning, mainly Vygotsky's assertion that talk and thinking are intrinsically connected. Instead, there is a notion that knowledge is embodied in practices, communities, and technologies, and that thinking emerges from a dialectical relationship between "the cerebral, the material, and the social" (Ellen, 1977, p. 136). Distributed views of learning are closely related to historical representations of engineering knowledge as emergent from everyday problem solving practices. In particular, distributed cognition locates tacit knowledge 'in the wild,' and provides a case for learning engineering through observation of the designed world.

Erving Goffman was the first to suggest that meaning about human behavior could be ascertained through the observation of small moments of everyday interactions,

and he compared these "everyday presentations of self" to a theatrical performance (Goffman, 1983). Distributed theories of learning extend the interaction order to the material environment, because we can observe learner actions and interactions within distributed systems (Pea, 1993; Hutchins, 1995); and knowing and learning emerge from these everyday interactions with the natural and designed world (Abrahamson & Lindgren, 2014). Pickering (1995) described this phenomenon as "entanglement" and wrote that the social and material are constitutively engaged in everyday life in ways that simultaneously constrain and afford knowledge in practice. Fenwick and Edwards (2013) add to this argument, as they described embodied knowledge as a "performative ontology," arguing that: "material things are performative and not inert… They act together with other types of things and forces to exclude, invite, and order particular forms of participation." Learning not only emerges from interactions with the material world, but also through observation. Material and technical artifacts can store information for later use (Hutchins, 1995), and artifacts embody cultural and disciplinary knowledge and practices across time and space: "In terms of cultural history, these tools and practice of the user community that accompany them are major carriers of patterns of previous reasoning" (Pea, 1993, p. 53). As tools are used in practice, distributed intelligence blurs the boundaries between the individual and the other actors and tools in the network. As tools become more ubiquitous to social practice their embodied histories and intelligences become harder to see. However, over time, as embodied tools and structures become less useful in light of larger cultural shifts, users modify and adapt tools to meet their evolving needs (Alvarado & Herr, 2003). In this sense, functional subsystems routinely reconfigure over time to meet situated needs and contexts. In the context of

learning environments, we would expect functional subsystems to vary across contexts; and should invite adaptation and reconfiguration of engineering curricula and projects to allow for the emergence of culturally-relevant subsystems in each classroom.

Distributed cognition and intelligence activity systems are often observed in the context of problem solving activities, which makes them particularly relevant to engineering learning frameworks. For example, Pea (1993) adapted George Polya's problem solving process in the context of distributed intelligence, and described how problem solving can be approached as either 'whole component' or 'parts of the whole' processes. In whole component approaches, problem finding and representation are distributed in the environment, tools, and among people; and task components are distributed during collaborative activities in the form of roles. Parts-of-the-whole problem solving is distributed as social construction, such as co-constructing a conversation or tool use. In Hutchins research, all aspects of the distributed systems come together to support the same cognitive function, such as flying a plane or navigating a ship. Pea surfaces more heterogeneity in these systems by describing the diverse tasks and roles taken up in collaborative work. However, neither discuss how the practices of synthesis and abductive reasoning are able to bring together seemingly disparate pieces of information among broad and diverse networks in the process of problem solving, as is often described in literature on professional design practices and design thinking theory (Razzouk & Shute, 2012; Cross, 2008; Adams, et al., 2011). There is need for theoretical work in engineering learning that identifies and surfaces how synthesis is the process of bringing together seemingly unrelated knowledge across a distributed knowledge system to solve situated problems in context.

Understanding the distributed nature of knowledge and being able to describe and map functional subsystems allows us to design learning environments and arrange sociomaterial engagements to support specific types of learning trajectories. In addition, embodied knowledge grounds disciplinary learning in the observable, everyday contexts in which learners can leverage relevant activity systems to meet their specific needs (Abrahamson & Lindgren, 2014). A benefit of distributed design is that thinking and memory functions are offloaded or stored in the environment, which allows the learner to engage in more invention and innovation when working to solve novel problems (Pea, 1993). This is particularly significant in areas of engineering problem solving and learning. Traditional translational learning models follow a memory and recall function, which focuses students' energy and attention on transferring information from one context to another. A distributed model of engineering locates knowledge in the world, and would include instructional scaffolds to help students access, organize, and synthesize parts of a functional subsystem to design solutions for classroom engineering problems. Distributed approaches to engineering learning, prioritize innovation and problem solving over recall and application, which are stated goals of several K-12 and undergraduate engineering policy documents (NRC, 2012; ABET, 2005), and also more reflective of processional design practices (Cross, 2008).

Using the *cultural learning pathways framework* (Bell et al., 2012), our research design situates engineering knowledge and practices within a system of dynamic temporal and spatial student learning contexts, that were rooted in local community practices, but are ultimately oriented towards cultivating broadly defined disciplinary identities and expertise in students. This framework is appropriate for our research

questions as it is an anchor for focusing instructional work around the notion that learners are continually navigating across multiple settings and coordinating multiple practices in relation to their positioning and sociomaterial contexts of activity. In terms of curriculum and activity design, the cultural learning pathways framework seeks to position students' everyday knowledge and experiences (found in the wild) as a foundation for disciplinary learning.

Methods

Context

This yearlong ethnography was a design-based research study at the classroom level (The DBR Collective, 2003) that was nested in a larger design based implementation research (DBIR) study at the district level (Penuel et al, 2011) in partnership with two local school districts and area nonprofit organizations. The aim of the larger DBIR project was to understand how curriculum adaptation could be used as a professional development model for implementing practice-based instruction at scale. The partner teacher, Ms. Jones, is a long-term partner with the university in research on culturally-responsive instruction that builds on students' everyday interests and expertise in relation to science learning, and has participated in ethnographic studies and curriculum co-design with our research group for over ten years. Her experience and history in this work greatly informed this research design, including pedagogical approaches and instructional tools designed to surface how distributed knowledge from across the many contexts of students' lives could be used to support science learning through engineering design tasks.

I used qualitative methods including ethnography (Cresswell & Clark, 2007; Fetterman, 2010; Ball & Ormerod, 2000), case study (Patton, 2002), and interview (Merriam, 1998) to understand the distributed networks that students leveraged during engineering design activities across settings. Erickson (1986) described how ethnography is used to describe particular examples of general findings. While this study was situated within only one elementary school classroom, I believe the findings generally can be applied at scale, with changes only to particulars related to the affordances and constraints of specific engineering learning settings. I used ethnographic fieldnotes (Emerson, Fretz & Shaw, 2011) to document my observations, and used "thick description" to recreate detailed written accounts and reflections from the field (Geertz, 1973). Through the process of weekly memos, I analyzed my data as it was collected, which distinguishes ethnography from other forms of qualitative research. In addition, I video and audio recorded classroom observations and interviews (Hall, 2000; Jordan & Henderson, 1995), and compared and combined fieldnotes with video content logs for more thorough accounts of classroom activity, including interaction analyses of students' talk and material engagements.

The majority of my ethnographic observations occurred during classroom science activities, with some additional observations during other subjects, fieldtrips, recess, afterschool, and evening family programs. Therefore, I used self-documentation methods (Clark-Ibanez, 2004; Tzou & Bell, 2010; Reeve & Bell, 2009) to elicit students' engagements with engineering practices and activities during out-of-school time. Self-documentation is a qualitative methodology by which students collect photographic data to provide a visual representation to share aspects of their lives outside of an observable

context. Participants included 28 linguistically and culturally diverse fifth-grade students. Observations primarily occurred in a fifth grade urban classroom, and I followed students as they participated in four off-site fieldtrips, worked with five community and disciplinary experts in the classroom, and engaged in eleven formal engineering projects and activities across settings including the classroom, fieldtrips, and family engineering nights at the school. Data included the following:

- 79 ethnographic fieldnotes (~170 hours of student data)
- 110 hours of classroom video (from 73 school observations)
- 30 hours of student engineering design work across settings (11 engineering projects)
- 3 self-documentation tasks (113 coded representative pictures)
- Student written reflections on engineering (142 coded excerpts)
- 19 student design team interviews,15-25 min each (~600 coded excerpts)

Analysis

The unit of analysis for study is the activity system leveraged by design teams as they designed solutions to specific engineering design tasks across settings. Students engaged in eleven engineering design projects that ranged from 30 minutes to three weeks in length, over the course of the year. Longer design projects included multiple design tasks, and many iterative cycles of problem solving for each task. Ultimately, students each engaged in hundreds of micro cycles of iterative problem solving throughout the course of this study. The data for this analysis drew mainly from video recordings of students engaging in engineering design work. These videos were used to guide design team interviews with students- during which students would share their inspirations and motivations during problem solving activities, to help me construct the distributed functional system that supported their design decisions and problem solving

approaches. The analyses include both interaction analysis of video, and interpretations of interview excerpts to share students' own sensemaking through the video data.

Theoretical decisions about research are embedded and engrained in the way researchers collect, frame, and process video data (Hall, 2000; Jordan & Henderson, 1995). The theoretical assumptions behind my video collection were informed by viewing the whole class as a community of learners, and smaller, case study groups. To capture small group work, I focused each camera on a two sets of case study students as they participated in engineering activities. However, some limitations surfaced from focusing on small group design work during data collection. I know from fieldnotes, classroom observations, and student interviews that teams did cross-pollinate ideas. Students would sometimes talk to classmates across the room, or just watch other design teams work, and these interactions were important for redesign decisions, and demonstrated that design cognition was distributed among the class. However, my case study video frame often missed these intergroup exchanges, which truncated my video recording of the functional systems related to small group problem solving. Student reflections during design team interviews filled in many of these missing gaps. In addition, functional systems extended beyond the classroom walls- into homes, communities, and virtual environments; student reflections, artifacts, and self-documentation photos enabled me to reconstruct these systems to a meaningful degree in the absence of observing them directly. In addition to analyzing students' discourse and gestures during engineering design work, I also coded student talk, interview responses, and artifacts to surface larger trends across engineering projects. The codes that were most relevant to this study were related to the *model of engineering instruction* and

student outcomes [See Table 4.1]. *Model of instruction* refers to the frameworks used for instruction, and included sub-codes: applied science, problem-solution co-evolution, model for inquiry, distributed & synthetic, and apprenticeship. *Student outcomes* refers to the type of learning that emerged through the engineering design activity. These outcomes were elicited during student interviews and describe the student-identified purpose of an engineering activity, as well as their emergent STEM-linked identities and perceptions of engineering as a discipline. Sub-codes for outcomes included agency, identity, nature of engineering, fulfilling a need, aesthetic, fun, solving a problem, disciplinary knowledge, and science content [see Table 4.2 for how model of instruction related to our engineering projects].

