HEGEDUS, THERESA, Ph.D. Engineering Education for Youth: Diverse Elementary School Students’ Experiences with Engineering Design. (2014)
Directed by Dr. Heidi B. Carlone. 319 pp.

Lingering concerns over the persistent achievement gap amidst the trend of an increasingly diverse society have been compounded by calls from the Oval Office, the National Science Board, and nationwide media to also address our current creativity crisis. Now, more than ever, we have a responsibility to produce a STEM-capable (science, technology, engineering, and mathematics) workforce to meet the demands of our rapidly changing local and global economic landscape. Barriers exist in our traditional educational system, which has historically limited underrepresented groups’ affiliation and membership in the disciplines of science and engineering. The recent incorporation of engineering into the latest science education reform efforts presents an opportunity to expose students as early as elementary school to engineering practices and habits of mind, which have the potential to stimulate creative thinking skills through engineering design.

This qualitative study was designed to examine the ways in which engineering education has the potential to promote creativity and academic competence in elementary science classrooms. As a part of my study, a diverse group of students from two fifth-grade classrooms took part in a 10-12 hour, engineering-based curriculum unit (Engineering is Elementary) during their regular science instructional time. Using a sociocultural lens, to include cultural production and identities in practice as part of my framework, I analyzed group and individual performances through classroom observations, student interviews, and teacher reflections to better understand the meaning students made of their experiences with engineering.

Findings from the study included the ways in which creativity was culturally produced in the classroom to include: 1) idea generation; 2) design and innovation; 3) gumption/resourcefulness; and 4) social value. Opportunities for collaboration increased through each stage of the unit culminating with the design challenge. Engineering teams required cultivation by the teacher as students negotiated spaces for collaboration through challenges of competition versus compromise; assumed versus assigned roles; management of verbal versus non-verbal communication; and shifts from teacher-as-authority-figure to peers as sources of knowledge and inspiration. The engineering design challenge provided an ideal context for broaching socio-scientific issues and attention to ethical considerations. Students made reference to their growing environmental awareness and developing moral reasoning in their definitions and reflections on green engineering. Throughout the course of the unit, successful students, struggling students, and students with uncertain trajectories established themselves as competent and efficacious engineers.

Implications of the study include ways to assist teachers in recognizing and cultivating creativity and collaboration in addition to effectively incorporating socio-scientific issues as part of the engineering (and science) curriculum. I also present recommendations for promoting equity in classroom engineering, pre-service teacher initiatives, and strategies for capitalizing on the complementarity between science and engineering.

ENGINEERING EDUCATION FOR YOUTH: DIVERSE ELEMENTARY SCHOOL STUDENTS' EXPERIENCES WITH ENGINEERING DESIGN

by

Theresa Hegedus

A Dissertation Submitted to
the Faculty of The Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Greensboro
2014

Approved by

Committee Chair

To Eric, Haley, and Ryan; without your love and support this journey would not have been possible. You are my foundation. You have kept me grounded and on course, cheering me on through my successes and disappointments. I am the most fortunate person on Earth to have you as my loving family. Not to be forgotten, much love to my Great Dane, Riley. You have been a faithful companion, remaining dutifully by my side throughout graduate school. To you, I award an honorary canine degree. My love for you all has no bounds.

APPROVAL PAGE

This dissertation written by Theresa Hegedus has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

Committee Chair ____________________________________
Heidi B. Carlone, Ph.D.

Committee Members ____________________________________
Pamela Lottero-Perdue, Ph.D.

____
Catherine E. Matthews, Ph.D.

____
Edna Tan, Ph.D.

____
Date of Acceptance by Committee

____
Date of Final Oral Examination

ACKNOWLEDGEMENTS

First, I am eternally grateful to my parents, John and Britt-Marie Vries, for teaching me what it means to work hard. Your unconditional love and thoughtful guidance helped me to be fearless in the face of challenge. To my sister and brother, Jennifer and Tim, for always believing in me. To my mother and father-in-law, Gail and Joe (Pils), who have treated me as one of their own, offering unwavering love and support when I needed it the most.

I would also like to recognize my fellow science education graduate students, Lacey Huffling, Aerin Benavides, Cailisha Petty, and Pat Conetta, for letting me know I was not alone in this journey. I also want to acknowledge the Young Education Scholars headed by Traci Bellas, who made up our unique doctoral cohort. You all made this process manageable and fun.

I would like to thank the fifth-grade students and two dedicated teachers whose participation and perspectives made this study possible. I would also like to recognize the supportive administration that allowed me to be a regular fixture at these two schools.

Thank you to the dedicated research team that made this project run so smoothly. I want to gratefully acknowledge, Melony Allen, Holly Downs, Aundrea Carter, and Sage Washington for being such supportive partners. I want to acknowledge the generous funding our research team received from the Museum of Science in Boston that allowed this project to come to fruition.

To my committee members, I am eternally grateful. To my Chair, Heidi Carlone, your selfless mentorship has been a tremendous gift. Your trusted guidance and steadfast belief in me have helped me realize my intellectual goals. I have gown tremendously under your leadership. To Catherine Matthews, thank you for your kind support and valuable recommendations. You are a remarkable role model in the field of science education. To Edna Tan, thank you for your research expertise and critical feedback that allowed me to grow as a new scholar. To Pamela Lottero-Perdue, your perspectives on engineering education have been invaluable. I appreciate your supportive mentorship.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

As educators and researchers, we have all heard the resounding call to do our part to close the achievement gap. However, the disparity in academic performance among groups of students in comparison to their White and Asian peers persists despite reform efforts (Lee, 2012). Projections from the 2010 Census indicate a trend toward an increasingly diverse population in the U.S., which further complicates existing problems with equity and achievement (U.S. Census Bureau, n.d.). According to The New York Times, Census officials have reported that we are on target to become a ‘plurality nation’, where no single ethnic or racial group will make up the majority (Cooper, 2012). Indicators of the achievement gap in our increasingly diverse society consist of performance on standardized testing, access to key opportunities (advanced coursework) and resources, and the level of attainment in school and future employment (NEA, n.d.). Among the groups particularly vulnerable to the achievement gap are African American (NEA, 2008) and Hispanic/Latino students (Gándara, 2005; NEA, 2007; Verdugo, 2005). Briefs produced by The Alliance for Excellent Education (2014) document connections between poverty and the achievement gap revealing the economic factors at play and the potential impact on our nation’s economy.

Not surprisingly, a new challenge has emerged amidst these lingering concerns of school performance and achievement from non-mainstream groups. A reported talent gap has surfaced, particularly in STEM-based fields (Science, Technology, Engineering, and Mathematics), as a new problem facing educational professionals in our global and increasingly competitive society (Williams, 2014). It is important to note that the phrase *talent gap* is not in reference to students' lack of inherent talent, rather our lack of cultivation of that talent. According to The Huffington Post, "finding qualified talent, retaining them and finally, maximizing their potential for the companies' and their own benefits" is the point of concern (Moritz, 2014, para. 1) as is the "increasing need for employees with a wider breadth of knowledge and more sophisticated skills than in times past" (para. 2). Similarly, the National Science Board's (2010) report on the next generation of STEM innovators called for development of unrecognized talent in students for improved academic performance as well as cultivation of future STEM innovators. Mann, Mann, Strutz, Duncan and Yoon (2011) highlighted the importance of integrating engineering into the K-6 curriculum as a way to develop and discover talents in students as more than "strength in mathematics and science; communications, literacy, teamwork, and leadership talents are also critical to the success of engineering design projects" (p. 639).

Adding to the call for equity in student achievement and talent development are reports of a creativity crisis, where opportunity and innovation are failing to be properly "nourished, renewed, and maintained" (Florida, 2004, p. 9). The New York Times reports companies like Google are looking for a unique skill set in their potential employees to include emergent leadership, humility, collaboration, adaptability, and a love for learning (Friedman, 2014). With these educational challenges in mind, cultivating talent early in school needs to take a more direct and concerted approach. STEM educators must therefore modify their approach to teaching to meet the changing demands of today’s society.

The purpose of my study is to understand the ways in which engineering education has the potential to promote creativity and academic competence in elementary science classrooms. I begin this chapter by examining the challenges and barriers to access students from diverse backgrounds face in traditional science classrooms. I focus specifically on the culture of testing and accountability that has become the overarching focus in schools limiting creativity and diverse students’ affiliation and membership in STEM disciplines. In this study, I direct my attention to science and engineering education as my focal areas of STEM. Next, I discuss the upsurge and increased recognition of engineering in science classrooms due to its recent incorporation in the *Next Generation Science Standards* (NGSS Lead States, 2013) and the potential affordances of engineering education for youth. Finally, I address the current dearth in the research literature regarding equity and engineering education, particularly at the elementary school level. I argue that introducing engineering as early as elementary school may provide students with opportunities to engage their creativity and promote a level of academic competence that has not been achieved in traditional science classrooms as they are currently structured. The introduction of engineering education partnered with progressive inquiry-based science education may provide a new avenue toward reaching these goals. Perhaps, engineering is the catalyst that is needed to intentionally develop creativity and reduce the lingering achievement gap for students. However, we need further research to understand this potential.

The Equity Problem

First, it is important to recognize the barriers to access and membership students continue to experience in science classrooms today. Perhaps barriers to diverse membership are due to the historically enduring legacies science carries in its backstory. Science has earned status as a place for a limited number of middle-class, mostly White males from Western cultures (Lee, 1997). Despite reform efforts, science has continued to reinforce its exclusive form of membership, as it remains elite, gendered, and competitive. For example, Brickhouse, Lowery, and Schultz (2000) studied four female, African American middle-school students' learning in the form of engagement in science practices and whether or not they saw themselves as the kind of people who affiliate with science in school. The authors found that science instruction across 7th and 8th grades did not provide students with a variety of ways to engage in science. The emphasis was on grades and participation, rather than conceptual understanding, and top track science classes were reserved for the compliant students. Some of these young women were seen as "loud" by their White teachers and exhibited a willingness to violate traditional, gender norms (p. 444). This moved them further away from the expected "obedient schoolgirl" persona that was more highly valued in the science classroom (p. 456). In this way, it was difficult for the young women to participate authentically and affiliate with science according to these rigid, gender-specific expectations. Interestingly, the young women who aligned with the traditional gender norms were recognized as "scientific" even if their participation and engagement was more focused on compliance than scientific performances. In this way, doing well in science meant doing well in school.

Similarly, Carlone (2004) studied the enactment of a reform-based curriculum with young women in a reform-based high school physics classroom and the meanings of *scientist* and *science* that were culturally produced in that setting. Carlone proposed that a broader, more inclusive curriculum had the potential to disrupt prototypical science education in this setting and transform these young women's engagement with and typical performance in science. However, the students clung tightly to their "good student identities" (part of the classroom culture) not wanting to take risks and transform their participation in the classroom due to fears about grades and passing the course. The larger structures of school and classroom culture as well as the historical legacy of prototypical science education dominated their engagement with physics and affiliation as "science people." These results support the idea that traditional structures influence students' willingness to engage in reform-based efforts.

Learning science and engaging in science-related identity work is difficult for students from non-dominant cultures because of the "exclusive nature of school science culture" (Calabrese Barton & Tan, 2009, p. 51). Developing a sense of belonging in a community of learners where the practices are defined by the dominant culture presents challenges for children of low socioeconomic status and can be quite isolating. Carlone, Haun-Frank, and Webb (2011) proposed that to achieve equity in science education, students must navigate a new figured world where normative scientific practices emerge through special attention to the social and cultural aspects of learning. This sociocultural perspective on learning suggests that a transformative or new *figured world* (Holland et al., 1998) of school science learning is one where the status quo does not get reproduced. In a new figured world of science, students have access to and have the opportunity to get recognized for certain performances (e.g., new *normative scientific practices* such as leveraging cultural resources or community-based knowledge) to become labeled as smart in science, thereby resisting traditional conceptions of what it means to be a science person (Carlone et al., 2011, p. 465). Carlone et al. (2011) argued for science curriculum and pedagogy that "includes the experiences, worldviews, learning styles, funds of knowledge, and/or interests of students from diverse backgrounds" (p. 479). In their study, the classroom that adopted a "we" language and culture (group-level versus individual accomplishment) was more inclusive and less competitive making for more collaborative investigations in science (p. 470). It is important to understand the experiences and interests of students from non-dominant cultures, specifically children from low socioeconomic backgrounds, can be quite divergent from the dominant norm and require the special attention of educators if equitable practices are to prevail.

These examples highlight the ways in which the discipline of science carries with it a distinct socio-historical legacy of power, intellectual elitism, and exclusive membership (Carlone, 2004; Hammond & Brandt, 2004). Science as presented to students in prototypical, traditional classrooms often consists of indisputable, objective, fact-based knowledge imparted to students in a structurally hierarchical manner, which is often decontextualized and mechanistic in its delivery (Barton & Yang, 2000; Brickhouse, 1994). Science, presented in this way, denies the cultural capital that students from diverse backgrounds bring to school as well as the possibility of optimizing engagement and interaction in the process of scientific inquiry and exploration (Barton & Yang, 2000).

The social structure of our schools often limits inclusion of a wide variety of students by privileging a hierarchical system and narrow notions of what counts as learning and successful performance (Lee, 2003). To make science more equitable in school today, we must broaden participation, interest, affiliation and ultimately, what counts as competence (Carlone, Haun-Frank, & Webb, 2011). Previous reform measures such as AAAS Project 2061 initiated in 1985 and the National Research Council's initiation of the National Science Education Standards in 1996 have been implemented to promote equity, facilitate more inclusive classroom cultures, and introduce progressive pedagogical strategies with some success. However, traditional science classrooms continue to need a catalyst to stimulate much needed change in social dynamics and opportunities for students to engage academically and creatively in the 21st century. Perhaps the infusion of engineering practices can provide a new avenue for reform.

The Creativity Problem

The trend toward increasing accountability and high-stakes testing measures leaves little room for creative thinking and innovation (Jones, Jones, & Hargrove, 2003; Mayer, 2011; Nichols & Berliner, 2007; Sternberg, 1999, 2005, 2011), highly coveted qualities in today's world and competitive global economy. It becomes difficult to broaden participation and achievement in any subject area when attention is so tightly focused on measuring and comparing students through testing. As a Nation we need to produce students who are capable of solving problems and who are invested in acquiring the skills and knowledge necessary to be productive citizens in today's world. Even more importantly, students who rise to a position of competency in much needed STEM fields have the potential to become advocates for themselves and their communities. For example, a study by Calabrese Barton and Tan (2010) explored how low-income urban youth developed agency and science identity in a community-based learning environment. Students were allowed a sense of freedom and choice in the projects they pursued allowing them to function as community science experts, becoming both producers and critics as they engaged in science. In this project, the students "transcended the technical cadence and register of canonical science and in the process claimed a sense of ownership over the science content" allowing them to develop agency and science identities in the process (p. 224). Students authored themselves as producers and critics of science in the figured world of community-based science. Empowering students in this way helps them make informed decisions that are relevant to their lives and have a platform in which to advocate for what they value and hope to cultivate in their communities. Therefore, the purpose of developing science and engineering education in schools is two-fold, for the continued development of students' creative potential and their ability to advocate for themselves and their communities.

Opportunities to be creative in science are largely absent in today's schools where the focus is placed heavily on standardized testing of measured analytical and memory skills based primarily on discrete mathematical and verbal abilities (Mayer, 2011; Sternberg, 1999, 2005, 2011). However, the *Next Generation Science Standards* provide a vision for K-12 science education that includes dimensions of *Engineering, Technology, and Applications of Science* as a way to enhance students' abilities to acquire and apply scientific knowledge (NRC, 2012). This latest revision of the standards infusing principles from engineering, attempts to challenge the status quo and is situated within the goals of promoting 21st century learning and innovation skills including, critical thinking, collaboration, communication, and creativity (P21, 2009). The context of engineering has the potential to provide students with opportunities to explore science in new ways that challenge their abilities to think creatively and perform themselves as competent science learners. Perhaps the introduction of engineering education into the science curriculum can help address the creativity concern as well as persistent concerns about student achievement.

One problem, however, is that we do not currently have widespread contexts in school science that cultivate creative practices and intelligences (Sternberg, 2011). These contexts would include opportunities for students to actively engage in critical thinking, problem solving, and inductive reasoning in the realm of science (Van Tassel-Baska, Quek, & Xuemei Feng, 2006). This type of thinking requires opportunities for students to imagine, wonder, create, design and innovate. As Sir Ken Robinson (2006) stated so persuasively, "my contention is that creativity now is as important in education as literacy, and we should treat it with the same status" (03:05).

What is currently lacking is a firm understanding of how to teach to promote creativity and how to cultivate those practices in our students within our current educational model. Regular references are made to twenty-first century skills (P21, 2009) that include creativity, but we seldom see guidelines for practice in our teacher education programs or professional development for teachers. Because of this, the concept of creativity is often broached abstractly, leading to a lack of understanding as to how creativity emerges in practice and how to recognize and cultivate it effectively in our students.

Early conceptions of creativity were focused on understanding individual creative genius and intellectual capacity through psychological research attempting to measure one's level of creative giftedness (Craft, 2001). Currently, and more relevant to education, is the recognition of an "ordinary, everyday " (Craft, 2001, p. 13) or "democratic" (NACCCE, 1999) creativity that proposes that all students can be creative. Creativity is now more regularly viewed as part of the social system rather than as an individual focus, where qualitative characterizations take precedence over measurement (Craft, 2003). Craft (2001) explained, "Creative thinking is often equated with originality, the generation of ideas, and with a range of problem-solving strategies (sometimes referred to as 'creative production')" (p.16). Despite these more modern characterizations, creativity remains difficult to define with consistent terminology.

Creativity is currently viewed as a core concept in education and a "fundamental life skill" which builds "human capital" necessary in a rapidly developing world (Shaheen, 2010, p. 166). According to Shaheen (2010), many countries have begun to include creativity in their educational policies. Preparing students for the twenty-first century and necessary creative higher-order thinking skills has been the recent focus of school curricula in Japan, Germany, China, Scotland, and Singapore to name a few. Japan holds creativity as the most important educational objective and Singapore lists creativity as one of its eight core skills and values (Shaheen, 2010).

Even more encouraging, qualitative research has been performed in elementary school classrooms in the United Kingdom (Woods, 1990; 1993; 1995), providing some information about pedagogical strategies that may foster creativity with this population of students. Woods' work identified relevance to pupils' interests, ownership of knowledge, control over pedagogy, and innovation as key elements in cultivating the creative process. Additionally, assessment strategies have pointed to areas of focus for educators with regard to evaluating novelty of ideas, resolution (how products meet human needs), and the ability to synthesize unique parts of a product into a coherent whole (Besemer & Treffinger, 1981; Craft, 2001). These elements of creativity provide a starting point from which we begin to understand how creativity unfolds in practice and where our initial focus should turn toward a better understanding of this abstract concept. Creativity is operationalized for the purposes of this study at the end of the chapter (see Definitions of Significant Terminology) and is explored further in Chapter II.

The Significance of Engineering Education

The push for STEM education comes with a call for broadening participation to inspire diverse skill development to fulfill a need for innovative students with high-quality STEM proficiency (NCSL, 2014; The White House, n.d.). President Obama launched the *Educate to Innovate* initiative in 2009 in response to our country's failure to produce students who can perform and achieve in STEM-based disciplines in comparison to their international peers. Obama has continued to speak further on the importance of STEM education stating,

> One of the things that I've been focused on as President is how we create an all-hands-on-deck approach to science, technology, engineering, and math… We need to make this a priority to train an army of new teachers in these subject areas, and to make sure that all of us as a country are lifting up these subjects for the respect that they deserve. (Third Annual White House Science Fair, April 2013)

It is not a new problem that we face a shortage of qualified STEM professionals in the U.S. (NSB, 2008). As early as the turn of the century, we faced a fifty percent attrition rate for students enrolled in engineering education in colleges and universities, further complicating the need to fill our engineering ranks (Wicklein, 2006). Out of the four million students who graduated high school each year in the U.S., only two percent obtained an engineering degree from an engineering school in the U.S. (Orsak, 2003). As these statistics highlight, students have not been adequately prepared to pursue STEM fields in higher education or to enter STEM-based careers based on their limited exposure to these disciplines in their K-12 educational experience, especially engineering (Rockland, et al., 2010). Projections are that only about 2.5 percent of freshmen females of all races hope to pursue engineering degrees (NSF, 2009). Reaching female students from all backgrounds and ethnicities early in their education has become a priority, as the number of females obtaining engineering degrees remains disproportionately low at 23 percent (NSF, 2014). In 2011, underrepresented groups (African Americans, Hispanics, American Indians, and Alaska Natives) accounted for about 12% of students enrolled in science and engineering graduate programs, while Caucasian student enrollment was at

47% (NSF, 2014). Adding diversity to the field of engineering and overcoming historically enduring legacies is indeed a challenge. Perhaps, it is a challenge that can be initially addressed by dropping the veil of mystery on engineering through early exposure and introduction to the educative possibilities engineering education may afford youth at the elementary school level.

An initiative to promote innovation has clearly been set with a focus on STEM disciplines and development of students' creative and innovative skills. It is here that I draw the focus of my dissertation in accordance with this vision of addressing the creativity crisis, with a personal interest and desire to pursue the potential affordances engineering education for a diverse population of students as part of the current science curriculum.

The affordances of engineering education in K-12 classrooms are not clearly understood, as this is a relatively new research area, compared to K-12 science education research. The publication of the *Framework for K-12 Science Education* has placed engineering as a formal part of K-12 science curriculum (NRC, 2012). This move is part of the call to promote STEM literacy, outlined as the importance of (1) ensuring success in employment, post-secondary education, or both, and (2) preparing students to be competent, capable citizens in a technology-dependent, democratic society (Katehi, Pearson, & Feder, 2009). The *Framework* also provides rationale for including engineering and technology alongside the natural sciences 1) to reflect the importance of understanding the human-built world; and 2) to recognize the value of better integrating the teaching and learning of science, engineering, and technology (NRC, 2012, p. 2).

While the move to incorporate engineering into the *Framework* is a positive one for the field, the context of engineering and its potential benefits remain poorly understood in K-12 education. Early research however, indicates engineering may promote learning and achievement in other STEM fields, specifically science by making it relevant to children (Lachapelle & Cunningham, 2014). Engineering projects and design challenges can provide motivation for students to participate and exhibit their creativity and competence in novel and authentic contexts. Elementary-aged students have exhibited they are capable of learning physics and math concepts in the context of engineering, where "kindergarten students arguing about frictional forces in their axles and third graders interpolating a calibration graph" becomes an unexpected norm (Rogers & Portsmore, 2004, p. 18).

Engineering education also has been shown to have the potential to provide opportunities for students engage and think creatively in different ways than the traditional science curriculum allows by stimulating interest, motivation, and the ability to solve real-life problems (Brophy, Klein, Portsmore, & Rogers, 2008). Brophy et al. (2008) described multiple studies (Fleer 1999, 2000; Johnsey 1995; Roden, 1999; Roth, 1996) conducted with preschool to elementary-aged students indicating the significance of developing "open-inquiry learning environment around realistic and complex problems" (p. 373). For example, in Fleer's (1999; 2000) pilot study, three to five-year old children designed either a fictional friend or a home for a mythical creature based on a story they were read using a simple design process. Remarkably, these young students were able to move though the iterative stages of a basic engineering design process including planning a design, using their prior knowledge of materials to make decisions about construction, and evaluating their final products. Due to the natural curiosity that children possess, exposure to engineering education as early as pre-school school holds promise for engaging youth, promoting creativity, and stimulating interest in future career pathways in STEM fields (NRC, 2012).

Study Goals

It is for this reason that I focus my attention on youth and engineering in an effort to study the benefits of introducing engineering concepts as early as the elementary school level. The intellectual goals of this study are to gain insight into the affordances of engineering education for cultivating youths' engineering habits of mind, with a specific focus on creativity, collaboration, and attention to ethical considerations (Katehi, et al. 2009). These are three of the six habits of mind outlined by the Committee for K-12 Engineering, a group of experts on diverse science and engineering subjects from the National Academy of Engineering and the Board on Science Education at the Center for Education, which is part of the National Research Council. These three habits of mind are unpacked further in the next chapter. Additionally, I seek answers to the question of what engineering looks like in practice and how students author themselves and get positioned by others as they engage in the unit. I argue for the need to study the inclusion of engineering habits of mind and design principles in the science curriculum as a way to improve academic performance and affiliation with STEM.

On a practical level, I believe this study holds promise for addressing the challenge of a *talent gap* and the need for students with STEM skills in addition to the persistent concerns over student performance and the achievement gap. It may be possible to uncover different points of access and entry for students into STEM fields by examining new ways of approaching a long-standing problem.

On a personal level, I am motivated to pursue this line of thinking due to my extensive work with gifted students. I believe there are limited opportunities for students from diverse cultures and backgrounds to be recognized for their intellectual strengths, where typical meanings of competence trump all other possible entry points for students with potential. I argue that engineering education with a focus on engineering habits of mind can provide possible answers to these lingering questions. The research questions that inform my study include:

1. What engineering habits of mind emerge as significant during students' engagement with an Engineering is Elementary (EiE) green engineering, solar energy unit?
    a. How does creativity emerge during the engineering unit?
    b. In what ways do students collaborate during the engineering unit?
    c. In what ways do ethical considerations play a role in students' understanding of the engineering unit?
2. How do students author themselves and/or get positioned by others during the engineering unit?

Definitions of Significant Terminology

Attention to ethical considerations is the ability to see the advantages and disadvantages of a technology and its potential impact on people and the environment (Katehi, Pearson, & Feder, 2009).

Creativity in this context is the driving force behind engineering design and innovative thinking. In engineering, creativity involves the development of original ideas that have value produced as the result of iteration, idea incubation, risk taking, tolerance for ambiguity, and learning from failure (Kazerounian & Foley, 2007).

Collaboration is the way that groups or teams can leverage their knowledge, varying perspectives, skills, and aptitudes to tackle a design challenge (Katehi, Pearson, & Feder, 2009).

Communication is a way that group or team members can collaboratively convey information to clients and/or best understand a consumer's wants or needs. Communication is the process of explaining and justifying design solutions to effectively translate the results to clients (Katehi, Pearson, & Feder, 2009).

Communities of practice are "formed by people who engage in a process of collective learning in a shared domain of human endeavor" (Wenger, 2006, para. 2). In this case, the classroom community is considered the *organization* where collective learning takes place as part of a broader learning system, where activities like problem solving, seeking experiences, collaboration, and discussion represent practices.

Cultural production is a theoretical construct that helps us to better understand how groups of students for example, produce meanings locally (e.g., "the space of education and schooling") as the result of their everyday interactions (Levinson, Foley, & Holland, 1996, p. 14). The meanings that are produced during participation/practice have the potential to either reproduce prevailing meanings (e.g., schooling, engineering, or engineering habits of mind) or possibly contest/transform the status quo (Carlone, Johnson, & Eisenhart, 2014).

Engineering can be defined as the "process of designing the human made world" (Katehi, Pearson, & Feder, 2009, p. 27). The field of engineering is an inherently creative process of "design under constraint" (Wulf, 1998, p. 28) with the goal of modifying the world to satisfy human needs and desires. The developers of EiE define an engineer as, "Someone who uses his/her knowledge of science, math, and creativity to design objects, systems, and processes to solve problems" (EiE, 2011, p. 36).

Engineering Habits of Mind are the "values, attitudes, and thinking skills associated with engineering" that are essential for citizens of the 21st century to include: creativity; collaboration; communication; optimism; systems thinking; and attention to ethical considerations (Katehi, Pearson, & Feder, 2009, p. 152).

Identity work is the dynamic process of "negotiating meanings of our experience of membership in social communities" (Wenger, 1998, p. 145).

Identities-in-practice is a phrase that reflects how identity is produced and negotiated through lived experiences, participation, and engagement in particular learning communities. "What narratives, categories, roles, and positions come to mean as an experience of participation is something that must be worked out in practice" (Wenger, 1998, p. 151).

Non-dominant student is a term used to describe a population of students who are not considered part of the dominantly White, middle-class mainstream. The dominant or mainstream group is classified by “social prestige, institutionalized privilege, and normative power”, rather than their numerical majority (Lee & Luykx, 2007, p. 173). Non-dominant students represent diversity in terms of race, ethnicity, language, culture, or socioeconomic status.

Normative scientific practices are the regularly occurring “scientific practices in which students are held accountable to be considered competent” (Carlone, 2012, p. 13).

Optimism is the ability to see opportunities and possibilities in every design challenge (Katehi, Pearson, & Feder, 2009). Optimism represents the belief that potential solutions can be obtained and successfully implemented.

Prototypical science education represents the traditional view of science education as narrowly constructed, does not attend to issues of equity, and “treats social issues, technology, and engineering as diversions” (Carlone, 2004, p. 394).

Science is the study of the natural world where the process of scientific inquiry is used to generate new and useful knowledge (Katehi, Pearson, & Feder, 2009). Science and engineering are represented as mutually reinforcing disciplines in this study, of equal stature and significance.

Science equity as envisioned from a cultural anthropological approach “centers on making science accessible, meaningful, and relevant for diverse students by connecting their home and community cultures to science” (Bell, Lewenstein, Shouse, & Feder, 2009, p. 213). This perspective allows for alternative ways of knowing and values the knowledge students from diverse backgrounds bring to school. Understanding the role of culture and context in science learning helps to make science more accessible to all students.

STEM (Science, Technology, Engineering, and Mathematics) is the acronym used to convey these four interrelated disciplines/content areas. Science (the "S") and Engineering (the "E") are the highlight of this study. Additionally, Technology (the "T") is part of the discussion in this study represented as students' simple and complex products of the engineering design process.

Systems thinking "equips students to recognize essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behavior of individual subsystems" (Katehi, Pearson, & Feder, 2009, p. 152).

Talent gap is the decrease in production of a STEM-capable workforce, unable to meet current societal demands. In this study, "talent" is not meant to represent innate ability, rather skills and abilities to be developed through stimulating educational experiences.

CHAPTER II

LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

I begin this chapter with a review of the literature regarding engineering education. I build upon information contained within the field of engineering and its history, highlighting points of convergence and divergence with science. I introduce Engineering is Elementary (EiE), the engineering curriculum that will be the focus of my study to provide a rationale for my choice of curricula and to introduce the elementary engineering design process. After developing the context of engineering, I delve into particular engineering habits of mind and engineering practices that are relevant to educating our youth equitably in a globally competitive society. Furthermore, I explore issues with equity in engineering education to signify the potential affordances and constraints exposed within the field. Finally, in my conceptual framework I reveal two theoretical frameworks that inform the study—cultural production and identities in practice—both situated within a sociocultural perspective.

Literature Review

Engineering Education

Engineering education has only recently become a focus in U.S. K-12 classrooms, spurred on by President Obama's administration as an educational priority in the form of STEM education (NRC, 2010). While science and mathematics have been the primary focus of most reform-based measures, the engineering branch of STEM began to emerge formally in classrooms as early as the 1990's (Katehi, Pearson, & Feder, 2009; NRC, 2010). Due to its relatively recent emergence in U.S. classrooms, there have been a limited number of research studies devoted to student achievement and learning outcomes resulting from the enactment of engineering curricula. The National Research Council recommends studies to analyze "how design ideas and practices develop in students over time and determining the classroom conditions necessary to support this development" (Katehi, et al., 2009, p. 7). The call for research to fill these gaps in the literature to determine the benefits of engineering education in K-12 classrooms has become an educational priority (Cunningham & Carlsen, 2014).

General claims regarding the benefits of engineering education and the potential for engineering to improve performance in science and mathematics are promising but difficult to substantiate as, "only limited reliable data are available to support these claims" (Katehi, et al., 2009, p. 6). Additionally, reported benefits include increased student attendance and retention, improved technological literacy, and students choosing future engineering career paths, however "the paucity and small size of studies and their uneven quality cannot support unqualified claims of impact" (p. 7). The gap in the literature with regard to substantiated benefits and resultant impacts on student academic performance and interest currently remain anecdotal and require further uniform and long-term research. The call for research to corroborate claims of positive benefits is critical now more that ever with the need to remain globally competitive, to educate a "global citizenry", and to empower individuals to "affect technological change" in the movement to infuse elements of engineering, as part of the push for STEM, into K-12 classrooms (Lachapelle & Cunningham, 2014, p. 1).

To understand the potential benefits of incorporating engineering into K-12 education, it is important to establish a firm grounding what it means to engineer. The Committee for K-12 Engineering Education, mentioned in the previous chapter, put forth three general principles that define what it means to engineer (Katehi, et al., 2009). According to the Committee, engineering education should 1) emphasize engineering design; 2) incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills; and 3) promote engineering habits of mind (p. 151). Engineering habits of mind include “systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations” (Katehi, 2009, p. 3). The integral relationship between science and engineering and the prospect of development in each discipline serving to benefit the other is intriguing for the future of school science and engineering education.

A brief history of engineering. Science and engineering share a history of similarities in their patterns of emergence indicating the integral nature of these important disciplines over time. Sunny Auyang (2004), author of *Engineering—An Endless Frontier,* proposed that the history of engineering could be divided into four overlapping phases or revolutions: 1) pre-scientific revolution; 2) industrial revolution; 3) second industrial revolution; and 4) information revolution.

Auyang characterized the pre-scientific revolution as a time of tinkerers, practical artists, and craftsmen (i.e., “Renaissance engineers”) who relied on imagination and ingenuity to ask how and why things work the way they do. Some of the first engineers were referred to using the Latin term “ingeniator” (ingenious one). Leonardo Da Vinci was considered one of these early Renaissance engineers (Parsons & Woodbury, 1976).

During the industrial revolution, early artisans transformed into modern engineers as they adopted scientific approaches and structural mathematical analysis to solve practical problems as part of the scientific revolution (Auyang, 2004). This age also gave rise to university-based engineering education (Armytage, 2003). The second wave of the industrial revolution brought forth many different branches of engineering grounded in principles of physics and chemistry (e.g., chemical, electrical, aeronautical engineering) and graduate schools emerged as engineering education advanced (Auyang, 2004).

In the post World War II era, engineering continued its shift toward research and development as science and technology continued to advance. With advancing computerized technologies and a stronger research focus, engineering continued to develop its systematic knowledge base and theory development to “firmly [establish] itself as a science of creating, explaining, and utilizing manmade systems” (Auyang, n.d., para. 2).

Science and engineering share knowledge and methods, but each approaches nature with a different emphasis. Auyang (2005) stated, “Scientists strive to understand nature, engineers to transform nature for serving people.” (p. 1). Although their emphases at times are distinctive, it is important to note that the disciplines are constantly interacting and mutually supporting and both allow for diversity in expertise. Engineers can function as “engineering scientists” who engage in applied scientific research, engage in design and development, or perform as entrepreneurs in the business landscape (Auyang, 2004). In the next section, I further explore the nuances of science and engineering practice and how each discipline helps us to make sense of the world.

Science and engineering. It is important to further operationalize the term engineering to better manage the juxtaposition between the field of engineering and the discipline of science. Wulf (1998), former president of the National Academy of Engineering, presented his view of what an engineer does in a paper presented at a conference sponsored by the Engineering Foundation and the National Science Foundation by making a comparison to science, "Science is analytic-it strives to understand nature, what is. Engineering is synthetic-it strives to create what can be" (p. 28). Wulf (1998) emphasized that engineering is *not* applied science. He defined engineering simply as "design under constraint" (p. 28). Wulf specified what he considered constraints by elaborating that engineering involves "creating, designing what can be, but it is constrained by nature, by cost, by concerns of safety, reliability, environmental impact, manufacturability, maintainability, and many other such 'ilities'" (p. 28). The conceptual parallels between "design discourse" in engineering and "inquiry-related discourse" in science education provide opportunities for "border crossing" between disciplines and the ability to capitalize on the "creative methodological approaches" of each (Lewis, 2006, p. 255). Engineering design is the crux of most engineering pursuits and creativity is at its core. The powerful combination of science inquiry and design-based engineering suggests a partnership that has the potential to improve student learning outcomes and engagement in the “S” and “E” components of STEM (Cunningham & Carlsen, 2014).