Table 4.1. Codes and Sub-Codes

Codes & Sub-Codes	Examples
Model of Instruction *applied science* – learning precedes application. Specific science principles are taught before the engineering project with the expectation that they will guide design decisions. *problem-solution co-evolution*- learning emerges from the doing of design work. Productive friction and points of failure drive further investigation and solution seeking. *model for inquiry*- engineered artifacts, models, or prototypes are used for inquiry practices, with the goal of creating generalizable claims from models. *distributed & synthetic*- learning emerges through prior experience, visual observations, and critiques of designed artifacts. Solutions form from the synthesis of distributed knowledge across settings. Functional systems develop in relation to particular design solutions. *apprenticeship* – learning emerges in partnership with more knowledgeable others.	"It's kind of like we made our own laws." "I think it did because since we already had the scientific principle down, we could actually just think of it in our own way and try to recreate it, but try to make it better." "I feel like engineering maybe builds off of science, maybe. Because there are multiple different types of science and engineering is a part of it in like seeing if you need this, you have to build this… it uses science."

Outcomes *agency* – engaging in engineering helped students feel ownership over new knowledge in ways that led to action in their lives. *identity* – students self-identify as being (or wanting to be) engineers. *nature of engineering* – engineering projects, fieldtrips and working with experts shaped how students viewed engineering as a profession. *fulfilling a need* – students viewed engineering as a way to meet everyday needs and wants. *aesthetic* – students identified visual or artistic aspects of a project as being important for use. *fun* – students engage in engineering for enjoyment. *solving problems* – students use engineering practices to solve everyday problems. *disciplinary knowledge* – students identified generalizable design features or specific engineering practices as central to their problem solving processes. *science content* – science content related to curriculum and district learning goals for an activity.	"When I grow up I want to be an architect or engineer." "How we did engineering today is that we built something that was fun." "Being an architect is cool because you can create different things." "I learned more about engineering by teaching me that building and making things is hard and it takes a long time." "[engineers] make computer models for their ideas."

Study Design

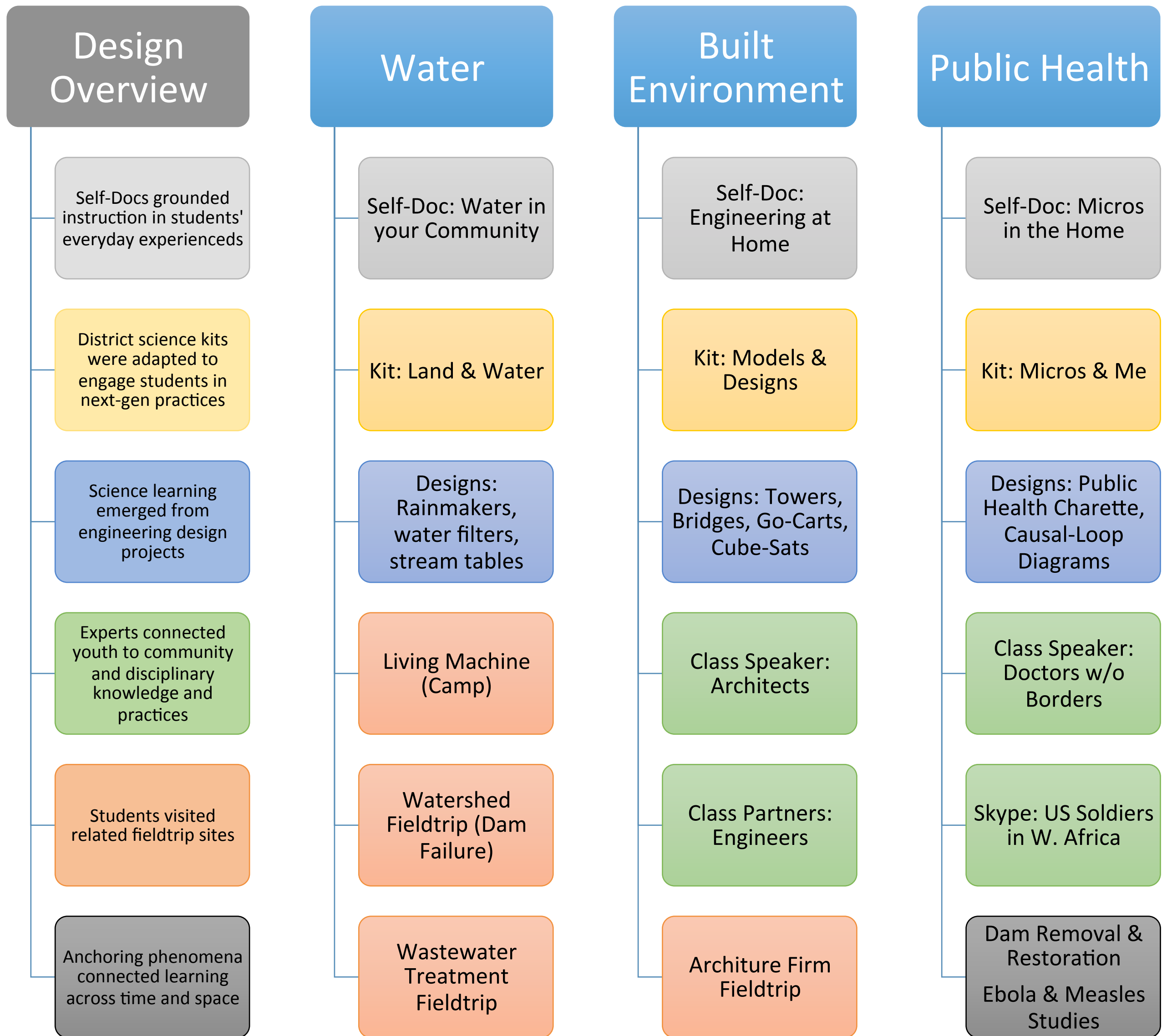
The engineering practice of synthesis was leveraged to connect distributed knowledge pieces across time and contexts during engineering projects. Ms. Jones and I designed multiple arcs of connected learning trajectories across our yearlong study, and my analysis focused on which of these components students leveraged during situated engineering tasks. The three primary arcs of learning oriented around the school district scope and sequence for fifth grade science, which included lessons and science kits

related to land and water (earth science), models and designs (physical science), and health (biology). At the start of each of these learning arcs, we used self-documentation methods to focus learning on students' everyday and lived experiences within the larger community. This foundational research about engineering in students' everyday lives was then leveraged to design learning contexts, adapt district science kits, and create tools to connect these experiences to engineering design projects and science learning goals in the classroom.

We used distributed scaffolding (Puntambekar & Kolodner, 2005) throughout the lessons to help create hybrid design spaces that leveraged students' outside interests and expertise (Barton et al., 2008; Roth & Barton, 2004; Roseberry et al., 2010) and community-based knowledge (Kelly, 2014; Bell et al., 2013) to cultivate student learning of science through engineering. Informal scaffolds included in-the-moment teacher questions, prompts, and student small group discussions. More formal scaffolds included design prompts to support students' small group discussions about engineering project goals and decisions, formative assessments including science journal entries and exit tickets, and reflective artifacts, such as multimodal tables and diagrams that asked students to connect their engineering solutions to both everyday knowledge and scientific principles. We included both community and disciplinary experts, and visited multiple fieldtrip sites to broaden the visible network of distributed knowledge for this project. These design moves also gave the entire class of students a shared set of distributed knowledge experiences to draw from during engineering projects. Lastly, we used socio-technical anchoring phenomenal from current events stories to connect the three learning arcs, and situate engineering and science practices within contemporary socio-technical

contexts. These anchoring phenomena included an early investigation around the impacts of the Elwa Dam construction and restoration on neighboring communities and wildlife, and the 2015 national Measles and international Ebola outbreaks. [See Figure 4.1 for an overview of our curriculum and research design work.]

Figure 4.1. Connected Research Design for Distributed Knowledge Across Setting



[See Appendix 2: Engineering-Related Science Kits and Anchoring Phenomena, and Appendix 3: Cross-Setting Engineering Activities, for more details about each component in this table.]

Findings

Finding 1: Engineering knowledge is distributed along a matrix of diverse types of experiential and formal knowledge

This first set of findings answers the research question: What types and sources of knowledge do youth leverage when solving engineering design problems across settings? For youth in this study, engineering solutions and knowledge were embodied in people, places, practices, and objects that they encountered across settings and in their everyday lives. Students collectively leveraged and synthesized these diverse sources of knowledge during engineering design projects. Team members, material artifacts, iterative problem solving, and more knowledgeable others all served critical roles in the design process. Four domains of knowledge emerged from students' design work across settings including fieldtrips, home, and the classroom. These four distributed domains were: everyday knowledge, tacit knowledge, technical knowledge and disciplinary knowledge. These emerged through the interactions of individuals in social contexts rooted in cultural histories and in exchange with the environment, which included material, technical, and natural components. The four domains are defined as follows:

- Everyday Knowledge: knowledge learned through everyday experiences and practices at home, in the community, and virtually.
- Tacit Knowledge: the unarticulated knowledge that emerges through the doing of an activity. In terms of engineering, tacit knowledge emerges as students iteratively work with models. Material affordances and constraints of these models, as well as natural laws guide the emergence of tacit knowledge.

- Technical Knowledge: the knowledge that emerges during skilled work that may or may not be connected to the generalizable principles that define disciplines (and disciplinary knowledge). Technical work for youth often emerged from apprenticeship and apprenticeship-like models or work with more knowledgeable others, including parents and online communities, and was related to the development of everyday expertise.
- Disciplinary Knowledge: the generalizable ways of knowing that define a profession or formal school discipline. Disciplinary knowledge most often connected to working with experts in this study.

Each of these knowledge types was associated with a particular set of experiences for youth. For example, students most often located everyday engineering knowledge as being associated with play, chores and practice-based learning such as playing a musical instrument or participating in sports. Students shared that the practices of building things and iteratively learning through trial and error were the same practices they used during engineering problem solving in the classroom. Tacit knowledge emerged from the doing of design work across settings, and was as diverse as the activities and engineering problems they engaged in- what Donald Schön (1992) referred to as 'knowledge in action." Material 'tinkering' and learning through the problem-solution co-evolution model of instruction were the primary way of gaining tacit knowledge. Technical knowledge was most often associated with apprenticeship models of learning that were in partnership with parents, peers, and virtual resources. Students shared accounts of cooking and building with adults, fixing household items and cars with parents, and learning gaming strategies from friends and online tutorials as ways in which they developed technical expertise. Lastly, disciplinary knowledge emerged through

apprenticeship models of instruction and partnerships with experts. Experts became a critical component of our research design work aimed at connecting distributed knowledge, engineering problem solving, and related science knowledge, as experts were able to surface connections between disparate pieces of information, and supported synthesis during engineering design work. For example, classroom speakers from Doctors without Borders were able to connect the three district curriculum arcs (land and water, engineering design, and public health) by surfacing the role of infrastructure and clean water in preventing disease outbreaks. In addition, experts provided disciplinary language and real-world examples that connected students' engineering design work to professional contexts. Understanding the nature and location of distributed knowledge for youth, allowed us to design learning environments that connected these distributed knowledge pieces and experiences from across settings for use during engineering projects in context. The case study below shows how the sociomaterial arrangement of an out-of-school learning environment enabled youth to draw on everyday experience and connect it to disciplinary knowledge, in partnership with experts.