Currently, no national standards exist for engineering education placing it at a disadvantage among science, technology, and mathematics, which all have national standards of their own (Bybee, 2011). Instead of creating a separate set of standards and potentially “silo-ing” engineering from the other STEM disciplines, Bybee has advocated instead for STEM literacy standards for a more integrated approach. The publication of the *Framework for K-12 Science Education* and *Next Generation Science Standards* (NGSS Lead States, 2013) made a move toward integration by placing engineering as a formal part of the K-12 science curriculum (NRC, 2012). While a positive move, the inclusion of engineering was not without professional tension due to the unavoidable epistemic differences between the disciplines and how engineering is reflected in the practices. The differences in the epistemic practices of science and engineering help us to recognize their potential for solving unique technical and theoretical problems (Cunningham & Carlsen, 2014; Kelly, 2010). The importance of integrating the disciplines cannot be underrated as each informs the other in important ways.

Historically, it was the technology of artisans (for example, with the development of the steam engine) that came first (Morales & Coop, 2006). Later, scientists, who understood the value in invention, analyzed and studied the laws of thermodynamics at work in the engine, giving rise to theories and laws. Today however, scientific investigation and engineering design are more mutually reinforcing (Katehi, 2009). According to the commission for K-12 engineering education,

> …engineers modify the world to satisfy people's needs and wants. Of course, in the real world, engineering and science cannot be neatly separated. Scientific knowledge informs engineering design, and many scientific advances would not be possible without technological tools developed by engineers. (Katehi, et al., 2009, p. 27)

The inclusion of engineering in the *Framework* holds promise for the discipline and the future of engineering education, but also raises many questions as to the inevitable comparisons and positional hierarchy engineering will encounter in comparison to the historically well-established discipline of science in K-12 education. Bybee (2011) noted "the power and position of science and mathematics in STEM education and the tendency to say STEM when one really means science or mathematics is a significant barrier" (p. 27). The structure of the *Framework* was designed around three dimensions: 1) scientific and engineering practices; 2) cross-cutting concepts (unifying concepts that apply to science and engineering); and 3) disciplinary core ideas (NRC, 2012). It is difficult to clearly interpret engineering's status or position within the *Framework* due to its integration with science in some parts and its unique disciplinary distinction in others. In this way, the eight scientific and engineering practices in the *Framework* represent an inconsistent integration of epistemic practices (Cunningham & Carlsen, 2014). These distinctions will be developed in the sections that follow the current list of science and engineering practices. The practices outlined in the *Framework* are presented as follows (NRC, 2012):

1. Asking questions (*for science*) and defining problems (*for engineering*)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data

5. Using mathematics and computational thinking
6. Constructing explanations (*for science*) and designing solutions (*for engineering*)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information (p. 42)

Interestingly, practices one and six make a distinction “for science” or “for engineering.” The other practices do not. For example, practice one (*asking questions*) is specified as a science practice. The distinction is that in science, questions are asked about natural phenomena to produce general explanations and/or develop theories that are empirically answerable in the name of *progress*. Practice one for engineering is *defining problems*, which has a *product* as the outcome. However, engineers also ask questions in the process of defining a problem. Engineers can design a system or technology to meet a human need or desire once questions are asked, criteria are established, and problems are defined. What becomes confusing in the *Framework* is that one of the three distinct core ideas for engineering, ETS-1.A, is similarly *Defining and Delimiting an Engineering Problem* (NRC, 2012, p. 203). *Defining problems* is therefore listed as both a practice and a disciplinary idea.

Practice six also has a dualistic nature. *Constructing explanations* is designated as a science practice. The goal of science is to construct theories. Logical, empirically testable explanations of phenomena are a hallmark of *constructing explanations* in science. On the other hand, practice six consists of *designing solutions* for engineering as a systematic process for solving problems. Rather than *explanations*, *designs* are the focus. Criteria, constraints, trade-offs and the possibility of more than one right answer drive this practice for engineering. Again, core idea ETS1.B: *Developing Possible*

Solutions comes very close to the practice of *designing solutions.* This overlap between engineering core ideas and practices does not appear to be the case with any of the remaining six practices or the core idea ETS1.C: *Optimizing the Design Solutions*. Optimization is not explicitly stated in any of the eight practices, rather loosely inferred. Katehi el al. (2009) define optimization as, "[d]etermining the best solution to a technical problem[, which] requires balancing competing or conflicting factors" (p. 43).
It is worthy of mention that optimization is a critical element of engineering design, but does not attain a commensurate level of status as such in the *Framework*.

Engineering design and scientific inquiry converge on many salient points (Lewis, 2006). Each discipline consists of a series of processes to include, 1) uncertainty as a starting reasoning condition; 2) brainstorming or analogical reasoning; 3) mental models and visual representation of ideas; 4) need for testing; 5) dependence on content knowledge; 6) proceeding under constraints (albeit different ones); 7) resolution of day-to-day questions; and 8) being constrained by paradigmatic thinking (pp. 271-272). Science and engineering diverge with regard to their purpose (science inquiry as "inherently speculative" and engineering design as "invariably instrumental"); the role of constraints, trade-offs, failure, and context; and the practicality of tests (p. 272). Taking an integrative approach to design and inquiry capitalizes on their combined and independent strengths. As educators and students come to explicitly understand these points of convergence and divergence in the process of approaching and solving real world problems, they may better understand what counts as knowledge in these areas (Rockland et al., 2010).

Perhaps it is inevitable that combining the standards for the discipline of science and the field of engineering would be fraught with some controversy or speculation as each has its history, status, and position to uphold. However, it is important to understand that the conflation can be potentially problematic to science and engineering professionals and presents points of contention moving forward. Awareness of potential critiques may allow for a more responsive view of the standards.

The Engineering is Elementary (EiE) curriculum. To capture the need for practical, authentic, and socially beneficial epistemic practices in science classrooms for the development of a socially just society, researchers at the Museum of Science in Boston developed the *Engineering is Elementary* (EiE) curriculum project in 2003. The purpose of centering their curriculum in the elementary classroom is grounded in children's natural curiosity and inclination to design and build (Cunningham & Lachapelle, 2014). Engaging children in aspects of engineering at an early age to include design-based problems, modeling, and iteration can be a powerful motivator for learning relevant science for youth from diverse backgrounds (Shunn, 2009). According to an age-appropriate proposed model for K-12 engineering knowledge content, youth in grades K-5 are developmentally ready for creative and conceptual design due to their naturally "wild imagination[s]" (Locke, 2009, p. 25). In fact, Locke suggests children as young as three to five years old begin making things from materials using oral and visual planning with a creative peak occurring between ten and eleven years old. A more gradual and steady rise continues until another peak is reached in adolescence. The EiE curriculum has been designed to capitalize on the *wild imaginations* of children in an attempt to motivate and captivate the interest of youth about engineering.

Since its inception, over 6.2 million students and 71,000 teachers have utilized the EiE curriculum (Lachapelle & Cunningham, 2014). Implementation of a comprehensive engineering curriculum in relatively uncharted territory provides opportunities to study the enactment of creative and collaborative design principles inherent to the field of engineering. EiE is based upon four inclusive principles that capitalize on the importance of learning in real-world contexts, presenting authentic engineering design challenges, scaffolding student work, and demonstrating that all students can engineer (Cunningham & Lachapelle, 2014).

The Engineering Design Process (EDP), which undergirds the curriculum's structure, focuses on the iterative process of engineering underscored in the EiE curriculum: *ask, imagine, plan, create, and improve*. These non-linear elements combined with the engineering habits of mind can be utilized to examine how students make meaning of the human-made world and the creative processes embedded in engineering education. The graphic representation in Appendix A provides a model of the engineering design process as visualized by EiE developers along with the engineering habits of mind that are the focus of this study. The elements of the EiE curriculum relevant to this study are developed more extensively in Chapter III.

Engineering Habits of Mind and The EDP

In this section, my objective is to elaborate on the engineering habits of mind and the process of engineering design. These elements are represented in the graphic found in

Appendix A. Rather than develop an extensive list of each habit of mind and tease out the singular elements of the EDP, I present them here as a collective unit of iterative practices and processes that are highly interactive and dependent on one another. However, I give creativity a position of significance based on the current local and global interest on emphasizing creativity in education. I reveal creativity as a driving force behind engineering design and innovative thinking. Additionally, I explore collaboration and attention to ethical considerations, habits of mind that I consider focal points in the EiE unit of study.

Creativity. The context of engineering may provide students with the opportunities to explore science in new ways that challenge their abilities to think creatively. According to the *Framework for K-12 Science Education*, the importance of developing students' opportunities to competently engage in science and engineering practices can have a "profound effect on human society, in such areas as agriculture, transportation, health care, and communication, and on the natural environment" (NRC, 2012, p. 210). Infusing engineering practices into the school science curriculum presents opportunities for acknowledging and promoting students' creative potential that are often unrecognized or underdeveloped in school. The creative components of design and the fundamentally creative processes brought forth in design and inquiry challenge the traditional structures that are a part of curricula as presented in schools today (Lewis, 2006; Warner, 2003).

The concept of creativity is a difficult one to grasp, as there is no universally accepted definition (Treffinger, Young, Selby & Shepardson, 2002). Creativity is, however, an integral component of both science and engineering. Scientific knowledge generation involves “human imagination and creativity” (Lederman, Abd-El-Khalick, & Schwartz, 2002, p. 236). It is one of the basic tenets of the nature of science in that “creativity is a vital, yet personal, ingredient in the production of scientific knowledge” (NSTA, 2000) and “science is a blend of logic and imagination” (AAAS, 1997). Creativity is also one of the engineering habits of mind and inherent to the engineering design process (Katehi et al., 2009). Engineering offers some unique opportunities for students to be creative opening up possibilities for transformative learning experiences and new ways of thinking and engaging with the world.

Runco (2005), professor of psychology at the University of Georgia’s Torrance Creativity Center, defined creativity as the ability to pretend and imagine in youth, the capacity for original work, and the development of personal interpretations with the possibility for transformation. Following this line of thinking, the implementation and cultivation of creative practices incorporated into the EiE curriculum for elementary school students appears to align with a critical stage of development providing possibilities for growth and intellectual transformation. Making the connection between creativity and intelligence, Runco (2005) defined creative giftedness as, “(a) an exceptional level of interpretive capacity; (b) the discretion to use that capacity to construct meaningful and original ideas, options, and solutions; and (c) the motivation to apply, maintain, and develop the interpretive capacity and discretion” (p. 303). Runco suggested that cultivation of students’ interest, intentions, and motivation are vital to creative development and that exposure to situations that foster these abilities can lead to creative production.

Furthermore, Amabile's (1996) componential model of creativity helps to shed light on the mixture of skills and abilities evident in creative practices. Amabile proposed three variables that were necessary for creativity to occur including: domain-relevant skills (knowledge, technical skills, and specialized talent); creativity-relevant skills (personal factors – a tolerance for ambiguity, self-discipline, and risk-taking); and task motivation (Kaufman & Plucker, 2011). Amabile (1995) also recognized the importance of social networks and resulting social acknowledgement in the expression and appreciation of creative work in this statement,

> It is trivially obvious that there would be no creativity whatsoever without the person and his or her cognitive abilities, personality dispositions, and other personal resources, *nor* would there be any creativity whatsoever without a context in which to create – a context of resources, education, exposure, encouragement, stimulation, and appreciation. (pp. 423-426)

In this description of creativity, it appears that a culture of creativity can be developed in practice, in specific contexts. Studying specific contexts and the meaning that students make of creativity as well as the other emergent engineering habits of mind (collaboration and attention to ethical considerations) is a point of focus for my study.

Additional attempts at defining the abstract nature of creativity take into consideration the social and cultural dimensions that evolve through group cultivation of creativity (Sawyer & DeZutter, 2009). The distribution of creativity as part of a system of people, tools, and the environment provides a point of origin for creativity and collaboration in practice for our studies that take place in the elementary classroom. Defining creativity in these ways emphasizes the "power of the imagination to break away from [the] perceptual set so as to restructure or structure anew ideas, thoughts, and feelings into novel and associative bonds" (Khatena & Torrance, 1973, p. 28). Additionally, a focus on fluency, flexibility, and novelty serves to emphasize the interaction among person, process, situation, and outcomes (Amabile, 1983; Rhodes, 1961).

The ten maxims of creativity. Kazerounian and Foley (2007), Fellows of the American Society of Mechanical Engineers, compiled a list they coined the *Ten Maxims of Creativity in Education* as a way of judging current engineering education (see Table 2.1). Persad and Athre (2013) further delineated the maxims into: 1) thought processes for students; 2) teaching/learning styles conducive to creativity; and 3) encouraging motivation and inspiration along with descriptions of each subcategory to highlight the creative practices involved at each stage.

Thought processes for students highlights creativity as an open-minded practice, involving the process of idea generation and iteration requiring fluency and flexibility of thinking. The search for more than one right answer is seen as a creative pursuit. Well-implemented brainstorming strategies or techniques can allow for creativity to emerge. Isaksen and Gaulin (2005), building on the work of Osborne (1953), studied the benefits of brainstorming for creativity and creative problem solving as a collaborative rather than individual process. In their study, Isaksen and Gaulin examined idea generation and fluency in nine differently structured groups.

Table 2.1 Creativity Maxims as Applied to Engineering Education

Thought Processes for Students	***Description:***
1. Keep an open mind	Seeing common things in a new light; the best answer isn't always the most obvious one; pay attention to the unexpected
2. Ambiguity is good	Uncomfortable wait time can be good; keeping possible answers slightly out of reach can be good practice for idea generation
3. Iterative process that includes incubation	Time must be allowed for the stages of: preparation, incubation, illumination, and verification; "back burnering" ideas is essential
4. Search for multiple answers	Look beyond one right answer; teach proper brainstorming techniques; require alternate solutions
Teaching/Learning Style Conducive to Creativity	***Description:***
5. Reward for creativity	Positively reinforce creative ideas and solutions; explicitly encourage creativity in action
6. Learning to fail	Mistakes can lead to deeper understanding; learning how something does NOT work offers insights into how it MIGHT work
7. Encouraging risk	Risk-taking is a trait of creative individuals; constructive critiques encourage creative solutions
Encouraging Motivation and Inspiration	***Description:***
8. Lead by example	Share stories of innovators in science and engineering; share how progress has been made in these fields in previous work
9. Internal motivation	Make topics of study relatable to students; emphasize how the topic influences the students' lives beyond the classroom experience
10. Ownership of learning	Allow students ownership or control of the learning process; encourage student choice

[1]

---

[1] *Note:* Adapted from Kazerounian & Foley (2007); Persad & Athre (2013)

They found that groups that utilized a trained facilitator outperformed individual brainstorming without facilitation. Facilitated groups produced on average 126.5 non-redundant ideas as compared to 58 for the individual (nominal) sessions. The authors determined that “face-to-face interaction” was required “to provide insights about procedures and variables impacting real-group process gains” (p. 322). Facilitators who followed Osborne’s (1963) original recommendations for best practices in brainstorming saw the most fluency in ideas (see Table 2.2). The recommendations included what should be considered before, during, and after a brainstorming session. Becoming an effective facilitator requires training. Some of the steps to preparing a productive brainstorming session include defining roles and responsibilities, establishing ideal group size (5-7 participants), providing a focused problem statement, and ensuring equal member rank/status/power among members. Managing criticism among members and reinforcing follow-through on the creative process are also critical elements for effective group brainstorming sessions.

Table 2.2 Brainstorming Best Practices

Before brainstorming	• Prepare the group • Prepare the task • Prepare the environment
During brainstorming	• Dealing with judgment • Maintaining group commitment • Enhancing the process structure
After brainstorming	• Follow-through • Evaluation • Implementation

[2]

---

[2] *Note:* Adapted from Isaksen & Gaulin (2005)

Teaching and learning styles conducive to creativity involve explicitly rewarding creativity as it happens. Additionally, learning to fail and taking risks are creative practices that can be explicitly introduced, taught, and cultivated for optimal learning. Especially intriguing is *learning to fail.* Through optimization, failure (a traditionally negative word) becomes an opportunity to learn and move forward, strengthening one's beliefs in their abilities to persist and be ultimately successful (Lottero-Perdue & Parry, 2014; Persad & Athre, 2013). In an interesting twist of perspective, failure can be considered fun while working as a tool for analysis and redesign (Cunningham & Lachapelle, 2014). Learning to fail also has the benefit of moving away from the "one right answer" mentality that persists in school. The maxim of *searching for multiple answers* encourages this practice. There are many ways to approach a design problem. In a classroom, many students can be "right" with different solutions. This moves us away from the climate of multiple choice testing where one correct answer is the expected outcome. Hung, Chen, and Lim (2009) discussed the term *productive failure* using bowling as a case study suggesting that productive learning is not always manifested as successful performances. The authors suggested that learning from experiences with failure has implications for designing educational experiences, moving K-12 students' performances from experiences of failure to experiences with success in a productive manner.

To motivate and inspire creativity in students, relevance and ownership of learning emerge again (as mentioned previously in Chapter I) as important along with exposure to the creative works of others. Research suggests educators need to be cheerleaders for taking risks in order to inspire creativity and innovation in their students (Kazerounian & Foley, 2007). The iterative process of engineering provides an ideal setting to start making these shifts in thinking toward a more creative environment for learning.

Components of the engineering design process, including defining problems, designing solutions, and optimizing designs (NRC, 2012), enable students to engage in these creative practices and the engineering habits of mind in ways that are not traditionally encountered in school. The teacher and their students become collaborative partners in the creative process by applying these maxims in the context of engineering. While engineers in practice routinely experience and rely on many of the ten maxims covered in this section, I have not been able to locate scholarly references where teaching is explicitly focused on addressing these maxims through the process of design with elementary-aged students. I have had to draw heavily on my decade of experience as a science educator to make many of these aforementioned assumptions. This is a gap in the literature I hope to fill.

The social and collaborative nature of engineering. Engineering is a highly social enterprise where people work in teams in a collaborative way to solve real world problems (Katehi et al., 2009). Authentic challenges that promote the social and epistemic practices of a discipline can create learning opportunities that are more profound for youth (Cunningham & Lachapelle, 2014). Developers of engineering education curricula that have these goals in mind provide an opportunity to create contexts that reach and benefit a wide range of students through authentic learning experiences. Teachers providing feedback on their experiences with the EiE curriculum in particular supported these statements by stating, “students made connections with the real world, including recognizing engineering in everyday life” (Lachapelle et al., 2011, p. 153). While teacher statements such as these are encouraging, more research is warranted in empirical studies to fully justify these claims with elementary-aged students.

Smith, Sheppard, Johnson, and Johnson (2005) conducted a meta-analysis of cooperative learning research in the Journal of Engineering Education consisting of a review of 305 studies to determine the relative efficacy of cooperative, competitive, and individualistic learning with college-age students. The analysis revealed that cooperative learning environments promoted individual achievement and academic success over competitive and individualistic approaches. Specifically, cooperative learning promoted “meta-cognitive thought, willingness to take on difficult tasks, persistence (despite difficulties) in working toward goal accomplishment, intrinsic motivation, transfer of learning from one situation to another, and greater time spent on task” (p. 5).

In earlier work, Smith (1995) outlined methods for implementing effective cooperative learning in engineering classrooms, specifically informal cooperative learning groups, formal cooperative learning groups, and cooperative base groups. Informal cooperative learning groups are short-term, lasting anywhere from a few minutes to a class period, characterized by focused group discussions and “turn-to-your-partner” discussions during lecture-based instruction. Base groups are more long-term with students working over the course of the semester providing support, assistance, and encouragement to one another. Smith (1995) described formal cooperative groups as more nuanced than the previous models, having the greatest potential for positive learning outcomes. Smith (1995) warned against the “pseudo-learning groups” characterized by teacher-assigned groups with social hierarchies and competition among members. Essential elements of effective formal cooperative learning groups include: 1) positive interdependence (focus on joint performance); 2) face-to-face promotive interaction; 3) individual accountability/personal responsibility; 4) teamwork skills (leadership, decision-making, trust-building, communication, and conflict-management skills); and 5) group processing (feedback, facilitation, and reflection) (Smith 1995; Smith et al. 2005). These groups are generally small, consisting of 2-4 people with similar interests, distributed knowledge and experience among members. Special attention to group structure, teamwork development, and proper instructor facilitation appear to be critical for successful cooperative learning to occur.

A survey of over 6,000 undergraduate engineering students similarly revealed that teamwork in the classroom lead to student satisfaction and learning benefits for students when the instructor was mindful of best practices for setting up cooperative learning environments (Oakley, Hanna, Kuzmyn, & Felder, 2007). Conclusions from the study revealed that students are not inherently able to function successfully in team-based learning environments and that “if a flawed or poorly implemented team-based instructional model is used, dysfunctional teams and conflicts among team members can lead to an unsatisfactory experience for instructors and students” (pp. 270-271).

Interestingly, in another survey-based study of 513 engineering students, females receiving a course grade of “B” reported a greater use of collaboration as an effective learning strategy (Stump, Hilpert, Husman, Chung, & Kim, 2007). The study suggests that traditional emphasis on facts and skill acquisition in engineering education and competitive grading practices may have been a factor in the recruitment and retention of women to the field. Therefore, providing support for collaboration and cooperative learning opportunities and decreasing emphasis on competitive, grade-driven learning environments is important to inclusive membership and self-efficacy for engineering students.

The collaborative process in engineering. In engineering, searching for multiple answers is desired and considered part of the creative process (Kazourian & Foley, 2007). Collaborative creativity is possible as engineers work in design teams relying on distributed cognition (Sawyer & Dezutter, 2009). A vital component of the collaborative process is communication of final design solutions to clients and consumers through explanation and justification (Katehi, Pearson, & Feder, 2009). Situation-dependent design problems are therefore driven by human need and have social value. The analytical work of engineers is more centralized than it is in science, focusing specifically on designs and the constraints imposed upon them. Constraints serve as a type of data for engineers (e.g., specific client needs, cost, safety, manufacturing, environmental □awareness, culture, and global factors) that must be balanced to optimize their designs (Brophy, Klein, Portsmore, & Rogers, 2008). During analysis, scientists rely on systematic questioning and analytical (convergent) deductive reasoning attempting to arrive at the right answer or confirmation of laboratory results. Scientists who use convergent thinking strategies trust “a specific answer, or a specific set of answers, [exist] for a given question" as they attempt to converge on the facts (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 206). Engineers rely on an "iterative loop of divergent-convergent thinking" (p. 104). In this way, the cyclic nature of the design process alternates between the knowledge domain and the concept domain allowing for flexibility in thinking.

The collaboration and teamwork necessary in engineering design also allows for "multiple routes to gain social status" (Cunningham & Lachapelle, 2014) disrupting traditional sorting mechanisms and social hierarchies (Carlone et al., 2011). Collaborative engineering design challenges have the potential to disrupt traditional conceptions of competence in the science classroom. A more level playing field opens up possibilities for students to take on new roles within their groups and assume new "smart" or competent student identities. In these group contexts, "being viewed as smart [can lead] to gains in power, authority, and autonomy" (Hatt, 2012, p. 453). Hatt studied the socialization of kindergarten students during a yearlong ethnography. Specifically, she examined the ways in which student readiness was judged and how students got sorted in school based on these perceptions of readiness. In this study, "smartness" was culturally produced and a form of cultural capital in school. Distinctive from the traditional model of school socialization, collective engineering design decisions require qualitative and quantitative data and an objective evaluation of the criteria and constraints of a problem. Instead of "perceived smartness" driving decisions, students rely on more objective data in making informed decisions in a collaborative fashion (Cunningham & Lachapelle, 2014). Beyond general knowledge claims, engineering students have the opportunity to develop technologies in designing solutions that showcase alternative forms of expertise with practical application than those typically seen in the science classroom (Cunningham & Carlsen, 2014).

Youths' natural inclination to socialize and collaborate with peers combined with the collective, team-based nature of engineering has the potential to open up possibilities for students to assume new roles and competent engineer identities in the classroom. These opportunities are increased when supported by an instructor skilled in facilitating cooperative learning strategies in the engineering-based classroom.

Attention to ethical considerations. Thinking about the interconnectedness and collective nature of the engineering habits of mind and the design process aligns well with the notion of engineers as systems thinkers. This is a critical way of thinking and making sense of the world for students because it "equips students to recognize essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behavior of individual subsystems" (Katehi et al., 2009, p. 152). The ability to think both locally and globally is an essential skill for students to develop in today's society for their benefit and for the benefit of their communities. Equally as important is attention to ethical considerations. If students are to become knowledgeable advocates for themselves and their communities we hope that they learn to "draw attention to the impacts of engineering on people and the environment; ethical considerations include possible unintended consequences of a technology, the potential disproportionate advantages or disadvantages of a technology for certain groups or individuals, and other issues" (p. 152). Carlsen (1998) emphasized the need for interconnectedness and a stronger interdisciplinary approach to teaching between science and the “other” STEM disciplines for the good of the individual and community in his argument for a more technologically situated perspective to science teaching. Carlsen argued for a revolt from silo-ed science subject-matter teaching toward a vision where “teachers who innovate are likely to be teachers who clearly understand that science includes sociological and technological dimensions” (p. 52).

Sadler (2009) conducted a review of 24 empirical studies with the purpose of exploring how using socio-scientific issues (i.e., science-related social issues) as a context for student learning might impact learning in science. Outcomes of the studies investigated included how teaching for socio-scientific issues (SSIs) might influence student interest and motivation, higher-order thinking (including creativity), content knowledge, understanding of the nature of science, communities of practice, and moral sensitivity. Sadler proposed that SSI contexts promote engaged citizenry and increased scientific literacy for students and that carefully constructed communities of practice facilitated the learning process. However, Sadler also noted, “while SSI-related learning experiences are being implemented and researched, the manner in which these experiences are conceptualised and implemented tends not to be very consistent with a vision of SSI communities of practice” (p. 36). Sadler proposed moving beyond traditional science teaching goals toward more SSI-based curricula and interventions that help to break down the boundaries between science and other disciplines. Engineering curricula that infuses SSI-related experiences may provide such a context for generating student interest, motivation, and increased moral sensitivity to global issues.

Lewis and Leach (2006) touched upon some of the hesitation that science teachers face with regard to teaching about SSI as a part of the school curriculum. Time constraints, difficulty deciding what is relevant to teach, and the rapidly developing nature of science were cited as concerns for educators. The authors claimed that some science educators continued to see science as value-free and primarily objective and therefore avoided introducing values and uncertainty into their teaching. Also important, teachers felt they lacked the necessary skills and confidence to effectively manage these kinds of classroom discussions.

Sadler (2004) argued teaching with socio-scientific issues helps to promote informal reasoning skills and argumentation necessary in science. Sadler stated that this context could provide one path toward meeting reform goals and a "powerful vehicle for teachers to help stimulate the intellectual and social growth of their students" (p. 533).

For these reasons and to best explore the meaning of the engineering habit of mind, attention to ethical considerations, the engineering unit that will be the focus of my study is centered on green engineering through the use of solar energy and the preservation of natural resources. This unit is explained further in Chapter III.

Equity in Engineering Education

While I have argued that engineering habits of mind and the design process can afford intellectual and social opportunities for students in general, it is important to understand what opportunities exist for students from diverse, non-dominant backgrounds to engage in engineering and a trajectory for future careers. The developers of EiE propose,

> Engineering has the potential to reach ALL students. Teachers regularly report that struggling, unremarkable, or withdrawn students blossom during EiE lessons. These students contribute, stay on task, and often voluntarily continue the engineering challenges in their out-of-school time. (Cunningham, 2009, p. 15)

The optimized, practical, design-based, collaborative goals of engineering education mentioned previously have the potential to open up possibilities for engagement of students from diverse backgrounds that the systematic, traditional mode school scientific practices have historically limited. One of the core principles of the EiE curriculum is that *everyone can engineer*. Cunningham and Lachapelle (2014) argued that engineering as presented in the EiE curriculum creates environments for learning where all students' ideas and contributions have value. The resultant opportunities for students to acquire social capital, student agency, ownership, and the expanded roles in these settings may "afford opportunities for equitable productive engagement for all students" (p. 15). According to the developers of EiE, students can work collaboratively through the iterative engineering design process in a manner that has the potential to level the playing field, allowing students to take charge in production and decision-making in their "moment-to-moment actions and interactions" of "[engineering]-in-the-making" (Kelly, Chen, & Crawford, 1998, p. 34). While studies to support these claims of equity are fairly limited beyond studies authored by EiE curriculum developers, I outline a few here to establish encouraging findings from design-based studies focused on improving science learning for youth from non-dominant groups.

Fortus et al. (2004) conducted a study on the implementation of three different design-based science units with ninety-two 9th and 10th grade students to determine the impact on science learning. The authors noted that participants were from a mid-western, urban industrial town composed primarily of blue-collar families. Resultant pre- and post-tests were statistically significant for science knowledge gains. Additionally, during the units students were given the opportunity create, modify, and improve their design-based models, which led to a sense of personal ownership not traditionally seen other inquiry-based science pedagogy. In another study conducted in an urban, high-needs setting (Silk, Schunn, & Cary, 2009), 8th grade students from two science classrooms took part in an engineering-based *Design for Science* unit on electrical alarm systems. As in the previous study, pre- and post test results were statistically significant for science learning. The engineering design unit also provided opportunities for diverse and economically disadvantaged students to engage in formal scientific reasoning in a rich and meaningful context, whereas previous inquiry strategies had proven less effective. The authors recognized the potential oversimplification of assessing the complexity of formal scientific reasoning using multiple-choice assessments. However, they justified their methodology by using a validated instrument of formal scientific reasoning, the *Classroom Test of Scientific Reasoning*. These studies reveal the possible positive influences of design-based instruction on science learning for youth from diverse backgrounds.

Challenging traditional, exclusive notions of science education, what counts as "good" science, and who gets recognized as a smart science person (Carlone, 2004; Carlone, Haun-Frank, & Webb, 2011) might aid us in recognizing what opportunities are afforded by engineering education and the engineering design process and what might represent a “smart engineer person.” Moving away from narrow, traditional conceptions of what counts as science and who gets recognized as a legitimate science person enables students from diverse backgrounds with varied life experiences to become producers of science and scientific knowledge rather than passive recipients of canned, textbook-based, cookbook-style science instruction (Basu & Barton, 2007; Carlone, 2004). Standardization and high-stakes accountability have moved to the fore in public education, emphasizing uniformity “produc[ing] cookie-cutter students rather than maximizing the potential of all students” (Pandina Scot, Callahan, & Urquart, 2008, p. 40). The time has come to disrupt this status quo approach to teaching and learning in science education. Engineering may be one way to tackle the problem.

The real-world context and open-ended nature of the EiE curriculum and other design-based curricula, with a focus on students making social and societal connections, may promote interest and motivation in students who are usually left at the margins (Cunningham & Lachapelle, 2014). Kolodner et al. (2003) conducted pilot studies to design *Learning By Design* (LBD) curriculum units for middle-school students. For example, in one of the pilot studies the students designed and tested mechanically powered miniature vehicles (balloon cars) while concurrently learning about physical science concepts. The goal was to introduce students to skills necessary to become successful decision makers and critical thinkers in the modern world. What the researchers determined as most important, after an extended period of piloting LBD mini-challenges and grand challenges with middle school students, was to create a classroom culture where iteration and collaboration are highly valued by the students and the teacher. The authors reported, “When teachers think about learning as iterative refinement coupled with a culture of collaboration and help to make that happen in their classrooms, students engage enthusiastically with learning” (p. 542). These real-world, design-based challenges proved to be highly motivating for students.

Additionally, similar design-based science curricula have been shown to narrow the achievement gap for African American students (Mehalik, Doppelt, & Schunn, 2008). In a comparative study by Mehalik et al. (2008), 466 middle school students were exposed to a traditional scripted inquiry electricity unit and 587 took part in a design-based systems approach by building electrical alarm systems. As part of the design group, students were able to articulate their own needs for their designs helping to tackle the common question, *Why do I need to know this?* Results indicated superior performance in the design-based group, especially for the low-achieving African American students in the study. The ability to ask their own questions and investigate their own ideas gave ownership to students who might usually be left at the margins. In this case, engineering design opened up possibilities for realizing progress in science reform by creating new opportunities for students from diverse backgrounds to interact and engage in scientific and engineering practices in ways that privileged multiple epistemologies.

Unfortunately, engineering, in some ways, suffers the same elitist history as science particularly at the college-level and beyond. Limited participation in engineering fields among women and underrepresented groups remains the norm.

> Simply put, a student who comes from an economically disadvantaged background outside the dominant culture and who attended a resource-poor high school does not have the same odds of contributing to the gene pool in

> engineering as a student from a family within the dominant culture of median or above median means, and attended a resource- rich school district. Because of this, engineering suffers the loss of individual diversity. (Foor, Walden, & Trytten, 2007, p. 103)

The science and engineering indicators from Chapter I provide evidence of this lingering exclusivity, where women and underrepresented groups continue to display lower participation rates in science and engineering (NSF, 2014). The "black box" metaphor (Pinch, 1992) that has commonly been used to describe the mystifying elements of science that keep many people at arm's length can also be applied to engineering. Teaching to promote understanding of the nature of science and how scientists actually perform scientific inquiry has helped to make science more accessible and tangible for students (Lederman, 2010). It is equally important to dispel misconceptions about engineers and engineering to students, particularly at an early age to broaden opportunities for participation and affiliation. In a "draw an engineer test" (DAET) study for K-12 students, Knight and Cunningham (2004) found that "student's images and stereotypes about engineers and engineering are important, since perceptions of careers are closely linked to whether students feel they can enter into those careers" (p. 7). Opening the black box of engineering has the potential to provide alternative forms of membership and affiliation with STEM disciplines and possibilities for unique skill development for students who otherwise might not ever be exposed.

Women currently make up only about a third of the science and engineering workforce (NSF, 2014). Despite their continued disparity in numbers women have not been altogether absent as members of the engineering profession. For example, *Engineer*

Girl (http://www.engineergirl.org) is a website that aims to excite and encourage young women to become engineers. *Engineer Girl* (NAE, n.d.) has a page dedicated to great women in engineering history. The website chronicles the accomplishments of women such as Edith Clarke, the first woman to earn an electrical engineering degree from MIT in 1918. Additionally, modern women from varied backgrounds and ethnicities are also celebrated on the *Engineer Girl* website to inspire girls to learn more. For example, an African American Ph.D. candidate in Industrial and Systems Engineering from North Carolina A&T State University is highlighted as a role model for young women interested in careers in engineering. Students can write in to dialogue with women in engineering to learn more about their journeys through the often-challenging system of barriers that have historically limited participation. Websites such as this one, invite possibilities for students who have traditionally been excluded due to gender, race, or ethnicity. This, of course, is just one step toward opening up membership and affiliation in engineering to traditionally underrepresented groups. Participation in engineering early in school is another important step in the process.

Another prominent gatekeeper to engineering is perceived mathematical ability (Winkleman, 2009). According to Winkleman, mathematics (and also science) carries with it a perceived intellectual status. Winkleman (2009) emphasized, “Engineering, however, is more than mathematics (and engineering science), for engineers must also communicate effectively, deal with people in a team environment as well as carry out complex design activities, to name a few” (p. 311). While advanced mathematics skills are a necessary part of engineering education, there is some concern that close-ended, detached instruction of mathematics may limit diverse students' affiliation (Cardella, 2006). Students who may have stronger creative, open-ended problem-solving abilities among weaker math skills may feel alienated by mathematics and therefore engineering, even though they may possess strong, creative design capabilities. In fact, Tolbert and Cardella (2013) proposed that an over emphasis on the development of mathematical thinking skills in pre-college engineering education to the exclusion of design thinking skills restricts the creative and innovative practices necessary in engineering careers.

After conducting two qualitative case studies of undergraduate engineering students in practice, Winkleman (2009) suggested, "If design is to flourish within engineering [programs], discourses need to be altered such that the various paradigms within the curriculum are equally [honored]" (p. 315). Perhaps the perceived intellectual status embedded within each of the STEM disciplines needs to be more carefully approached to be sure that these status-limiting gatekeepers can be minimized through more equitable representation.

Summary: Literature Review

In this section of the chapter, I have attempted to explore past and current perspectives of the disciplines of science and engineering, focusing on areas of convergence and divergence. I situated the context of my study by providing an introduction to and rationale for the implementation of an EiE unit and my particular focus on green engineering. My emphasis on the engineering habits of mind: creativity, collaboration, and attention to ethical considerations positioned within the engineering design process provides a model in which to better understand the process and practices necessary to engage in the sociological and technological dimensions of engineering. Additionally, I provided a special consideration to equity and the possibilities of engineering education to afford opportunities for engagement and affiliation for a diverse body of students, as the need to broaden participation in STEM is vital in today's society both locally and globally. In the following section, I develop the conceptual framework that will guide my investigation.

Conceptual Framework

The sociocultural perspective provides a broad lens with which to examine the myriad constructions (tools, practices, activities, culture, history) that influence learning. The benefit of a sociocultural lens includes a shift toward a larger (macro) unit of analysis beyond that of the individual (micro) learner (Carlone, Johnson, & Eisenhart, 2014). Broadening conceptions in this way opens up possibilities for understanding the multi-faceted nature of learning for people in any context, culture, or domain. I plan to explore the many facets of engineering education through a sociocultural lens to make sense of what engineering looks like in the elementary school classroom and the group-level and individual meanings that youth make of engineering in practice.

I have argued thus far that engineering education and the creative potential that can be leveraged as a result presents the opportunity to provide a context for broadening participation and affiliation in science education, opening up a more expansive, flexible understanding of the nature of science and engineering for more equitable engagement of students. This study draws on two conceptual tools to create a framework grounded in practice theory (see representation in Appendix B). Specifically, I draw upon cultural production (Eisenhart, 2001; Levinson, Foley, & Holland, 1996; Willis, 1981) and identities in practice (Holland, Lachicotte, Skinner & Cain, 1998; Lave & Wenger, 1991; Wenger, 1998) as anthropological approaches to better understand the patterns of behavior that emerge in practice as students engage in the process and practices of engineering. The flexible nature of these approaches allowed me to attend to "both to larger societal structures and to the ways individuals exhibit agency in everyday practices, working together to fashion cultural meanings that may reflect, contest and/or transform meanings implied by those structures" as I observed students in practice (Carlone & Johnson, 2012, p. 157).

Cultural Production

If the goal is to challenge the status quo of prototypical science education through the enactment of a new and innovative engineering curriculum, examining students' social practices of students through a cultural production lens is fundamental (Carlone, Johnson, & Eisenhart, 2014). Cultural production allows for analysis of "local meanings produced by groups in everyday practice" and the ability to examine the dynamic, open-ended, and possibly transformative aspects of the culture that gets created in the science classroom by classroom actors (p. 15). Engineering education is a novel prospect for elementary school classrooms; therefore it is important to establish what it means to engineer at this level. Several questions arise as we consider engineering education as early as elementary school. For example, What does engineering look like in practice in an elementary school classroom? What opportunities exist for students to author themselves as successful and productive scientists and engineers? These are the types of questions that drive my study as I strive to better understand what engineering looks like in practice and how students negotiate a place for themselves in the classroom in this context.

The roots of cultural production. First, I explore the roots of cultural production and how this theoretical approach has been applied to science education. In the 1970s, critical studies of schooling emerged to bring a new perspective to the social inequalities that "exacerbated or perpetuated social inequalities" (Levinson, Foley, & Holland, 1996, p. 5). During this time, *social reproduction* was coined as the term to explain how ideological norms of class structure were socially reproduced in schools. Pierre Bourdieu, a French sociologist and anthropologist, expanded these ideas to encompass the cultural aspect of reproduction based on class privilege or "modes of domination" (p. 5). Bourdieu (1977) studied the influence of social resources and/or cultural and symbolic capital that gave dominant groups their economic advantages. However, Bourdieu's approach had limitations due to its primary focus on class structures, European-American populations, and a simplistic view of school (Levinson et al., 1996).

By the 1980s, Paul Willis' (1977) early ethnographic research about "working class lads" and subsequent work regarding his emergent views of cultural production (Willis, 1981) broke down earlier conceptions of students as the passive recipients reproduction theory proposed. The working class lads rejected middle class ideology and therefore played a dynamic role in their own socialization in school. The school structures alone did not determine students' fate. In this way, cultural production became “a more dynamic, open-ended and potentially transformative force” than previous models (Carlone et al., 2014).

By early 2000, Buxton (2001) and Carlone (2004) became pioneers for using a cultural production lens in science education literature. Buxton conducted an ethnographic study of two groups in a molecular biology research lab, an all-male group (Cool People’s Bay) and an all-female group (Chick’s Bay), to study how good scientific practices and norms were operationalized in this setting. The Cool People’s Bay actively protected their resources, culturally reproducing competitive norms. The Chick’s Bay resisted convention opening up space and resources for others, including tutoring opportunities. As mentioned earlier, Carlone (2004) studied young women engaged in an Active Physics high school curriculum. The cultural production lens allowed for examination of broader meanings of science and scientist (emerging science identities) and the ways in which the high school students took up or resisted scientific practices in the classroom. The methods used by these scholars to explore the culturally produced meanings of practices and cultural norms in the context science education opens up possibilities for similar explorations in engineering education.

For clarity, I present a particular definition of culture that best fits my proposed study, which can be difficult due to the abstract nature of culture (Schram, 2006). I align with the view of culture as a “way of seeing” socially interactive patterns (Eisenhart, 2001a, p. 20). This involves examining how groups and individuals impact and are impacted by social structures and agentic actions as they engage in collective practice in a particular context over time. Matching up well with the lens of cultural production, Eisenhart (2001b) defined culture as “affected but not determined by history and structure, actively appropriated or ‘produced’ in groups to bring order and satisfaction to experiences” with possibilities for both reproduction and transformation (p. 213). Eisenhart’s definition aligns nicely with my focus on the epistemic practices (ways of knowing in engineering; science-in-the-making) that the field of engineering affords as well as the habits of mind it promotes (Carlone, Johnson, & Eisenhart, 2014; Kelly, Chen, Crawford, 1998). I am interested in understanding how students draw on personal and classroom resources during the implementation of the engineering unit and what possibilities there are to engage in and experience new ways of knowing, being, and belonging when engaging in collaborative design and everyday practices in the context of engineering. Defining culture in this way helps to set the stage to critically examine the *group-level* and *individual* meanings students make of the process and practice of engineering. The culturally and socially produced meanings that are the focus of this study are the “social image” of an engineer and the ways in which meaning making occurs in local practice (Carlone, Haun-Frank, & Webb, 2011; Holland & Lave, 2009).

Tonso (2006) studied the social image of engineers through “campus engineer identities” that emerged in practice during a quasi-longitudinal study about seven student-engineering teams. Tonso revealed a comprehensive list of 126 engineering identity terms that were common ways to describe engineers or engineering majors on campus. The terms were subsequently sorted and grouped in to three main categories to include: “nerd”, “academic-achiever”, and “social-achiever” terminology. Tonso queried the participants further to better understand how students made sense of being an engineer and performed themselves on campus. Tonso reflected on the significance of the projected social images of engineers on campus in this way:

> This process provided a way to account for the pull of the status and power garnered by earning scientific and engineering credentials (identifying with engineering), without losing track of the push that ideologies of privilege deliver to many students (being identified and elevated, or misrecognized and cast out, as an engineer). This points up the importance of taking cultural forms for identity seriously, not only because they have enormous influence, but because they encode a remarkable understanding of what students face when trying to develop into scientific and engineering selves. (pp. 303-304)

I was curious to uncover the “social image” of engineering that emerges in practice in the elementary school classroom where diffuse notions of what it means to be an engineer may or may not have had an influence on students’ conceptions of engineers and engineering. As students engage in the process and practices of engineering, I pay particular attention to what shapes their identities as they work both independently and collaboratively in this context.

In another study on identity work, Carlone, Haun-Frank, and Webb (2011) explored similar issues of social image in a reform-based science classroom. In this study of two fourth grade classrooms, the authors focused their efforts on identifying what it means to be scientific by examining the normative, cultural practices taken up in school science. The authors revealed that when students were well-supported by the teacher in a collaborative environment where scientific knowledge was shared and ideas were privileged so that all students felt that their contributions were valued, more students affiliated with what it meant to be scientific, including students who traditionally would have been left at the margins. The culturally produced meaning of “smart science student" was more broadly defined than is the case in prototypical science education. Students, even those typically at the margins, felt their contributions were a valued part of the classroom community. This study and the previous one help to expose the tensions and challenges that students face when pervasive and sometimes hard-to-see structures are present that can limit participation and affiliation in social contexts. Uncovering what counts as a "smart engineer student" in this context may provide interesting clues for addressing issues of status, power, and privilege in the classroom, or perhaps the reproduction of traditional conceptions of competence.

An advantage of the cultural production lens is its dynamic nature. Culture is produced "in practice" and is therefore fluid and flexible with possibilities to see the potential for transformation of the status quo (Carlone, Johnson, & Eisenhart, 2014). A cultural production lens informs my study by indicating points of transformation or resistance and the potential of engineering in practice to influence classroom dynamics.

Identities in Practice

Many strands of sociocultural perspectives have diverged from earlier historical models of learning (Lewis & Moje, 2003). The concept of "practice" is present in many of them particularly in the work of Lave and Wenger (1991); namely situated learning, legitimate peripheral participation, and communities of practice (Wenger, 1998). Lave and Wenger (1991) described knowledge acquisition as situated in activity, within a particular context, and culture. Learners can become members of communities in practice as they engage in learning through social interaction. This interaction can be viewed as a form of apprenticeship as learners move from a position of novice to expert as a result of these interactions. In practice, members of a community share resources (i.e., experiences, tools, stories, strategies for problem solving) through time spent in social interaction (Smith, 2009). Guitierrez and Rogoff (2003) highlighted the need to distinguish that participation takes place in cultural communities as a dynamic process and that specific traits assigned to regularities in participation or membership are not static or ethnically derived. In this sociocultural view, learning is defined as transformation of participation rather than as “transmission of knowledge from others or of acquisition or discovery of knowledge by oneself” (Rogoff, 1994, p. 209).

Calabrese Barton (2007) described legitimate participation in the context of learning science in urban settings. Learning through practice or participation “centralizes the embeddedness of the individual in the sociocultural world and the ways in which new knowledge is negotiated and remains situated in context” in this manner “learning science is doing science” (pp. 335-336). Practice, presented in this way as embedded in social activity and cultural context, is how students learn according to the sociocultural perspective. This situated, conceptual understanding of learning through practice can help in understanding the process of learning engineering and doing engineering in elementary school.

Grounding the engineering design process and habits of mind within the lens of practice theory in the form of identities in practice (Holland, Lachicotte, Skinner, & Cain, 1998; Wenger, 1998) allows for a close examination of the contexts of identity that students navigate in the complex domain of science and engineering education. The concept of identity is a complex one that has assumed many definitional forms.

Holland et al. (1998) define identity as self-understanding with strong emotional resonance, conceptualized and developed in social practice, and developed over a person's lifetime. Wenger (1998) further elaborated to describe identity work as a dynamic process involving "issues of non-participation as well as participation, and of exclusion as well as inclusion…includ[ing] our ability and our inability to shape the meanings that define our communities and our forms of belonging" (p. 145). In describing the complexities of identities in practice, Wenger characterized identity as: negotiated experience; community membership; learning trajectory; nexus of multi-membership; and a relation between the local and the global.

Applying this perspective, *negotiated experience* in the engineering classroom would involve examination of the "narratives, categories, roles and positions" (Wenger, 1998, p. 151) that emerge as students engage in design and situated problem solving. The interplay of participation and reification (the possibility of human meaning) in a particular community of practice are part of the process of identity work. *Community membership* in the context of engineering would be defined through the dimensions of mutual engagement, joint enterprise, and a shared repertoire of practice. Engineering design challenges present an ideal context in which to study and view these forms of interactions, particularly with collaboration as a habit of mind. *Learning trajectories* allow for students to draw from their collective life experiences to make sense of a new phenomenon, connecting the past, present, and future. Types of learning trajectories that Wenger outlined include: peripheral (may provide access or may never lead to full participation); inbound (as a newcomer—future participation); insider (continued practice and evolution); boundary (spanning, linking, and/or sustaining identities across boundaries), and outbound (leading outward toward new experiences) (pp. 154-155).

These potential trajectories may provide a lens for observing students' identity work in the classroom during design challenges. The *nexus of multi-membership* reminds us that there are many identities to reconcile as students negotiate a place for themselves in the science classroom. Students are held accountable in different ways in different contexts. Establishing what practices students are held accountable to in the context of engineering will give rise to their forms of membership. Challenges may be encountered as "learners must often deal with conflicting forms of individuality and competence as defined in different communities" (p. 160) particularly in the complex navigation of the school environment.

Finally, identity as a *local and global interplay* brings us back to the focus on cultural production and the balance between structure and agency. Wenger notes, "we come together not only to engage in pursuing some enterprise but also to figure out how our engagement fits the broader scheme of things" (p. 162). The engineering habits of mind, creativity, collaboration, and attention to ethical considerations, are points of focus in the study of identity work and cultural production in this context "toggl[ing] between structure and agency, micro- and macro-levels of analysis, and group-level and individual meanings" (Carlone & Johnson, 2012, p. 165).

Authoring and positioning. For the purposes of this study, I will further concentrate my focus on the space of authoring and positioning that Holland et al. (1998) outlined to best understand how students make a place for themselves in the unfamiliar territory of engineering. Tan and Barton (2008) conducted a case study of two Latina middle-school students who were able to successfully author identities in practice by challenging the traditional world of school science. The girls were able to negotiate a space for themselves that allowed for infusing elements of their life-worlds with those of school science. For example, one student reinvented a rote flashcard review strategy by developing a "bone song" with accompanying dance moves. The simple act of creating this unsolicited song enhanced her learning, incorporated her love of pop culture, and stimulated additional interest in the topic among her peers. Students' space for authoring occurs when social discourses and practices are leveraged to their benefit (Holland et al., 1998). In this case, the girl's improvisation actually functioned to change/impact the larger class culture in subtle ways. The individual and group-level agency students must possess in finding their "voice" or space in a certain context "fills personal authorship with social efficacy, for identities take us back and forth from intimate to public spaces" (p. 272). Similarly, the unique opportunities afforded by engaging in the engineering design process, working collaboratively to solve problems that fulfill a human need or desire allow for multiple points of entry to engage and assume new roles in the science classroom. Perhaps, the engineering design process can provide agentic opportunities for students to leverage their creative engineering talents and minimize power differentials in ways that have not been routinely afforded in the traditional science classroom.

Positionality in the context of engineering can provide a view of how students experience their social position in cooperative-learning groups to establish power, status, rank, respect, and legitimacy (Holland et al., 1998) as creative engineers among their peers. Students negotiate their membership by “developing certain ways of being in the science classroom while engaging in activities and tasks and in relating to the teacher and their peers” (Tan & Barton, 2008, p. 48). One of the specific ‘ways of being’ that will be of primary interest in this study is how students experience engineering practices and habits of mind in the context of the engineering unit. Another focal point of the study is to examine students’ negotiation of status through the successful enactment of these practices. Students’ positioning and navigation of classroom structures may determine the group-level meanings of what counts as being a smart engineer in this setting.

Summary: Conceptual Framework

To conclude this section of the chapter, I have provided my conceptual framework for studying the cultural production of engineering in the elementary school classroom. Using a sociocultural perspective and an anthropological approach provides me with an opportunity to discover the meanings students make through their everyday interactions and experiences with the engineering curriculum. I outlined how I will specifically attend to students identities in practice and the dynamic work they perform to negotiate their experiences both locally and globally. Careful attention to how students negotiate a space for themselves during engineering design process, situated problem solving, and engagement in specific engineering habits of mind will provide me with a more clear understanding of the benefits of engineering education for youth.

CHAPTER III

METHODOLOGY

In this chapter, I develop how I conducted my study. First, I map out my research methodology, in which I provide rationale for my research approach and perspective. I revisit my research questions to establish the direction I take with data collection and analysis. Next, I provide a comprehensive overview of the structure of the EiE curriculum and the solar energy unit that was the focus of this study. Additionally, I provide context for the larger EiE Seed Leadership research project from which my study emerged. I follow by describing the context of my student-based study to include the two school sites and participant pool. Finally, I explain my research design and conclude with a discussion of the validity and ethics related to this study. Instruments for data collection and analysis are referenced and contained in the accompanying appendices.

Research Methodology

I conducted this study in the interpretivistic tradition, which aligns with the belief that reality is “socially constructed, complex, and ever-changing”, serving to inform us about the cultural patterns of social group interactions (Glesne, 2011, p. 8). I utilized an ethnographic approach to best understand and make meaning of the cultural patterns that emerge due to the intensive study of “human dispositions” and the “reality and power [they have] in everyday experience[s]” (Schram, 2006, p. 96). Ethnographic methods aligned with my research design in that I was looking to get at the meaning students made of the practices and habits of mind encountered in the engineering design process through examination of the “values, beliefs, and behaviors” they exhibited regularly as they interacted in the classroom (p. 109). Below, I reference my research questions from Chapter I to guide the focus of my inquiry and analysis.

1. What engineering habits of mind emerge as significant during students’ engagement with an EiE green engineering, solar energy unit?
    a. How does creativity emerge during the engineering unit?
    b. In what ways do students collaborate during the engineering unit?
    c. In what ways do ethical considerations play a role in students’ understanding of the engineering unit?
2. How do students author themselves and/or get positioned by others during the engineering unit?

The Structure of the EiE Curriculum

The EiE curriculum, developed by the Museum of Science in Boston, is focused on supporting the development of engineering literacy (MOS, 2014). The National Assessment of Educational Progress (NAEP) defines technological and engineering literacy as a student’s ability to apply technology and engineering skills to real-life situations (NCES, 2014). EiE has produced twenty hands-on engineering-based units each focused on a different field of engineering, in a particular context, with real-life problems to be solved. Focusing on the multiple fields of engineering is important to help dispel the myth that engineering is a singular discipline. According to Petroski (2011), while engineering shares characteristics of science and the humanities it remains “a culture unto itself and thus separate from each of them" (Ch11, 3:05). The sciences and the humanities are referred to in the plural form as "distinct collections of things" (Ch11, 3:13) and thus they are given advanced status, while engineering is always referred to singularly. This presents a misconception or a misinterpretation of the many "engineerings" that actually exist and the many benefits to society that result from the practice of this field.

The solar energy unit, *Now You're Cooking: Designing Solar Ovens* (Engineering is Elementary, 2011), which was the focus of this study, is set in the field of green engineering. Green engineering has been recently incorporated into the field of sustainable engineering, which takes into consideration the cultural, social, and economic factors encountered when designing technologies. Within this particular field of engineering, students learn about the environmental impact of thermal insulators and conductors, the life cycles of common resources, and the use of the sun as a renewable energy source. Not coincidentally, this EiE unit on energy aligns nicely with the North Carolina Essential Standard for fifth grade science, 5.P.3 *Explain how the properties of some materials change as a result of heating and cooling* (NCDPI, n.d.). Specifically, the clarifying objectives: 5.P.3.1 and 5.P.3.2 further highlight the focal areas of this unit. For example,

> 5.P.3.1 Explain the effects of the transfer of heat (either by direct contact or at a distance) that occurs between objects at different temperatures. (conduction, convection or radiation).
> 5.P.3.2 Explain how heating and cooling affect some materials and how this relates to their purpose and practical applications. (NCDPI, n.d.)

The real-world problems that are presented in this and all of the EiE units allow students opportunities to connect engineering principles to other disciplines (Lachapelle & Cunningham, 2014).

Each EiE unit is designed within a specific structure consisting of a preparatory lesson and four unit lessons. The preparatory lesson is designed to help address common student misconceptions about what technology is and what engineers do. The preparatory lesson consists of a *Technology in a Bag* lesson where students examine examples of technology encountered in daily life, learn to construct a definition of technology, and understand that engineers design technologies to solve real-life problems.

The first lesson after the preparatory lesson is centered on an engineering story. The storybook for each EiE unit introduces an engineering design challenge. Here, students are presented with the engineering design process (EDP), a simple five-step iterative process for how to approach the engineering design challenges in the units. The key components of the EDP include: *ask, imagine, plan, create, and improve*. The main character is faced with a problem that students help to solve. The engineering stories help to reinforce literacy skills while introducing students to places around the world, diverse, multi-cultural characters, and unique problems to be solved. Lesson one is designed to take about three to four 40-minute lessons to fully implement. The storybook for the solar energy unit is set in Botswana and is titled, *Lerato Cooks Up a Plan*. In this particular context, firewood is in short supply and Lerato (the main character) and her family make a decision to use solar powered cookers as an alternative, environmentally-friendly method for cooking their food.

Lesson two is designed to be implemented in approximately one 40-60 minute lesson and provides a broader view of the highlighted engineering field, in this case green engineering. In this lesson, students learn about the life cycle of paper and relate topics such as recycling, renewing, and reusing materials by analyzing their own use of paper in the classroom. These concepts of environmental conservation and use of natural resources are applied later during the design challenge as they are central to Lerato's problem.

Lesson three in any EiE unit focuses on how scientific data inform engineering. The scientific data obtained over the course of approximately two sixty-minute lessons are analyzed, helping inform choices made during the design challenge. In the solar energy unit, students analyze the conducting and insulating properties of a set of shredded or flat materials (e.g., foam, newspaper, aluminum foil, plastic) by conducting a scientific investigation. Students determine how well shredded materials (which take up more space) or flat materials (which allow for more continuous air space) perform as insulators. Additionally, students consider the environmental impact of material use. The results of this investigation are used to inform their choices of materials in their solar oven designs.

The final lesson, lesson four is planned to take approximately three 50-minute class periods. It is within this series of lessons that students get to put the engineering design process (EDP) and all they have learned thus far into practice. Students design, create, and improve solutions to the problem that were originally introduced to them in the storybook. In this case, students are challenged to apply their green engineering skills to design an effective solar oven that makes use of good insulators and has the least environmental impact. Throughout the process students ask questions, imagine, plan, create, test and improve their designs to find the most optimal solutions.

Seed Leadership: Teachers' Preparation to Teach EiE Units

As part of a larger research venture associated with this student study, six teachers took part in an EiE Seed Leadership project led by our research team (Carlone, Allen, Carter, Hegedus, Washington) in the summer of 2013 prior to the fall implementation. Two of the fifth-grade teachers who became part of my dissertation study participated in this collaborative weeklong training session. During the 40-hour workweek, our team facilitated teachers' understanding of the structure and delivery of the EiE unit they implemented in the fall.

To start, the research team familiarized the teachers with the structure of the EiE units, introduced the engineering design process, and conducted the *Technology in the Bag* preparatory lesson. In the first few days of training, we facilitated instruction for the whole group on the structure and implementation of the unit, *Best of Bugs: Designing Hand Pollinators.* As part of this process, we helped teachers in making connections to the North Carolina Essential Standards and how the unit aligned with the standards at different grade levels.

On the third day of training, the teachers split into three-person, fourth-grade or fifth-grade groups. The fourth-grade teachers chose to implement the *Solid as a Rock: Replicating an Artifact* unit in their classrooms and the fifth-grade teachers chose the *Now You're Cooking: Designing Solar Ovens* unit. We dedicated the remainder of the week to learning about the respective units, participating in collaborative planning, brainstorming curricular connections, and trouble-shooting for how best to implement the units within the limits of the instructional day.

During the week of EiE teacher professional development, we administered pre- and post-surveys and conducted pre-implementation interviews to capture information about the teachers’ existing science teaching practices, how they understood and experienced the EiE curriculum and engineering practices, and their goals and expectations for the implementation of their chosen EiE unit. The research team also collected data during the sessions in the form of field notes, video, and audio recordings of planning and discussion, engagement, and participation with the units.

I chose two of the fifth-grade teachers to follow to the classroom for my student-based study, which was embedded within the larger teacher-based project. The third fifth-grade teacher that was part of the summer professional development was not included in my student study because he taught in another district where I was unable to obtain IRB approval for student data collection.

Site Selection

As part of my work on the EiE Seed Leadership team headed by my doctoral advisor, I was able to gain access to local research sites that offered a diverse pool of public elementary school students from the Piedmont area in North Carolina. As a result, I was granted access to a population of students of varied gender, socioeconomic backgrounds, cultures, and ethnicities. Purposive sampling was applied to the sites and individuals in that they were intentionally selected in order to best learn about the central phenomenon (Creswell, 2012). The students we included in the study were representative of the Piedmont area in school contexts where the mission of administration and faculty was to promote Science, Technology, Engineering and Mathematics (STEM) education. Our team's goal was to gain access to public elementary schools that maintained a collaborative partnership with the local public university, where our team was situated. Gaining access through a collaborative relationship serves to foster relationships that result in rich data collection. Establishing the most productive type of relationships in a research site and respective samples is a goal of purposeful selection (Maxwell, 2013). There were five total schools in the EiE Seed Leadership research project. I chose two of these schools to be the focus of my student-centered study.

School site 1: Monroe elementary. The first school (Monroe, a pseudonym) that was one of my research sites was located in a suburban area in the Piedmont of North Carolina. The school opened in 1956 and was converted to a traditional magnet school in 1992, one of the first in its district. It is currently designated as a Title I school and therefore receives federal funding to support student success and achievement. Students at the school take part in a combination of traditional and more modern teaching practices. The students wear uniforms that consist of the school's official colors.

At the time of my study, the school enrollment was approximately 300 students. The population of students at Monroe was ethnically and socioeconomically diverse. The majority of students were African American (68%) or Hispanic (15%). Only seven percent of the students were Caucasian. About three quarters of the students in attendance qualified for free or reduced lunch. Furthermore, the school website indicated that approximately 11% of the students were identified as exceptionally challenged (i.e., EC status; students with individualized education plans) and 12% were English language learners (ELL). These demographics made for a widely diverse population of students to include in my study.

School site 2: Landon elementary. This school (Landon, a pseudonym), located in the same district as Monroe, was established in 1928 and served students in PreK-5. There were approximately 420 students enrolled at the school at the time of my study. Landon had a history of being a school of progress, indicating high academic growth in years 2007 and 2008. At this school, approximately 42% of students were Caucasian, 38% were African American, and 15% were Hispanic. Approximately half of the students at Landon were eligible for free and reduced lunch. This school was on record for receiving Title I status and federal funding during the 2013-14 school year. Unfortunately, I was unable to obtain information from the public record about the students EC or ELL status as I did for Monroe. School and district websites are maintained inconsistently and limited information was publicly available for this school beyond the reported demographic statistics. All in all, Landon appeared to represent the diverse population of students I was looking to include in my study.

Participants

I studied students in two fifth-grade elementary classrooms during the implementation of a unit from the EiE curriculum, which consisted of roughly 10-12 instructional hours. In grades three through five, students engaged with an advanced version of the EiE curriculum, which included more complex reading and writing skill components than in grades K-2.

There were 20 students enrolled in Monroe's fifth-grade classroom. I obtained full IRB student assent and parent consent for all twenty students in this setting. The class was split evenly by gender with fifty-percent female and fifty-percent male. The representative student demographics in this class were consistent with the distribution of the school (see Table 3.1). The teacher in this classroom was a female of Latina origin with 22 years of teaching experience. She had been teaching at Monroe for a total of 10 years.

There were 24 students enrolled at Landon, however, I was only able to obtain IRB consent from sixteen of these students. Nine of the students were female and seven were male in this sub-section of students. The representative student demographics are listed in Table 3.1. The veteran teacher in this classroom was a Caucasian female with 23 years of teaching experience. She had been teaching at Landon for six years.

Table 3.1 Student Participant Demographics

Gender	**Landon Elementary**	**Monroe Elementary**
N=	16	20
Females	9	10
Males	7	10
Ethnicity		
AA*	1	15
Caucasian	8	1
Hispanic	3	1
Biracial	4	2
Asian	0	1

*Note: AA = African American

Students worked in cooperative groups during the enactment of the EiE curricular units. The number of students per group was at the discretion of the teacher and a function of the class enrollment. I observed the class as a whole as well as small cooperative groups in action during the course of the unit. I attended every session in both classrooms with the exception of three sessions at Landon and one session at Monroe, which were covered by other members of our research team. At times the fall implementation schedule overlapped among our school sites, requiring that research team members be distributed among sites to ensure full coverage.

Optimal group configurations consisted of three to four-person, mixed gender student groups. Additionally, it was beneficial for my study to have students placed in heterogeneous groups based on general academic ability. I believe diversity in student ability grouping is optimal for studying hierarchies and power differentials in the classroom and how students make meaning of the practices encountered in the engineering challenges. Choosing the proper school context and appropriate collaboration with the classroom teacher would afford such group dynamics.

I observed whole class dynamics as well as the small group work of student engineering teams. Ideally, my goal was to concentrate specific attention on the identity work of a non-dominant successful student, a struggling student, and/or a student who surprised the teacher and researchers with their classroom performances. Due to the "ever-changing landscape" of qualitative research it is not always possible to know who will be studied in a particular context, but choosing the appropriate site helps in navigating the dynamic nature of participant selection in a qualitative research setting

(Lichtman, 2010, p. 13). Additionally, smaller sample sizes allow for a researcher to present the complexity of the research site through the study of a few particular individuals and cases (Creswell, 2012).

My conceptual framework and research questions attended to the cultural production of engineering education and identities in practice (authoring and positioning of students) and were best examined through the observation of diverse students' engagement in the engineering design process in cooperative learning groups as described above. Sampling students from just two classrooms and cooperative groups provides a manageable solution for one researcher to carefully examine the interaction and engagement of students involved in complex creative practices. My goal was to get an idea of what was happening in each engineering student team, with particular focus on the students teachers predicted as potentially successful, struggling, or those with an uncertain trajectory. In addition to extensive field notes, audio equipment was required to capture the nuances of group dynamics and individual student participation during group work, which I develop further in the following sections.

Data Collection

The primary sources of data collection for this study were classroom observations (using an observation protocol as a guide) through the collection of field notes and documented contact summary forms, in addition to audio data collected during student cooperative group time in the classroom (see Appendices C & D). Additionally, student artifacts in the form of pictures of student designs and EiE-guided student paperwork were collected as samples of student engagement and production during the design process.

First, I collected data to observe students in their cooperative learning groups and their resulting interactions in the form of descriptive and analytic field notes (Glesne, 2011) and contact summary sheets to summarize salient findings as the research progressed (Miles & Huberman, 1994). The observation protocol consisted of three main parts: 1) student experiences during the EiE unit (investigative, communicative, and epistemic practices[3]); 2) student identity work (authoring self and positioning by others); 3) engineering habits of mind (specifically, creativity; collaboration; and attention to ethical considerations).

In Part I of the protocol, my attention was focused on student experiences during the EiE unit. I was specifically looking for what it meant to be good at engineering. The investigative, communicative, and epistemic practices served as a guide for what to look for in student performances; for example using tools, question asking, or justifying answers. I also paid attention to social and collaborative dynamics in the form of equity, access, and/or any power hierarchies that were evident during student interactions. In Part II of the protocol, I focused my observations on what students were doing, saying or producing (Spradley, 1980). I looked for how students were authoring themselves during the unit; for example affective displays, bids for recognition, or holding the floor. Instances of positioning by others might include a student being looked upon as a leader or someone to be avoided. In Part III of the protocol, I centered my observations on the

---

[3] Source: Carlone, 2012; Kelly & Duschl, 2002

engineering habits of mind. I was looking particularly at what values, attitudes, and thinking skills were associated with engineering and fundamentally what it meant to engineer during the unit. Throughout each stage of the four-part unit, I observed students engaged in the engineering design process and the meaning they made of the habits of mind, particularly creativity, collaboration, and attention to ethical considerations (see Appendix C for further details about the Observation Protocol). Additionally, because my role involved an *observer as participant* role (Glesne, 2011) and therefore some interaction with participants, I needed to collect audio data as added security for capturing the myriad interactions that occurred in the classroom. In this way, I was able to capture the many facets of classroom culture and student interactions without limiting my connection to participants or the potential for developing a status of "trusted person" (p. 63). While I conducted the majority of observations at Monroe and Landon, the research team provided full coverage when scheduling conflicts arose between sites.

Secondly, with help from the EiE Seed Leadership team, I conducted semi-structured interviews with students upon completion of the 12-lesson EiE curricular unit (see Appendix E for Student Interview Protocol). I chose the semi-structured interview due to the flexibility offered by the combination of pre-formulated questions with the opportunity for open-ended questioning and answering (Schensul, Schensul, & LeCompte, 1999). Our time spent in the classroom prior to the interviews served to help build rapport and trust with the youth (Patton, 2002).

The interview was structured into three parts. Part I consisted of seven questions and was designed to get at students' perceptions and experiences of the EiE unit. During

Part II of the interview, we conducted a card sort activity (Carlone, 2012) to get at students' meanings of the five phases of the engineering design process: *ask, imagine, plan*, *create*, and *improve*. There were thirteen total cards in the card sort that reflected a mixture of prototypical, traditional classroom practices and expected engineering practices. In alignment with Carlone's (2012) interview protocol, students were asked questions about the cards in three phases: first, whether or not they were held accountable to these practices during the unit (yes, no, or maybe); second, to determine their meaning of each practice and/or an example of an instance when they had to perform each practice; and third, students were asked to choose three cards that they felt they absolutely had to do to be successful during this unit. Asking questions in this manner helped to get at the students' meanings and narratives of their experiences with the engineering design process. Part III of the interview was focused on having students reflect on the design process and the products they created in lesson four. The overall structure of the student interview, allowed me to obtain an understanding of the cultural production of engineering through the voices and actions of the students. The interview provided insight into students' perceptions of engineering in practice as a result of their participation, what they felt they were held accountable to do during the unit, how they perceived themselves and others, what they valued and did not value, and the aspects of the unit they most connected with. These data provided a way to examine individual and group-level responses to the engineering unit and whether or not prototypical classroom performances persisted, or if new ideas of what it means to engineer were produced in the classroom community.

Lastly, data collection was supplemented by samples of student work. We collected artifacts associated with the components of the curriculum such as designs, drawings, sketches, and plans from brainstorming sessions. These items served as additional evidence to support the data from observations and interviews, which is discussed further in the next section. Also, a comprehensive validity matrix can be found in Appendix F. The matrix links my research questions to my proposed methods, including analysis plans, potential threats to validity and rationale for strategies.

Data Analysis

During the study, I attempted to maintain an ongoing analysis of my descriptive observations of the actors, activities, and place (Spradley, 1980) during the teachers' implementation of the EiE curricular units. Analytic memos and contact summary forms enhanced the field notes by allowing me to expand on the findings in an iterative process.

Using Spradley's (1980) semantic structure analysis, I moved systematically through transcribed student interviews searching for categories and/or domains of cultural meanings in the data. This analysis was grounded in the practices and discourse of the participants to identify semantic relationships. Next, I conducted a taxonomic analysis by organizing and collapsing those domains further, examining the hierarchy of terms. Finally, I performed componential analyses to look for points of contrast, tension, and/or contradiction. Resulting themes were triangulated with data from field notes (classroom observations, including contact summary forms) and audio recordings of student interactions. I coded and organized my data using Excel spreadsheets to become intimately familiar with the content of student interviews. Additionally, I was able to use

Excel as a qualitative analysis tool as I moved through stages of simple to more advanced thematic analysis. Excel has traditionally been used as a number-crunching software capable of handling large amounts of data, but it has many features that make it a good choice for qualitative analysis (Meyer & Avery, 2009). I was able to conduct multiple forms of analysis in an efficient and comprehensive manner using Excel and its many attributes, including data preparation, presentation and display techniques, quantitative capabilities, and the ability to manage students' comments and quotes embedded within my analysis. This allowed for increased rigor in my methods.

I also examined pictures of student artifacts (from the design phase) to compare with student reflections of their products during the interviews. These data along with the audio recordings was triangulated or crystallized with the interview and observational data, making for a rich account of students' experiences with engineering in the setting (Tracy, 2010).

Validity

I considered potential threats to validity to account for the possibility of alternate explanations or interpretations of phenomena (Maxwell, 2013). There may be more than one way to interpret data in a qualitative study. Patton (2002) outlined three key related elements for credibility in qualitative inquiry including, credibility of researchers, rigorous methods, and the philosophical belief in the value of qualitative inquiry. Each is discussed as they relate to my study.