This case study took place during a daylong field trip to a joint engineering and architecture firm not far from the students' school. The fieldtrip started with tours of the facility, overviews of some of the firm's current building projects, and talks by architects, engineers, and interior designers who surfaced connections between their career paths and prior STEAM learning. During the afternoon portion of the fieldtrip, two architects and a structural engineer led the students in a design challenge related to a current client's request: to build a bridge that would connect two corporate buildings on a nearby suburban campus. The engineer, Nate, introduced the design challenge by introducing the

design problem, to connect two buildings on a corporate campus. He noted that there were several problems embedded in the main design problem: 1) the buildings were different heights, 2) the bridge had to span across a railway, and 3) it had to look nice because it would be visible to clients. Criteria for the bridge design were low cost, safety, and preserving the land below and around the bridge. The safety of the students' designs would be measured by how many bricks the bridge could hold when placed between two tables. The constraints were time and materials. Each student group was given cardboard strips, string, straws and duct tape for their bridge design. Nate clarified the design challenge by adding that the first challenge was to make the flimsy cardboard strong enough to build a safe bridge. Before breaking students into design teams, Nate developed students distributed knowledge by sharing images of common bridge designs developed for similar contexts, with emphasis on the firm's previous work. When students broke into small groups, they were then given time to reflect on bridge designs that they were already familiar with from their everyday lives. Therefore, students came into this project with a distributed knowledge system that included real-world precedence, expert examples, everyday observations from their communities, and prior experience constructing projects during play and other related activities. One group of four students (Hannah, Josh, Lela, and Mia) constructed a truss bridge that supported the greatest number of bricks during the design challenge. Below is an interview excerpt of the group reflecting on their bridge design, and the distributed knowledge system that inspired their final product.

> Researcher: In this bridge, there are different aspects. It sounds like the architect, Nate, inspired the idea for the trusses?

Hannah: Actually no, it was Josh. That was Josh's idea.

Researcher: Oh Josh, that was your idea to add the trusses?

Josh: I just didn't know what it was called.

Researcher: Where did you see this idea for these triangles?

Josh: from a bridge.

Researcher: So you saw that from a bridge that you saw in real life?

All students: Yeah.

Lela: There is a bridge nearby that looks just like this one.

Researcher: What was your building process like?

Hannah: We were sort of just planning as we were building- we were planning building at the same time.

Researcher: You were planning and building at the same time?

All: Yeah.

Researcher: Did you sketch before you built it, or did you just dive right in?

Lela: Yeah, we just built.

Researchers: Was there anything new or surprising that you learned?

Mia: As we were trying to build the bridges, an architect came over and told us about this word called "truss."

Lela: He said that our bridge had a lot of trusses in it because we were trying to build so much armor to keep it up, and that trusses were a way to make things strong without using a lot of materials.

Researcher: And your bridge is called "Trust the Truss," right?

All: Yeah.

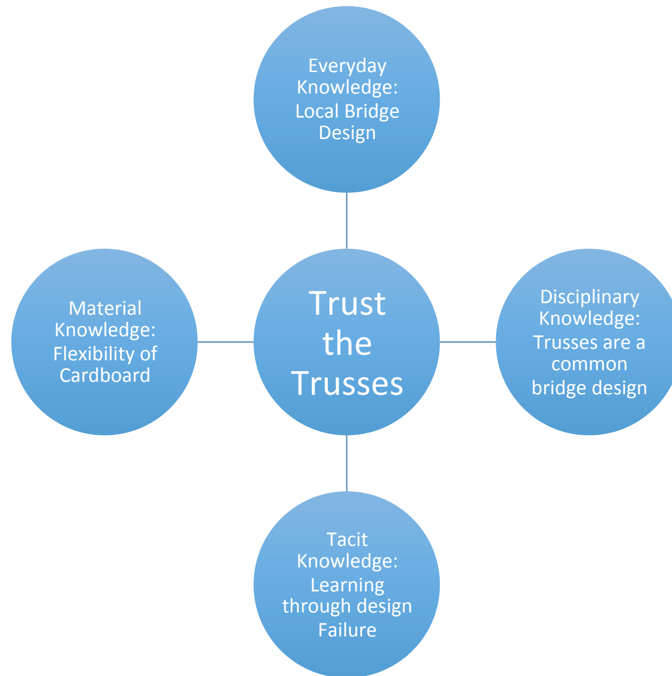
This example is representative of common responses from each of the design teams. Students used their everyday experiences and knowledge of both the form and function of bridges, to successfully approach this design challenge. Reflections from Josh's design team show how experts and teachers can help students bridge their everyday knowledge with disciplinary ways of knowing an artifact. While Josh recognized that triangles provided strength for his design, the architect introduced the disciplinary terminology and principles behind "truss" bridges. Figure 4.2 shows the local truss bridge that inspired this group's design, and Figure 4.3. shows the resulting design solution. Note that material limitations led the group to alter their design during stability and strength tests. While the bridge was intended to be positioned with the scaffolding facing up, students inverted the structure to provide a more stable foundation for the bricks. When Lela reflected on this material limitation she said, "I learned that failure is good too. That's how we learned that [thin cardboard] ... if you just use [thin cardboard] that won't work- well it will do stuff, but you need more like armor to keep it up."

Figure 4.2. Truss Bridge from a neighborhood park

Figure 4.3. Truss the Trusses student bridge

In this example, the functional subsystem was distributed across time and space [Figure 4. 4], and included elements of a local bridge from students' past observations, professional examples from earlier in the day, students' creativity and in-the-moment design decisions, and material limitations that surfaced through construction. Figure 4.4 maps the functional subsystem and associated knowledge types leveraged for the Trust the Trusses design solution.

Figure 4.4. Functional Design System for Trust the Trusses



All students were able to refer to "the bridge nearby," and all were able to talk about how trusses added strength to the bridge design, and was a common engineering design feature found in structures that needed added strength. In another design team interview, a student, Nick, also shared the emergent disciplinary principle that "triangles were the toughest shape," that surfaced while engaging in design revisions with one of the architects on the fieldtrip. Further, tacit knowledge emerged during the doing of the design work. Material limitations, including the extreme flexibility and instability of the thin cardboard when laid flat guided many of the emergent design solutions. Lastly, Josh shared how the proximity of design teams near each other and as a result of the final design challenge inspired him to think about future bridge designs that he would want to build, "This helped me learn more about engineering because I saw other groups' work

and I got some pretty cool ideas for future reference." This example highlights the democratization of knowledge and expertise with distributed framework for learning because youth brought experience from their everyday lives that ground problem solving in engineering design and experts bridged language and ideas without changing the nature of student design work (Gutiérrez & Vossoughi, 2009).

Finding 2: Practices of modeling, observation, and reflection connect knowledge across settings

The following findings answer the second research question: How does the practice of synthesis connect knowledge across settings? Models embodied synthesis and abductive reasoning of distributed intelligences, and had their own material intelligence that connected knowledge across time, space, and people, and allowed for emergent science learning through iterative testing as inquiry. There were two types of models that supported problem solving in this study: static and dynamic. Static models included constructed artifacts in the world that existed in students' memory, or were accessed using online searchers or self-documentation photos. Dynamic models are models in motion, and included both virtual and real-world models that moved. Static models served as design precedence and as inspiration during the engineering problem solving process. When looking at static models, students often focused on model structures (parts) and their functions (purposes). In the preceding Trust the Trusses example, student focused on how "trusses" added extra support to a bridge within the constraints of using flexible cardboard to solve the design challenge. In everyday contexts, students often referred to building things and using Lego as providing them with expertise in using

static models. The excerpts below highlight the role that a static sketch model supported two students' (Elias and Hannah) reflections about their 'make-a-turn' go-kart design.

This case study supports research findings that note how sketches embody the history of design ideas, and the evolution of problem solving over time (Suchman, 2000; Braha & Maimon, 1997). [*Note: Elias designed a make-a-turn go-kart by tightening the rubber band on the left side of the go-kart while allowing slack in the rubber band on the right side of the go-kart. This shifted the front chassis to the left- thereby creating a go-kart that successfully turned on its own.]*

Hannah: Did anyone here accomplish make a turn?

Elias: (Gestures by raising and waiving with hand to indicate that he accomplished the make a turn challenge.)

Hannah: You did? How did you do it? (Hannah gets up and moves to the empty seat next to Elias.)

Elias: You know how when you pull one side [of the chassis] tighter? It like pulls the wheel? The other wheel so like, if you roll it, it's gonna like… (Elias takes out his science journal and starts sketching his working design for a turning go-kart, then gestures towards the drawing) So like this- one side is short and the other is long.

Hannah: So, if [the rubber band] is wound tighter on one side, it will turn? (Hannah points to parts of the drawing in Elias's notebook as she asks her questions.)

Elias: Yeah. Like you make this rubber band like tighter? The like, the wheels push this wheel. (Elias gestures to parts of the drawing in his science notebook.)

Hannah: And this one is straight? (Hannah points to the drawing in Elias's notebook.)

Elias: Yeah. This wheel is pushing, going… the rubber band is pulling this wheel to the other so it's like turning a little. (Elias gestures to various parts of his sketch as he talks.)

Elias's go-kart sketch served as an artifact to mediate discourse during this interaction (Schön, 1983, Roth et al., 2001). Surprisingly, the sketch in this segment actually mediates discourse around the principles of the designed artifact better than the artifact itself. Conversations around this sketch and other paper-based reflective artifacts were actually more focused on design thinking and decisions than during the designing of the artifact itself. In contrast, when students were actually constructing the go-karts, their talk centered on getting materials, and manipulating the materials to finish within the given time frame. The contrast of these segments, highlights the important role that sketching and modeling play in the design process and the essential role of reflection and conceptualization during design activities. This is also mirrored in the literature on professional design practices (Dorst & Cross, 2001; Purcell & Gero, 1998). Later in this activity, Ms. Jones asked Elias to reflect on what inspired the group's design decisions for the make-a-turn challenge, and in his response Elias surfaced the nature of tacit knowledge and how it emerged during the iterative moments of observation, reflection and testing of his model go-kart. In addition, he referenced classroom peers as experts and inspiration for his group's final working design solution.

Ms. Jones: Okay. So maybe your personal experience was from testing the go-kart?

Elias: Come to think of it- how did I think of that?

Ms. Jones: Were you just testing? You just did a lot of tests?