As instruments of our own research, it is vital for researchers to be aware of their subjectivities and credibility as researchers (Patton, 2002). Addressing issues of credibility in the appropriate manner helps to shape our inquiry and the potential outcomes of a study (Peshkin, 1988). Peshkin points out that we must be mindful of our subjectivities and monitor ourselves and our subjective beliefs appropriately in our research in order to "create an illuminating, empowering personal statement that attunes [us] to where self and subject are intertwined" (p. 20). As I focused on uncovering the power differentials and inequities that might exist in a school setting that contains diverse populations of students, it was important for me to reflect on my White, middle-class upbringing as a potential validity threat. If my perspective or subjectivity remained "untamed" I may have presented a biased reflection of the research site, muting the emic voice (p. 21). I needed to be careful to be conscious of what I was seeing, what I was not seeing, and the meaning I was making of that observational data.

Rigorous methods should also help to safeguard against potential validity threats. Tracy (2010) described the rich rigor that emerges through the use of appropriate theoretical constructs, proper context and sample size, abundant time spent in the field, and the quality of data and its analysis. The conceptual framework I present for this study is complex and nuanced drawing from practice and cultural production theories. Additionally, I have thoroughly explored the context of engineering to get at its complexities and students' potential for interaction. The elementary public school research site affords the opportunity to include diverse students from varied socioeconomic backgrounds and ability levels. Sample size in qualitative research is often small (in this case, n=2 classrooms; N=36 students) in comparison to quantitative research, but allows for more nuanced descriptions and interactions with the population being studied (Creswell, 2012). Failure to reach data saturation can be a concern with a small sample size and single research site. In this case, two fifth-grade classrooms and a pool of thirty-six students should add quality and substance to the study. The rigor of the data collection and analysis has been adequately addressed through the implementation of Spradley's semantic structure analysis and use of Excel software as discussed previously.

Finally, thoughts on generalizability, philosophical beliefs in the value of qualitative inquiry, and epistemological commitments are important to address when considering potential validity threats. Formal generalizations experienced in quantitative research are the product of statistical analyses and random representational samples. External generalizability achieved in this manner is not applicable to qualitative inquiry. Instead, Tracy (2010) described the term *resonance* as being more appropriate for qualitative inquiry in its "ability to meaningfully reverberate and affect an audience" (p. 844). Resonance serves to promote "empathetic validity" through its aesthetic merit (affective impact), transferability, and naturalistic generalizations (p. 844). In this manner, findings can be extrapolated to other contexts to inform theory and practice within cases through feelings in personal knowing and experience (p. 845). If the narrative from the research tells a compelling story that people can connect with, they will feel spurred to action to transfer these findings to influence their own research setting or situation (Tracy, 2010). The quality, credibility, and potential power of qualitative inquiry are at the hands of the competent, conscientious researcher.

Ethics

An awareness of ethical issues that arise during qualitative inquiry must be of paramount concern to researchers as these issues “permeate every phase of the research process” (Denzin & Lincoln, 2005, p. 21). Some of the first procedural issues I was aware of in this proposed study related to gaining access and working with human subjects (elementary-aged students) in an educational context (Tracy, 2010). To gain access to schools in our local educational system requires approval from the Institutional Review Board of the University and the local school district. This process is lengthy and complex. A carefully conceived and thorough explanation of the purpose of the study along with potential promises, risk assessment, and assurances of confidentiality are just a few of the many steps required to gaining access to a site (Patton, 2002). Wording on all documentation must be clear, concise, and understandable by all parties that are privy to the research. For example, it is important to be sensitive to English language learners and non-native speakers, providing translated materials, if necessary, to ensure that full understanding is achieved. My research agenda could not compromise my subjects in any way as I strived to achieve access to a site of diverse participants that would provide rich, contextual data.

Patton (2002) described the personal and interpersonal nature of qualitative inquiry as “naturalistic” methods of interviewing and observation that “[open] up what is inside of people” (p. 407). The sensitive and sometimes intrusive nature of qualitative data acquisition makes it even more important to be aware of my voice, reflexivity, and accurate reporting of student voice in textual representations (Lichtman, 2010).

Also important to note, is my potential bias about the power of engineering and engineering education for youth. I have taught science to students for over a decade with a strong foundation in design, making use of the core principles of engineering in my instructional practices. I am aware that this bias can potentially color my perceptions of students' experiences with the EiE unit. I kept these biases in mind as I interpreted results of the study and made determinations about the benefits of engineering education.

Finally, as researchers we must be mindful of our impact on others and attempt to establish interdependence between researcher and participants. Extending this form of partnership beyond the completion of the study is critical as we share our results with the public audiences. Our "exiting ethics" continue long after the study is complete when we represent our participants verbally and on paper avoiding unjust or unintended consequences (Tracy, 2010, p. 847). Our voice becomes their voice, and we must be sure to use it wisely.

CHAPTER IV

CREATIVITY AS AN ENGINEERING HABIT OF MIND

Introduction

In this chapter, I address my first research question: What engineering habits of mind emerge as significant during students' engagement with an EiE green engineering, solar energy unit? Creativity, collaboration, and attention to ethical considerations emerged as significant engineering habits of mind during my analysis of student interview data, field notes, and audio recordings of group interactions. Each habit of mind is unpacked in the following sections as they unfolded during the engineering design process (EDP). The habits of mind I emphasize highlighted students' engagement during the unit, students' particular areas of focus, and the practices they felt they were held accountable to perform to be considered competent and successful engineers.

Earlier, in Chapters I and II, I outlined some essential elements of creativity from the literature. I defined creativity as the driving force behind engineering design and innovative thinking. To reiterate, in engineering, creativity as a habit of mind involves the development of original ideas that have value produced as the result of iteration, idea incubation, risk taking, tolerance for ambiguity, and learning from failure (see Table 2.1). Findings from this study indicate that many of the elements of creativity (as they related to the EDP) were evident in students' descriptions of their engagement and participation during the solar energy unit. While many students described broadened conceptions of creativity as it related to engineering, others clung to a more traditional vision of creativity as focused on aesthetics. During my analysis, four main themes emerged from the data to help understand the meaning students made of their experiences during the solar energy engineering unit centered on the habit of mind—creativity.

The four main creativity themes that surfaced from analysis of student interviews consisted of creativity represented as: 1) Idea Generation; 2); Design and Innovation 3) Gumption/Resourcefulness; and 4) Social Value.

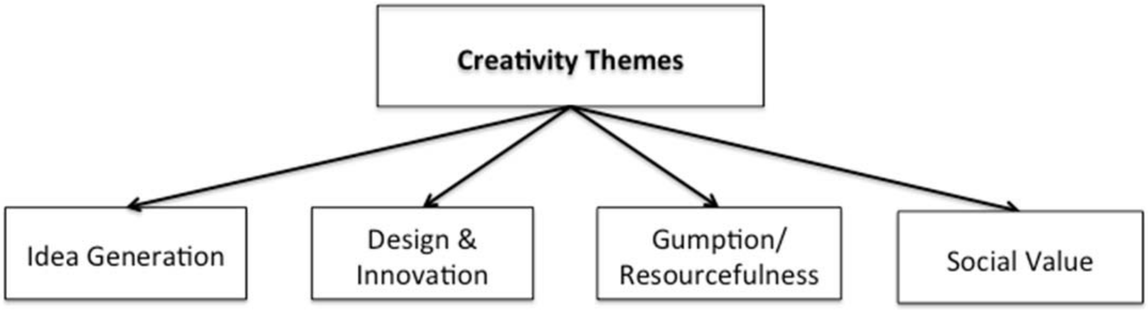


Figure 4.1 Overview of Emergent Creativity Themes

The card sort portion of the student interview provided the most comprehensive establishment of the themes with additional portions of the interview lending support (e.g., Interview questions: *Describe YOU in three words during the engineering unit; During what stage of the unit did you feel most/least creative? Who is the most creative person? Describe what you liked/disliked about the unit;* and *What were the hardest/easiest parts of the unit?*). Observations of students' engagement during the unit, audio recordings, and field notes provided support for the findings from the interview. I begin by reviewing the salient findings from portions of the interview and the practices that aligned with each theme.

Creativity as Idea Generation

The essential thought processes necessary for creative development (i.e., idea generation) according to Kazerounian and Foley (2007) include, 1) keeping an open mind; 2) having a tolerance for ambiguity; 3) engaging in the process of iteration and incubation; and 4) the search for multiple answers (see Table 2.1). I explored these creative processes through analysis of four of the card sort items from the student interview to better understand how students creatively generated ideas during the EiE unit. The cards that provided evidence for the theme, *idea generation*, were 1) ask questions; 2) be curious; 3) imagine; and 4) get the right answer (see Figure 4.2).

In the card sort portion of the interview, we asked students to sort through a stack of thirteen cards containing words that represented practices they may have experienced in the engineering unit (see Appendix E for Student Interview Protocol). Some cards reflected prototypical (traditional, "school-y", archetypal) practices such as, *follow directions, get the right answer,* and possibly *make good choices*, depending on the students' interpretation. For example, *make good choices* could be interpreted by students as deciding to exhibit proper, expected classroom behaviors or alternatively, in reference to good engineering design choices about materials to include in the solar ovens. Students sorted the cards into 'yes', 'no', and 'maybe' piles whether or not the practice was something they were held accountable (or expected) to do during the engineering unit.

Then, students elaborated on their positional choices and the meanings they made of the practices.

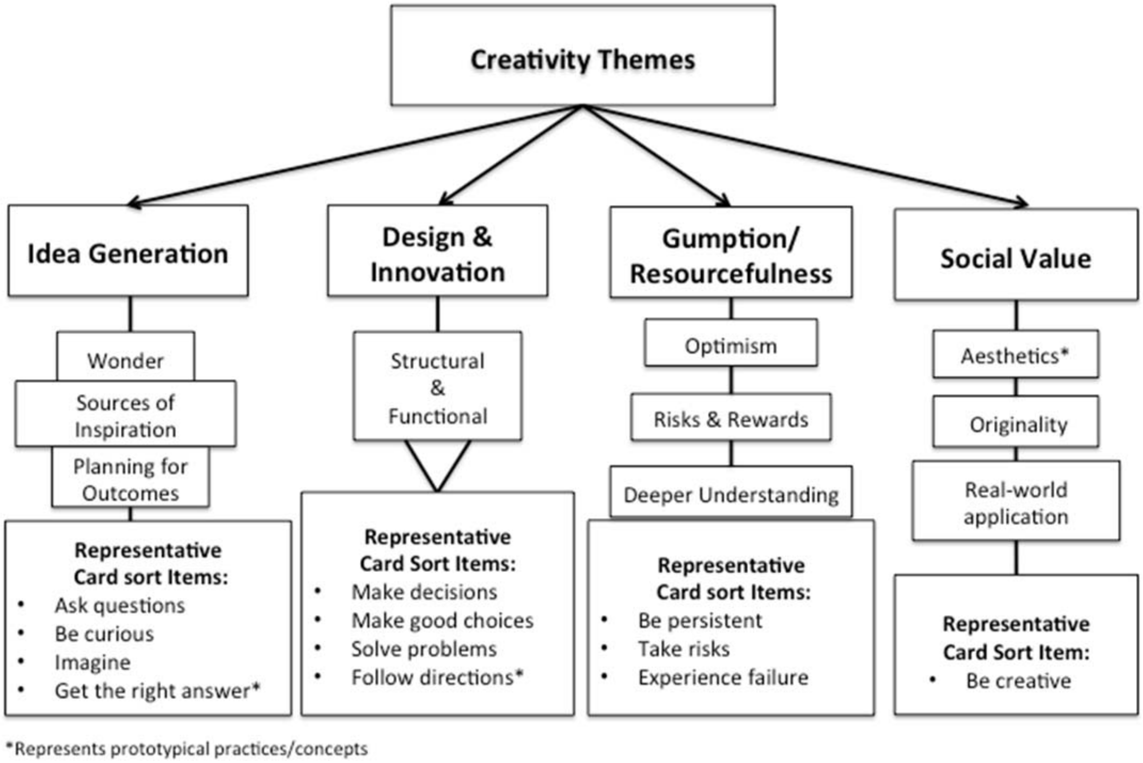


Figure 4.2 Sources and Expansion of the Creativity Themes

I looked collectively at students' responses to the card sort items specific to *idea generation*. The theme evolved to include students' descriptions of wonder, required sources of inspiration, and involved specific planning strategies in the process of students visualizing their prospective design ideas and possible outcomes.

The cards *ask questions* and *be curious* stimulated similar responses from students. Students made comments about these two cards such as, "You have to ask questions, to be curious" and "Yes, because it goes with asking questions. You're curious, you don't really know what's going to happen." About two-thirds of the students responded that these were practices that they were held accountable to do during the solar energy unit (see Figure 4.3).

Asking questions required a source of inspiration for students. Sources could include looking within as an internal source for ideas (oneself), generating ideas from/with peers, or looking to the teacher for direction. The latter source provided evidence for a sense of students' dependency on an authority figure (the teacher) and a lack of internal and/or communal inspiration. Perhaps, this was borne from a persistent prototypical notion that the teacher is the ultimate authority in the classroom and the person to seek for answers to questions. It was evident that questions posed to an authority figure were typical practice during the first few class sessions of the unit. At Landon, many students (more than half the class) kept their hands raised for the duration of the storybook portion of the lesson as they learned about the problem and the design challenge (Field notes, 9/26/13; 9/27/13). For example, my reflections of these sessions included: *kids are curious; lots of hands being raised; >50% of hands are raised to answer Ms. Collins' questions; lots of hands up; about 3-4 students have their hands up constantly (they are dying to contribute their ideas)* (Field notes 9/26/13).

Some students asked questions as a form of self-talk and an internal source of inspiration for decisions that had to be made about the solar oven design. Students also asked questions to weigh options even when an answer was not imminent.

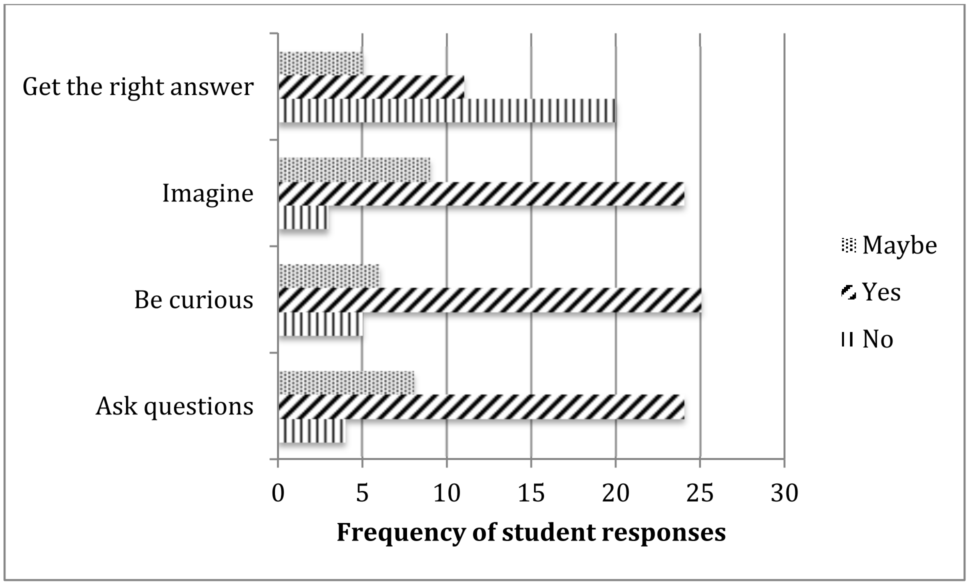


Figure 4.3 Idea Generation: Representative Card Sort Items[4]

> Liam: You have to ask questions to maybe yourself so that you can test out the...what you're testing.
>
> Interviewer: You ask questions to yourself?
>
> Liam: Mm hmm (affirmative).
>
> Interviewer: Is there any other time where you had to ask questions?
>
> Liam: Yes. We had to ask questions about what's better for the box shredded paper or regular newspaper.
>
> Interviewer: When you ask the questions, did you always have an answer?
>
> Liam: No, not always. (Landon student interview, lines 219-227)

> Raul: Well, I think that you were supposed to ask yourself how you would think to assemble your parts, what would be good insulators and choosing stuff like that. (Landon student interview, lines 147-148)

---

[4] All card sort data is from combined sites.

Other students looked to their partners for inspiration in making decisions about how to approach the design challenge. Students generated ideas from an external source, discussion with peers.

> Interviewer: Okay, for instance give me an example; what does that mean to ask questions on the unit?
>
> Miriam: Ask questions about the experiment and about more materials, I ask my partner about that material. (Landon student interview, lines 156-157)

> Russell: Ask other people what they think we should put in there. (Landon student interview, line 188)

> Jaden: You need to ask questions. You can ask your partner a question or your teacher, or whoever is in there a question about what, I mean, what is going to happen or what should we do. So, I think it would be great to ask questions. (Monroe student interview, lines 269-271)

Asking questions of peers and looking inward in a form of self-questioning was a surprising shift from the expected model of asking the teacher (authority figure) questions.

However, several students continued to exhibit a dependency on looking to an authority figure (the teacher) for *the* answer rather than branching out to discover the unknown either independently or with their peers.

> Heather: I think I maybe was expected to ask questions because that was a new unit in science, and we didn't really know anything about it until she (*the teacher*) taught us. (Monroe student interview, lines 149-150)

> Megan: Because that was part of the engineering design process. We had a little chart and it was part of it and she (*the teacher*) told us that that was our first step and we had to do that. (Landon student interview, lines 172-174)

> Tommy: Well, you have to I guess know about this unit you have to ask what step is next and what if we're allowed to do this with our solar oven or do that. (Landon student interview, lines 166-167)

Some students questioned their teachers for confirmation of ideas and for assurance. It was difficult for some students to break free from a typical, traditional, linear step-by-step process and adherence to following classroom rules and authoritative hierarchies. For others, searching for inspiration from within or from the wisdom of peers provided the information necessary to explore their design ideas and approach the challenge without trepidation.

Self-described curious students were willing to pursue many ideas and wondered about the outcomes and future implications of their design ideas. For many, the unexpected was intriguing and stimulated interest to pursue new ideas.

> Jabari: I say yes, because when you're curious like you're thinking like you're saying I wonder if this would work or it wouldn't. (Monroe student interview, lines 183-184)

> Jenna: Yes, because it goes with asking questions. You're curious, you don't really know what's going to happen. (Monroe student interview, lines 188-189)

> Kayla: It's kind of like ask questions, but just wonder what you're going to do while you're doing it. (Monroe student interview, lines 141-142)

> Megan: Had to be curious about what you thought the temperatures would be and what you thought was good and if you didn't make it, you had to try it again and be curious and try different things. (Landon student interview, lines 187-189)

For these students, unknown outcomes piqued curiosity. Not having *the* answer or an expected outcome made the challenge interesting and spurred their engagement and participation.

Responses to the card, *imagine*, also signified the development a "creative mindset." According to Jordan from Monroe, "we need to first kind of imagine a solar oven and kind of get a good creative mindset of what you what you kind of like to do." Another student, Faye, described imagining as considering outcomes, "you wanted to look into the future kind of, and see if you could see how it would work out." Imagining by creating an image or picture in your head is how many students described their thinking processes during the unit.

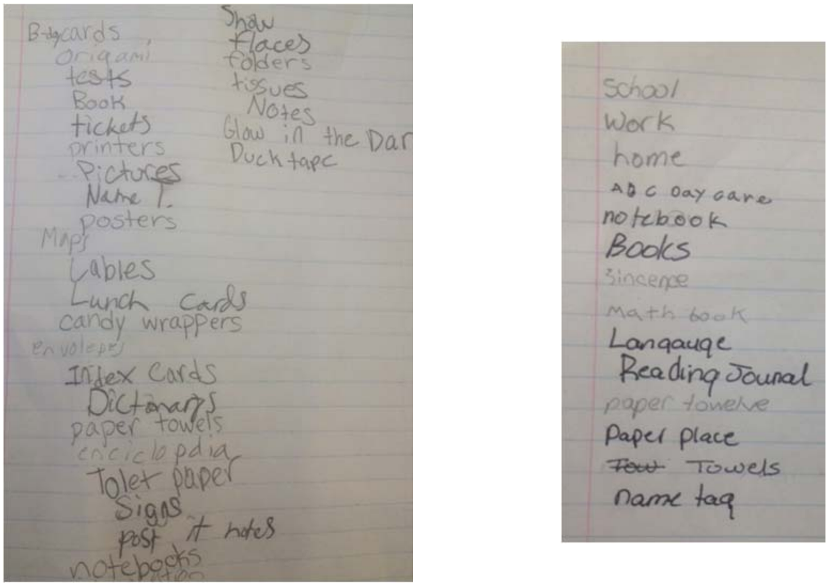
> Katrina: What it meant to imagine during this unit is like I was picturing in my head what would it look like or what would it do if I used this and so I started different imaginations that I had in putting together and it really worked. (Monroe student interview, lines 170-172)

> Calvin: Imagining means to picture what it looks like in your mind instead of telling it out loud. (Monroe student interview, lines 175-176)

Some students interpreted *imagine* as a stage of planning where you wrote down your ideas and created drawings as a way to brainstorm ideas. Joel from Landon explained, "You had to imagine because, so you can have a plan and see what we were going to put in [the oven]." As part of imagining, Joel was considering a plan for possible materials to use to insulate his solar oven. The teachers guided students through the process of idea generation by asking them to jot down ideas in the initial planning stages. Megan remarked, “[the teacher] told us to imagine what we thought would be good and we wrote down some ideas.” Planning sometimes included drawing diagrams. Sarina noted, “You need to draw a diagram or you should need to think about it, draw it out to see what would it look like and stuff.” Initial brainstorming practices to look beyond just one right answer fueled students’ ideas for possible designs. However, some of the brainstorming sessions were loosely structured, time-driven, and involved competition among some teams, lacking the best practices outlined previously by Isaksen and Gaulin (2005). For example, my field notes revealed that Ms. Collins provided a very brief statement of instruction before students brainstormed about the uses of paper in part two of the unit.

> Ms. Collins asks the students to write down the uses of paper in our world today. They are to write for a minute and a half. Students excitedly write as fast as they can—some groups take turns writing and adding to their list; others have a scribe. Tommy’s group seems to be in competition to get the most items on their list. I see words like: name tags, books, lunch cards, toilet paper, paperdolls. (Field notes, 9/27/13).

The competitive group produced a large number of non-redundant ideas while the turn-taking group struggled to produce an extensively fluent list given their turn-taking strategy and the minute-and-a-half time restriction. The structuring of these idea-generating sessions may require additional teacher professional development to produce more optimal results (see Figure 4.4).



B-day cards
origami
tests
Book
tickets
printers
Pictures
Name T.
posters
Maps
Lables
Lunch Cards
candy wrappers
envolepes
Index Cards
Dictonarys
paper towels
enciclopdia
Tolet paper
Signs
post it notes
notebooks

Shaw
flaces
folders
tissues
Notes
Glow in the Dar
Duck tape

School
Work
home
ABC Day care
notebook
Books
Sincence
Math book
Langauge
Reading Jounal
paper towelve
Paper place
~~Tow~~ Towels
name tag

Figure 4.4. Brainstorming Session: Competitive Group (left) Versus Turn-Taking Group (right)

The final card for this theme, *get the right answer*, was included because of the number of students who responded ‘no’, this was not expected of them during the unit. Over half (roughly 56%) of the students indicated that getting the right answer was not a priority. This card represents prototypical practices in classrooms today, especially in an environment of high-stakes testing and accountability. It was encouraging that more than half of the students looked beyond this traditional mindset. Sasha from Landon explained, “It's not about getting the right answers, it's about doing our best.” Tommy, also from Landon stated, “There’s no right answer with engineering, usually” as he considered how answers are obtained in the field of engineering. Some saw searching for multiple answers and trying out new ideas as a way to learn.

> Jordan: Get the right answer. I actually kind of need to say ‘no’ to it mainly because it's okay to get the right answer, but I mean sometimes ... I said maybe

> because sometimes it's okay to get the right answer, but sometimes it's good to get the wrong answer so you can learn from that mistake. (Monroe student interview, lines 173-177)

Enjoying the process also involved letting go of notions of getting the right answer. Students appeared to appreciate the process better when they released themselves from ‘being right’ to simply learning during the process.

> Meagan: You were expected to not get the exact thing that held [the materials in the solar oven] perfectly or whatever. You were expected to have fun and design new stuff and create new things and learn about it. You're not expected to have the exact answer the first time. (Landon student interview, lines 242-244)

In this case, creative exploration involved trying out many ideas, keeping an open mind, and being comfortable about not knowing *the* answer. However, Megan implied that eventually the goal was to achieve a correct/workable solution. In this excerpt, she moves back and forth in her thinking indicating that she is not completely assured that no right answer exists in engineering. Elements of the unit began to initiate multiple-solution thinking (creative maxim 4 from Table 2.1), but it was hard for students to move beyond traditional thinking practices. Perhaps, this needs to be a point of focus and an area of more explicit instruction for teachers.

Summary: Creativity as Idea Generation

For some students, the process of *idea generation* during the EiE unit involved stepping away from bounded, traditional conceptions of thinking and learning toward one of wonder, multiple sources of inspiration, and plans for future outcomes. Asking questions, being curious, and imagining were regular practices during the unit and were integral to idea generation as part of the engineering design process. Students began to develop “pictures in their head” in the process of imagining during the unit. During the unit, some students felt free to seek multiple sources (beyond the teacher) for information and ideas, appearing to enjoy the creative process of developing their solar ovens. According to Kazerounian and Foley (2007), the teachers’ role (maxims 8-10) is to encourage motivation and inspiration in their students to promote creativity. Shifting away from the traditional role of teacher as authority figure is a good first step.

Brainstorming for ideas either independently or with peers allowed students to generate multiple solutions to the problem of designing a solar oven while conserving natural resources. The creative process starts (not ends) with an idea and requires a safe and encouraging environment for brainstorming (Isaksen & Gaulin, 2005). Dependence on authority figures to provide *the* answer can limit opportunities to be creative and seek new information from multiple sources. Teacher professional development is required for brainstorming to be fully effective in developing flexibility of thinking and idea generation. Teachers need to function as informed facilitators in the process, guiding students in the collaborative process of idea generation for these practices to be truly effective. When teachers are seen as the ultimate authority students may be limited in their ability to look to others (or themselves) for inspiration.

According to Isaksen and Gaulin (2005), pursuing more than one right answer is a creative pursuit. Getting the right answer continued to have a strong hold on students, but surprisingly more that half welcomed unexpected outcomes. Students who described themselves as creative designers kept an open mind and pursued alternative solutions for their solar ovens, willing to accept the unexpected and start over if things did not go as planned. Moving toward thinking about the possibility of multiple solutions to a problem will require explicit practice and instruction.

Creativity as Design and Innovation

The theme of *design and innovation* emerged in student interviews as both functional and structural entities. The primary components of this theme included the structural (physical/mechanical aspects) of designing a solar oven and the uniquely functional (useful/practical aspects) that informed the designs. The combination of the structural and functional elements of design aided students in developing uniquely creative product solutions.

As mentioned previously in Chapter III, the EiE units are structured into four main parts or stages. The four main unit lessons included: 1) a multicultural engineering story; 2) a broader view highlighting the engineering field of focus (i.e., green engineering); 3) how scientific data inform engineering (i.e., materials testing); and 4) a design challenge to solve a problem (i.e., EDP put into practice). During the interviews, we asked students to reflect about a stage of the unit where they felt the most and least creative. This is important to mention here because of the overwhelming response from students that the design stage (part four) was where they felt most creative. Fourteen out of sixteen responses from students at Landon indicated that the design challenge was where they felt the most creative. Similarly, at Monroe all but one student mentioned the design challenge as a place where creativity was maximized. Talk early in the unit about the prospect of designing a solar oven sparked immediate interest in students. I observed

Tommy from Landon physically jump out of his seat toward the end of the lesson on day one as he realized they would be helping the main character solve a problem by designing their own solar ovens, he shouted, "Yes!!" enthusiastically as class wrapped up for the day. During the design phase of the unit, many students connected creativity with the open-ended nature of the challenge allowing for the freedom of choice and autonomy these tasks afforded.

> Interviewer: Part four? Why did you feel so creative there?
>
> Isaac: Because you got to choose what you wanted to put in [the oven]. (Monroe student interview, lines 147-148)

> Lucas: We were going to get to build it. We got to make our own [oven]. This time we don't have to follow any instructions on how to build it. (Landon student interview, lines 125-126)

> Eli: Because you get to choose how you want to design it. (Landon student interview, line 105).

The one student from Monroe, who did not mention design, indicated that during materials testing she felt most creative.

> Candace: Because we had a timeline up the board where we had stuff that we material [tested] – so nobody in the class looked at the board all day…just put stuff to see how it's…I looked at the board to see which material's best so I used foam, shredded and newspaper flat because newspaper flat was kind of a good insulator and kind of a bad one, but foam was a really good one and so I put it inside the box.
>
> Interviewer: So you used that information to make a decision and you felt creative in that?
>
> Candace: Mm hmm (affirmative). (Monroe student interview, lines 119-125)

Choice and autonomy appeared to play a key role in students feeling creative. Making decisions about what materials to include in their solar ovens, how those materials would be placed structurally, and a lack of rigid instructions or rules promoted creativity according to students.

Functional aspects of design also presented opportunities for students to feel creative in addition to structural aspects of design driving creativity.

> Jabari: The one that I feel the most creative was the box (the solar oven).
>
> Interviewer: Part four?
>
> Jabari: Yeah. Part four on creating the box.
>
> Interviewer: How come?
>
> Jabari: I say this is the most creative one because you actually creating some that you wouldn't think that people will use and it's kind of like a new thing that we'll have in the future.
>
> Interviewer: What does creativity mean to you?
>
> Jabari: Creativity means to me is like when you're creating things and trying to make something better and you want to make it nice. (Monroe student interview, lines 115-124)

The practical and useful (functional) impact of Jabari's design is what promoted feelings of creativity. Jabari reflected on being able to design and build something that can be put to use now and in the future (practical value), the lasting effects of an innovative design. Even students who did not identify design (part four) as their most creative moment during the unit cited the functional aspects of design in their responses.

> Faye: I felt most creative when we were talking about, Tsoane (a character from the story) said that it would take like three hours just to cook one cup of tea, and it wouldn't get that hot. So my brain got moving there. I thought, "Wow, if we could…," this was before I knew that we were going to make a solar oven, "Wow, if we could improve Tsoane's oven, and make it better." Well, I thought I could do some really good stuff. Like if it's popcorn, I could maybe put some, a little bit of paper, some foam. I would actually…
>
> Interviewer: So you had some ideas already cooking in your head?
>
> Faye: Yeah, I did. (Landon student interview, lines 167-175)

Faye identified the engineering story (part one) as her most creative moment, however her explanation provided a glimpse of her creative visions for design and their practical uses of engineered technologies for people.

Following the idea of developing the functional and structural aspects of design as creative and innovative processes, the three card sort items from the student interview that most closely aligned with the *design and innovation* theme included: *make decisions; make good choices;* and *solve problems.* The more prototypical fourth card sort item – *follow directions*, was also included in this theme because following directions, although usually interpreted as a prototypical classroom practice, was considered a practical and necessary element of engineering in functional and structural design according to some students (see Figure 4.5).

Thirty total students (roughly 83%) recognized the card, *make decisions* as a practice they were held accountable to do during the EiE unit. Five students said ‘maybe’ and only one responded ‘no’. Overwhelmingly, students described this card as decisions about materials, choices about what to include in their solar ovens as good insulators and conductors, and how to best align and position their ovens to maximize absorption of heat from the sun. Once again, the freedom of choice and autonomy set the stage for a creative environment for design.

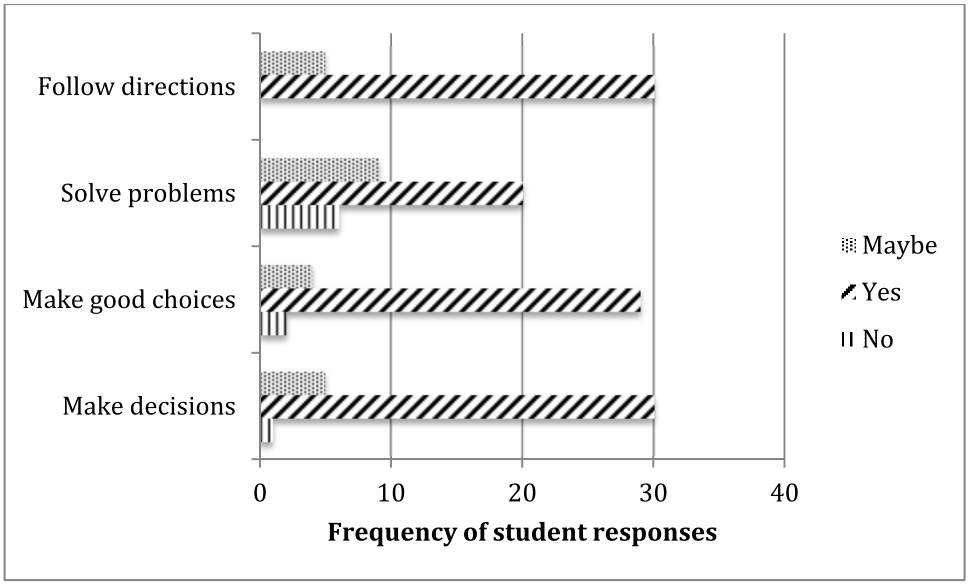


Figure 4.5. Design and Innovation: Representative Card Sort Items

Students described their experiences with making decisions during the design process, particularly focused on the choice of materials to include in their solar ovens. They concentrated specifically on optimizing the effectiveness of their ovens and trying out their ideas for the best insulators and conductors.

> Bruce: Yeah. I would put it under yes because we had to make lots of decisions ... because there [were] lots of different materials that we had to choose from ... and we chose from some weird ones that some people did choose. (Monroe student interview, lines 185-187)

> Leah: Yes, we got to make a lot of decisions.
>
> Interviewer: Did you? Okay. Kind of about, like what you were telling me about the ovens?

> Leah: Yeah, choose what we were going to do, and what materials we're going to use, and where to place it so it could be directly in the sun. (Monroe student interview, lines 199-202)

> Interviewer: What kinds of decisions did you have to make?
>
> Callie: Like should I put this over on the walls or on the floor? Or maybe should I get more materials and put on all the walls? (Landon student interview, lines 239-241)

> Interviewer: So you had to make decisions? That was expected?
>
> Megan: Yes, because you had to decide which one was good for insulating, which one was good for the environment. You had to make decisions about that stuff. (Landon student interview, lines 181-183)

Students described making decisions as an integral part of the design process and appeared to exhibit a sense of control over the outcome of their solar ovens. They were invested in making the oven as effective as possible through their choices and innovative ideas. One pairing of students from Monroe (Leah and Franco) were particularly elevated in status among their peers as being creative in their solar oven design because they chose to insulate the lid of their oven, while others had only considered insulating the body of the oven itself.

> Candace: Franco and Leah. I think they're the best engineers because they had – they used all the materials they had to make – they thought about how to take the heat energy in the solar oven.
>
> Interviewer: Okay.
>
> Candace: While I was looking at them building stuff and getting my own creativity, I saw them glue cotton balls around their lid. (Monroe student interview, lines 142-147)

> Isaac: The most creative would be Leah's.
>
> Interviewer: Okay. What made them a creative pair?
>
> Isaac: The part about putting the materials on the top.
>
> Interviewer: Oh yeah. On the lid. They did do that, didn't they? I don't think many other people did that so that was kind of a neat idea. And it seemed to work well for them, didn't it?
>
> Isaac: Yeah. (Monroe student interview, lines 161-167)

Ms. Warner encouraged groups to share their designs with the class during whole-class debriefings. I observed students proudly sharing their choice and positioning of materials, indicating what worked well and what needed revision. Students curiously asked questions to other groups about their choice of materials and how they got their ovens to work effectively to hold heat. For example, Franco asked Calvin, "Show us what you did to get the tin foil to stay on there?" Leah continued the inquiry by asking, "What is under the tin foil?" and Jordan added, "Do you think you should have used cotton balls?" Each student was eager to learn from the decisions of others (Monroe field notes, 11/14/13).