Elias: Oh! Now I remember- I saw that on Kevin's and Kyle's go-kart. They made one rubber band tighter, but I remember when I saw that pulled. Oh now I see. It was tighter so that's how it kept going back. So, I loosened them and it didn't go back as much. So I kept making it looser. So now when I did this one (he gestures to the sketch in his science notebook)- when we tried to make it turn- when we started. I saw that you should make one side tighter, so that the rubber band pulls the wheel and it will make it turn.

Ms. Jones: That's great. So your previous experience was a previous experiment. Or watching other people test their go-karts.

In a later interview, Elias also used this sketch to elicit further recall of his design inspiration, and referenced working with his Dad as a way in which he developed technical knowledge of how cars work, "I seen like sometimes my Dad's like little car breaks down, so we like fix it, and see if it like turns or not. I see when it turns, like one wheel is closer to the other. Like make a turn (the classroom engineering design challenge), like these wheels is like (gestures on a piece of paper) really close to each other, and these wheels are like farther, and then it would like turn." Elias drew on a distributed network of knowledge and experience to design a working solution to the make a turn go-kart. Everyday knowledge included watching his classmates design and test their go-karts, technical knowledge included working with his Dad on cars, tacit knowledge surfaced during iterative design work, and disciplinary knowledge emerged during the reflective activity in which his group was asked to surface the design

principles behind his working design. The science principles are listed in Table 4.3, and this group suggested that to make a go-kart turn, designers need to "create an unbalanced force."

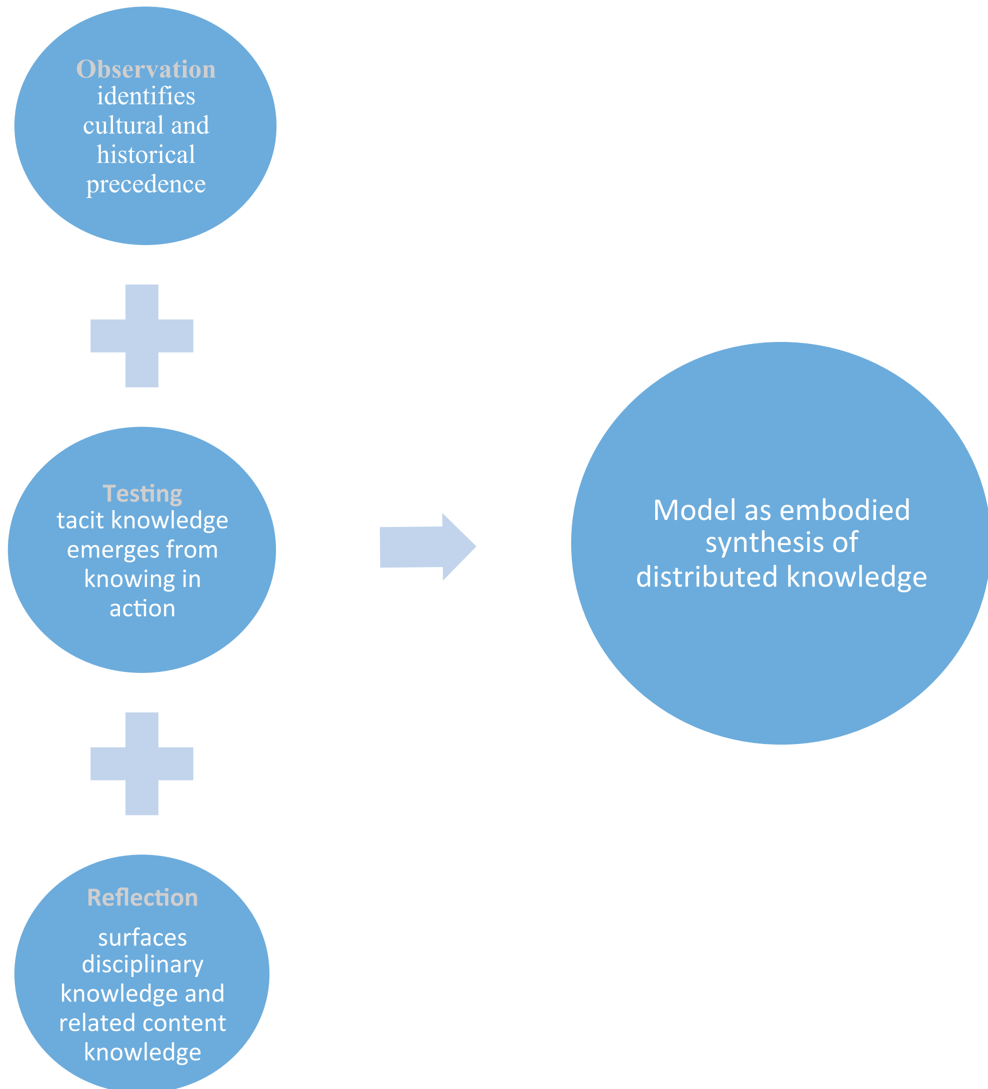
Students also leveraged knowledge of dynamic models and simulations to solve engineering problems in the classroom. Dynamic models surfaced the behavior of engineered systems over time and under specific environmental conditions (Hmelo, Holton & Kolodner, 2000), and were essential components of students' problem solving across contexts for this study. Students often surfaced video games, specifically Minecraft, as a context in which they engaged in virtual modeling in their everyday lives. In addition, students discussed using dynamic models as the primary way in which knowledge emerged through the act of doing design. The excerpt below describes a project context, and highlights the role that emergent and tacit knowledge from Minecraft supported students' problem solving in relation to designing a self-propelled go-kart that can travel up a steep ramp. In the game, Minecraft (a sandbox game where players construct virtual worlds from blocks and pursue their own adventures), students regularly had to construct tracks for their minecarts to move people and materials around in virtual space.

> Ms. Jones: "How did you know how to optimize your kart?"
>
> Paige: You know like the minecarts (in Minecraft)- They have these railings and they're like these special ones that make it go faster and slower… and minecarts go slower up hill and when they're carrying weight… you don't need special railings to go downhill… they go faster downhill when they're carrying weight.
>
> Ms. Jones: And so how did that help you know what to do with your go-kart?

Paige: The railings are like traction, and also like the tension in the rubber band that turns the wheels. You need a lot of tension on the rubber band for it to unwind fast enough to get the go-kart uphill.

In this excerpt, Paige leveraged the behavior of minecarts traveling on inclined tracks to surface the mechanisms that allowed for that behavior. Paige referred to these mechanisms as "traction," and in later discussions the teacher bridged this everyday speech with the term, "friction" to bring students into both everyday and disciplinary ways of referring to the physical forces that act on an object, which was the primary learning goal for this set of lessons. Although students in this class were just beginning the study of physical science and natural laws, their go-kart models reflected a deep, tacit understanding of natural laws through the manipulation of everyday materials. In these examples models served three functions. The first function was as to embody distributed knowledge through synthesis in the construction of an artifact. The second function was to provide a context for the emergence of tacit knowledge through "knowing in action." And the third function was to facilitate disciplinary talk. In these cases, models were sociomaterial tools that both embodied and produced knowledge through the accompanying practices of observation, reflection, and testing.

Figure 4.5. Models embody synthesis of distributed knowledge systems for new knowledge creation



Finding 3: Instructional designs are related to learning outcomes

This set of findings answers the third and fourth research question: How is the design of engineering learning environments connected to particular youth outcomes and perceptions of engineering? and How can we design engineering learning environments that connect youth's everyday knowledge and experiences to classroom science learning goals? We used a variety of instructional approaches as we engaged students in eleven engineering projects across settings, and found that instructional approaches were related to learning outcomes and science knowledge. Table 4.2 provides a brief description of each engineering project along with its dominant instructional frameworks, which were each defined in Table 4.1.

Table 4.2. Summary of Engineering Projects

Engineering Project	Description	Model(s) of Instruction
Go-Karts (District Science Kit)	Students created prototype go-karts as directed by a Models and Designs district go-kart kit to generate data for 6 go-kart related activities. Including pulling weight and a self-propelled go-kart. These go-kart designs followed periods of direct science instruction about force, that students were expected to apply to their porotype models. Students then used prototypes as models for inquiry.	Applied Science Model for Inquiry
Go-karts (Adapted for Reflective Science Learning)	Students designed go-karts to meet six different design challenges including, make a turn, go straight, stay between the lines, going uphill, bust a barrier, and go the distance. Students used tacit knowledge to guide their initial design decisions. Distributed scaffolding and reflective whole group scaffolds were used to elicit common science principles along all designs. Student redesigned each go-kart with these science principles, prior knowledge and peer designs for their final design challenges.	Distributed & Synthetic Co-evolution

Rain Makers	Students engineered "rain makers"—a simulated rain system—to measure how varying the intensity of rainwater would impact erosion and deposition on a model stream bed.	Model for Inquiry
Classroom Water Filters	In concert with the rain maker project, students designed and tested water filters to understand how rain gardens reduce and filter runoff to local watersheds.	Co-evolution Model for Inquiry
Living Machine Filters	During an overnight environmental education fieldtrip, students used everyday materials to engineer water filters that would act like a "green machine" to filter wastewater.	Co-evolution
Towers	Students engaged in a short design challenge to build a tower that could hold a tennis ball in the wind. Local architects assisted with students' designs during a classroom visit.	Distributed & Synthetic Apprenticeship
Bridges	Students visited a local integrated architecture and engineering firm and engaged in a bridge design challenge with architects and engineers.	Distributed & Synthetic Apprenticeship
Gingerbread Houses	After viewing a gingerbread house competition organized by local architects, students designed and built gingerbread houses for a similar in-class exhibit.	Distributed & Synthetic
Community Engineering Night	Families of 5th grade students completed the popular marshmallow challenge, and viewed their children's engineering projects from class. Together we discussed ways to support students' engineering interests outside of the classroom.	Co-evolution Apprenticeship
Design Charrettes	To understand professional design practices, students participated in a design charrette in which they redesigned their indoor recess space.	Distributed & Synthetic
Cube Satellites	Students used sketching, excel-based models, and physical models to design and build model cube satellites. They wrote mock NASA research proposals to fund specific CubeSat missions in partnership with local aeronautical engineers.	Applied Science Distributed & Synthetic Apprenticeship

Instructional models varied by project origins. Professionally designed curricula most often used applied science and model for inquiry approaches to instruction. Teacher created engineering projects were more likely to engage students in the problem-solution co-evolution approach to learning. In the classroom, co-evolution models took on an ad-hoc tinkering approach to learning. For example, both iterations of the water filter design (fieldtrip and classroom) used a problem-solution coevolution approach to design, in which learning emerged through iterative design work and learning from failure. Students engaged in mostly ad-hoc design work during these projects, with little reflection on why specific materials or approaches worked. Project success was variable over time, meaning that students would have success with early water filter designs, and then experience more failure later on. After multiple attempts at construction, only one group eventually constructed a working water filter that met project goals. When we reflected on working and failed designs with the class, students shared that they did not know how water filters worked, and many shared that they were unfamiliar with many of the materials used for the project. One of the key materials for the design was a coffee filter, but students shared that they did not know what a coffee filter was, nor how it was used; and that they came from families who drank tea. This surfaced during students' project work, as few students recognized that coffee filters acted as a basin to both hold and filter material from water. Through these projects, we learned that students' prior experiences with materials, design problems, and contexts were important foundations for developing working solutions. Our later curriculum design work was more grounded in youth's experiences, and resulted in more successful engineering design work by students. In addition, we also

recognized that students needed more background knowledge on the artifacts they were tasked with constructing. Students in this class had no background knowledge related to how water filters work. They were able to use tacit knowledge that emerged from design work and prior experiences to filter large material, such as sand and gravel from their water samples, but had no context for how to filter smaller and dissolved material from a water sample. In later engineering projects, we had students conduct online searches and use self-documentation photos to research and document how similar engineering problems were designed in other contexts. Despite the ad-hoc and high rate of failed water filters, student shared that the projects were fun, and taught them to "test early and often" and "learn from failure." Therefore, learning outcomes for these approaches included *fun* and *nature of engineering*. We were able to use this project to develop a classroom culture that embraced failure and learning from others, which set the course for productive project construction later in the year. In addition, students frequently related outcomes from the water filter projects to similar iterative activities outside of the classroom, including homework and sports. These findings support other research that connects knowledge in practice as foundational for authentic learning (NRC, 2012; Manz, 2012).

As we engaged in our own iterative design-based research cycles aimed at creating an equitable framework for engineering learning, we started to design scaffolds that helped students synthesize distributed knowledge across settings. In this sense, we recognized that youth brought diverse experiences and observations to the classroom that were foundations for successful problem solving during engineering projects. Penuel (2014) argued for the use of 'signature tools' to coordinate learning across settings.

Artifacts such as self-documentation photos, sketches, online searches, and partnerships with experts all served as signature tools that connected knowledge from across settings, and supported successful engineering design practices and science learning in the classroom. The case study below describes the evolution of a go-kart unit over time along to highlight the connections between instructional models and learning outcomes, including classroom science learning goals, in more detail.

The first go-kart activity was implemented from a commercially available Models and Designs science kit for upper-elementary classrooms. The original kit foregrounded science principles through an applied science model of instruction. The teacher taught mini-units on Newton's Laws of Motions before each go-kart activity, and students completed worksheets as part of these science lessons. Students were then asked to construct go-karts with recipe like directions that had each student construct the exact same 'standard' go-kart models [see Figure 4.6 for an example of the standard go-kart design.]

Figure 4.6. Standard Go-Kart Design

Students then used these 'standard' prototypes to test Newton's Laws of Motions through a series of single-variable experiments. One test measured how far the go-kart

would travel based on how many times the rubber band was wound around the rear axle (i.e. 2 winds, 5 winds 10 winds), to test the relationship between force and distance. Another activity had student attach weights to their go-kart, and instructed them to measure the distance the go-kart traveled with each series of weights (i.e. 0 washers, 5 washers, 10 washers) to test the relationship between weight, force, and distance). Other activities followed a similar format. Each go-kart activity included specific instructions for how students should record their data. Student groups then aggregated their data on a shared class table, and collectively took averages of the whole class data set to make generalizable claims from their tests. In this sense, the Models and Designs kit used a *model for inquiry* approach to engineering design. This approach proved problematic for science learning and student engagement. First, the classroom results didn't always prove known theories. For example, when students aggregated their data for the weight vs. distance test, their data showed that heavy go-karts traveled farther than light go-karts with the same number of axel winds- this is the inverse of what the tests should have proved. Ms. Jones had to add multiple lessons about measurement, speed, weight, and distance to correct for these findings. Further, students reported that these original lessons didn't feel like engineering. One student shared that building a prototype was "like someone else had done the engineering for them." Other students shared that their prototypes often didn't work correctly, so they ended up adapting and "engineering" them anyway. In addition, the repetitive and highly-scaffolded nature of the original lessons resulted in reduced engagement over time. At the start of the go-kart activities students were excited to build and test go-karts. However, they eventually felt constrained by the limitations of each activity, and were frustrated by the material failures

that often occurred during construction, including snapped rubber bands, and slippery wooden wheels that would lose traction on the classroom carpet. Overall, student interest and classroom energy quickly faded over time, and students reported being "ready for the project to end." This suggests that overly scaffolded, recipe-like engineering activities reduce students' engagement and interest in engineering over time, and reduce motivation during model construction.

Following the original go-kart lessons, Ms. Jones and I adapted the original Models and Designs kit to allow for more agency and creativity in relation to go-kart designs. The adapted unit engaged students in six go-cart design challenges: 1) climb a ramp, 2) go the distance, 3) stay between the lines, 4) make a turn, 5) pull a load, 6) bust a barrier. Student worked in small groups and had the freedom to create their own go-kart designs from available materials (dowels, small and large wheels, rubber bands, tape, and binder clips). Rather than creating a highly-scaffolded approach to student design work, we used a reflective scaffold that asked students to engage in iterative cycles of observation, modeling, reflection, and summary through the course of each design challenge [see Table 4.3], and we posted these reflections to a large table at the front of the classroom. The cycles of this process built on those described in Findings 2 of this paper, and Figure 4.6 above.

Table 4.3. Example of a Whole Group Reflective Scaffold

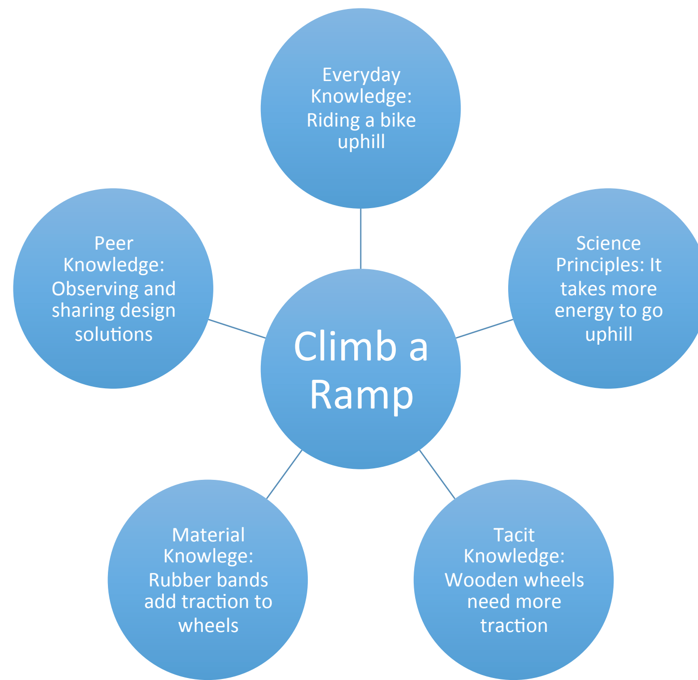
Challenge	What do you already Know?	What Worked?	What did we learn?	Engineering & Science Principles
Climb A Ramp	When I bike uphill it's easier when I'm moving fast.	The ones that worked had lots of traction and a lot of winds [of the back axle/ rubber band]	You need lots of traction and energy to get up the hill.	When working against gravity, you need more energy.
Go The Distance	We had ideas from Minecraft because the Minecraft have these railings. They only go if you have them. The railings are like tractions. Also, if you have these special railings, it can go further.	It's like a grown up bike. If it is a toddler bike it does not go that far but with a grown up bike one peddle of the bike will go farther than a toddler bike.	We learned that if the wheels were bigger, it would go further. Because you wind it, then the go carts would go further.	A wheel with more circumferences will go farther in one wind.
Stay Between The Lines	I experienced we have to make the go cart go straight so we have to have the same amount on both sides so it is even then it will go strait. So in order to make it work, we needed to make it exactly balanced.	We made it work by using smaller wheels so they could be small enough to fit in the lines and we tried to make the go carts as light as possible. And we used more traction so the go cart can go and not get stuck.	We learned about that the big wheels will make the front wheels go straight and not turn. And that when it doesn't work, we optimize it! Plus, we defined the problem and developing them.	Your go-cart has to be balanced in order to go straight.
Make A Turn	Our personal experience was from watching other peoples' go-carts on	We made it turn when we tightened one rubber band more when we were winding it up.	What we learned was that if we tighten one rubber band more while winding and	To make a turn, create an unbalanced force.

	previous challenges.		adding extra rubber bands on the extra tightened wheel, it will turn.	
Pull A Load	Our personal experience was that the cart that goes the farthest has BIG wheels. So, we thought that giving it bigger wheels would pull the load farthest.	We think that the people with the go-carts who had bigger wheels were more successful because their cart went farther with their load during the challenge.	We learned that if you have bigger wheels the go-cart goes farther when you wind it. The go cart will also go far with the load in the challenges.	When it's heavier we need more energy to make the go-cart go.
Bust a Barrier	Riding a scooter down a hill and crashing into a fence.	The go-kart worked when we added books to it to make it heavy.	We learned that heavy and fast go-karts work.	When there's more force it can knock down a heavy barrier.

We began each design challenge by arranging students in small groups, and asking them to reflect on how everyday object have met similar challenges in other contexts by asking, “What do you already know?” [Table 4.3, column 2]. For the ‘climb a ramp’ challenge, one group of students reflected that it was easier to ride their bikes uphill if they “were going really fast,” and posted their answer to the shared table. Other groups shared experiences from videogames and play that also provided examples of everyday objects can successfully climb a ramp. After students shared their everyday reflections, design teams had a short period of time to construct, test, and optimize their initial go-kart designs. During this time, students were not asked to record or sketch their progress, as we these types of requirements impeded successful iterative problem solving in prior projects. In the middle of the class period, we asked groups to briefly share “what worked” during their initial round of tests, and to record it on the class reflection table.

We engaged students in a brief whole-group discussion around what can be learned from workable solutions, and how they could be summarized into science principles to guide future go-kart design work [Table 4.3 columns 3-5]. Lastly, students revisited their go-kart designs to apply working principles to their re-designs. This adaptation to the original Models and Designs Kit employed a distributed & synthetic model of instruction, and allowed for the emergence of science principles and workable solutions through a co-evolution model of learning. Below is a representative functional system that emerged for one design team. It also led to positive learning outcomes for youth, as described in interview data below. Further, energy levels and excitement increased over time for youth during this adapted go-kart unit, which was a stark contrast to students' interest and engagement during the original Models and Designs unit.