When students from Monroe were asked to name the most creative person or group, half (50%) of the students in the class mentioned Leah and Franco and their creative ideas for designing the lid of the solar oven. Their innovative design ideas were celebrated and emulated by several of the student groups. During the improve phase of the unit, groups adopted Franco and Leah's ideas to design their own oven lids, because Leah and Franco had achieved the highest temperatures during initial testing.

> Franco: …then [the temperature] went to 95 and 96 then to 100. Then 100 to 103, 104 then 110. It went quickly up to 110!

> Interviewer: Mm hmm (affirmative).
>
> Franco: Then it went 110, 111, 112, then to 114! Then when Leah moved it, the temperature went down and it went to 110. (Monroe student interview, lines 313-319)

Other student groups recognized Leah and Franco’s success with achieving high temperatures on initial testing and optimized their ovens using these innovative ideas.

> Interviewer: How do you feel about the box that you and Jordan put together?
>
> Heather: I feel really good, but then I think we should have more cotton balls. You should see the way that Leah ... right there ... and Franco put their box together. Really cool one ... was really hollow, and stuffed up with cotton balls, and newspapers, and magazines. (Monroe student interview, lines 283-287)

> Interviewer: Could you tell me a little bit about what you did to make your oven? Tell me about what you went through and what you were thinking?
>
> Isaac: From Leah's idea, we got to put stuff on the top.
>
> Interviewer: Oh, yeah. I see that you have cotton balls there lining the top. And you got that idea from Leah's group?
>
> Isaac: Mm hmm (affirmative).
>
> Interviewer: Okay. What else did you do? Even in the beginning before you started doing your improvements, what were some of the things you were thinking about when you were putting your oven together?
>
> Isaac: Use some of the other people's ideas.
>
> Interviewer: Okay. So, learning from other people?
>
> Isaac: Mm hmm (affirmative). (Monroe student interview, lines 292-304)

Groups shared creative ideas particularly during the improve phase of the design process. Students made decisions about structural adaptations based on what they saw from other groups and the results achieved in the initial testing phase.

The next card sort item, *make good choices*, was frequently associated with choice of materials used in the design process, much like *make decisions*. Over 80% of students indicated that they were held accountable to *make good choices* during the unit (see Figure 4.5). Only three (two from Landon) of the 36 total students interpreted *make good choices* in a prototypical way. Protoypical descriptions included listening to what the teacher tells you to do, not wasting materials (tape), and working well with a partner you did not choose (i.e., good, compliant classroom behavior).

> Sasha: If the teacher is telling you how to do the project you have to make the good choice to listen to her. If you don't make the good choice you won't hear her and you won't know what to do. When you ask her she'll say, "I just told you the directions." (Landon student interview, lines 321-324)

However, the majority of students interpreted *make good choices* in terms of their solar oven designs, the possible materials to use, and the unique ways they might be added structurally to their ovens. Modifying materials was a choice that students realized they had and an innovative strategy for design.

> Interviewer: What did it mean to make good choices?
>
> Eli: Good choices for the insulator inside [the solar oven].
>
> Interviewer: What were some of the things you would think about for insulators?
>
> Eli: What to put inside it.

> Interviewer: Things like what would you have to think about the stuff to put inside, like what were the things you got to choose from?
>
> Eli: Felt, cotton balls, construction paper.
>
> Interviewer: Were they all the same like shape and things like that?
>
> Eli: The cotton balls?
>
> Interviewer: Yeah.
>
> Eli: You kind of spread them out.
>
> Interviewer: You could change the shape? Okay. (Landon student interview, lines 202-213)

Students found that they could modify materials to meet their needs. One way students accomplished this was by spreading out the cotton balls to increase the surface area.

While only 20 out of the total 36 students indicated that they were accountable to *solve problems* during the unit, the nine ‘maybe’ and six ‘no’ responses highlighted that some students did not completely make the connection that an engineer is someone who designs technologies (the solar oven) to solve a problem (how to avoid using up natural resources while cooking foods). Some students appeared to focus on the ‘problem’ portion of the card sort item as something to be avoided. One student answered ‘no’ “Because I thought, everything was going to work to the end” (Katrina, Monroe student interview, line 194). Another student remarked on the importance of direction from the teacher and prospect of being “wrong.”

> Kayla: Follow directions (*reading the card*).
>
> Interviewer: Were you expected to do that?

> Kayla: Yes.
>
> Interviewer: You look at me very seriously...yes. What does that mean?
>
> Kayla: She said follow the directions because some people were confused and they did it wrong at first.
>
> Interviewer: Oh, okay.
>
> Kayla: Then they had to start over and they all ended up doing it right. (Monroe student interview, lines 203-210)

However, despite the traditional notion of a ‘problem’ in school, over half of the students discussed elements of problem solving optimistically in their design process.

> Leah: Like when [the temperature] started dropping [with our solar oven], we had to figure out what was happening and why it was dropping, how can we like, make it so it will rise back up? So we're just thinking and thinking and Franco had said "Well why can't we just move it into the sun just a little bit more?" So we had moved the box up just a little bit and we had turned the thermometer just a little bit to the side, and it actually started to rise a little bit!
>
> Interviewer: Okay, so it sounds like you had to do a lot of thinking.
>
> Leah: Mm hmm (affirmative). (Monroe student interview, lines 238-244)

Leah and Franco learned to make structural and positional adjustments to their ovens during the testing process, constantly problem solving to improve their oven’s performance. Other students returned to discussion about materials choice and placement as a problem to be solved.

> Sarina: The first time we just put in aluminum foil, felt and foam in a solar oven and we took it out and put it outside, out in the sun. It didn’t work that well.
>
> Interviewer: First try wasn’t so great?

> Sarina: Yeah. The temperature went up about ninety-two and it didn't go very high. Next time we put shredded paper and cotton in plastic bags and our temperature rised up to a hundred and twenty-eight.
>
> Interviewer: Wow! So the different materials you chose made a difference. Okay, so you were solving some problems with your oven?
>
> Sarina: Yeah. (Landon student interview, lines 253-261)

The falling temperatures stimulated motivation to try new design solutions in the shade and maintain high temperatures in the sun. Angling reflective oven lids and positioning the oven toward the sun provided some ways to maximize the oven's heating potential. We observed students moving actively around their ovens and shifting the position of their lids to achieve maximal reflection from the sun. We heard calls for teammates to "turn [the oven] toward the sun!" and "leave [the lid] open" during the sun testing phase (Monroe, student audio, 11/13/13). Students were quickly shooed out of the way if they inadvertently cast a shadow on the ovens. One student remarked, "our temperatures started to go down because people kept walking in front of [the oven]" (Monroe, student audio, 11/13/13). Students used their creative design ideas to confront these potential problems.

The final card for this theme, *follow directions*, also carried some of the same prototypical undertones as *make good choices*. Interestingly, some creative thinking emerged from students about following directions that was somewhat unexpected with this often prototypically interpreted card. Prototypical responses included being sure to listen to the teacher to avoid making mistakes or getting in trouble.

> Heather: Yes. We had to follow directions, because if we didn't follow directions we might have did something wrong or either get in trouble. (Monroe student interview, lines 206-207)

> Isaac: If you don't follow directions, than you won't know what to do. The teacher might get mad because you didn't follow directions and pay attention. (Monroe student interview, lines 248-249)

> Lana: Yeah. We have to do that all time. (Landon student interview, line 236)

Thirty students reflected that following directions was important to success during the EiE unit. While many (about 50%) students overtly described the punitive repercussions of not following directions (i.e., getting in trouble; teacher getting mad; doing something "wrong"), there were a few students who thought of this card more creatively with regard to materials choice and listening to the ideas of others.

> Dwayne: There wasn't really that much directions, just like try to get the right materials and stuff.
>
> Interviewer: Okay, so maybe not as many as regular science class or about the same?
>
> Dwayne: We have a lot of directions to follow but…I don't know. (Monroe student interview, lines 218-221)

> Interviewer: Okay, what does it mean to follow directions during this unit?
>
> Chad: To listen to others, like their answers. (Landon student interview, lines 137-138)

> Raul: Maybe because there wasn't much directions for making the box, but they were for how you were going to list your items and stuff like that.

> Interviewer: There weren't a lot of directions you had to follow, but there were some things you had to think about?
>
> Raul: Yeah. (Landon student interview, lines 206-210)

> Jordan: Follow directions, maybe, because following directions is still kind of a good thing but you want it to be creative and sometimes if you're trying to follow the directions sometimes you can't be creative so you can put maybe. (Monroe student interview, lines 195-198)

The students in the above excerpts struggled with the idea of separating the prototypical notion of following directions and compliance (n=5 students characterized this card as 'maybe') from their ability to manage existing classroom structures and find their way toward creative design ideas. It is also important to understand that in lesson three (scientific investigation) students needed to follow directions during materials testing to ensure a fair test and reliable results. Although students did not remark specifically about following directions specific to lesson three, this was a more instruction-laden part of the unit and could have contributed to some if their positive responses.

Summary: Creativity as Design and Innovation

Creativity emerged during the engineering design process for students as part of their participation in the EiE unit. The structural and functional aspects of design allowed students to experiment and test their ideas by putting them into practice. Students considered the physical structure and practical uses of their solar ovens by pursuing their innovative ideas. They manipulated and modified materials and positioned of their ovens to maximize effectiveness. Due to the open-ended nature of the design challenge students had freedom of choice to make decisions about materials to include in the solar ovens providing them with a sense of autonomy and control. However, prototypical ideas about the necessity of following structured classroom rules and the comfort/familiarity of having defined tasks still lingered in the periphery for some students, which may have restricted creativity.

As a point of comparison, in a qualitative study of 144 high school students' ideal vision of contemporary science, Osborne and Collins (2001) described "a world of science-in-the-making, of future possibility and uncertainty where their views can begin to matter providing an essential dose of salience and significance" (p. 461). The authors attempted to get at students' perspectives on the science curriculum as it is taught today. In 20 different focus groups, students provided their vision of what should be included in effective science curricula such as, a move away from recall and basic comprehension of concepts (in a climate of high-stakes testing), relevance, greater autonomy, exploration of contemporary science content, practical work, and opportunities for discussion. Similarly in my study, it appears that engagement in design challenges that incorporate elements of science and engineering in an open-ended, autonomous way have the potential to stimulate creativity through design and innovation. According to Kazerounian and Foley's (2007) Ten Maxim's of Creativity, *ownership of learning* (maxim 10) is essential for encouraging motivation and inspiration in students. Students who are allowed ownership and control of their learning have increased opportunities to express and develop their creative skill set.

Creativity as Gumption

Teaching and learning styles conducive to creativity include reward for creativity, learning to fail, and encouraging risk (Kazerounian & Foley, 2007). Creativity during the EiE unit included periods of optimism (positivity), involved risks and rewards, and ultimately the potential for deeper understanding according to students (see Figure 4.2). The development of the theme, *gumption* (defined as shrewd or spirited initiative and resourcefulness by Oxford University Press, 2014), highlighted these concepts as forms of creativity.

The card sort items that best represented this theme were: 1) *be persistent*; 2) *take risks*; and 3) *experience failure*. Of all the card sort items, *be persistent*, ranked highest (31/36 or 86% of students said 'yes') amongst students as a practice they were held accountable to do during the EiE unit. Only one other card sort item, *be creative*, ranked as high and will be discussed as a final theme in the next section.

According to students, being persistent during the unit represented trying hard, experiencing occasional frustration, and optimistically holding out for future rewards (successful solar oven designs). A common mantra among students was, "We didn't give up easily. We kept trying and trying." (Jaden, line 352). Teachers from both sites also encouraged persistence either directly through verbal encouragement or indirectly through the classroom atmosphere.

> Interviewer: Do you feel like you were expected to be persistent?
>
> Raul: Mm hmm (affirmative). I also noticed that some people when their boxes didn't do so good, they were closest to the control box said, "Aw man, I guess I have to make better my box." (Landon student interview, lines 192-195)

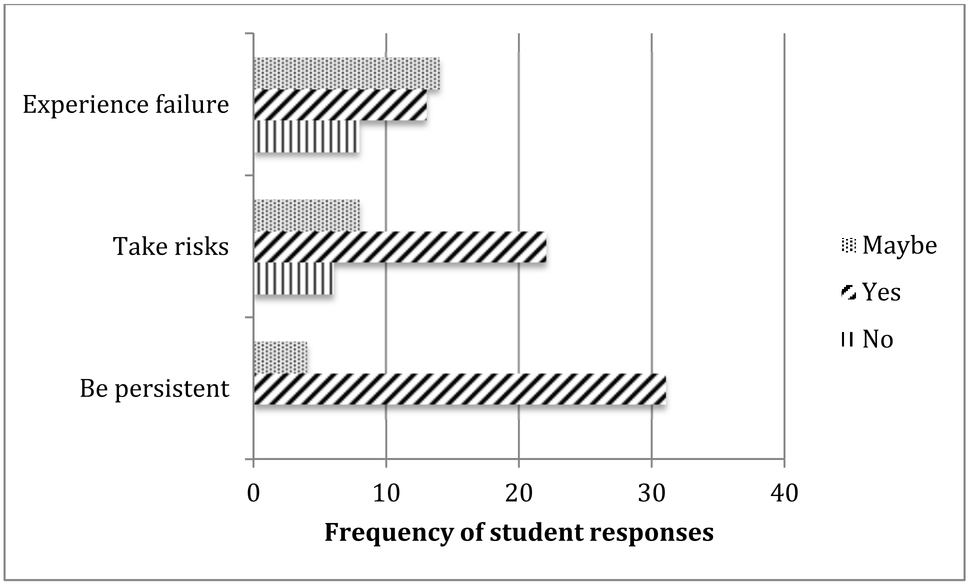


Figure 4.6. Gumption: Representative Card Sort Items

> Raul: Because Ms. Collins said that some engineers even though their technology didn't work out how they planned, they didn't give up and they tried to improve it. (lines 232-234)
>
> Kayla: Miss Warner ... she said, "Don't give up yet." Just like it's the poster in the back of her room that says,…"Don't give up easily. You have to keep trying until you get it right."
>
> Interviewer: Very cool. Tell me about that saying again ... the poster?
>
> Kayla: On the poster it says, "You're not done until you quit." (Monroe student interview, lines 181-186)

The culture of the classroom in each instance was one of encouragement and persistence with a particular focus on the improve stage of the design process. Partners also played a role in fostering persistence. According to Katrina, "[W]hen I was working, when Jacquelyn was gone, I tried to work by myself and see can I do different things, but I actually that realized I needed a partner to help me" (Katrina, lines 188-190). Students appeared to hold out hope of improving their designs to increase the effectiveness of their solar ovens.

> Callie: Yeah, because if you say that you didn't do very good, don't say that. Just say "Oh! Well, that's what I don't do for when I improve my design." (Landon student interview, lines 270-271)

> Jane: When we were testing the solar ovens we had to ... My oven, before we improved it. It didn't hold on the heat that long.
>
> Interviewer: Mm hmm (affirmative).
>
> Jane: But then we had to improve it and I didn't give up.
>
> Interviewer: Yeah. You didn't give up after it didn't work as well as you wanted it to, right?
>
> Jane: Mm hmm (affirmative). (Landon student interview, lines 285-290)

> Tommy: Well, the first time we tested our solar ovens and it heated up and then it cooled down. Ours only went, it cooled down to 82 degrees so internally it only went up two degrees. But, you have to keep trying if you want to be successful and so next time we tested ours it only went down to 92.
>
> Interviewer: Ah, ok. So, the improvements made a difference.
>
> Tommy: Yeah. (Landon student interview, lines 223-229)

Although most students saw their reward as a successful engineering design, some (two from each site) clung to the prototypical notion of reward in the form of grades.

Interviewer: You were expected to hang in there?

> Isaac: Mm hmm (affirmative).
>
> Interviewer: Because if you don't hang in there, what might happen?

> Isaac: You could fail, get a bad grade. (Monroe student interview, lines 231-234)

> Megan: Yeah, because if you're not persistent then you would not get a good grade or whatever and we were persistent on how we did our boxes because we tried it twice. We did it once and if that wasn't as good of a thing, we tried it again and we learned the second time that the shredded stuff was actually a better insulator, so, yeah. (Landon student interview, lines 223-227)

The prospect of failing for these students was closely linked to how they would be assessed in the form of grades, a typical motivator in classroom settings.

Students who persisted also discussed another part of the creative process, *taking risks.* This practice was similarly linked to the improve phase of the design process as being persistent was. Students claimed they took risks in the materials they chose to use to insulate their ovens, not knowing if the temperatures of their solar ovens would respond as expected.

> Interviewer: And that would be like, do something that you're not sure will work, or that you're not sure is going to be correct, but you go for it anyway (*clarifying the card meaning for Faye*).
>
> Faye: Well, I think [that] might have been actually a yes. We didn't know if the materials were going to work out, and we were kind of scared. So we just tried them the first time, and then thought, "Oh, we should make these better and make them stronger." So we did. (Landon student interview, lines 218-221)

> Leah: Because we weren't sure that like the newspaper and cotton balls were actually going to work, because they were like, two different things, and it's like, the newspaper was at the bottom the cotton was at the top, and we didn't know how that was going to turn out, because it's like we didn't think it was going to be hot enough, because it's just paper and cotton and we were like "Warm up. Warm enough." (Monroe student interview, lines 184-189)

Many students maintained a positive outlook about their designs and materials choices despite unpredictable results in the temperatures of their ovens. When asked if they were expected to *experience failure*, students struggled with the term “fail” as it is typically associated with negative experiences in school (i.e., failing a test; getting a bad grade). More students responded ‘maybe’ (14 students) to the card sort item than ‘yes’ (13 students). Eight students responded, ‘no’ that experiencing failure was not expected of them during the unit (see Figure 4.6). Some students felt that the teacher buffered them from experiences with failure. For example, Faye explained, “No. Because Ms. Collins didn't want you to feel like you failed. You just made a mistake and that you wanted to improve it. You didn't fail” (Faye, lines 253-254). Even when lingering thoughts of grades and passing persisted, hints of optimism were evident as students explained what it means to experience failure.

> Interviewer: What would it mean to fail?
>
> Isaac: It means to ... be ... not pass.
>
> Interviewer: Okay. So what would not passing look like in this activity?
>
> Isaac: Maybe if making your solar oven, they could cut a hole in something? Like a big hole in an important part.
>
> Interviewer: So, you might make a mistake?
>
> Isaac: Mm hmm (affirmative).
>
> Interviewer: And what happens if you fail? Is it all over?
>
> Isaac: Try again. (Monroe student interview, lines 210-219)

Students who responded ‘yes’ and ‘maybe’ described experiencing failure optimistically, as an opportunity to improve and obtain a deeper level of understanding through continued practice and perseverance.

> Callie: Well, mistakes help you learn, so I'm going to put that in "maybe." (Landon student interview, line 260)

> Megan: Because sometimes you didn't experience failure, but if you did, then you'd learn from that failure, whatever, and you'd make better choices next time.
>
> Interviewer: Okay, so it's not necessarily what you were expected to, but you might experience some failure?
>
> Megan: Yeah. (Landon student interview, lines 215-219)

> Interviewer: Were you expected to experience failure?
>
> Tommy: Yes.
>
> Interviewer: Yes, and tell me what that means.
>
> Tommy: It’s part of the engineering design process. You don’t really fail, but …
>
> Interviewer: But, you get to improve and, yeah …
>
> Tommy: Yeah. (Landon student interview, lines 208-213)

> Jordan: Yes, experiencing failure was a good thing because once you experience the failure you can maybe learn from that mistake and do better. (Monroe student interview, lines 162-164).

The engineering design process that was part of the EiE unit provided students with opportunities to optimize their solar ovens to be maximally effective. During the initial period of outside sun and shade testing of the solar ovens, Callie (Landon student) had already begun to share her ideas for improvement, noting the parts of her solar oven that needed changing. She made a public declaration to revise so that others could hear (Field notes and contact summary form, 10/3/13). Ms. Collins then shared with me that she had also heard other students talking about possible revisions in their designs.

During the debrief period following the sun and shade testing of the ovens, Ms. Collins responded positively to students' optimistic comments about revision. About three quarters of the students raised their hands that their solar ovens' temperatures were higher than the control box. Ms. Collins informed students that they would be working on improvements of their designs the next day in class. Ms. Collins highlighted the designs that maintained a high temperature in the shade as potential models to emulate. One female student remarked that the improvements would make the ovens "work faster and trap heat better" (Field notes, 10/3/13). Ms. Collins reminded students that the ovens might not get hot enough to "cook a baked potato" because that would require temperatures of 350 degrees. Another student optimistically replied, maybe [they could cook a potato] if they really improved [the oven]" (Field notes, 10/3/13). Ms. Collins commended him on his positive attitude. Reward for creative solutions in the form of encouragement from either the teacher or peers allowed students to search for alternative solutions and worry less about "failing" in the traditional sense. The improve phase of the project allowed for opportunities to have a second chance at restructuring their designs for improved effectiveness. In this case, most students rose to the challenge.

Summary: Creativity as Gumption

Students with *gumption* exhibited styles conducive to creativity that included persistence, risk taking, and positive experiences with failure during the engineering design process. For students who approached the challenge with optimism, the reward was an effective solar oven and a deeper understanding of the inner workings of the task itself. Learning how something did *not* work provided students with insight into what *might* work. The nature of design in engineering is a creative process where "successes [are] very likely preceded by instructive failures" (Petroski, 2012, p. 47). Students who consider failure as an "essential feedback mechanism" for design are more likely to have a growth mindset (Dweck, 2008), where failure is celebrated as an opportunity to learn (Lottero-Perdue & Parry, 2014). However, a fixed mindset (Dweck, 2008) persisted with some students as failure was looked upon as something to be avoided. Students who took a more prototypical stance to failing focused on their ability to pass or earn a good grade in the unit. Alternatively, students who proceeded optimistically (with *gumption*), balancing risks with rewards, acknowledged successful design experiences during the unit.

Creativity as Social Value

The theme of creativity as *social value* emerged from students' descriptions of what it meant to *be creative* from the card sort portion of the interview and from students' descriptions of the most creative person in their class. As mentioned previously, the card sort item, *be creative* (along with *be persistent*), obtained the highest number of 'yes' responses from students as a practice they were held accountable to do during the unit.

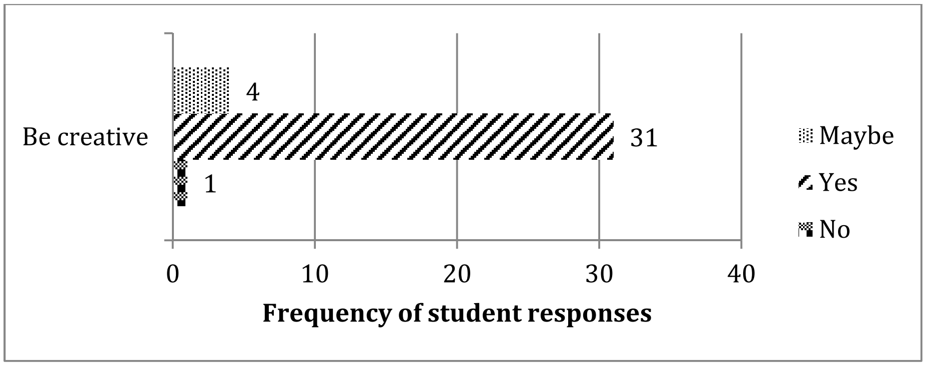


Figure 4.7. Social Value: Representative Card Sort Item

Sir Ken Robinson, author, educator, and recognized creativity and innovation expert, believes that creativity is the *process* of developing original ideas that have *value.* Robinson repeats this creed in the myriad of lectures, TED talks, and books he has written on creativity. So far in this chapter, I have examined the *process* of creativity in the form of idea generation, design and innovation, and gumption. In this section, I aim to get at students' meanings of the *value* of creativity during the EiE unit, particularly the *social value* of the products created as a part of the engineering design process. I examine creativity in the form of *social value* as "the generation of a product that is judged to be novel and also be appropriate, useful, or valuable by a suitably knowledgeable social group" (Sawyer, 2012, p. 8).

The solar ovens that students designed (their *products*) during the EiE unit originated from 'good ideas' and trying 'new things'. Students discussed their desire to be original in their design ideas, not to merely copy others' ideas.

> Faye: You had to think what you were going to do, and just be creative and think, how this is going to work out. If it's going to be good. Just think of your own idea. Don't copy somebody else. (Landon student interview, lines 284-286)

> Callie: Yeah, because you don't want to just take somebody's idea and you're just "Oh! I don't want to do this anymore, so I'm just going to use that!" Just put everything all over the place.
>
> Interviewer: Okay. You had to think about that?
>
> Callie: Mm hmm (affirmative). (Landon student interview, lines 294-298)

> Jabari: Be creative. I put this in the yes. I say you should be creative, I think it was important to be creative because being creative you're thinking like a new thought and being creative you think of new things and that you think might work and might help you out with your project.
>
> Interviewer: Might be better than what you had thought before, right?
>
> Jabari: Mm hmm (affirmative). (Monroe student interview, lines 260-265)

Students also discussed originality and development of new ideas as a process of imagination. Isaac explained that being creative is "sort of like imagine; to be creative with the solar oven, with the [materials] in there; and have good insulators and stuff" (lines 253-254). Chad described being creative as "drawing a picture in your head" (line 143). Katrina also remarked, "That's almost like imagine because when I was being creative I just tape[d] different things together or to make it thicker or I would just put them all together to make something like a different tool" (lines 207-209). These students valued originality in ideas as part of the creative process.

Some of the students' original ideas were based on examples seen in real life. One student's ideas were stimulated from watching another pair apply the idea of house insulation.

> Tommy: Oh, Eli and Callie, they made their, this was really cool. They stuffed cotton balls inside the pieces of foam and felt, so it was kind of like…

> Interviewer: Oh, like in between?
>
> Tommy: Yeah, so it was like the pink stuff in the house of a wall and that's how where I got that idea.
>
> Interviewer: Ah, so you got your idea from kind of paying attention to what other people were doing?
>
> Tommy: Yeah.
>
> Interviewer: Awesome, awesome. Yeah, because I remember you told me that, when I was looking at your oven, you told me about how you thought it was like house insulation.
>
> Tommy: Yeah.
>
> Interviewer: That's a really good connection. (Landon student interview, lines 137-149)

Another student was impressed by the creativity of a pair of students who applied their knowledge of how the color black absorbs heat into their solar oven design.

> Faye: They added cotton balls around their cup, and they added a little black, and they actually had some stuff on the outside. And theirs got super hot. It got condensation on it.
>
> Interviewer: Oh yeah, I saw that.
>
> Faye: So, I was like, "Wow, they must have done something super brilliant." Or there might have been a tiny leak in it to make the condensation go in. But I thought, they probably knew that black was very warm, and that they should put stuff on the outside…(Landon student interview, lines 191-198)

In another example of students applying ideas from real life, Callie (Landon student) revealed that her idea to use black paper in her design came from studying her oven at home. She said her oven at home was black inside, so she added black paper to her solar oven (Field notes, 10/3/13). Real-world application also included consideration of the impact of material choices for the solar ovens and whether or not the environment would be affected by their ideas. Callie reflected about Megan's design, "[S]he did a great insulator. She used, maybe, three materials" (lines 197-198). Minimal use of materials in the design meant that the impact score would remain low and fewer natural resources would be used up in the process.

For some students (5/36 or roughly 14%), a traditional conception of creativity focused on aesthetic value emerged in their descriptions of their products. These students described the artistic talents of individuals and the visual appeal of their designs as important to creativity. Jacquelyn remarked on Franco's artistic talents as important, "Because he knows how to design stuff, he knows how to draw, he knows…He's like the best artist in the school" (lines 85-85). Being creative to some students meant an aesthetic focus was important.

> Interviewer: What is being creative with your solar oven mean?
>
> Jordan: It means design your own solar oven of how you want it to look like.
>
> Interviewer: Does that mean decorating it really beautifully or does it mean putting the right kind of stuff in it, or what?
>
> Jordan: Decorating it beautifully of how you want it to be. (Monroe student interview, lines 169-173)

> Raul: Because some people thought of like coloring or wanted to use stuff or I noticed that some of them were coloring their boxes (Landon student interview, lines 214-215)

These students placed value on the aesthetic appeal of the solar ovens, recognizing creativity in a slightly different, yet more prototypical, artistic sense than many of their peers.

Summary: Creativity as Social Value

Students' descriptions of what it meant to be creative during the EiE unit were focused on the originality of the design, the ability to apply design ideas to real life, and the prospect of visual appeal. While being creative in some instances was dependent on artistic ability, more often the collective group placed value on the appropriateness and originality of designs.

A focus on aesthetics can be either a prototypical conception or can lead to development of products with distinctive value in engineering. During the EiE unit, students who referred to creativity aesthetically did so in a prototypical sense, focusing on the colors used to decorate the solar ovens or the artistic ability of the designer. Aesthetic value presented in this way associates aesthetics with beauty, usually a peripheral/surface level concern for engineers (Faste, 1995). It is important for students to understand that there are aesthetic implications to engineers' work and that aesthetics do play a role in the creative process. Faste, Professor of Mechanical Engineering at Stanford University, stated that engineering decisions impact the aesthetics of products and that perceptions of quality remain important in design. It is important that conceptions of value related to aesthetics be explicitly discussed with youth that are learning about the practice of engineering.

Originality of ideas was valued by students as they reflected on their own and others’ designs, however they were not opposed to borrowing a good idea or using examples from everyday life in their designs. In studying group creativity, Sawyer (2012) noted that novelty is often not enough. The social group judges products for their value. The students in both classrooms developed a sense of creativity as social value as they examined the results of their efforts and others’ with the solar oven designs.

CHAPTER V

COLLABORATION AS AN ENGINEERING HABIT OF MIND

Collaboration is an integral part of the engineering design process and has been highlighted as a habit of mind by the Committee for K-12 Engineering (Katehi et al., 2009). All too often, cooperative learning in school involves students working in pre-assigned pseudo-learning groups (Smith, 1995) where interest is not shared, competition is present among members, and fears exist about individual performance ranking. Students have actually been found to achieve more working alone than in these pseudo-learning groups. To be truly effective, Smith (1995; Smith, Sheppard, Johnson, & Johnson, 2005) advocated for cooperative learning groups in engineering classrooms that are composed of five essential elements: 1) positive interdependence; 2) face-to-face promotive interaction; 3) individual accountability/personal responsibility; 4) teamwork skills; and 5) group processing. In this section, I will examine the engineering design process and the ways in which students interacted cooperatively to produce their design products to address part two of the first research question: In what ways do students collaborate during the EiE solar energy unit?

Spaces for Collaboration

In previous sections, I outlined the four progressive stages of the EiE solar energy unit. It is important to return to the organization of the unit here as the structure played a role in the nature of collaboration at different phases of the unit (see Figure 5.1). The opportunities for collaboration (student interaction and cooperative learning) and the level of complexity in the practices expected of students increased with each stage of the unit. Ultimately, the design challenge (part four) is where student engagement and interest was determined to be the highest and collaborative opportunities were greatest based on evidence from student interviews, classroom observations, field notes, and audio recordings of student group work. In the following sections highlighting the four parts of the unit, I showcase the less collaborative and more collaborative opportunities available to students to provide points of contrast for the enactment of the curriculum during different stages of the unit.

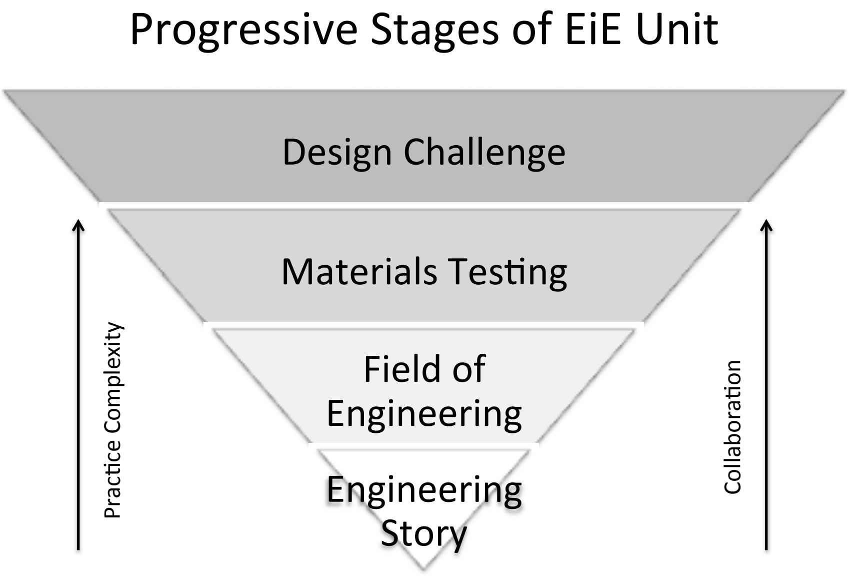


Figure 5.1 Progressive Stages of the EiE Unit

The Engineering Story

Ms. Collins' class. In both classrooms the engineering story portion of the lesson, *Lerato Cooks Up a Plan*, was primarily enacted as a whole group endeavor. The storybook was 45 pages long, including vocabulary and character glossaries. The multicultural story was divided into seven chapters infused with hand-drawn, black-and-white pictures of the characters in action. Ms. Collins (Landon teacher) read the story aloud to students standing at the front of the room while images from the story were projected onto the board for students to see. Lively, whole-group discussion was infused into portions of the story, particularly at the end of each chapter. Ms. Collins reviewed vocabulary, discussed the context of the story, and developed the characters during four sessions that lasted approximately 45 minutes to an hour each (see Table 5.1). For example from the field notes,

> Ms. Collins also introduced students to the problem facing the main character (Lerato) during this time, the depletion of natural resources by burning fires to cook food. An excerpt from the field notes on the first day of the unit highlighted the type of participation from students during these whole-group sessions.
> Ms. Collins asked, "What do you think life might be like in Botswana?"
>
> Many students are eagerly raising their hands to answer questions posed (*especially Callie and Tommy*). All suggestions are given equal weight. Ms. Collins calls on many students to answer questions (*many hands are raised*). She is encouraging and prompts students to think deeper or offers alternative suggestions when they are off track.
>
> Students display high energy and enthusiasm (*lots of hands raised*). The students are very eager to participate in the conversation (*some are popping out of their chairs to answer questions*). One boy, Tommy, is thrilled that they will be building their own ovens.
>
> Students exhibit verbal fluency ("genre"; "Earth friendly"; "natural resources") as they respond to questions about the context of the story.

> Students are highly focused on the development of the story and exhibit control as the teacher choses one student at a time to answer from the many hands raised. Some students keep their hands in the air for most of the lesson, waiting to be called. (Field notes, 9/26/13)

Ms. Collins made a strong effort to call on each of her students during the story portion of the unit. Many students had their hands raised during the reading of the story, excited to share a personal story or to answer a question posed by Ms. Collins. While the energy level was high during this stage of the unit, student-student interaction was not optimal. Whole group, teacher-led discussion was the primary mode of instruction in part one of the unit.