Figure 4.7. Climb a Ramp Functional System



When we asked students to tell us about building go-karts in the adapted unit compared the original kit, one student reflected that her go-karts "worked better than the standard go-karts" from the original kit. Another student shared that "it was more fun to test her own ideas" than build a standard design. Lastly, one student described how learning science through reverse engineering helped her feel like the science concepts were her own: "We had the science principle, but we could actually just think of it, and use it in our own way and try to recreate it. It's like we created our own laws." Through the course of these projects students shifted their understanding of engineering from a profession and a discipline to a problem-solving process that allowed them to combine diverse types of knowledge and experience to solve novel engineering design problems in the classroom. In contrast to the applied science model of engineering learning, we found that reflective scaffolds supported science learning in personally meaningful ways, and gave students agency over their knowledge.

This reflective table became an effective design tool that we began to incorporate into more design activities in the classroom. We found that it helped students engage in more systematic design practices and helped them bridge everyday and science knowledge as they applied it to iterative problem-solving processes. Further, students shared that the reflective tool not only improved their designs but helped them learn from their classmates in ways that they were not able to during previous design challenges. During focal group interviews students also noted that the bridging of everyday knowledge and scientific principles helped them see their classmates as expert scientists and engineers, and helped them see the importance of connecting different types of

knowledge during design work. When I asked students, "How did making this chart help you see the big picture about creating a working go-kart model?" One student, Paige, replied, "When you're engineering, you're trying new stuff, but sometimes you can actually use the things you already know, and also science, and add them together and make [designs] work." Alana added, "When we were looking at everybody else's ideas on the chart, it was kind of a bit easier because we looked at their experience from it, and got to use it in our own projects." Lastly, Josh shared, "We were able to see what worked and use that to make our own designs. We could connect things that weren't always obvious."

Literature on the epistemological alignment of science and engineering note that the major difference between the two fields is their purpose and goals. Braha and Maimon (1997) argued that problem solving is at the core of both disciplines, yet research shows that scientists and engineers go about solving problems in very different ways. Scientists use analysis to systematically understand the problems in order to identify underlying rules that could lead to optimal, generalizable solutions, while engineers use synthesis to explore many possible solutions until they find one that is workable for a specific context (Lawson, 1994). Building on Lawson's observations, research suggests that science is a problem-oriented field that uses analytical reasoning around evidence to build generalizable theories about the natural world. In contrast, engineering is solution-focused and uses synthesis to find particular solutions for specific contexts (Council, 2009; Lewis, 2006; Lawson, 2006; Lawson, 1994; Scopes, 1997; Vincenti, 1990; Rowe, 1991; March, 1984; Sherrett et al., 2013; Koretsky et al., 2014; Razzouk & Shute, 2012; Schön, 1983; Schön, 1992). The key to engineering instruction

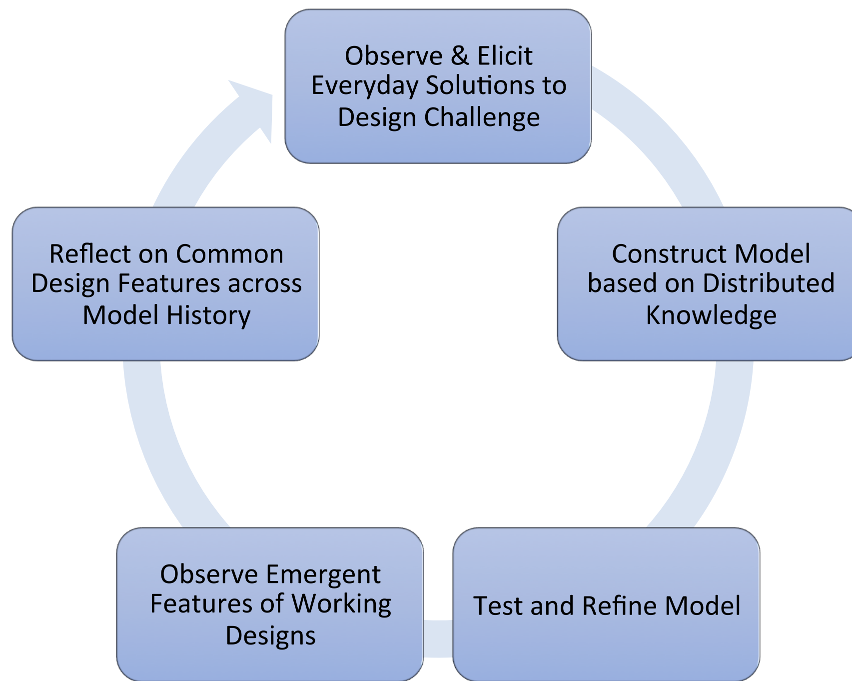
is that surfacing these principles is not the end in itself. Instead, the principles are then used to optimize the design during the iterative process (Koretsky et al., 2014; Kolodner, 2002; Schön, 1983; Stokes, 1997; Crismond, 2001; Dorst & Cross, 2001; Razzouk & Shute, 2012). Despite the differences between engineering and design, existing research on classroom science instruction has done little to bridge the two fields, which is why applied science models of engineering persist in classroom settings. Teaching science principles through direct instruction, and engaging students in building activities is an easy and traditional approach that sought to meet the larger aims of science classrooms. However, in this study we found that reflective scaffolds elicited science principles as part of an emergent and distributed knowledge approach to problem solving. This approach positioned students as developing experts with agency over their own knowledge and artifact creation.

Designing for equitable approaches to engineering design in science classrooms

Although knowledge used in the problem solving process is distributed, engineering designs themselves are situated in place. Theoretically, there are tensions between the situatedness of engineering design, and the need to produce generalizable theories in support of science learning within the classroom context. Through synthesis and heterogonous learning networks, students were able to bridge the everyday and contextual with disciplinary and generalizable ways of knowing to meet both engineering design requirements, and the broader learning goals of the fifth-grade science curriculum. Equitable engineering instruction should allow for multiple entry points when studying engineering design problems. Figure 4.8 is a conceptual model of our distributed engineering problem solving process that emerged from the yearlong ethnographic study

of eleven engineering major engineering design projects that encompassed hundreds of microcycles of iterative design in the classroom.

Figure 4.8. Distributed Problem Solving Process



Recognizing the distributed nature of knowledge in the world, and leveraging these diverse knowledge types in the classroom opens up research portions of engineering problem solving to a broad set of readily available information and data that is grounded in students' lived experiences. Unlike most approaches to engineering design that begin with 'asking questions,' 'identifying a problem,' or 'developing a solution,' distributed approaches to problem solving begin with *observation.* Observation situates knowledge

in the world, rather than in the learner. In addition to observation, reflection was an important practice for connecting learning across settings. In particular, it was essential for connecting everyday experiences and observed knowledge with science and engineering disciplinary knowledge and classroom learning goals.

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Appendices

Appendix 1: Engineering-Related Science Kits and Anchoring Phenomena

Implementation	Description
Land & Water	Seattle school district science kit. Students construct prototypes/ models of a stream bed and then observed how water flowing at different rates impacted erosion and deposition. Ms. Jones implemented a revised version of a PSEP engineering enhancement from the prior year.
Elwha Dam	Ms. Jones had students do a case study of the Elwha Dam to surface social justice issues around engineering projects, and how "defining the problem" can mean different thing to different communities.
Ebola in West Africa & the US	Ms. Jones is passionate about public policy and current events and always finds ways to integrate them into her lessons. The Ebola outbreak became an anchoring topic to connect engineering, health, water quality, and social justice in the classroom this year.
Water Quality & Disease	With the help of visiting doctors from Doctors without Borders, the class learned that lack of indoor plumbing, water treatment, and sanitation infrastructure was a leading factor in why Ebola spread so quickly in West Africa.
Models & Designs	Seattle school district science kit. The go-kart unit was the focus of this year's PSEP enhancement for engineering.
Micros & Me	Seattle Schools science kit. I did fewer observations of this kit, but Ms. Jones included discussions of public health and infrastructure with these lessons.
Measles Outbreak & Vaccines as Technology	Ms. Jones had students discuss the measles outbreak and connected vaccines to technology and engineering, and related these topics to public health.

Cube Satellites	As part of a larger partnership with Boeing, UW, and the Teaching Channel, Ms. Jones developed a two-week engineering lesson on cube satellites, and force and motion in space. Boeing engineers assisted in developing tools and integrating content into these lessons.

Appendix 2: Out of School "Connected" Engineering-Related Activities, Fieldtrips, and Experts

Implementation	Description	Time
Self-Doc: Engineering at Home	Student took pictures and completed a self-doc worksheet to share how they viewed and engaged with engineering in their everyday lives.	3 days at home
Self-Doc Engineering at School	Students took pictures and shared with the whole group how they viewed and engaged with engineering at school.	1 hour
Residential Environmental Education Camp	Students learned about how the camp's living machine used natural methods to clean wastewater. Students designed water filters with the help of camp instructors and discussed elements of water purification and filtration.	3 days 2 nights
Guest Speaker from Doctors without Borders	A doctor who had worked with nurses in West Africa spoke to the class about the Ebola outbreak, what caused it, and how to prevent the spread of disease. Connected wastewater, infrastructure, and public health for the class.	1 hour
Guest Speakers: Architects from local firm	Three architects from a local integrated engineering/architecture firm talked to the class about engineering, their work, and engaged students in a tower design challenge.	2 hours
Field Trip to Architecture Firm	Students visited the architecture firm and learned about the work of diverse engineers and architects, saw the tools that they regularly used including software, sketching tools, and 3D printers. Architects led a design challenge.	4 hours
Fieldtrip Professional Gingerbread Displays	After the architecture firm, students viewed professionally designed gingerbread houses as inspiration for their own designs.	1 hour

Skype Call: US Soldier Helping with Ebola Outbreak in West Africa	Students Skyped with a soldier from the first US military team to build an Ebola clinic in West Africa. The discussion focused on design aspects of the clinic and ways to reduce the spread of the disease.	30 minutes
Skype Call- Doctors without Borders Volunteer in Africa	Students Skyped with a Seattle-based doctor who was in West Africa treating Ebola patients. The discussion focused on public health, Ebola treatment, and local infrastructure.	30 minutes
Family Engineering Night	Families and students engaged in a design challenge at the school, and teachers shared their perspectives on math and engineering learning with parents.	2 hours
Wastewater Treatment Field Trip	Students visited a local wastewater treatment facility. The instructor focused his discussion and tour on the engineered aspects of the facility and highlighted the human dimensions of engineering design.	4 hours
Guest Speakers: Satellite Engineers	Engineers from Boeing and Blue Origin (a rocket engineering firm in Kent) visited the classroom while students were constructing their cube satellites and offered feedback about student designs.	2 hours

Chapter 5: Pedagogical Approaches for Cultivating Students' Critical Sociotechnical Literacy in the Science Classroom

Overview

In this dissertation I described various disconnects between how engineering is conceptualized and taught in K-12 settings and how youth engage with engineering in their everyday lives. In Chapter 2, I identified gaps in research on engineering learning, particularly in relation to constructing equitable engineering learning environments that build on youth's everyday interests and expertise. In addition, I provided examples from the history of engineering to argue that everyday and tacit knowledge, and technical expertise are and have always been central to engineering problem solving, and can provide examples for how to broaden participation in engineering for minoritized youth. In Chapter 3, I used students' conceptions of engineering to construct a broad and inclusive definition of the discipline; and found youth's descriptions closely aligned with recent policy documents that defined engineering as "a systematic and often iterative approach to designing objects, processes and systems to meet human needs and wants" (NRC, 2012, p. 202). Through surveys, self-documentation, and interviews, I also found that youth in this study strongly identified as engineers and engaged in engineering-related activities and practices across the contexts of their lives. In Chapter 4, I argued that distributed and synthetic models of engineering instruction were more likely to produce youth learning outcomes of positive engineering-linked identity and interest, and promote student agency in knowledge construction. I provided examples of how the practices of modeling, observation, and reflection enabled youth to synthesize distributed

knowledge from across settings to support classroom science learning goals in ways that were personally-relevant for students. In this concluding chapter, I ask the question: How can we design learning environments to help students critically understand the intrinsic and systemic sociotechnical relationship between people, communities, and the built environment? I propose the term *critical sociotechnical literacy* to describe the multiple realities of engineering solutions in real-world contexts, which include the power of the designed world and its designers to shape individual and community actions and agency.

Sociotechnical Literacy

Traditionally, technological literacy has referred to the purely technical aspects of our designed world. Louis Bucciarelli (1994) began his ethnography, *Designing Engineers*, by recalling a phone survey of technological literacy that asked users to explain how a telephone worked. Bucciarelli used this example to note that there are multiple dimensions of technological literacy that can include knowing "how things work," but argued that it should also include knowledge of how designs are used and applied (Bucciarelli, 1994; Wells, 2013). The *Next Generation Science Standards* adopted both of these views in outlining standards for Science, Technology, Society, and the Environment (Lead States, 2013). The three strands of learning for these standards are: (a) students understand that engineering, technology, and science are interdependent, and (b) society guides the adoption of these principle, and (c) their application can have impacts on the natural world. These standards address the transdisciplinary nature of STEM fields (Figueiredo, 2008), and surface the impact that technology can have on the natural environment. However, these standards do not explicitly surface the impacts that engineering and technology have on individuals and communities- particularly the

impacts 'successful designs' have on minoritized youth and their communities. For this reason, technological literacy should be expanded to include the critique of designed spaces to surface how infrastructure (the build environment) shapes superstructure (culture) (Marx, 2010). This perspective of technological literacy locates engineering design solutions within a broader sociological context, and surfaces the critical role of systems thinking in engineering planning.

The sociotechnical nature of engineering means that problem-solving techniques need to draw on information from diverse fields. Braha and Maimon (1997) argued that synthesis is at the core of design thinking, and wrote "design is the process of putting together or relating ideas and /or objects in order to create a whole which hopefully achieves a certain purpose" (Braha & Maimon, 1996, p. 147). The Framework and NGSS implicitly connect engineering and social science by advocating that design solutions should be oriented towards solving human problems and fulfilling human needs and wants. There are advantages and disadvantages to this framing of design. The advantage is that it invites engineering into social science classrooms and vice versa. However, there are few existing instructional models for how equitable approaches to problem solving through engineering and technology would look at scale. Research in support of integrating design and social science note that engineers and designers often design artifacts, space, and processes for public use but don't always take into consideration the greater public good or the social impacts of their designs (Nieusma & Riley, 2010; Riley, 2008; Riley, 2003; Law, 1987; Petroski, 2011). Further, researchers argue that many philanthropy models of engineering take on neocolonial constructs as they impose top-down solutions on communities, rather than including community voice as central to the

problem solving process (Pawley, 2012; Riley, 2008; Nieusma & Riley, 2010; Bardzell & Bardzell, 2013). Pawley wrote that client-driven design often means that designers and engineers are solving problems that benefit institutions and people in power at the cost of the broader community, and argued that when framing engineering as solving problems, students need to be taught to ask, "Solving problems for whom?" In addition to providing more supports for design thinking, next generation engineering curricula should also provide supports that help teachers employ equitable interdisciplinary approaches to problem solving that that include the engineering practices of modeling, synthesis, and systems thinking, which invite students to consider the systems-level impacts of their designed solutions.

Technology, Power & Society

For millennia engineering in the name of social and technological progress has been used as an engine of oppression by dominant groups (Riley, 2008, Claris & Riley, 2012). Historically, these have included but are not limited to building railroads to fuel western expansion and settlement in the US, further displacing indigenous nations and peoples. The choice of where to build roads and public transportation in rural areas (such as Alaska)- opening access for some communities and barring and limiting access to others (including access from emergency support systems). The location of grocery stores and affordable healthy food, creating food deserts for some Americans in a nation of an expansive and wasteful food supply. And lastly, the construction of dams throughout the central and western US that displaced water from some communities, diverting it to cities, and areas of commercial and industrial interest (Reisner, 1993). Contemporary

issues include choices around automation and which industries will displace its workers, and the construction of oil infrastructure across Indigenous lands. The term "eminent domain" is a lexical representation of how dominant groups define "greater good" in anonymized ways that position out minoritized communities, oftentimes with dire consequences for those groups impacted. Despite the fact that the built environment can both afford and constrain the way communities and individuals are able to construct their everyday lives, and can perpetuate oppression through the anonymity of artifact, literature notes that engineers receive little to no training in the social aspects of their work, and often self-identify as working in purely technical fields (Adams et al., 2001; Stevens & Hall, 1998 Nieusma & Riley, 2010; Bardzell & Bardzell, 2013; Smith & Katz, 1993). Young learners are also brought into a purely technical view of engineering through traditional engineering education frameworks, in ways that limit their ability to both identify with the field as future professionals, and to critically engage with the impacts of the built environment on their everyday lives (Riley, 2008; Riley, 2003; Nieusma & Riley, 2010 Bardzell & Bardzell, 2013). Bang and Vossoughi (2016) noted this trend in education by arguing that, "Without expansive views, equity work becomes directed toward more effective forms of compliance and participation in inequitable systems and forms of life. More simply, these efforts become singularly focused on increasing non-dominant students' mastery of dominant forms. In our view undertaking equity-oriented work driven by a commitment to epistemic heterogeneity demands theories of change, forms of praxis, and axiological commitments to be more carefully examined, articulated, and theorized as part of scholarship and practice" (Bang and Vossoughi, 2016, p. 175). Critical sociotechnical literacy invites learners to critically

reflect on who defines what counts as technology and engineering, and who benefits from its implementation in the world, in order to situate sociotechnical phenomena in social and historical contexts.

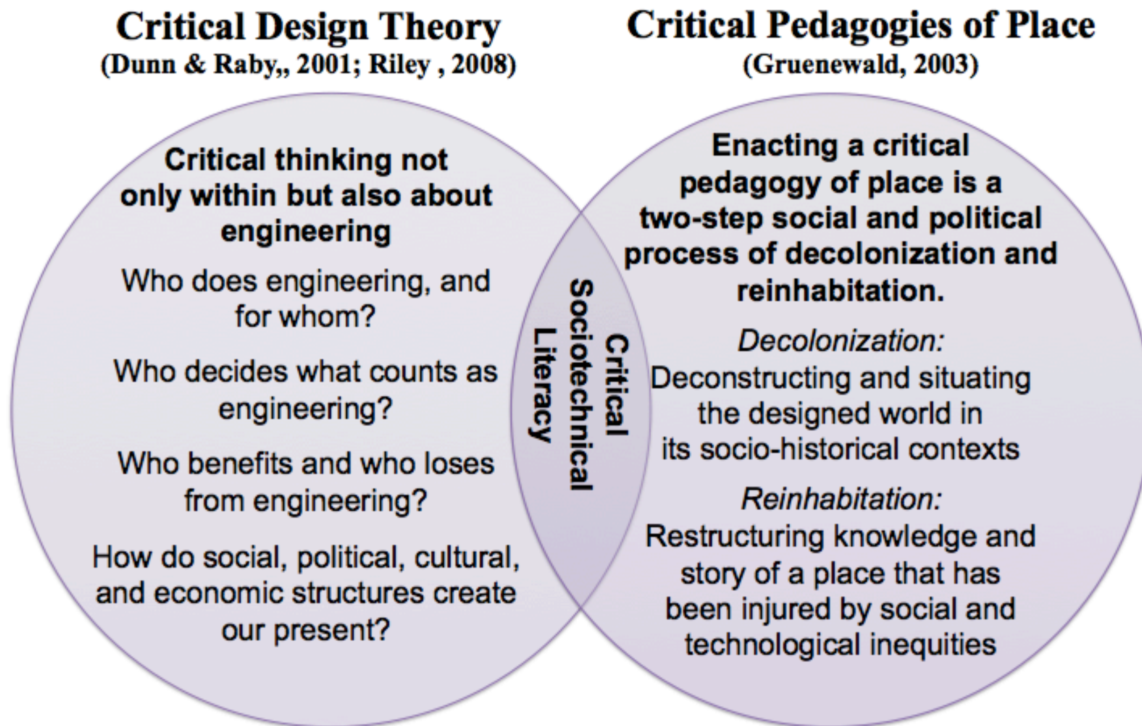
Critical Sociotechnical Literacy: A lens for equity in engineering learning

Donald Schön (1992) argued that design is a primarily social and dialogic activity—that dialogue can be exchanged with people, materials, and institutions; because of this dialogic relationship, design is cultural. It calls for normative judgments in the process of creation by defining what a "need" or "solution" is. For this reason, structural inequalities are written into our designed world. Equitable engineering learning and engineering-linked identities require student to be able to "read" the sociotechnical landscape in order to derive meaning about the self in relation to historical and present representation of space. I use the lens of critical theory to argue that learners can and should actively critique and seek to understand the historic and everyday ways that engineering, technology, and the designed world impact their own lives, communities, and society in general (Kellner, 1989). CHAT theorists argue that infrastructure, or base, determine the nature of superstructure, or broader cultural paradigms, through a unilateral relationship between infrastructure and society (Marx, 2010). Critical theorists differ from earlier CHAT ideologies in that they see the potential for a two-way relationship between infrastructure and superstructure through agency and empowerment of citizens. For the framing of critical sociotechnical literacy, I leverage two other critical theories—critical design theory (Riley, 2008; Pawley, 2012; Nieusma & Riley, 2010; Bardzell & Bardzell, 2013) and critical pedagogy of place (Gruenewald, 2003), and argue that this

critical lens of engineering is at the foundation of all chapters and empirical work in this dissertation.