Ms. Warner's class. Ms. Warner (Monroe teacher) utilized her teammate (the ELA—English/Language Arts teacher) to cover the engineering story with students. This strategy helped her to better manage the limited time available for science during the instructional day while still being able to cover this important component of the unit (see Table 5.2 for Ms. Warner's schedule of implementation). I did not have access to students during their ELA time. Ms. Warner reported that the ELA sessions lasted 45 minutes each (ELA block period) for a period of two weeks. However, one student remarked during the student interview that interaction among students was not a primary objective during ELA time. For example, one student shared the following during her interview,

Table 5.1 Ms. Collins' Teacher Implementation Schedule

Day of Implementation	Date	Content Coverage	Duration
Day 1 (session 1 – ELA time)	9/26/13	Part 1: Storybook	1 hour
Day 1 (session 2)	9/26/13	Preparatory lessons: What is an Engineer? Tower Power activity	1 hour
Day 2 (session 1 – ELA time)	9/27/13	Part 1: Storybook session continued	1 hour
Day 2 (session 2)	9/27/13	Part 2: Review life cycle assessment; Life cycle of paper introduced – brief brainstorming session	45 minutes
Day 3 (session 1 – ELA time)	9/30/13	Part 1: Storybook session continued	1 hour
Day 3 (session 2)	9/30/13	Part 2: Green Engineering—Paper use & Life cycle assessment of paper activities (*Calculations done in another math session – not observed*)	1 hour
Day 4 (session 1 – ELA time)	10/1/13	Part 1 & prep lesson: Review of technology & engineering worksheets; continued reading of Chapters 5 and 6 from story; brief brainstorming session about the story	1 hour
Day 4 (session 2)	10/1/13	Part 3: Materials testing	1 hour
Day 5 (session 1)	10/2/13	Part 3: Materials testing continued (*Unscheduled lesson – not observed*)	1 hour
Day 5 (session 2)	10/2/13	Part 4: Solar oven design	1 hour
Day 6 (session 1)	10/3/13	Part 4: Solar oven design	1 hour
Day 6 (session 2)	10/3/13	Part 4: Testing solar ovens outside	1.5 hours
Day 7	10/4/13	Part 4: Improving and testing solar ovens (making S'Mores)	1.5 hours
Total: 12 sessions observed			Total time: 13:45:00

Table 5.2 Ms. Warner's Teacher Implementation Schedule

Day of Implementation	Date	Content Coverage	Duration
Day 1	10/29/13	Preparatory lessons: What is technology? What is engineering?[5]	1.5 hours
Day 2	10/30/13	Part 2: Green engineering; Prep lesson continued: Tower Power	1 hour
Day 3	10/31/13	Part 2: What is technology? (Continuation of prep lesson); Life cycle of fire; Life cycle paper assessment activity started	1 hour
Day 4	11/1/13	Part 2: Continuation of Life cycle of fire and Life cycle assessment of paper activity	1 hour
Day 5	11/4/13	Part 3: Materials testing	1 hour, 10 min
Day 6	11/6/13	Part 3: Materials testing continued	1 hour, 20 min
Day 7	11/12/13	Part 3: Synthesizing data from materials testing session; brief group planning for oven design	1 hour
Day 8	11/13/13	Part 4: Designing and testing solar ovens	1 hour, 15 min
Day 9	11/14/13	Part 4: Debriefing solar oven data	1 hour
Day 10	11/15/13	Part 4: Improving solar ovens; Testing with S'Mores	1 hour, 10 min
Total: 10 sessions observed			Total time: 11:25:00

---

[5] Part 1 of the unit (the storybook) was covered during ELA time with another team teacher (not observed). These sessions were 45 minutes each over a period of two weeks.

> Interviewer: What about the stage where you felt maybe the least creative?
>
> Jenna: The book part, because we didn't really get to do anything creative. All we did was just listen to Miss Kramer read and try to choral read and then we tried to echo read. That's all we did, with the book. (Monroe student interview, lines 152-154).

Ms. Warner confirmed that these sessions were primarily designed as whole-group instruction (Ms. Warner, personal communication, September, 14, 2014).

Both teachers preferred teacher-led instruction to introduce the storybook portion of the unit to students. While classroom-based discussion was energetic in most instances, there were limited opportunities for students to interact and engage in discussion amongst their peers about the problem, the context, or the characters in the story. The task complexity in part one was low as reported by a student from Landon:

> Megan: The easiest part would probably be the storybook.
>
> Interviewer: That was ... why was that easy?
>
> Megan: Because we just had to listen. [Ms. Collins would] read it and explain it to us like how it worked and stuff so we understood. (Landon student interview, lines 123-129)

In the case of The Engineering Story (part one), both teachers relied on more structured, teacher-led instruction rather than incorporating other more collaborative pedagogical strategies. This style was not mandated by the curriculum, nonetheless was taken up by each teacher as the preferred mode for delivering the story portion of the unit to students. It is unclear if teacher-led instruction in this part of the unit was preferred for its classroom management appeal, time saving ability, or traditional notion of classroom-based storytelling.

In the following Figure 5.2, I highlight the potential spaces for collaboration during each stage of the unit along a continuum. The continuum ranges from minimal opportunities to collaborate (i.e., structured, teacher-led discussion) to maximal opportunities to collaborate in the form of a combination of whole-group and team-based discussion and interactions. The pedagogical strategies employed by each teacher for each part of the unit were placed along the continuum to highlight the opportunities for collaboration in each classroom.

The Field of Engineering

Ms. Collins' class. Both teachers handled part two of the unit similarly, introducing the field of engineering as a whole-group endeavor with a few brief moments of engagement in small group work. The guiding question for this part of the unit was: *How do life cycle assessments help green engineers analyze the environmental impacts of a technology?* Part two of the unit had students examining personal paper use and the life cycle assessment of paper (i.e., reduce, reuse, recycle). This portion of the unit was expected to take approximately 65 total minutes to be properly covered.

Ms. Collins taught her EiE lessons twice daily during the first four days of the unit. She used the hour-long morning sessions (ELA time) to cover the storybook (part one). Ms. Collins began part two of the unit during the afternoon session of day three of implementation (see Table 5.1). She spent the first 15 minutes of class reviewing what they covered in the story from the morning session.

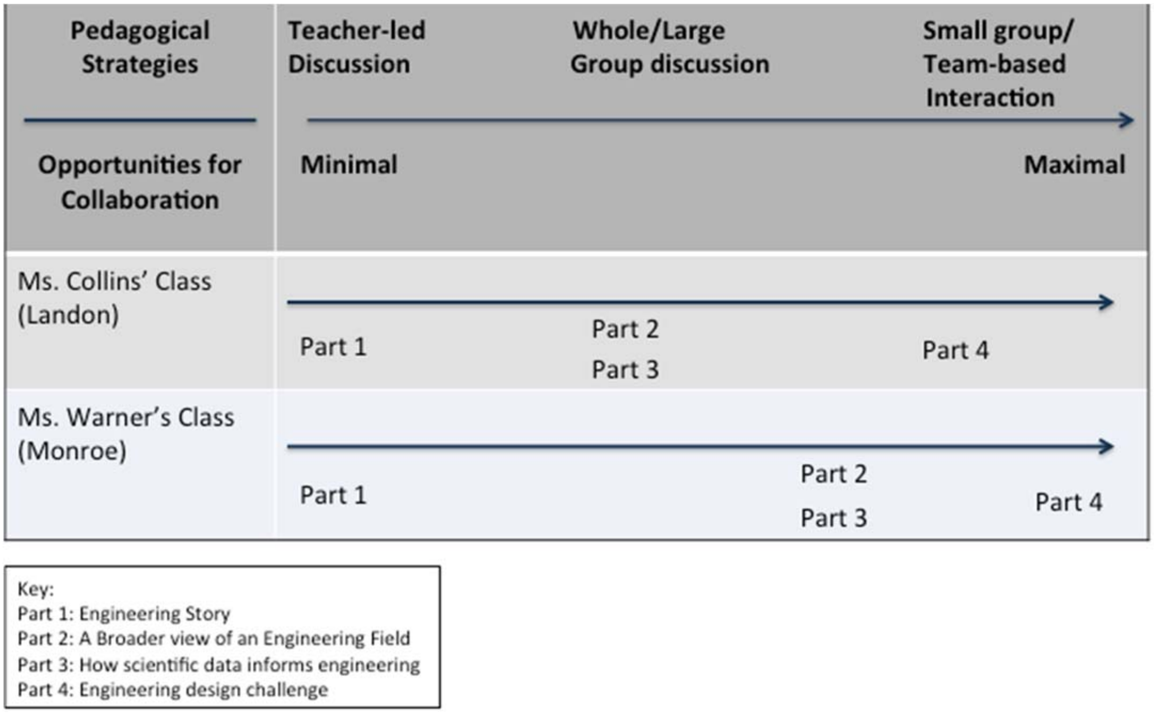


Figure 5.2 Collaborative Spaces During the EiE Unit

Here, she reviewed the life cycle of fire from the story and several vocabulary terms (i.e., resources, environmental impact, pollution) in a whole-group session with students. After this review, Ms. Collins introduced to students that they would be collecting data about how much paper they use in the classroom in a single day. The prospect of this proposed investigation prompted one student to blurt out, “Cool!” (Field notes, 9/30/13). Students had index cards taped to the top corner of their desks to place tally marks on to chart their paper use, chiefly an individual task. Whole class, teacher-led discussion resumed for another eight minutes as the class added definitions and examples to two key terms: *resources* and *environmental impact*. During these whole-group sessions, students were highly engaged and many had their hands up eagerly waiting to be called on to share their ideas. However, cooperative-learning opportunities remained minimal 26 minutes into the lesson.

Almost a half an hour into the lesson, students were divided into groups of three or four and assigned with arranging cards that represented the life cycle of paper, including the terms: reduce, reuse, and recycle. Ms. Collins provided some instructions about how to proceed with the task and assume roles in the group.

> Ms. Collins: There are 7 cards and 3 or 4 members in your group. When we last worked in a group, I noticed that one person took charge. Everyone has to take a card. You have on your card… it says *step* and then *blank*. Each of you need your own card… lay them out in order from beginning to end. Everyone needs a card. Give each person a card. And you'll find extras. Maybe two cards to some people, but not everyone will get 2 cards. (Field notes, 9/30/13, session 2)

After the students completed the task (a total of eight minutes), Ms. Collins asked them to assess the degree of difficulty as a "thumbs up" or "thumbs down"—most students responded with thumbs down ("this was easy"). The remaining 20 minutes of class reverted back to the teacher-led instructional model as Ms. Collins reviewed the life cycle of paper activity with some student input.

In Figure 5.2, I placed Ms. Collins' enactment of part two of the lesson just beyond whole-group discussion due to the engaging, yet primarily teacher-led discussion and the eight-minute span of small group work that lacked elements of a strong cooperative learning experience. The level of practice complexity was also quite low during the period of small group work, as indicated by students' "thumbs down" responses. One student commented on the lack of creativity required during the structuring of this portion of the unit.

> Interviewer: Why do you think that was the least creative part?
>
> Liam: Because we just sat. They just told us.
>
> Interviewer: They just told you what it was?
>
> Liam: We didn't get to guess or figure out what it was by ourselves. (Landon student interview, lines 136-139)

It appeared that Liam (and perhaps other students) desired more of a challenge and active role in the learning process as the class learned about green engineering. Opportunities to collaborate were emerging, but not fully cultivated in part two of the unit.

Ms. Warner's class. Ms. Warner centered a total of three lessons (one hour each) on part two of the unit (see Table 5.2). On day two, the lesson began with a 10-minute review of the previous lesson introducing the concepts of engineering, technology, and the engineering design process (EDP). Next. Ms. Warner showed students a brief video of a NASA materials engineer (a Hispanic male) to students introduce to the potential for diversity in the field of engineering. The next eight minutes were spent re-orienting students to the setting of the story (Botswana), the problem of depleted natural resources, the field of green engineering, and the goal of reducing environmental impact. During this time, Ms. Warner showed another video of a young girl designing a prototype to solve the problem of a dripping, melting ice cream cone to stimulate interest in the engineering design process.

The last half-hour of class was focused on the Tower Power (team-building) activity where students were charged with building a structure out of index cards and tape to support an object 12 inches off the surface of the table within 15 minutes, a preliminary design challenge. Ms. Warner emphasized to students that planning and teamwork were vital to the process. Students were placed into five groups of four. Students assumed either active (spokesperson, designer, builder) or passive (tape holder, index card distributor) roles in their groups. One group composed of three girls and a boy experienced some conflict initially. The tension arose because one of the girls (Missy) wanted to contribute to the design, but felt the others in the group were not accepting of her ideas, particularly the spokesperson, Jenna. Eventually the issue was resolved through compromise with guidance from another adult in the room. However, most groups worked productively toward the goal of constructing a stable tower. Below is an example from field notes and a contact summary form that day.

> A wide variety of designs were evident (ice cream cone designs, segmented, telescoping, card houses, etc.)
> Calvin created a triangular design that supported the object. He problem solved how to get it to support the "egg" until it worked (*persistence*).
> Students all applaud each other after groups share. High level of respect noted. (Contact summary form, 10/30/13)

> Jabari speaks for his group and tells about how they made their ice cream cone design; "I did it in my head" (*Jabari's group created an original telescoping design*). (Field notes, 10/30/13)

The post-construction debrief lasted about 12 minutes with each group sharing their design ideas. The whole class applauded each group after the towers were tested and the design ideas were shared as a show of support, even if the challenge was not fully met according to the initial guidelines.

Ms. Warner structured the next two lessons on part two of the unit to include coverage of the life cycles of fire (the characters' dilemma) and paper (classroom usage). These sessions followed a similar pattern in the classroom consisting of a brief review of the previous lesson, introductory teacher-led discussion, small-group activity work, followed by whole-class discussion facilitated by Ms. Warner. Ms. Warner crafted whole-class discussion to spur interest in upcoming activities. An example from the field notes provides a glimpse into the energy of the classroom.

> Ms. Warner: How can we not cut down all those trees and make something better? So, you all will be green engineers today. (*All students cheer, sit up in seats, say "YAY"*) So, that's what a green engineer does. A green engineer is going to look and say, 'How can we not hurt our environment as much? How can I make something better?' So, what plan can they come up with to improve, people still need to eat, they need to cook their food, they need to stay warm, they need to warm up their food[6]. So how can they make it better? So, we are going to look at the life cycle of paper today.
>
> Students: Paper?! (*Student's surprised responses*) (Field notes, 10/31/13)

Small-group work followed this set-up discussion. Students began to anticipate upcoming activities with enthusiasm. Students were paired according to their seat placement, provided a poster board and a set of cards to arrange in order about the seven steps in the life cycle of paper. The student groups approached the task differently. One group was focused on talking with each other about where the steps should go. One group struggled to compromise initially. For example, as Franco made suggestions his partner was taking cards away and critiquing Franco's placement choices. Four of the paired

---

[6] Ms. Warner presents a slightly different version of *improve* here for students than what is presented in the EDP. Here, she talks about improving existing designs versus improving a design they have created.

groups tried to make decisions based on the way the scissor marks lined up rather than on the content of the cards. Only about three of the pairs attempted to use a logical sequence for how to order the steps. Some students struggled to justify their placements during the whole group recap because of their varied approaches to the task. For example,

> Ms. Warner: What is Step 1? (*Students call out, "The trees grow and are cut down."*) Are we agreeing? (*All students respond 'yes.'*)
>
> Kyree: Step 2 - Logs from the trees are cut down in small pieces. (*All groups agree.*)
>
> Heather: Step 3 - Machines roll the pulp (*Every group disagrees.*)
>
> Ms. Warner: I see disagreement. Jacquelyn, why do you disagree?
>
> Jacquelyn: Because before you make it into paper you have to get the ingredients right. (*All groups agree.*)
>
> Ms. Warner: Heather do you agree?
>
> Heather: We were doing it but [my partner] didn't agree until now.
>
> Ms. Warner: Step 4 (*All in agreement that machines role the pulp into long sheets; No additional discussion.*)
>
> Leah: Step 5 - Paper is transported to different stores to be sold. (*Half of the students agree and half disagree.*)
>
> Bruce: Step 6 - The paper is thrown away and carried by garbage trucks to landfills.
>
> Ms. Warner: I see lots of disagreement. Kyree, why?
>
> Kyree: I disagree because it's the recycling bin one. (*All students disagree with his response.*)
>
> Heather (*disagrees*): Because you can get it from the store, you have to buy it first. (*Still some agreement and disagreement. Ms. Warner sees there is some confusion and then probes for more.*)

> Ms. Warner: Jacquelyn, you disagree, why?
>
> Jacquelyn: Because people; wait never mind, we agree.
>
> Ms. Warner: I would agree with that because what do you do when you go to the store: You buy it and use it.
>
> Franco: The paper is carried away by garbage trucks to the landfill. (*Step 7*)
>
> Ms. Warner: Franco said it is taken to the landfill. (*Everyone agrees.*)
>
> Heather: The one that says *reuse* has 2 arrows so it goes to the bottom.
>
> Ms. Warner: That's right. This arrow says one goes to the landfill and the other says we recycle it. (*Students came to a group consensus about the order. Now each group fills in which step is the correct number for each step of the life cycle.*) (Field notes, 10/31/13)

Ms. Warner toggled between whole-group and paired group work for this portion of the lesson. The variety in pedagogical strategies also helped to promote student buy-in during this phase of the unit and initial experience with working in teams. Student groups took different approaches to the task, with varying results. The reflection portion of the lesson allowed students to work through their decisions for card placement and justify their answers. For Ms. Warner's class, part two of the unit was located on the continuum between the whole group and student pairings on Figure 5.2 to represent the balance of teacher-led and small-group collaborative work.

Materials Testing

Ms. Collins' class. Part three of the unit was focused on materials testing. The guiding question for part three was: *What materials are good thermal insulators and also have a low impact on the environment?* According to the teacher's manual, this portion of the lesson could be divided into three parts consisting of one hour each at minimum. Each teacher decided to structure portions of the lesson to best meet the needs of their class and limitations of time according to their school schedule.

Ms. Collins implemented materials testing on day four during the afternoon session. She completed the extension of this lesson at an unscheduled time the following morning when researchers were not present because the opportunity presented itself unexpectedly. The materials testing session was planned to consist of a controlled experiment to test the performance of flat and shredded materials as insulators, analysis of data and materials to determine environmental impact, and discussion of potential solar oven design options that utilize materials wisely.

The first 20 minutes of the lesson on day four consisted of Ms. Collins introducing the basic structure of the solar oven students would be designing and accepting ideas students eagerly shared.

> Raul: I have an idea to use foam block as a good insulator (*He uses the terms "insulator" and "conductor" in his descriptions.*)
>
> Tommy: Is plastic wrap that goes on sandwich bags a good insulator? (*Students quietly consider this. Ms. Collins shows a diagram of a solar oven on the overhead. She asks about the term "reflector."*)
>
> Jane: You can reflect light into the box.
>
> Meagan: Clear plastic can go over the top.
>
> Callie: [Insulation] is for getting heat trapped inside the box.
>
> Ms. Collins: Think about light coming through windows in the classroom.
>
> Megan: The clear window [in the oven] will allow you to see what you are cooking.
>
> Liam: A metal sheet would allow heat to be conducted in.

> Jane: If it gets hot enough inside the box, would closing the reflector trap the heat? *(Ms. Collins tells students about the boxes they will get tomorrow—a few students gasp with excitement as she shows them.)*
>
> Tommy excitedly shares his ideas for getting it really hot inside [the oven]. (Field notes, 10/1/13)

After a brief whole-group discussion of the properties of the materials they would be testing, Ms. Collins separated students into six groups of four. Student teams were assigned a material to test for its insulating properties (aluminum foil, plastic grocery bags, newspaper, cotton t-shirts, felt, or foam) in a cup with a thermometer. Students had to decide amongst themselves what role they would assume (recorder, temperature reader, cup holder, etc.) in their groups. They recorded the temperature of the materials in the cups in 30-second intervals. First, they measured the temperature of the air inside the cup and then they recorded how well the temperature was maintained when submerged in an ice bath. Time ran out just as the experiment concluded with the last temperature reading. After the experiment, Ms. Collins shared with me that as she was monitoring students during the testing, many appeared to have difficulty reading the thermometers accurately and some struggled with how to record their data properly on their worksheets.

Although students were placed in small groups to conduct the experiment, their work together was very carefully scripted and sequenced. Students who broke protocol during testing were gently reprimanded and redirected (e.g., “Raul, return to your table, it’s time to take our temperatures again”). There was not ample opportunity to engage collaboratively and meaningfully with their peers before, during, or after the experiment other than in the whole-group discussion during the first 20 minutes of class. The testing phase lasted approximately 30 minutes, followed by 10 minutes of teacher-led recap of the initial findings (e.g., thumbs-up or thumbs-down to indicate if their materials were good or bad insulators).

I placed Ms. Collins' class on the continuum on Figure 5.2 just outside the border of whole-group and student pairings due to the scripted nature of this session and the limited time and opportunity to collaborate with peers.

Ms. Warner's class. Ms. Warner allowed for a total of three sessions (totaling three and a half hours) to complete the materials testing portion of the unit. The first 40 minutes of the first session were centered in whole-group discussion reviewing the problem from the story, viewing pictures of different types of solar ovens from around the world, and providing an overview of the parts of the solar oven.

Students were actively participating in the discussion, making connections to their lives. Ms. Warner allowed for many student voices to be heard, while emphasizing taking turns and being respectful.

> Ms. Warner: What do the solar ovens all have in common?
>
> Dwayne: They all have glass, metal or tin foil.
>
> Candace: [The metal part] is for reflecting. *(Ms. Warner talks about how they can direct the lid of the solar oven to absorb heat from the sun.*)
>
> Ms. Warner: Why do you think it has to be closed?
>
> Jabari: Because heat can warm it up and not go outside of the box.
>
> Ms. Warner: Once the heat is in, we want it to stay in.
>
> Heather: Keeping the lid closed protects the contents inside and the covering is clear so you can see if the food inside is boiling—protects you from the heat. In

> case it splashes out and burns you. (*Heather is worried about how hot the oven will get.*)
>
> Dwayne: When the sun reflects off of the tin foil, [the heat] can go thru it.
>
> Calvin: How does the sun get in if it has a plastic cover? (*Ms. Warner asks students to try to make a real-life connection.*)
>
> Elise: The sun can shine through the plastic.
>
> Ms. Warner: What kind of thermal transfer comes from the sun? (*Jenna makes an attempt to answer, but hesitates.*)
>
> Kyree: Radiation.
>
> Ms. Warner: Traveling how?
>
> Bruce: Heat waves.
>
> Ms. Warner: The closer the waves, the stronger the heat.
>
> Dwayne: (*Making a connection*) When I used to play football, they used to hold hands in a circle and people would try to run through them, but when they stood closer together, people had trouble getting through. (Field notes, 11/4/13)

Ms. Warner worked with students to recall the science content they learned that preceded the engineering unit. Students shared their ideas about how the solar ovens would work, drawing from personal experiences.

The remaining 20 minutes of class were focused on making predictions about the materials they would be testing for their insulating properties. Students were randomly assigned in groups of two, three, and four students (mostly based on where their desks were located). They completed this portion of the lesson as a whole group with brief interludes of small group discussion. Student groups listed the properties of each of the six materials (flat or shredded) and made predictions about how they would perform as insulators or conductors on their recording worksheets.

The controlled experiment took place during the next session (day six, 11/6/13). Again, this session was mostly whole-group discussion infused with intervals of small group work. Ms. Warner made a point of reviewing how to properly read the temperature on the thermometer, using the overhead projector to visually instruct students. Students practiced reading the increasing temperatures on the thermometers as their partners held the bulb.

> Jabari excitedly starts to heat his hands to place on the bulb to heat it. Ms. Warner comes around to check on their group. She has assigned roles for each student.
>
> Ms. Warner: Elise, hold the bulb and Jabari can read the temperature.
> *(Elise is switched back as the bulb holder because Jabari is having trouble reading the thermometer.)*
>
> Calvin (*at another table*) is excited, “We got 98!” He is holding the bulb and watching the temperature rise. (Field notes, 11/6/13)

Next, student groups placed their assigned materials (shredded or flat) in their cups and testing took approximately 15 minutes. Testing was conducted with one partner from each group reading the temperatures and one partner recording. After the temperature data was collected, recorded, and shared the whole group made predictions about what would work as the best insulators or conductors.

> Dwayne: Tin foil, because it is real thin. It tears easily and maybe it is not a good insulator.
>
> Jenna: Foil is not good because I tried putting foil over a vent in my house once and it didn’t work. (*Drawing from prior experience*)

> Ms. Warner: Is foil an insulator or a conductor? If it grabs heat quickly, it's a good conductor. It transfers heat.
>
> Bruce: Newspaper, because it is easily burnt (*He thinks it conducts heat*.)
>
> Franco: (*Disagrees with Bruce*) People can put newspaper on their bodies to keep warm. (*Arguing for newspaper as an insulator*)
>
> Elise and Heather agree with Bruce. (Field notes, 11/6/13)

Again, in the course of discussion, students attempted to apply their new knowledge and form connections to their lives as they made sense of the new data that was recently collected.

The whole class synthesized the data in the final session (11/12/13) of materials testing. The teacher and students worked together to construct a graph-like continuum of their data on the board. The class recorded the insulating properties of the materials on the board to be used for decision-making in the design phase of the unit. During this hour-long session, students spent approximately six minutes in concentrated small groups discussing ranking of the materials with their partners. The final 20 minutes of class were focused on these small-group brainstorming sessions that included pre-planning for ideas about materials usage in their ovens.

Part three in Ms. Warner's class was placed on the continuum on Figure 5.2 between whole group and small group interaction due to the opportunities for students to discuss and problem-solve with their peers amidst a whole-group dynamic. As the complexity of the tasks increased, so did students' opportunities to collaborate, share ideas, and discuss options for the solar ovens

The Design Challenge

Ms. Collins' class. Ms. Collins' class devoted a total of four sessions over the course of five hours for the design challenge. The guiding question for part four of the unit was: *How can we use our knowledge of the thermal properties and environmental impact of materials, the Engineering Design Process, and our creativity to design a solar oven with minimal environmental impact?* During the design challenge, students in both classes were assigned in pairs to collaboratively navigate the engineering design process: *ask, imagine, plan, create,* and *improve.*

Ms. Collins used the first 35 minutes of class to review the results of the materials testing with students. She discussed environmental impact with students and what counted as a good insulator or conductor. Ms. Collins let students know that they would be working together during the *imagine* phase of the design process. She reviewed the environmental impact scoring sheet they would be using to record the number of units of materials used in the ovens and whether the materials were considered natural or processed resources. After this lengthy set up, students were allowed to begin brainstorming (individually, at first) ideas for their designs. Then, students spent five minutes sharing their ideas with their partners.

> Sasha's partner says to her, "I'm a jock not a science guy" (*Is he making up for his lack of ideas?)*
>
> One male partner is sitting by himself at the tables while Raul is over at the materials table checking things out and socializing. Ms. Collins tells Raul to return to his partner.

> Jane and her male partner are lifting the projection screen at the front board to get a better look at the cards posted there for good/poor insulators and low/high impact factors (*class data*).
>
> Russell and Faye are at the materials table planning together.
>
> A female student and Megan are sitting in chairs facing each other, writing on small white boards to get their ideas down (*It looks like Megan is helping her with what to record*). (Field notes, 10/2/13)

Some of the groups appeared to be off to a better collaborative start than others. In a subsequent session (10/3/13), Ms. Collins remained mindful of the limited time available to plan and prompted students to work efficiently.

> I am now going to give you 5 more minutes to recap with your partner what your plan is, what your units are, and where you plan to put those units. You have 2 sides to fill out that are different (*referring to the worksheet*). One is the diagram where you are drawing what you are putting in [the oven]. The other is a list of materials you plan to use. Ok, find your partners and let's finish this up. (Field notes, 10/3/13, session 1)

One student (Liam) expressed worry about how they would be assessed in this stage of the unit. Ms. Collins did her best to reassure students that the focus was on learning and working well with their peers rather than grades. She addressed the class as follows:

> Ms. Collins: Now, I don't know if you heard Liam asking about this yesterday. He was asking about grades and he was a little concerned about the grading of this and I said to him NO, your score of your oven will not affect a grade. I want you to hear that. What I grade is, I look at everything you do (*One student interrupts here*) and I look to see how you're doing it and the quality of your work.
>
> [Student]: What if you fail on it?
>
> Ms. Collins: Just a minute. Right now everybody is doing a fabulous job, ok? You're working well with your partners that you've been with. You've been doing a very nice job of the work you did yesterday. I took a look at [your planning

> sheets] and it looks like you responded pretty well. And, that is what I graded you on. Out of 5, I gave you a number to see how you did. (Field notes, 10/3/13, session 1)

After the discussion about grades, Ms. Collins carefully reviewed with students the units of measurement for materials and how to record the material usage on their scoring sheets. Before she released students to work with their partners on planning and design, she talked to the students about "compromise."

> So we are taking the information we learned about yesterday. We each had an opportunity to imagine. And, to determine what you thought should go into the solar oven. Then you got together and you put the plan together with your partner. During that time you did what you needed to do. I'm hoping you were able to compromise. Did anybody feel that they just had to say, "Yes, yes, yes"? Did anybody feel that their partner did that to them? (*No students raise their hands*). Wow! We are in this boat together aren't we? Very nice. Very nice job. I'm loving this because that's one of the really hard skills of people skills to really compromise. Did anybody get exactly what they wanted? (*Most groups raised their hands*) Is that because you both agreed on the same thing? (*Students respond 'yes'*). Ok, we are now at the point where we are going to create. It's now time to get materials. In order to do this, I will call 3 couples at a time. I'm calling you a couple because you're working together. Would 'team' be better? (*Students call out, "YES!"*). (Field notes, 10/3/13, session 1)

Ms. Collins' remarks were an attempt to ward off any potential problems before they began and to provide students with some guidelines for group decorum. Students appeared to listen attentively to her instructions. Ms. Collins was attempting to make the norms of collaboration explicit for students, letting them know that collaboration involves compromise.

Students were provided the remaining 20 minutes of class to plan and design the solar ovens. Groups worked diligently and even shared ideas across groups to incorporate ideas that they considered unique and potentially effective.

> Group 4—Callie and Eli (*They place felt on the bottom, foam on all four sides, aluminum foil on bottom, foil covering bowl, and they redesign with foil.)*
>
> Eli: I have an idea to put cotton balls in between the foam and the wall.
>
> Callie: Why?
> (*Eli, the apparent leader of the group starts to explain and before he is finished…*)
>
> Callie: Oh, I see, so the foam can insulate and the cotton balls can help keep the heat in! *(They make decisions about adding another layer of cotton balls. Students are thinking about house insulation, an idea used by another group).* (Field notes, 10/3/13, session 1)

In the afternoon session on day six (10/3/13), student groups went outside to test their solar ovens in the sun (for 30 minutes) and shade (for 10 minutes). Outside, the students were very enthusiastic when monitoring their temperatures despite the unseasonably warm day. Students shouted out the temperatures they were recording, "mine is at 100!" Students continued to shout out their ever-rising temperatures in a seemingly competitive manner, eager to see whose solar oven temperature would rise the highest. In the excitement, one student stepped on a thermometer and it broke. Ms. Collins handled this calmly by handing them a replacement thermometer and reminding students about safety and control. After returning to the classroom, Ms. Collins briefly shared that the control box with no insulation lost heat quickly. She asked students to raise their hands if their oven temperatures were higher than the control. About three quarters of the students raised their hands that their temperatures remained 90 degrees or higher in the shade. Russell and Faye experienced some trouble reading their thermometers accurately in the shade causing errors in their reporting. Callie excitedly mentioned that she already knew how she was going to improve her oven in the next session.

On the final day of the unit (Day 7, 10/4/13), students spent 30 minutes redesigning their solar ovens after a brief recap with Ms. Collins. This time, they were testing the ovens with S'mores (a graham cracker, chocolate, and marshmallow combination) in the inner cup. The students expressed excitement about what they would be cooking. Ms. Collins tried to focus students on what she considered their lack of attention to the use of shredded materials as insulators. In a previous session, she shared these concerns with the research team:

> I'm so disappointed right now. I'm just surprised they aren't filling in the air because I pretty much connected the dots yesterday. They're just doing crafts it looks like now. They are just excited about using materials. What happened yesterday was very good. But this seems really bad. Had we been able to build right after we talked, or if we had a different schedule, maybe it would have been different. I'm not sure though. But I don't know, like trying to explain to that kid right there about the notecard having to be on the outside of the box, he's not interested. They are on a deadline. They are crafting and having a good time. I'm so sad. But you know what? That's part of the engineering design process. Especially if they find out how it worked in other classes because they are very competitive. I know it's part of the process but I'm just a little disappointed right now. (Field notes, 10/3/13, session 1)

During the debriefing session, Ms. Collins encouraged students to consider the results from the initial solar oven testing and to use data to make informed decisions about improvements.

> Ms. Collins: This is what engineers do. They make improvements.
> (*She asks whether the shredded or flat plastic bag was the better insulator*.)
>
> Lana: Shredded.
> (*Ms. Collins is placing cards on the board to indicate which were the best materials to use for insulators. Shredded aluminum foil gets added to the board as a good insulator. Felt got the same temperature change, shredded vs. flat. Newspaper—shredded did better than flat. Ms. Collins asks students to draw conclusions.*)
>
> Jane: The shredded material fills up the air.
> (*Ms. Collins asks how many students used shredded materials—only about 2 or 3 groups indicated they used shredded. Ms. Collins asks what improvements do students now have in mind.*)
>
> Eli: Using black felt.
>
> Tommy: Using more cotton balls.
>
> Callie: Shredded aluminum foil around the cup.
> *(Ms. Collins tries to get them to think about the rest of the space in the box. Her frustration continues, as some students are still not quite "getting it."*)
> (Field notes, 10/4/13)

Students placed their improved solar ovens outdoors with the S'mores cups inside the ovens and were dismissed to lunch due to the time restriction of an early dismissal day. Ms. Collins later reported that the students enjoyed the S'mores, which were sufficiently melted after 30 minutes in the ovens.

I placed Ms. Collins' class along the continuum just beyond the whole-group discussion and entering into the realm of team-based interaction in Figure 5.2 due to opportunities for collaborative work among students during the design process. Despite the five hours dedicated to design, time continued to be a limitation in Ms. Collins' class. Dedicated group work at times took a back burner to teacher scaffolding and instruction. Some students expressed concern about how their work would be evaluated during this phase of the unit. Additionally, some tensions arose between group members during the design process and competition was a factor during testing. Even though Ms. Collins was faced with these group-level challenges, the students engaged maximally during the complex nature of the design challenge in their successful design teams.

Ms. Warner's class. Ms. Warner devoted three class sessions to the design challenge for a total of three and a half hours of class time. The first of these design sessions began with students receiving approximately seven minutes of set-up instructions, brief teacher instruction, and materials distribution. The remainder of the hour and 15-minute session was devoted to group work on the solar oven designs and testing.

The previous day (Day 7, 11/12/13), Ms. Warner devoted the last 10 minutes of class orienting students to the box models that will be used as solar ovens. She reviewed procedures for correctly placing the thermometers in the box and propping the lid for reflection of the sun. Calvin helped to pass out the box models to students so that they could spend the remainder of class time brainstorming ideas for types of materials to use and their placement with partners. Students were allowed to bring in items from home as long as they were recycled, reused, or reduced as in the story. The whole class discussed additional ideas for materials including: dried leaves (Dwayne's idea), t-shirts, cotton, and shoestrings. Ms. Warner shared the items that had been donated to the class to include: magazines, foam pieces, plastic bags, and newspaper.

During the short period of pre-planning time, I overheard Katrina and Jacquelyn say that they were going to cook "fried ants" in their ovens. A more serious Heather discussed how her group would use shredded foam on the inside the oven because it got a number-one ranking in their scientific testing. Her partner Jordan agreed, nodding his head as he examined the oven more carefully. Franco was contemplating the angle of the ruler that would be used to prop open the reflecting window, repositioning it to imagine how it would be angled to face the sun. After this pre-planning session, students had to return the box models and dismiss for lunch.

Ms. Warner limited actual time for construction on day eight (11/12/13) to 15 minutes so that the students would have enough time to go outside to test. This required student teams to work quickly and efficiently to assemble their ovens based on their pre-planning during the previous day's lesson. Heather and Jordan were busily tearing magazines, adding cotton balls, and shredded foam to their oven. Jordan constructed a double layer of materials to the interior.

Dwayne explained his thinking about his group's design to me as follows:

> Interviewer: So, is the foil just going to go on the bottom or on the bottom and the sides?
>
> Dwayne: It's going to go on the sides. We're going to put this (*a flat piece of foam*) on the bottom. (*Dwayne's partner Jake was trying to break in to add a comment, but Dwayne appeared to be ignoring him.*)
>
> Interviewer: Will that be on top of the foil?
>
> Dwayne: Um, no. This (*flat foam piece*) will be like on the bottom.
>
> Interviewer: And then the foil will go on top of the foam?
>
> Dwayne: Yes
>
> Interviewer: Are you using flat materials or shredded, or both?