Critical design theory (Riley, 2008; Pawley, 2012; Nieusma & Riley, 2010) asks learners to think critically not only within engineering, but also about engineering. It invites learners to ask the following questions: (a) Who does engineering, and for whom? (b) Who decides what counts as engineering? (c) Who benefits and who loses from engineering? and (d) How do social, political, cultural, and economic structures create our present? In addition, enacting a critical pedagogy of place is a two-step social and political process of decolonization and reinhabitation. Decolonization asks learners to deconstruct and situate the designed world in its socio-historical contexts, and reinhabitation invites learners to restructure knowledge and story of a place that has been injured by social and technological inequities. I argue that critical sociotechnical literacy lies at the intersection of these two theories (as shown in Figure 5.1).

Figure 5.1. Locating critical sociotechnical literacy



The field of critical design asks designers to think about the social implications of their designs and their impact on the social structure and sustainability of communities. It shifts the problem-solving process away from just addressing clients' needs to including the long-term needs and concerns of all those impacted by design decisions (Riley, 2008; Pawley, 2012; Nieusma & Riley, 2010; Bardzell & Bardzell, 2013). In this framework, Riley and Pawley both encourage designers to not only "define the problem" and "design solutions," but to ask, "Who is this a problem for?" and "Who does this solution serve?" During my dissertation data collection, the teacher and I took up this perspective as we designed iterative interventions for students to critically evaluate design decisions. This work became foundational to our iterative design cycles. Each time we engaged students

in an engineering design project, we also asked them to think about who defined their problem, and who their solutions would benefit.

Although knowledge used in the problem solving process is distributed, engineering designs themselves are situated in place (Crawford, 2009; Cross, 2011; Cross, 2008; NRC, 2009). In this sense, local knowledge, community desires, and the history of place are all central to creating culturally-responsive engineering solutions. Therefore, models of engineering learning can be productively thought of as a form of place-based pedagogy, and can draw on the instructional frameworks and guidelines for learning with specific places, people, and their histories in mind. This approach has been successfully used in K-12 landscape architecture lessons to develop youth's place-based identities and agencies around redesigning spaces within their communities (Johnson, 2009). For this reason, I leverage Gruenewald's theory on the critical pedagogy of place to describes the instructional approaches that the teacher and I designed for our systems-based lessons that focused on the social implications of engineered artifacts and design solutions. Gruenewald's theory combines both place-based and critical pedagogies in what he calls "the best of both worlds," as these two pedagogical approaches are intrinsically linked when we ask students to critically evaluate the infrastructure - superstructure relationships in their own communities (Gruenewald, 2003).

Designing to support youth's critical sociotechnical literacy in the engineering classroom

In our research we used the pedagogical approaches below to critically engage youth with sociotechnical issues related to technology and engineering design in local

and global communities. Our underlying belief for this research is that all engineering instruction is ultimately a political endeavor (Freire, 1996), and therefore engineering learning environments should invite learners to surface and critique the social and political implications of engineering design on local, national, and international communities. We had success with employing these instructional strategies in a fifth grade classroom, and argue that elementary-age children are not too young to engage in critical topics related to engineering and society. Our instructional approaches are described below. Although they are presented in a numbered list, this list does not imply a particular order or hierarchy to these practices.

1. Design for Sociotechnical Connections

Plan instruction as a system of learning opportunities to engage youth in critically thinking about the built environment as connected to agency, power, and cultural thriving. Connect learning across settings in ways that build on students' everyday knowledge (Bell et al., 2012), and anchor lessons in contemporary anchoring phenomena that situate engineering and technology in social contexts. In this work, we used the building and subsequent removal of the Elwa Dam and restoration of the Elwa River, to discuss community health, wildlife conservation, and land and water rights in the context of earth science, erosion, and deposition. For this investigation, students asked: "Who benefited from the construction of the Elwa dam?" "Who was most impacted?" "Will dam removal and habitat restoration restore power and health to historically impacted communities?" Students in this study also became interested in the 2015 Ebola outbreak in several northwest African countries; news coverage and several cases in the U.S. raised concerns about local health for youth in this study, and became a local issue in

spite of its global context. We organized several discussions and activities that surfaced connections between infrastructure, clean water, and public health and compared the relationship between infrastructure and health in the contexts of Liberia and the United States. For this investigation, students asked, “Why did Ebola become an epidemic in Liberia when it did not even spread to family members in the U.S.?” Critical design approaches surfaced the role of power, politics, and industry in relation to community health. For example, students learned that paper mill workers constructed the Elwa Dam for cheap power, at the expense of local indigenous community rights and long-term health. In addition, students discussed how Dam removal and restoration projects cannot fully restore impacted communities, as new communities emerged from historic decisions. In relation to the Ebola crisis, youth learned that political instability and limited resources in Liberia impacted infrastructure, and access to clean water and indoor plumbing, which enabled Ebola to spread quickly through households and communities, and among healthcare workers.

2. Include community and disciplinary experts to provide real-world connections.

In our research, we included local architects, engineers, and community members to talk about the impacts of engineering in the students’ own communities. In addition, we also invited volunteer nurses, doctors and engineers from Doctors without Borders (DWB) to discuss the nature of the Ebola epidemic in Liberia, and to surface differences in how disease epidemics impact people and communities in different settings. In the figure below, a DWB nurse showed a student how healthcare workers prevent infection when working with Ebola patients (Figure 5.2). Experts became critical components of our connected engineering work, as they were intimately involved with the technical and

social aspects of their fields, and were able to draw connections that were not always obvious in our research design. For example, a DWB volunteer surfaced the initial connections between clean water, infrastructure and public health that ultimately defined our yearlong ethnographic work (see student reflection in Figure 5.3). Expert knowledge from classroom speakers and fieldtrips was central to understanding the nature and complexity of technology in social and historical contexts.

Figure 5.2. Doctors without Borders volunteer dresses students in protective clothing

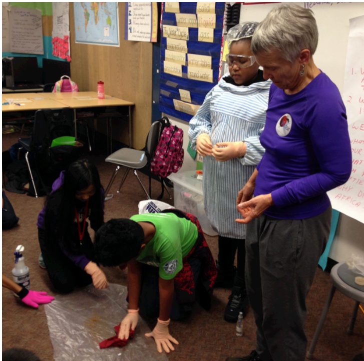


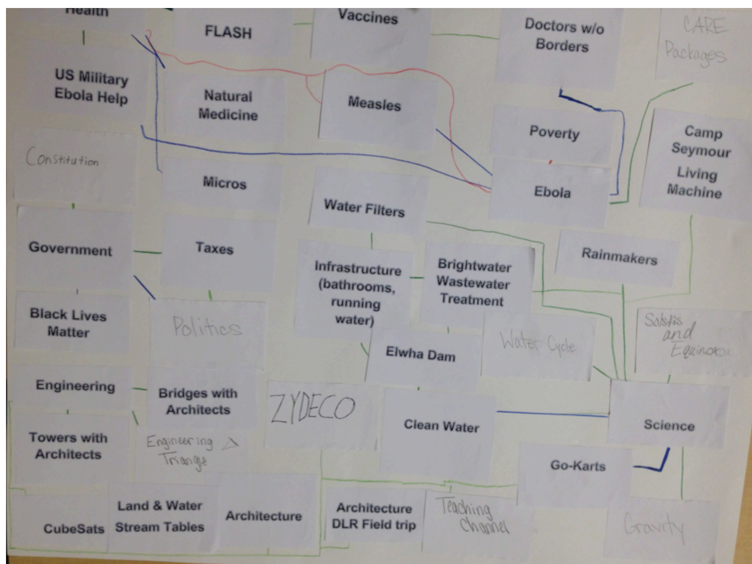
Figure 5.3. A student reflects on sociotechnical connections related to the 2015 Ebola epidemic

Some connections we can make about clean water and the spread of Ebola is toliets. If we can have clean water for toilets, then it might help Ebola. Also, if we have clean water, people could wash their hands and maybe stop the disease. Because alot of people don't wash their hands. And that makes more people get Ebola. Last, the spread of Ebola is caused by people vomiting and diharia.

3. Leverage Engineering Practices for Critical Engagement

Design practice-based approaches to learning that situate engineering design projects in social and historical contexts. Throughout this research, students engaged in engineering practices to critically define problems, model solutions, argue from evidence, and design solutions while asking: “Who does this benefit?” For example, students used systems thinking activities, such as causal-loop mapping (see Figure 5.4) to surface critical sociotechnical connections for the Ebola outbreak.

Figure 5.4. Causal-loop diagram situating public health in a sociotechnical framework



Systems thinking locates engineering solutions within complex socio-technical networks of interacting variables. Surfacing the complexity of design decisions can reduce the unintended consequences of implemented designs and allow designers to take on multiple perspectives around the impact of their designed solutions (Pawley, 2012; Riley, 2008). The first step in creating a causal-loop diagram was having students identify the broad range of variables related to disease outbreaks, as well as related topics

covered during classroom instruction. As you can see from Figure 5.4, one group of students included architecture, water filters, government, Black Lives Matter, engineering, and many other topics as being at least somewhat related to the 2015 Ebola outbreak. Causal-loop maps were an effective pedagogical strategy that enabled students to situate phenomena in broader sociotechnical contexts, and fostered the identification of emergent variables and complexity in engineering work. Systems thinking practices and artifacts scaffolded and organized student argumentation of complex phenomena.

4. Engage youth in participatory design solutions.

Systems thinking and causal loop diagraming enabled youth to situate engineering phenomena within complex sociotechnical systems (Adams et al., 2011). These diagrams can then be leveraged to help students identify variables for change and agency within the complex network of actors and artifacts. In this research, youth collected and sent supplies to volunteers constructing Ebola treatment facilities in Liberia. Students also engaged their parents and family members in discussions related to public health. For example, several parents were concerned that volunteers that had recently been in Liberia were in the classroom to talk about the Ebola epidemic. Students used evidence from expert visits, and from classroom discussion to alleviate their parents' worries and to advocate for learning about public health issues from volunteers who were helping. Students also related our Ebola investigations to an emerging measles outbreak both nationally and in their local community. However, in the context of the measles outbreak, youth surfaced how misinformation reduced vaccine rates among certain communities. Students related issues of power and privilege among families who chose not to vaccinate their children (and who often has access to quality healthcare), to communities who

would be most impacted by a measles outbreak (i.e. communities with reduced access to preventative and high quality healthcare).

Conclusions & Implications

The performative nature of engineering designs can be leveraged to teach students how to critique the designed world in ways that enable them to see how broader sociological constructs are related to quality of life, health, and personal agency. The act of critiquing the built environment involves reframing notions of individual agency that dominate neoliberal education environments. Instead, critical sociotechnical literacy surfaces the interconnectedness and complexity of living in a sociotechnical world, that privileges some individuals at the cost of many others. The NGSS Science, Technology, Society, and the Environment standards engage students in investigating, *how things work* and *how designs are used and applied*. Critical technological literacy adds to this framework by encouraging teachers and students to ask, "*Who benefits from this design, and at what cost?*"

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