> Dwayne: I've used flat so far. We haven't thought of nothing else yet, so… (Audio recording, 11/13/13)

Dwayne and his partner, Jake did not appear to be communicating well together during design, with Dwayne taking the lead in decisions about materials and placement. Calvin and Kayla seemed to have established a good working relationship as they listened to each other's ideas and lightheartedly motivated one another to move quickly because of time.

> Calvin: It keeps the heat inside!
>
> Interviewer: Flat paper will keep the heat inside? Is that what you found from your data?
>
> Calvin: Yes. C'mon Miss *(inaudible, he is talking to his partner, Kayla)* you're going slow.
>
> Interviewer: (*laughs*). Is she too slow for you? (*Calvin continues to playfully sass his partner*). So are you going to use all flat materials, then? That's your decision?
>
> Kayla: I think so.
>
> Interviewer: Okay.
>
> Calvin: We gotta cut fast!
>
> Interviewer: Okay, Calvin is on the move here with the fast cutting. (*I returned a few minutes later to see they had made a change in their design.*)
>
> Interviewer: What made you decide to take this foam out and put foil in instead?
>
> Calvin: Um, well, she (*Kayla)* said…
>
> Kayla: It wouldn't fit the right way.
>
> Interviewer: Okay.

> Calvin: So we had to snip it down! (*Ms. Warner calls for two more minutes*.)
>
> Kayla: Oh no! Two minutes! (Audio recording, 11/13/13)

Calvin and Kayla seemed to have a good rapport and were working fast to meet their deadline. Both were highly invested in accomplishing the goal of finishing the design in time and worked together despite a few decisional challenges.

The student teams were highly motivated to get outside and test their ovens. Whereas Ms. Collins' class dealt with uncomfortably warm outside temperatures, Ms. Warner's class experienced temperatures in the 40-50 degree range on their testing day. However, the sun was shining brightly.

Outside testing took the remainder of the session. Students enthusiastically recorded temperatures. Similar to Ms. Collins' class, students called out rising temperatures at regular intervals. Bruce shouted out, "72, 72, 73!" as his temperatures slowly climbed. Another student exclaimed, "we got 90!" after some time in the sun. Students were also highly active in the intervals between recordings because of the cold day.

> The ovens are placed in the sun. Students run up and down the adjacent hill trying to keep warm (it is only about 45 degrees outside, but sunny). Students are doing jumping jacks too. Calvin is rolling down the hill. At first, only a few students join in, soon all but a few are left at their ovens—Jordan (Heather's partner), Candace, and Missy stay behind to monitor their ovens. (Field notes, 11/13/13)

> Students are allowed to be silly and run, do jumping jacks, and play while they wait to record temps in the sun. It is really cold today and this is their way to stay warm. Ms. Warner does not get "worked up" about their rambunctiousness (Contact summary form, 11/13/13)

One pair of students, Franco and Leah, reported some high temperatures during the sun testing. Leah shared some of their initial results with researchers, “We started out with 82 and now it’s all the way to 112!” (Audio recording, 11/13/13). Franco added that their design of adding newspaper and cotton balls to the top of the oven (lid) kept the heat in. Another group, Heather and Jordan, described their layering strategy to trap heat. Heather added, “When I was designing in my head, I was like maybe we could put in one more layer in there” as she was already considering how they might improve their oven to cook more efficiently. Jordan continued by describing the three cotton ball layers they designed along with layers of foam. Jordan explained further, “We did it in layers, so that the bottom part would get heat, the middle part would get heat, and then the top part would get heat, so everything can get heat.” These teams appeared proud to talk about their designs and how they worked together to build and develop their ideas for insulating their ovens.

In the shade, students recorded drops in temperature. Some students (Dwayne and Bruce) experienced some difficulty in accurately reading their thermometers. Dwayne made the error of taking his thermometer out of the box to read it, which cooled it off significantly. Katrina and Jacquelyn stayed close by their oven, while Katrina called out temperatures and Jacquelyn recorded them crudely on a scrap of paper rather than recording on the worksheet Ms. Warner provided. Katrina and Jacquelyn maintained a calm, non-competitive demeanor throughout design and testing phases of the unit.

The next day (Day nine, 11/14/13), the class reconvened to debrief the solar oven data they collected in the previous session. Ms. Warner used the first 20 minutes of class to instruct students in how to access Google Drive to upload their group data so that the whole class would have access. Students used mini-laptops with an app to access the Drive, upload their sun and shade testing data from their science journals, and learn how to select "share" to invite others to view their data. Ms. Warner explained to students, "you and your partner are going to talk about your data once it is entered into the spreadsheet. [You] need to think about the materials [you] used and how they performed" (Field notes, 11/14/13). The next 20 minutes were spent with groups working together to enter data. Students considered their falling temperatures in the shade and thought about what modifications they might make during the improve stage.

During the final 25 minutes of class, Ms. Warner called the class together again so that each group could report their results. Students did so verbally while Ms. Warner projected the shared data on the overhead. Each group presented how their temperatures changed in the sun and shade as well as what materials they used to construct the ovens. Ms. Warner recorded students' use of materials on a table on the overhead. This data would be used to improve the ovens. For example:

> Calvin and Kayla—They share how they started with newspaper all around the box and how they added foil. After presenting, Calvin asks for questions about their design.
>
> Franco: Show us what did you use to get the tin foil to stay on there?
>
> Leah: What is under the tin foil?
>
> Jordan: Do you think you should have used cotton balls? (*Ms. Warner notes information about materials use and placement on the overhead*). (Field notes, 11/14/13)

> Franco and Leah show their oven to the class—Newspaper on the bottom and the top and edges. Cotton balls on top so when heat escapes; the cotton balls will stop it. Newspaper was used on the edges. They also lined their lid—more newspaper inside and on the top. They put a hole so the thermometer could go in. Questions from the group:
>
> Isaac: Did you use tape?
>
> Jacquelyn: Do you think that the cotton balls worked the best?
>
> Franco and Leah: Yes.
>
> Katrina's: Glue or tape on the lid?
>
> Franco: Tape. (*The class claps after their presentation*) (Field notes, 11/14/13)

Students asked questions of each other to determine what worked best and what did not. After the sharing session, Ms. Warner instructed students to reflect on what they wrote in their science journals, to look at others' ovens, and consider how they constructed their designs.

During the final session (Day 10, 11/15/13), students worked in their groups to make improvements on their solar oven designs for the first 30 minutes of class. Many groups decided to adopt Franco and Leah's idea to insulate the lid of the oven because their results were so impressive on initial testing.

> Interviewer: So, you are going with shredded newspaper, Heather? And, you got cotton balls?
>
> Jordan: …and newspaper in there.
>
> Interviewer: Yeah, you lined it with lots of layers of newspaper (*Jordan has been tearing newspaper to add to the oven. It is starting to look like a bird's nest inside.*)
>
> Jordan: Yeah, we wanted to put more layers in there so it can be warmer.

> Interviewer: Alright.
>
> Jordan: …and we're going to put the shredded newspaper, and then we're gonna put, um…Wait! Take that out! (*Talking to Heather*)
>
> Interviewer: When do the cotton balls go in? (*Insulating the lid like Franco and Leah's design*)
>
> Heather: After we put the foam in and put the layers of the shredded newspaper. Keep on shredding some newspaper, Jordan *(Telling Jordan what to do*)
> (Audio recording, 11/15/13)

Cotton balls became the material of choice after Franco and Leah reported their highest temperatures of 114 degrees Fahrenheit in the sun. Using shredded materials also became a popular material to choose because of its insulating properties.

Unfortunately, the weather did not cooperate for testing the improvements and cooking the S'mores on the final day. Instead, Ms. Warner asked students to reflect on their designs and the improvement process and to answer the following questions with their partners, recording their responses in their journals. The question prompts included:

> What materials did you use to insulate your solar oven?
> Why did you choose those materials?
> What parts of your first solar oven design worked well? How do you know?
> If your oven did not hold the heat very well, does this mean you failed?
> (*Ms. Warner has written "NO" to this prompt*)
>
> Ms. Warner: From this experience you can learn. That is what engineers do—they try—they analyze their solution—they improve—they try again—and keep doing this until they feel they have their best product. (*Additional questions are posed to students.*)
>
> How did you improve your design? Keep in mind environmental impact of materials.
> Why do you think this is going to work? (Field notes, 11/15/13)

Students worked on the reflection questions for about 25 minutes with their partners. Ms. Warner called the class to reconvene and share their improvements during the final 20 minutes of class. As before, groups presented their (improved) solar oven designs to the class and their peers asked clarifying questions. For example:

> Jaden and Isaac—(*Isaac is reluctant to initiate talking*) Isaac speaks and tells about their re-design using cotton around the edges of the lid (*Building on Franco and Leah's design*). They used tin foil and mostly modified the inside.
> Missy and Kyree—They added a lot of shredded foam and newspaper.
>
> Kyree: It would insulate the heat better (*Missy does not speak*).
>
> Elise: Why did you use so much tape? (*Ms. Warner asks Missy to speak up.*)
>
> Missy: It holds everything together.
>
> Jabari talks about reusability and trying not to use too much tape. Franco suggests next time not using as much tape.
>
> Ms. Warner (*Reminding students*): We are asking questions and helping. We are not criticizing. We can offer suggestions, but we are not saying, 'Well, why did you do that?' Think about how you say things. (Field notes and audio recording, 11/15/13)

Ms. Warner made a point to emphasize that students should maintain a collaborative atmosphere during their sharing session. She provided guidance for development of teamwork skills and problem-solving capabilities.

I placed Ms. Warner's class on the continuum within the shared group space of Figure 5.2 to indicate the high level of collaboration and team-developing orientation offered in the classroom during the design phase of the unit. Ms. Warner intentionally taught to develop and encourage teamwork skills. The culture of the classroom was one of support. Students applauded each other's successes during sharing sessions. Ms.

Warner incorporated technology to encourage collaboration and data distribution. Students learned to function as efficient pairs, in small groups, and in a collaborative whole-class dynamic during the engineering design process. The problem-solving atmosphere of part four of the unit provided the ideal context for developing these collaborative skills.

Summary: Spaces for Collaboration

Each teacher structured the solar energy unit with slight variations due to limitations of time allotted for teaching science, restrictions in the daily school schedule, the particular needs of their students, and their personal teaching styles. These pedagogical variations produced slightly different outcomes regarding spaces for collaboration. Minimal opportunities for collaboration were characterized in each class by more structured, teacher-led instruction (e.g., Part one, The Engineering Story). Maximal opportunities for collaboration occurred with a balance of dynamic whole-group instruction and team-based student interaction. These opportunities were optimal in both classrooms during part four of the unit (The Engineering Design Challenge).

Smith et al. (2005) have outlined specific guidelines for fostering collaboration in engineering classrooms. Problem-solving lessons provide a suitable environment for development of teamwork skills. Sufficient time practicing these cooperative, team-building skills allows students to become more fluid and flexible in their thinking. Problem-based learning is particularly suitable for engineering, which breaks away from the more subject-based learning frequently present in traditional schools (and science classrooms) today. Students learn to strengthen their collaborative skill set to function well as a productive member of a team, which is critical to the field of engineering.

The design phase (part four) of the solar energy unit provided optimal opportunities for students to engage in cooperative learning and collaborative interaction due to the complex nature of the open-ended design challenge in both classes. Intentionally teaching to cultivate collaboration among students appeared to be the most effective strategy for productive student work. Periods of reflection, group sharing, and encouraging an atmosphere of respect provided optimal conditions for learning. While teacher scaffolding is a necessary component of effective instruction it must be carefully balanced with student autonomy and freedom to explore through successes and failures.

This section has been focused on laying out the structure of the solar energy unit and how students and their teachers interacted during the process. In the following section, I take this analysis one step further to examine the emerging cultural production of collaboration present in each classroom. I do so by focusing on the engineering design process in part four of the unit and students' descriptions of their interactions during this stage.

The Cultural Production of Collaboration

The final portion of the student interview was designed to get a better understanding of students' perceptions of the engineering design process through a reflection of the process and the products they created (see Appendix E). Students were presented with a picture of their solar ovens in various stages of development to trigger their memories. The primary interview prompt was: *Tell me about the process you and* *your group members went through to make this product*. In this section, I explore the meanings that students made of the design process, in their words. I study the cultural production of collaboration by examining students' language, personal accounts, and perceptions; the ways in which they described their individual and collaborative experiences.

I applied interpretive strategies from Carlone et al.'s (2012) work as a guide for interpreting students' descriptions of their collaborative experiences. Specifically, I analyzed their interviews for "we" language (collaborative, group-level descriptions) versus "I" language (personal accounts, individual-level descriptions) to determine their perspectives on the design process. I acknowledge that the interview question prompt I used included asking students about the process of "you and your group members" or "their" products, potentially biasing their responses. However, I believe the students' choice of language was particularly telling, as they chose whether to talk about just themselves, their partners, or a mix of both. Student descriptions along with personal reflections of their work in the class and with their team provided a glimpse into the cultural production of collaboration in each classroom.

"We" Versus "I" Language

In the final portion of the interview, the research team asked students about their design process, challenges faced, personal accounts/stories, and how they personally felt about their final products. These supplemental questions included:

1. Tell me about the process you and your group members went through to make this product.
2. What were the challenges in creating this product? What were the easy parts?

3. What else would you like me to know about your engineering design product?
4. How do you feel about what you and your group members created?

I analyzed each interview, coding for instances of group talk ("we" language—e.g., we, ours, us) and instances of individual-focused talk ("I" language—e.g., I, me, my, mine) to get a better idea of how students conceptualized the design process. Students from both classrooms worked in assigned pairs. I also paid careful attention to the gender of group members and their ethnicities to determine if any patterns existed with regard to influences of demographics in the pairings.

The use of "we" versus "I" language was not overwhelmingly different in both classrooms, however students in Ms. Warner's classroom used "we" language about 10 percent more than in Ms. Collins' classroom when describing their products (see Figure 5.3). This aligns with the findings in the previous section where Ms. Warner's students spent more time working in pairs and collaboration was intentionally cultivated and reinforced during the unit. Looking collectively at the language usage in both classrooms, students talked about their products using "we" language approximately 62% of the time. "I" language was used less frequently, approximately 38% of the time. Representative samples of students' descriptions are explored in the following sections for each classroom to better understand the cultural production of collaboration through design.

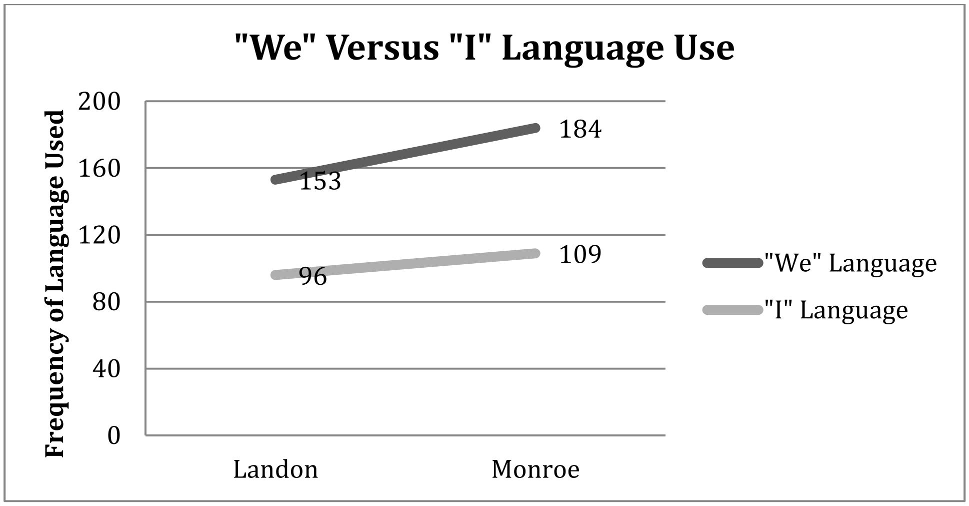


Figure 5.3 "We" Versus "I" Language Usage Among Students Describing Design Products[7].

Landon students' descriptions of products: Ms. Collins' class. Within most pairings, students experienced the development of camaraderie and worked on their design teams to build their teamwork skills. However, some groups struggled with compatibility issues that created tensions, hindering progress. The language students used to describe their products provided insight into these constructive or not-so constructive dynamics.

> Interviewer: So, tell me about the process you and your group members went through to make your product?
>
> Chad: A lot of talking.
>
> Interviewer: Okay what else?
>
> Chad: A lot of team work and sometimes **we** would like argue about who should do it but…

---

[7] Note: There were four more students at Monroe than Landon. These qualitative data are suggestive of broader themes rather than statistically significant quantitative data.

> Interviewer: How did you solve that problem?
>
> Chad: **We** solved it by just, **we** just listened to each other and then **we'd** choose who had the best [idea] and **we'll** take it as theirs.
>
> Interviewer: Okay, alright. What were the challenges in creating this product?
>
> Chad: Well, it was kind of hard because some of the teams … because some of them wasn't listening, within the last couple of days they started listening then they got better and they started working as a team. Their project got better and better. (Landon student interview, lines 182-195)

Chad reflected on the teamwork involved in solving the design problem, regularly using "we" language. Chad also mentioned initial hardships among teams that were resolved with time, improving the ultimate outcomes.

Other student pairs referred to themselves and their own contributions (when asked about their group work) toggling back and forth between "I" and "we" language (highlighted below for emphasis).

> Tommy: Because **we** had like so much units and **we** used a paper bag **we** used two different pieces of construction paper, both different color, two things of tinfoil cotton balls, felt…
>
> Interviewer: You were just going full tilt, huh?
>
> Tommy: Yeah.
>
> Interviewer: Ok, pretty cool. Well, how do you feel about your design, like how do you feel about what you guys produced?
>
> Tommy: When **I** looked at it originally, the first version, **I** was like it looks like it does everything and people were like wow, wow. But then, several people did, **I** think everybody did better than **us**…
>
> Interviewer: Wow.
>
> Tommy: …but when **we** fixed it.

> Interviewer: You mean according to the temperatures that they got?
>
> Tommy: Yeah.
>
> Interviewer: Ok.
>
> Tommy: But, it's not a competition. So, it doesn't really matter. **We** just try for our best and such. But, in the second version, **we** did a lot better. **We** got 10 degrees higher. And so, even if **I** could improve that one more time **I** know what **I** would do. **I** would add more cotton balls. (Landon student interview, lines 334-352)

Tommy used a mix of language to describe the design process. He began by talking with a team reference, but his language shifted to himself when he considered others' critiques of their work and ideas for solutions he had to improve the design. Sarina, Tommy's female partner who had a hearing impairment, also used mixed language talking distinctly at times about what she and Tommy each had contributed. Sarina slipped back into more of a group focus when she described how they managed the time restriction placed on their improvements. An example of Sarina's group talk included:

> Sarina: Then **we** put felt around the orange felt around the box. Then **we** put the plastic bags on the edges of the inside on the side of the wall so the heat could go through it.
>
> Interviewer: Oh, so putting the plastic bags you thought the heat would draw it in?
>
> Sarina: Yeah.
>
> Interviewer: Okay.
>
> Sarina: Then **we** took it outside and **we** came back inside and it didn't work out well.
>
> Interviewer: You didn't get the temperatures that you were looking for?

> Sarina: No. Ms. Collins gave **us** two more minutes to fix **our** project. So, **me and Tommy** grabbed cotton and then **we** grabbed, I grabbed the shredded paper. (Landon student interview, lines 359-368)

Sarina discussed how she and Tommy handled the challenge of improving their design within a limited time frame using mostly "we" language. Sarina shifted to "I" language when she reflected on part of the design process where she was unsure of their course of action, perhaps due to lack of communication between partners.

> Interviewer: Ah, now why did you choose to grab the shredded paper? What made you think of that?
>
> Sarina: It keeps the heat in.
>
> Interviewer: Okay. How did you know that though?
>
> Sarina: **I** learned it; we did an experiment of the cup.
>
> Interviewer: The cup experiment? Part three?
>
> Sarina: Yeah.
>
> Interviewer: Yeah. Okay.
>
> Sarina: Then **I** put it on top of the aluminum foil. **I** didn't cover the whole thing, the whole aluminum foil.
>
> Interviewer: Mm hmm.
>
> Sarina: Then **Tommy** put the cottons around the box and **I** didn't know why. (Landon student interview, lines 369-380)

One student, Raul (who had a male partner) predominantly reflected on the design process with a singular focus. He used "I" language 23 times during part three of the interview. For example:

> Raul: **I** put foam on the sides because the heat was going to travel through it and was going to get stuck over here on the foam, so that's what **I** thought and **I** put foam around the cups so that it could be more hot, and it would have more heat and then after **I** saw that **I** didn't use much shredded paper, like this other side, **I** thought that maybe **I** needed some, so **I** put shredded paper on the side. (Landon student interview, lines 271-275)

Raul focused on his role in the design process without reference to his partner. Observations of Raul's work with his partner indicated that they kept their distance and communicated infrequently, though not negatively. Raul did not appear to have tension or conflict with his partner as evidenced by his earlier comments on the "easiest" part of the unit. Raul reflected, "Well, for me the easiest part was the funnest one, which was putting the things together and working with my partner" (lines 112-113). Raul's use of language reflected his focus on individual accomplishments, rather than an adverse reaction to teamwork.

Collaboration was evident in Ms. Collins' class and appeared to represent a shift from regular classroom practices. Liam commented on how he liked the collaborative shift in practices.

> Liam: I like to build the solar oven and get a good result.
>
> Interviewer: What was the good result?
>
> Liam: Our S'mores got cooked.
>
> Interviewer: That does seem like a good result. Is there anything else that you liked about it?
>
> Liam: I got to work with other people 'cause normally we do a lot of independent work. (Landon student interview, lines 96-101)

Another student, Mina repeated this sentiment while reflecting on new opportunities for teamwork.

> Mina: I liked the way it let the partners that teamed up because the way the partners that teamed up in some groups, they don't really work together and I think that kind of helped them work together. Like me and [my partner], we didn't really work together until the unit and now we do stuff as a team. (Landon student interview, lines 145-148)

With practice, students began to appreciate and desire work as a team in Ms. Collins' class due to their experiences with the unit.

Monroe students' descriptions of products: Ms. Warner's class. The most successful paring, according to the students, was Franco and Leah. Their success was measured by the effectiveness and originality in their design. When both Franco and Leah were interviewed, each used a preponderance of collaborative "we" language as they described their design products. Franco used "we" language 28 times compared to "I" language nine times. Similarly, Leah spoke about "we" in her descriptions of the design process 24 times as opposed to singular language five times. For example, Franco explained how their idea to insulate the lid of their oven developed.

> Franco: **We** had to put stuff in our journal. **We** had to write what **we** were going to do about, what materials **we** were going to use. What **we** use were cotton balls, newspaper. That was at the first time. At the first time, the time was almost over so I was like think hard what **we** can do after this. **We** were like, "Okay. **Let's** do the top." **We** did the top (*designing the lid*). **We** cut it around and **we** put it. (Monroe student interview, lines 400-404)

Franco described his and Leah's process of creative idea generation and design implementation. His group-centered account provided evidence for their collaborative practice. Leah also referenced their process in a collaborative, group-centered way. For example:

> Leah: When **we** did our first design, **we** didn't think **we** had to add anything to the top of the lid yet, **we** had still stuck to, inside the box. So what **we** did was like, at this point in time **we** didn't shred any newspaper or stuff, **we** just took apart the paper, you know art paper they have...? **We** took it apart and just like, smooshed it down into the bottom, and then like, added all the cotton balls to the top? Yeah. (Monroe student interview, lines 295-300)

Franco and Leah's teamwork and resultant successes with design set a good precedent for others in the class. Many students followed suit and worked together to problem solve during part four of the unit.

Another pair, Elise and Jabari, commented frequently about teamwork in their reflections. Although they struggled at times because they had different ideas about what materials to use, they learned about teamwork and compromise.

> Jabari: Yeah. Plus actually **we** took, **we** improve[d] by taking the foam and put it under the part where **we** had the aluminum foil.
>
> Interviewer: What materials did you use?
>
> Jabari: **We** used all, **we** used the cotton balls, aluminum foil, the foam. **We** used shredded foam. **We** used shredded newspaper. **We** used regular newspaper. (Monroe student interview, lines 350-354)

> (*The interview continued with Jabari commenting on teamwork with Elise*)
> Jabari: I feel that **we** did good on our project and that I'm glad that **we** did not give up on **ourselves**. (lines 363-364)

During the improvement phase in class while she and Jabari were working, Elise asked me if she could say a few things about teamwork, knowing that I had my audio recorder with me.

> Elise: It don’t matter if we lose or win, it's just all about teamwork.
>
> Interviewer: How would you win or lose in this activity anyway? So, what would it mean to win?
>
> Elise: That means you have great teamwork. That you work very hard and put a little thinking, put a LOT of thinking in…
>
> Interviewer: Okay. So what would be losing?
>
> Elise: Not enough.
>
> Interviewer: Not enough work? Okay. So, if your oven didn't get the temperatures you wanted it to get, like if it didn’t hold the temperature like you wanted it to, is that a failure? (*Jabari jumps in to add…*)
>
> Jabari: It just means you needed to work harder on it, to put more ideas to it. (Audio recording, 11/15/13)

Elise and Jabari continued further to talk about their thoughts on compromise during design.

> Elise: It’s hard when we disagree, because I wanted to put in newspaper and he said, “I don’t think that’s really good.” I was like, “Ok, well let’s just see how it works.”
>
> Jabari: Newspaper’s in there. (*Pointing to where he added the newspaper to the oven*)
>
> Interviewer: See, we compromise (*laughs*)
>
> Elise: Well, I’m like, “Let’s just see how it works.” (Audio recording, 11/15/13)

During the course of the unit, Elise and Jabari developed teamwork skills that allowed them to speak up for their individual ideas, but also to be accepting of ideas from others. Their design product improved as a result.

The groups that presented with more “I” based language in Ms. Warner’s class were often the groups where individual members were absent for critical periods of the design phase. Frequent absences left one partner in charge to make decisions without the input of a team, producing more “I” language. Time became an added burden for this student.

> Interviewer: How do you feel about your project?
>
> Charis: **I** feel good.
>
> Interviewer: Yeah? Is there anything you want to share with me, at all, about your experience, or anything you want to tell me?
>
> Charis: **I** experienced independence.
>
> Interviewer: You did, too, because you were on your own for awhile. (*Her partner Bruce was absent.)* How did that feel?
>
> Charis: It feeled challenging, because [Ms. Warner] said we were kind of out of time.
>
> Interviewer: Yeah, you were kind of in a hurry there. (Monroe student interview, lines 243-250)

Other instances of “I” language emerged with personal compatibility issues. Students who just did not “get along” found themselves working less productively and their solar oven designs suffered in the process.

> Dwayne: My partner *(Jake)* had an attitude with me because I was trying to tell him. He wouldn't listen to me when he didn't know what he was doing.
>
> Interviewer: So that can be frustrating. That's probably why you described *frustrated*.
>
> Dwayne: And then like…ours was like the worst. It wasn't the worst but it just…
>
> Interviewer: The work that went into it?
>
> Dwayne: Yeah.
>
> Interviewer: Okay, that's honest. Do you think if you had a different partner you would have felt different or do you think you probably would feel the same?
>
> Dwayne: I think I would have felt different. (Monroe student interview, lines 102-110)

Dwayne and Jake's conflict represented a rarity in Ms. Warner's class. However, they were able to persist in a classroom built around collaboration and respect as indicated by Jake's comments about the group.

> Jake: **Me and Dwayne** had some nice good ideas, **we** came up with the same idea and **we** put a lot of things. **We** put aluminum foil when you go outside to [test] the temperature because last week it was cold and **we** don't know what kind of temperature it is because it was cold out there and there was sun out. (Monroe student interview, lines 69-73)

Ms. Warner identified Jake as a struggling student prior to the beginning of the unit. It is evident in this excerpt that Jake had some difficulty expressing himself, however he did indicate a certain level of camaraderie with Dwayne as he talked about their "nice good ideas."

In other instances when partners experienced conflict, they remained able to work together successfully on their design challenge in a collaborative way despite occasional tensions. Calvin experienced initial frustration that later resulted in celebrated successes with his partner, Kayla. Initially, Calvin described the design process as ‘hard’, “Because Kayla kept on telling me, ‘No, we ain’t putting this first. We’re putting *this* first’ and I kept on getting frustrated” (lines 107-108). After the completion of the unit, Calvin’s language shifted to a more group-centered tone despite their solar oven improvements not working so well.

> Calvin: So, **we** put some shredded foam in there and then **we** put some shredded newspaper and then **we** like put one cotton ball on top of the newspaper and the other on the very bottom and then **we** did the same on both sides.
>
> Interviewer: Do you feel like those improvements made a difference?
>
> Calvin: Yes.
>
> Interviewer: Okay, and how do you feel about what you and Kayla created?
>
> Calvin: I liked it, I think Kayla liked it, but when **we** did it the second time it dropped real low. (Monroe student interview, lines 117-124)

Kayla echoed Calvin’s optimism despite their difficulties with improvements. She remarked, “I feel good and proud, but then again it didn't work out as much as we thought it would” (lines 278-279).

Pairings in both classrooms were mostly opposite (male-female) gender groupings (see Figure 5.4). Gender groupings did not appear to have a bearing on group outcomes when compared to same gender groupings.

Finally, it is also important to note how students described themselves during the unit. During the interview, students were asked: *Describe YOU in three words during this engineering unit.* This question was designed to understand how student conceptualized themselves and their experiences during the unit. All of the words students used were cataloged and categorized into themes (look ahead to Table 7.2 for examples of specific students descriptors of each theme).

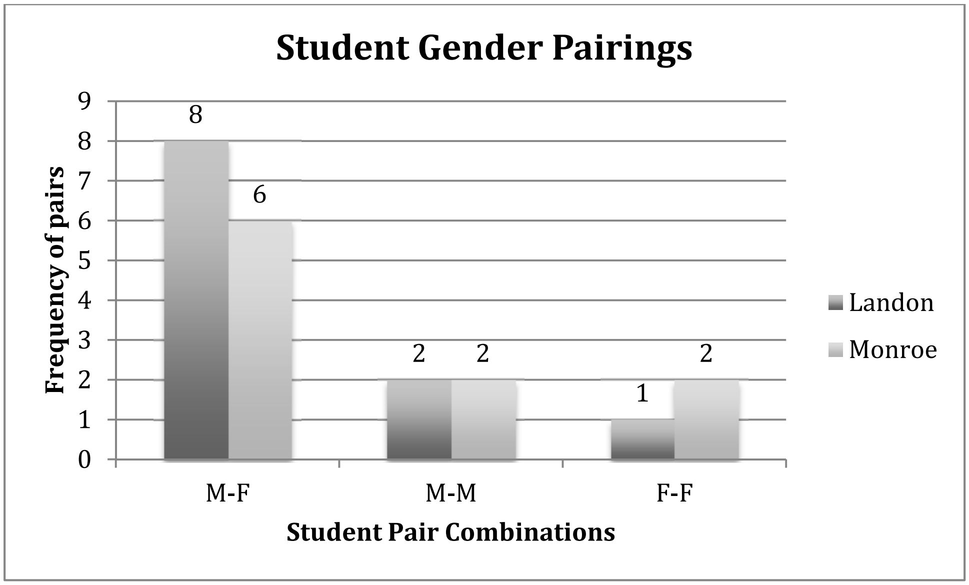


Figure 5.4 Student Gender Pairings During Design Phase

Almost half of the students used words associated with the theme: *social collaboration* (see Figure 5.5). Students used words such as, *helpful*, *caring*, *teamwork*, *encouraging*, and *supportive* to describe themselves during the unit. These identifying descriptors help to provide additional evidence of students' sense of collaboration and gravitation toward the social experience during the solar energy unit. The engineering design process, while challenging for students helped to provide opportunities to enhance their collaborative experience.

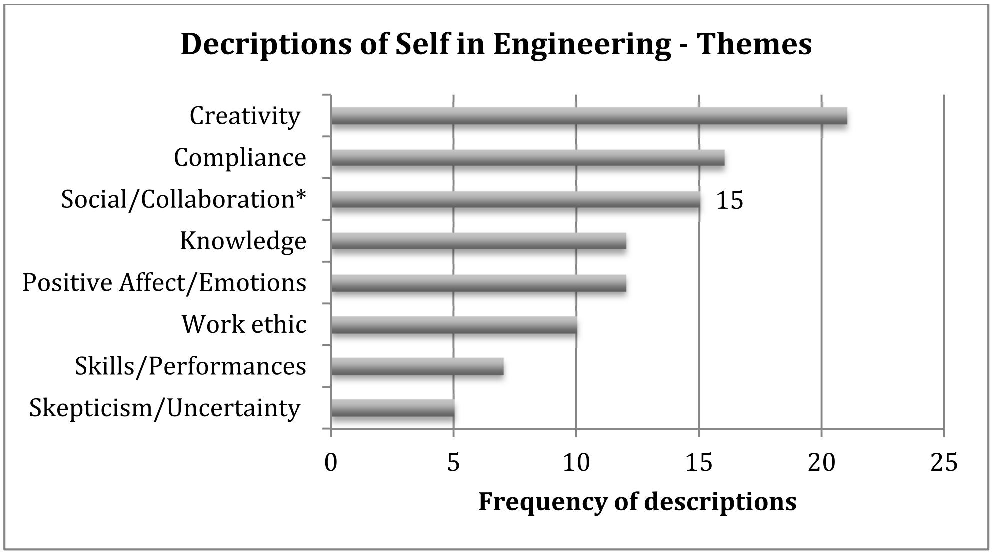


Figure 5.5 Descriptions of Self in Engineering Themes from Combined Sites

The cultural production of collaboration in each class involved shifts from: competition to compromise; verbal communication that was initially assertive and emphatic to more playful and lighthearted; and the assumption of roles that often led to bids for joint leadership (and "we" language) as students negotiated for a comfortable position or space within the design team. Students' joint mission to solve the problem set forth in the design challenge allowed them to work together more efficiently with shared goals and enthusiasm about the potential outcomes.

Summary: The Cultural Production of Collaboration

As indicated in the research on cooperative learning in engineering education, when students learn in collaboratively cultivated contexts they also perform better as individuals (Oakley et al., 2007; Smith et al., 2005; Stump et al., 2007). The development of teamwork skills does not happen without guidance. The engineering design process provides opportunities for students to develop their ability to work together in teams, but the teacher and the overall culture of the classroom must also work to cultivate teamwork.

The time Ms. Warner spent engaging students in a balance of whole-group discussion and team-based interaction allowed students important periods of reflection and opportunities to develop their teamwork skills and joint performances. These opportunities were also available in Ms. Collins' class to a lesser degree, due to the more structured classroom atmosphere. The emerging collaborative culture in each classroom was most evident during the design challenge (part 4). It was here that the practice complexity increased and students had the opportunity to engage more fully and autonomously with their partners. They made decisions about materials to include in their solar ovens, they made mistakes, and they learned from these mistakes during the process of designing and testing their solar ovens.

Students' reflections on their final design products and team performances shed some light on the types of interactions that occurred during the design phase of the unit. Students in both classrooms experienced moments of competition and tension more so at the beginning of the unit, which lessened with time spent problem solving and designing the solar ovens. Students did not choose their partners; rather they were mostly assigned to opposite gender groups. While assigned groupings can sometimes result in initial conflict, students learned to work collaboratively to solve problems. Again, guidance from the teacher and an environment that cultivated teamwork skills was key to the process.

In the following chapter, I discuss the engineering habit of mind *ethical considerations* and how students took up this habit of mind as a goal for improving the world for others.

CHAPTER VI

ATTENTION TO ETHICAL CONSIDERATIONS

There is an increased need to focus teaching on socio-scientific issues (SSI) in science education classrooms due to recent advances in science and the environmental challenges we currently face as a society (Sadler, 2004). Many science educators have argued for inclusion of socio-scientific issues in classrooms, however these issues tend to challenge students' "rational, social, and emotional skills" (Lindahl et al., 2011, p. 343) making teaching these issues problematic in school. Despite these obstacles, building classroom communities of practice that promote engaged citizenry and the development of scientific literacy as a way to negotiate SSIs remains an educational priority (Sadler, 2009). Interdisciplinary approaches and a variety of contexts for learning (e.g., the open-ended nature of engineering design challenges) have the potential to provide opportunities for this kind of learning to effectively take place in science classrooms (Lewis & Leach, 2006).

Attention to ethical considerations, an engineering habit of mind promoted by the Committee for Engineering Education in K-12 Education, can similarly provide opportunities to examine SSIs in engineering contexts through the "possible unintended consequences of a technology, the potential disproportionate advantages or disadvantages of a technology for certain groups or individuals, and other issues" (Katehi et al., 2009, pp. 5-6). In this study, the green engineering focus of the EiE solar energy unit allowed space for students to develop environmental awareness and attention to ethical considerations. In the following sections, I address part three of the first research question: *In what ways do ethical considerations play a role in students' understanding of the EiE unit?* Perhaps the context of engineering can provide an additional segue for effectively teaching and promoting attention to ethical considerations and SSIs in science classrooms.

Students' attention to ethical considerations emerged spontaneously during the interview process. Students made reference to ethical considerations via unsolicited responses about environmental awareness, a concern for preserving natural resources, and making the "world better." Evidence for these unsolicited, spontaneous responses appeared as students discussed their definitions of engineering, during portions of the card sort, as they reflected on their affinity for different portions of the unit, and as they described other students' "smart" performances. Students' attention to ethical considerations during the engineering unit was an unintended surprise during my analysis as SSIs are often difficult to broach and develop in science classrooms.

Defining Engineering: Students' Attention to Ethical Considerations

During the initial stage of the interview, I asked students, *What does it mean to be an engineer?* This question was designed to get at students' meanings of engineering immediately after their experiences with the unit. As expected, students' definitions contained varying levels of sophistication, which included broad-spectrum ideas about engineering, specific references the elements of the EDP, and some lingering misconceptions. What was most compelling was the number (32%) of responses that included attention to ethical considerations (see Figure 6.1).

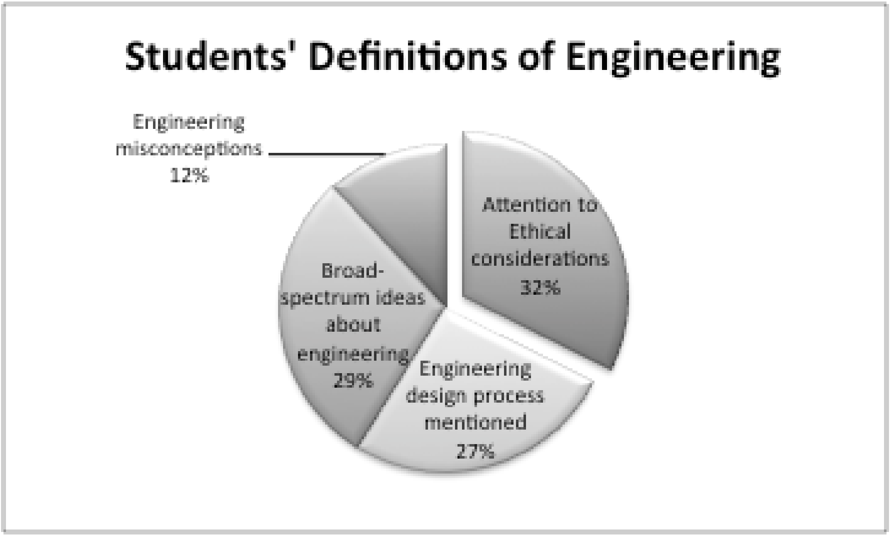


Figure 6.1 Students' Definitions of Engineering

Students' broad-spectrum ideas included talking about engineering in a general sense. These students failed to use multiple parts of the engineering design process (EDP) in their descriptions. They considered an engineer more broadly as an "inventor" (See Table 6.1). Students who referenced the EDP exhibited more sophisticated definitions of engineering to include more than one of the elements: ask, imagine, plan, create, and improve. Students who continued to carry misconceptions about what engineering is or what engineers do described them as people who "fix cars." Finally, students who made reference to ethical considerations in their definitions talked about the environment, preservation of natural resources, and/or helping mankind or the planet.

Table 6.1 Coding Students' Definitions of Engineering

Code	Description	Representative Student Quote(s)
Broad-spectrum ideas about engineering	Talks about engineering in a general sense; Does not use EDP in description; Thinks of an engineer as an "inventor."	"*Experimenting or building things…And testing them. Basically, inventor maybe?*" "*It's like a person who creates things*."
EDP mentioned	Mentions at least two elements of EDP: ask, imagine, plan, create, or improve.	"*Well, an engineer is someone who makes something to solve a problem. Or has his or her knowledge to improve*." "*[They] like to design something and if it doesn't work that time improve it; ask questions, and make a plan then make it*."
Engineering misconceptions	Has an unclear idea about what engineering is or what engineers do. Talks about science or "fixing" cars, etc.	"*You're going to have to try to be like a science person*." "*To fix things*."
Attention to ethical considerations	Talks about the environment; Preservation of natural resources; Helping mankind/the planet, etc.	"*What it means to be an engineer means that you're building something to improve but you build something that nobody in the entire world ever built, and you want to change that part in the world*." "*Being an engineer is you work stuff and make the environment better so you don't use up too much energy. So helping people and the environment.*"

Students reflected on what they had learned during the course of the unit in their definitions of what it means to engineer. It became apparent that students drew from what they had learned in the storybook and about the field of green engineering. For example, Bruce responded, “If you're an engineer, your goal is to try to improve something, and make sure that it's better for the environment” (Monroe student interview, lines 10-11). Bruce was asked if he could elaborate by providing an example. He reflected on what was covered in the storybook portion of the unit.

> I remember most about using up lots of firewood from *Lerato Cooks Up A Plan*. Before they had solar ovens they had been using and using wood...firewood. Before it would be just outside their village, but now they have to walk all the way to the lake to get some firewood. And when Lerato's sister came, she told her about all the resources she's been using up by making the fire because she's using lots of wood ... because you need wood first to keep it burning, and to strike the rock to make the fire come on. (Monroe student interview, lines 23-29).

Bruce also added his own creative ideas about how green engineers could conserve resources such as gas.

> Green engineering...instead of using gas, we could use something like water or dirt. Because if we use gas, we're using up lots of resources, and we have water and dirt all around us. It would be better to use water and dirt instead of rare stuff like gas. (Monroe student interview, lines 4-7)

Bruce looked upon green engineers as people who “make an invention that some people will use as objects to help them in their lives.”

Other students similarly reflected on elements of the storybook and the role of green engineers in protecting the environment.

> Callie: …a green engineer is someone who kind of improves stuff that either impacts the Earth as meaning it will hurt the Earth, and what you can do is just, like with the solar ovens, that's kind of...what the green engineer did. Because they're helping out the Earth instead of all the smoke, and the taking away all the trees, because if you don't have any more trees then you really can't live there anymore. (Landon student interview, lines 24-29)

The examples students used to explain what an engineer is and does appeared to rely significantly on what they learned from parts one and two of the EiE unit. The storybook particularly colored how students responded to the question of what it means to engineer. In another example,

> Interviewer: What do engineers do?
>
> Calvin: They help keep the environment safe because if you keep on making fires and fires and fires it'll pollute the air. When it pollutes the air the air will get dirty and we couldn't breathe oxygen anymore. (Monroe student interview, lines 22-25)

In this example, Calvin reflected on the characters in the story who relied on the burning of wood to cook their food and the resultant depletion of natural resources that occurred in the process. According to Candace (a Monroe student), engineers promoting positive changes meant being mindful "not to use too [many] resources." Jacquelyn (a Monroe student) added, "[engineering] means like you don't waste resources, [you] use them wisely." Emphasizing the problem that Lerato (the main character in the story) faced helped to establish an understanding for students about conservation of natural resources as a goal of green engineering.

Having a positive impact on our planet and making the world a better place to live also emerged in students' definitions of engineering. Concerns for the Earth included,

> Franco: We were testing [the solar oven] to see to not get a lot of resources from the trees and wood and stuff from our Earth. We wanted that the Earth to be like it is, to not kill the trees and stuff like that. (Monroe student interview, lines 66-68)
>
> (*Franco continued to explain…)*
> [Engineers] create something that nobody has ever seen, then to not destroy the Earth. (line 82)

Protecting the Earth and its natural resources kept emerging as students constructed their definitions of what it means to engineer.

> Jabari: What it means to be an engineer is you make things that are like things that people already made. You try to make it better and like…you create things to make the world better. So you won't like use things that we don't have to use. And...
>
> Interviewer: When you say use things we don't have to use, are you thinking about the solar oven unit?
>
> Jabari: Yeah, like we did with the project. We used things like…we didn't use tape while some people used tape, but you [weren't] supposed to. But we're using things that you can reuse like in the book that we read, about the solar ovens. It was telling us about [Lerato] using all the resources that they use. So like her sister came and brought the solar over in for them. And the little sister, she tried to make it better…So they will not use up all their resources. (Monroe student interview, lines 12-29)

Another student shared Jabari's sentiments about protecting the Earth to include a concern for people as well. Jordan (a Monroe student) explained, "Being an engineer is you work stuff and make the environment better so you don't use up too much energy. So helping people and the environment" (lines 20-21). Finally, Russell (a Landon student) summed up what it means to be a green engineer as, "If you're a certain type of engineer like a green engineer, you're looking for solutions to stuff that won't impact the environment."

During the course of the green engineering unit with the problem that was presented, many students developed an understanding of the need to conserve natural resources, protect the people and the environment, and possible steps that can be taken to improve future living conditions. Although the storybook and learning about the field of green engineering (parts one and two) were less desirable according to students as compared to the design challenge, it appears that many achieved the message of conservation and attention to ethical considerations.

Unsolicited Evidence of Ethical Considerations During the Interview

During certain portions of the card sort interview, students spontaneously commented on their concerns for the environment and conservation of natural resources while constructing their solar ovens as part of the EDP. Cards that prompted students to discuss the environment included, *ask questions*, *take risks*, *make good choices*, and *solve problems*.

Asking questions during the unit involved obtaining a better understanding of the purpose and process of constructing solar ovens. Missy (a Monroe student) reflected, “We had to ask questions about the solar oven and the environment to know why they made solar ovens.” Once students understood the purpose (to conserve natural resources) they were better prepared to make decisions about the types of insulators to use in their solar ovens. For example,

> Lana: When we were doing the insulation, we had to ask questions about how does it impact the earth and if they were good insulators.
>
> Interviewer: Okay, and asking about the impact of the earth? Why would you want to do that?

> Lana: We were being green engineers and green engineers they try not to impact the Earth, like impact it in a bad way, like damage it. (Landon student interview, lines 178-184)

Students took their role as "green engineers" seriously during the unit considering the risks and tradeoffs of using certain materials. Russell (a Landon student) reflected that taking risks was not something expected of them during the unit because, "We didn't want to make stuff that would hurt the environment." Bruce (a Monroe student) recognized some of the risk they took when deciding to use tape in their solar oven and how it was used sparingly. Bruce remarked, "The tape, it could of [fallen] off, so we took a risk and put just a little bit of tape so we wouldn't use a whole lot of resources." Again, the concern for the conservative use of resources was present among students.

For some, making good choices meant considering the impact of materials used during assembly of the solar ovens. For example,

> Megan: Because if you didn't, if you took all the plastic bags, because that was one of our materials, they're not that good of an insulator. They're okay as an insulator, but they're bad for the environment. Especially foam. It's just really bad for the environment because it's made out of toxic gases and if you filled your whole box with foam or whatever, it could be bad for the environment. (Landon student interview, lines 204-208)

Even though a material might have been a good insulator, if was not good for the environment students had to figure out which of the two materials they would rather include, a better insulator or one that was better for the environment. This is how some students described making good choices. Students were aware that some "bad materials" were "not good for the environment" so making good choices was paramount.

The card sort item, *solve problems*, was a part of the interview where students made repeated references to ethical considerations in the EDP. One student from Landon explained the problem in connection with the storybook.

> Faye: The problem we were expected to solve was we were supposed to imagine that we were in Botswana, and we didn't want those trees to lose and happen to us. So, we wanted to solve that problem, in making the solar oven. (Landon student interview, lines 267-269)

Fay connected the problem of the characters in the story (losing trees as natural resources) to potential problems we could similarly face. Another student, Joel from Landon, mentioned that solving problems included "see[ing] which [material] would hurt more of the environment." Environmental awareness in the form of making "greener choices" was another problem students felt compelled to solve. For example,

> Liam: We had to figure out a greener choice to cook something.
>
> Interviewer: What does "greener" mean?
>
> Liam: Make the solar oven so we don't have to keep wasting wood. (Landon student interview, lines 191-193)

Students also interpreted solving problems as reducing the potential impact on the environment during the EDP. Callie (a Landon student) noted that the goal of the redesigning the original solar oven was to "stop people from impacting the environment." Megan from Landon also considered pollution from burning wood fires and solving the problem by "hav[ing] good stuff for the air."

Without specifically asking students about environmental impact and conservation, they freely shared thoughts about their own personal ethical considerations during the EDP. The practices to which students were held accountable during the unit (*ask questions, take risks, make good choices,* and *solve problems*) carried with them a sense of personal responsibility about protecting the environment—an unexpected yet encouraging outcome. Students appeared rationally and socially invested in their work on the solar ovens.

A concept of students' emotional investment in ethical considerations occurred in the interview when students were asked about what they liked and disliked about the unit. Some students reported that they liked portions of the unit because it gave them a new way to look at energy and resource usage. For example, Miriam from Landon enjoyed making S'Mores in the solar oven, but also indicated that she "kind of like[d] making new things and seeing a new way not to use up energy." Another student echoed these sentiments about the positive aspects of creating the solar ovens as an alternative to "using energy." Finally, Jabari from Monroe summed up the lasting impact and legacy of green engineering as,

> What I liked about the unit was that you can...I liked about the story that it's time to teach the young kids about like how we can use less resources and so when the kids grow up then they can change the world and we don't have to cut down as many trees as we do now. (Monroe student interview, lines 79-82)

Each of these students expressed an emotional investment in improving environmental conditions and hopes to "change the world" as a result of their brief experiences with the engineering unit.

Some students reported that they did not like the wastefulness that comes with unrestricted use of natural resources. Missy from Monroe explained that she did not like "When people would cut down the trees and it ruins the environment." Wasting resources was frowned upon because "the fire is burning wood" thereby depleting our resources. Faye from Landon considered the impact of using particular materials in her solar oven (i.e., newspaper and foam) when she reported what she did not like about the unit.

> Well, something I didn't like is the newspaper. We put the newspaper, like shredded paper in, and I didn't really like that. Well, I kinda did, but the thing I didn't like was the foam, and how it had environmental impact, but I liked [the unit]. (Landon student interview, lines 142-144)

If materials produced a negative environmental impact, the response from students was also viscerally negative.

Finally, a few students described qualities of "smart" engineer students (Hegedus, Carlone, & Carter, 2014) that included attention to ethical considerations. As part of the interview, students were asked to identify three "smart engineers" in their classroom during the unit. Students listed three students, identified their "smart" qualities and indicated whether or not they affiliated with these qualities. In the process of interviewing students, select students mentioned environmental awareness as an indicator of being "smart."

Callie (from Landon) indicated that Tommy was smart because he used recycled materials during the design process. She prized his ability to incorporate what they had learned about the "life cycle" of materials and how to reduce impact on the environment.

Faye (from Landon) mentioned herself as smart along with three others, citing their concerns about the environment.

> Faye: And what I think about Mina, is that [she and] her partner, they came together like me and Russell, and they thought about this idea, and wondered if it was good, if it would make an impact on the environment. (Landon student interview, lines 57-60)

At Monroe, Missy included herself and two other girls as “smart engineers.” Missy included herself because she “know[s] that green engineering helps the environment”, “Jenna really gets this stuff”, and “Candace likes to help the environment.” Missy explained that their increased understanding of environmental impact developed as a result of “re-read[ing] the story to know what green engineering is.”

While only a small number of students highlighted “smart” qualities pertaining to environmental awareness, their unsolicited responses were worthy of mention when viewed collectively with other students’ “green” contemplations.

Summary: Attention to Ethical Considerations

Teaching to promote environmental awareness and attention to ethical considerations has been a challenge in traditional science classrooms. This brief foray into green engineering via a solar energy unit provided some unique opportunities to empower students to about socio-scientific issues that can potentially shape and change their world (Sadler, 2004). Sadler recommended students engage in periods of informal reasoning to investigate and feasibly solve problems that lack clear-cut solutions or one right answer. Engineering has the potential to provide such a context for learning as indicated by students' unsolicited responses during the classroom interviews. Lewis and Leach (2006) supported the idea of introducing students to novel curricula in the following summary of their research on SSIs,

> We believe that a school curriculum that develops an understanding of basic science concepts, ideas about the nature and limitations of science, ethical reasoning, and the skills of argument plus opportunities for students to apply these in a range of novel contexts would provide a good preparation for future engagement with social issues arising from the application of science. (p. 1285)

Practicing "skills of argument, and moral and ethical reasoning" (p. 1285) in a variety of contexts such as classroom engineering units and engagement with the engineering design process can provide opportunities for students to develop moral sensitivity and engineering habits of mind.

In the closing of Jabari's (Monroe) interview, he shared his feelings about the benefits of engineering education for youth. Jabari closed with, "I'll say that it's a good project for kids that want to change the world and make it a better place. So we won't [wear] out our resources and learn how to do new things every day" (lines 375-377).

CHAPTER VII

STUDENTS' IDENTITY WORK AS ENGINEERS

In Chapter II, I highlighted Wenger's (1998) characterization of identity work as: negotiated experience; community membership; learning trajectory; nexus of multi-membership; and a relation between the local and the global (see Table 7.1). Thus far, I have been able to address a few of Wenger's characterizations as I explored students' experiences in practice with the engineering-based unit. Students described their experiences through their narratives, group roles, and level of participation as they engaged in design and situated problem solving during the engineering design process. Students also shared in collaborative engineering practices as a form of community membership during the EDP in varying degrees through small-group pairings, whole-group discussion, and teacher-led instruction. I examined the practices that students believed they were held accountable to do in the context of engineering. How they experienced this new engineering community of practice provided some insight into their *nexus of multi-membership* as they reconciled different forms of membership in engineering. During the unit, students had to negotiate their group and individual roles as well as their perceived level of competence in the context of engineering, which I explore further in this chapter. By exploring students' attention to ethical considerations during the course of the unit, I was better able to understand students' navigation of local (classroom-based) meanings of green engineering within a larger global context. Time spent with students in the classroom during the unit, the interviews, field notes, and audio recordings provided a glimpse into what students were learning in the classroom and how that information might fit into the broader scheme of their lives, their roles, and participation in future learning experiences.

Examination of students' creativity, collaboration, and attention to ethical considerations as engineering habits of mind in the previous three chapters as part of research question one provided clues about students' negotiated experiences during the engineering unit. Research question two was designed to further examine elements of students' identity work in the context of engineering to obtain a better understanding of youths' experiences and identity work during an engineering unit. In this chapter I look to answer, *How do students author themselves and/or get positioned by others during the engineering unit?*

To address the question about students' identity work, I focused on students' descriptions of themselves during the engineering unit. During the interview, I asked students to describe themselves with three words. These descriptions of self provided insight into students' perceptions of self and their negotiated experiences (categories, roles, positions) during the unit. Secondly, I looked to examine students' affiliation with "smart engineers" and "smart students" in general to better understand their perceived positional status in the classroom.

Authoring Self in Engineering

During the interviews, I asked students from both classrooms to describe themselves in three words. This inquiry produced over a hundred descriptors.

Table 7.1 Identity Work Operationalized

Identity Work via:	**Operationalization**	**Examples in practice:**
Negotiated experience	Through lived experiences, we come to define who we are while also striving to understand our experiences through the eyes, actions, or words of others.	Students may come to see themselves as certain kinds of people during the engineering unit (“a leader”; “a creative designer”; “a smart student”). Others may see them as someone who is “good at engineering” or someone who “struggles in school.” These in-sync or out-of-sync experiences must be negotiated as one makes a place for themselves during the unit.
Community membership	Membership involves a compilation of our engagement, interaction, and what we bring from our personal life experiences as we work to establish a place for ourselves as competent individuals.	During the engineering unit, students work in whole groups and smaller teams, engaging in newly introduced engineering practices (i.e., optimization; balancing tradeoffs) and begin to establish a level of competence in this new social context.
Trajectories	This is how we participate within and across communities of practice. These are not fixed courses, rather paths that are in continuous motion. We are influenced by what is happening around us and perform ourselves accordingly as part of the learning process.	Students in the engineering unit may take a position of someone who has all of the answers/solutions to problems based on past performances or someone who takes on the position of observer-at-a-distance. Some students may be able to traverse varied positions across communities of practice.
Nexus of multi-membership	We belong to more than one community of practice (a nexus); Identity work within each distinct community can serve to reinforce membership or might cause conflict during this work of reconciliation.	Students negotiate space for themselves in their family community/culture, general school community, peer network, and classroom community. In this study, students also negotiate space for themselves as part of an engineering community.
Local/global interplay	Identity work is conducted within a particular community of practice, but also is directed outward and part of a broader, more global context.	Students learn about green engineering within a classroom context (i.e., solving the problem of insulating a solar oven for effective use) and also expand their place/positions as advocates for the preservation of natural resources more globally.

I made several iterative passes through the data to consolidate and categorize the many descriptors into more manageable themes. After collapsing initial categories further and examining the hierarchy of terms, I arrived with eight themes that helped to establish points of contrast in the data (see Table 7.2).

Table 7.2 Descriptions of Self in Engineering: Themes from Combined Sites

Themes	Representative Descriptors	Frequency of Responses
Creativity	*creative, inspired, curious, imaginative*	21
Compliance	*responsible, respectful, paid attention, listened*	16
Social/Collaboration	*helpful, caring, supportive, teamwork*	15
Positive Affect/Emotions	*fun, happy, playful, loved it*	12
Knowledge	*smart, clever, talented, intelligent, a learner*	12
Work ethic	*hardworking, focused, resourceful, pushed myself*	10
Skills/Performances	*drawing, reading, recorder, observant*	7
Skepticism/Uncertainty	*frustrated, rushed, tense, confused*	5

Table 7.2 depicts the eight themes along with representative student descriptors of self during the EiE experience.

Authoring Self as Creative

It was immediately evident that the data reflected how students placed significance on their creative performances. For example, Raul (Landon) used creative descriptors to explain how he experienced the unit.

> Interviewer: How would you describe being "*think-full*"?
>
> Raul: The engineering I had a lot of like ideas that I know some of them could be used and most also on the egg thingy, on the egg stand. (*Here, Raul is referring to the Tower Power building challenge.*)

> Interviewer: You were *thoughtful* and *think-full*. What was the third one maybe to describe Raul?
>
> Raul: Imaginative.
>
> Interviewer: Ah, Imaginative, can you tell me a little bit about that word?
>
> Raul: I was kind of imagining us like stuff that we would do with our solar ovens.
>
> Interviewer: I noticed that you also had drawn a picture during the Tower Power [activity]. That was cool, so you like to think things in your head?
>
> Raul: Mm hmm [affirmative]. (Landon student interview, lines 88-97)

In my contact summary form (9/26/13), I wrote that Raul was eager to share his drawn design for the Tower Power activity with me and to have me take a picture (see Figure 7.1) of his finished product to see that it was successful. I jotted down notes to reflect upon his creative performances during that lesson.

> I noticed a student, Raul, drawing a design without prompting and carrying out that design with his group when building their tower. He shared his design with me and described its attributes. It had stairs and a special podium with buttons to elevate and protect the "dinosaur egg" (see picture). [creative markers—original idea; getting lost in work; energy and enthusiasm] (Contact summary form, 9/26/13)

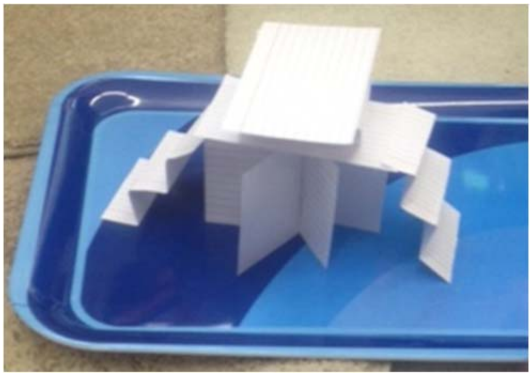


Figure 7.1 Tower Power Activity Design

During class, Raul was an enthusiastic and engaged participant during the engineering unit. Raul had many ideas he was eager to share during class discussions and was literally bursting from his seat in his attempts to share his ideas with the class. At times, this caused problems for Raul resulting in disciplinary reprimands from the teacher. An example from the field notes during the initial storybook session revealed,

> Raul gets out of his seat and Ms. Collins needs to redirect him. Ms. Collins whispers to Raul about behavior (*he is up front near her*) and he is asked to move a clothespin from a discipline board.
> (*Later in the lesson Raul shares his insights about the story*)
> Ms. Collins asks the class, "How does the rondavel impact the environment?" Raul answers (*he stands up while he talks*) – they talk about how the rondavel *(a mud and thatched roof hut)* does not impact the environment as much as our homes do. (Field notes, 9/27/13)

Curbing his enthusiasm and willingness to share proved a challenge for Raul during structured class time. However, his creative perceptions of self persisted after the unit was completed.

Another student from Landon, Tommy, shared his creative enthusiasm, describing himself as "inspired" during the unit. Tommy remarked, "Well, yeah, so I'm inspired because, you know, I decided to make my own solar oven at my house." Before the unit was even fully completed, Tommy shared that he had begun to construct another solar oven at home to apply his many "inspired" ideas.

Reflections of creativity were also evident from students at Monroe. Heather described herself as creative as she reflected on the EDP with her partner and the improvements they made.

> Heather: Describing me during the engineering? ... First one I would say is *really creative*.
>
> Interviewer: *Really creative*? Okay.
>
> Heather: The next one ... first was *very creative*. The second one is *think about stuff*. Even though sometimes I *think of stuff* at the last minute, sometimes I have to be really *creative* and I have to *think*. The plan ... when do the solar oven ... I didn't really know what we were going to put in there because we only had a few materials. My partner Jordan didn't bring in anything, so we only had a few materials. When we did it over to create it, we only had a few materials to put in there. But we changed it a little bit though. And we did better. We did better because the chocolate melted on our S'mores. (Monroe student interview, lines 46-55)

In the contact summary forms (11/1; 11/4; 11/12; 11/13; 11/15), Heather was frequently listed as "holding the floor" and "getting it." This was because she frequently shared her ideas and raised her hand to contribute to class discussion.

Jake from Monroe sometimes had difficulty expressing himself, but he also reflected on his "great ideas" during the unit.

> Jake: The words that describe me in engineering is, what describes me, I don't know. I sometimes don't know about myself. One that can describe me about engineering is *thoughts*, *thinking* and mostly *telling*.
>
> Interviewer: You said *thinking*?
>
> Jake: *Thinking*, *thoughts* and a little bit *telling*.
>
> Interviewer: What was the last word?
>
> Jake: *Tell*, that's the last word, like this is telling like, I got *great ideas*. (Monroe student interview, lines 261-271)

Jake expressed confidence in his "great ideas" that emerged as part of the project, thinking creatively to contribute to the EDP.

Authoring Self as Compliant

In contrast to the available creative space to think freely, imagine, and be curious, students also described themselves as compliant, which aligns with a prototypical subject position of school science. In some instances, students described themselves as “responsible” and “listeners” while also indicating their willingness to “participate” in class activities. For example, Sasha labeled herself completely with traditional, compliant descriptors.

> Interviewer: How would I describe you?
>
> Sasha: *Listening*.
>
> Interviewer: What else?
>
> Sasha: *Being quiet*, not talking when the teacher is talking.
>
> Interviewer: It sounds like you're saying you were being really respectful, is that right?
>
> Sasha: Yeah, and *keep your hands to yourself*.
>
> Interviewer: That sounds very respectful. (Landon student interview, lines 135-148)

Sasha was frequently pulled from class for special services, which made her participation during the unit sporadic and interrupted her flow during the lessons. Sasha’s perception of herself during the unit was closely tied to behavioral norms and may have impacted her engagement during the unit. Several students from both sites also described themselves as “good listeners”, which was categorized as a compliant behavior. Conversely, listening could also have been perceived during the unit as a behavior that promoted classroom collaboration. Listening to the ideas of others could contribute to the collective classroom experience. However, students did not fully elaborate on listening in a collaborative sense in this phase of the interview making it difficult to categorize "listening" as social collaboration.

Being "careful" meant compliantly following teacher's instructions. There was an incident where one of the long, glass thermometers broke during testing when a student stepped on it in their enthusiasm recording the rising temperatures in the solar ovens. Missy (from Monroe) explained that she was "careful" during the unit "so that the thermometer wouldn't break because then we wouldn't be able to measure the temperature." Many students recognized following the rules and standards of classroom decorum as expected classroom performances.

Authoring Self as Social

The third most prominent theme was social collaboration. In the previous chapter, I developed collaboration as an engineering habit of mind during the unit. Students described themselves and their social performances during this phase of the interview, providing additional evidence of the community effort involved.

Being "helpful", "supportive", and "nice to other group members" were recurring descriptors. In some instances "helping" others meant support in choosing the best materials for the solar ovens. It also meant supporting others' ideas. For example,

> Liam: I let people talk and explain their ideas and they listen to me when I set my ideas. If I could say that idea, I didn't want to just say, I wouldn't say, "No, that's not how we're going to do it." (Landon student interview, lines 90-92)

Encouraging others and taking on a “caring” role also emerged in students’ descriptions of self.

Faye explained how she considered the importance of their task, her role as an encouraging classmate, and how she cared about seeing the project through (at times leaning toward compliance).

> Faye: I think *caring*, I would be caring about the project. Because I really wanted this project to get done. I thought it would be very important. When I heard that one of the people's thermometers had broke, I was really *careful* when I was standing at my [solar oven]. I was like... you know how some people *encourage* stuff? I like *encouraging* [solar ovens] for science projects. Like, "Come on, you can do it, you can do it."
>
> Interviewer: So, *caring* and *encouraging*?
>
> Faye: Mm hmm [affirmative]. And I also thought of, I *pushed myself* a little to make this goal of it turning out to be good. So I pushed myself a little. So were mainly the three things. *Caring*, *encouraging*, and *pushing*. (Landon student interview, lines 117-126)

Caring also took on a more altruistic quality to involve concern for the environment. Charis explained,

> Interviewer: Okay, so let's talk about caring. When you say caring, do you mean caring towards others, or do you mean caring about the environment?
>
> Charis: Caring about the environment.
>
> Interviewer: Is that something *you* care about?
>
> Charis: Yes. (Monroe student interview, lines 56-63)

Other students reflected on their capacity for teamwork. Miriam (from Landon) stated, “I do like team work, I have good team work” when describing herself during the unit. Chad (from Landon) also described himself as a "teamwork person." Jaden explained his commitment to his partner as a form of good teamwork.

> Jaden: Yes, and I would help out my partner, Isaac. I said, 'Isaac, I will bring in, I'll, tomorrow, I will bring in cotton balls'. He said, 'Ok'. And, I didn't forget, I didn't forget to tell my dad, but it was at the last minute. I accidentally just forgot. But, as soon…
>
> Interviewer: That happens.
>
> Jaden: …as soon as I saw the folder, I was like, I have to call my dad and tell him that he needs to pick up the cotton balls and he did. (Monroe student interview, lines 140-146)

Students' commitments to their classmates, partners, and the environmental goals of the unit helped to provide insight to the social nature of their experiences and their roles in the EDP. Following their mostly positive social outlooks, the upbeat ways in which they reflected upon their engagement during the unit was the next most prominent theme.

Authoring Self as Emotionally Positive

Overwhelmingly, students described themselves in positive ways during the unit using words like "fun", "enjoy", and "happy." Mina (from Landon) described the pure joy she felt in anticipation of starting the unit; "when I found out that we were doing the project, I was so excited I was skipping." Leah described how she was "into it" during the EDP.

> Leah: I would have to say, like I was *into it*.
>
> Interviewer: Okay, "into it," that's good.
>
> Leah: Yeah, and that's when I did, keep creating stuff. (Monroe student interview, lines 87-89)

Leah described her motivation to develop and create their solar oven as a positive emotional experience and driving force to her group’s success.

Bruce (from Monroe) shared how his emotional enjoyment led to creative and unusual ideas. “I thought it was *fun*, because if you improve something it could be *fun*. If you improve cleaning up, you could make lots of things out of it, like roller skating on sponges” (lines 33-35). Bruce also described himself as “playful” during the unit. His free-flowing, creative ideas indicated his high level of enjoyment.

Tommy (from Landon) summed up his experiences in his “love” for engineering. He exclaimed, “I loved this, this whole unit, nothing could’ve been better than this.” Students clearly were emotionally invested in their experiences with the engineering design process.

Authoring Self as Competent

I lumped together the next three themes (having knowledge, skill, and as strong work ethic) as they were closely related in their focus for how students perceived their performances and level of competence as engineers.

Many students (about 1/3) described themselves as “smart”, “clever”, “intelligent”, and “talented” during the engineering unit. Students who described themselves as knowledgeable were predominantly students who did not have advanced (Academically and Intelligently Gifted—AIG) status, but rather general education and/or Exceptionally Challenged (EC status) individuals labeled themselves in this way. Only one AIG student from Monroe labeled herself as a knowledgeable “learner.”

Along with views of self as competent in engineering, students described themselves as having a strong work ethic describing themselves as “hardworking”, “resourceful”, and “focused.” Missy (from Monroe) explained, “I am *hardworking* because I made the solar oven and put the thermometer in the box and was working hard to see how high the temperature could go.” Similarly, Jaden explained how he could simply sum up his work ethic during the unit in two words.

> Interviewer: What words would you choose?
>
> Jaden: That’s easy.
>
> Interviewer: Ok.
>
> Jaden: I would choose *hardworking*.
>
> Interviewer: Ok.
>
> Jaden: *Focused* on what I’m doing. (Monroe student interview, lines 127-133)

In addition to knowledge and strong work ethic, students described skills and performances that defined their experiences during the unit. Skills students highlighted they performed well were being “observant”, “a good temperature recorder”, and confidently “great at everything.” Russell described himself assuredly as a “good placement person” referring to his work on the solar oven.

> Interviewer: Describe you in three words during this engineering unit.
>
> Russell: Very, *very good temperature recorder*.
>
> Interviewer: Okay. Very good temperature recorder. What else?

> Russell: Oh, very *good placement* because I was putting all the stuff in. (Landon student interview, lines 78-82)

Megan similarly remarked on her performances with temperature recording during the outside testing phase of the unit indicating that she was "observant."

> Interviewer: How you were observant?
>
> Megan: We had to ... when we tested our solar oven, we took them outside for the first time and we took them outside and we put the [thermometer] in. Then we had to wait 5 minutes and every 5 minutes we took the temperature and I was checking and like the [oven] was getting hot and we were getting condensation and stuff from the sun. (Landon student interview, lines 86-91)

Megan was enthusiastic about her increase in temperature. Each time the temperature rose, she shared this with me (Field notes, 10/3/13). She also assumed a gentle leadership role with her male partner, making sure he was up to speed during the testing phase (Contact summary form 10/3/13). Megan's observational and leadership skills indicated her level of confidence during the testing phase of the unit.

Student responses within the themes of knowledge, skills, and work ethic provided insight into their level of confidence and competence during certain phases of the engineering unit.

Authoring Self as Skeptical or Uncertain

Finally, there were some students who reflected with a negative tone as they described themselves during the engineering unit. It is important to note that only three of the 36 students (five total descriptors) responded in this way.

One of the three students, Dwayne (from Monroe) described himself as "frustrated" largely due to his communication difficulties (mentioned earlier in Chapter V) with his partner Jake. Jacquelyn (from Monroe) communicated frustration with the constraints of time stating, "I felt rushed", "I felt like I wouldn't be able to do it", and "I felt a failure." Jacquelyn explained, "We didn't have enough time to insulate our oven." It became apparent that time was a factor for the teacher as well as the students in effectively navigating the engineering unit during science instructional time. The third student, Mina expressed excitement, but also worry that made her feel "tired."

> Mina: *Excited* … and *kind of tired*.
>
> Interviewer: (*Laughs*) What makes you tired?
>
> Mina: Because I was working so hard then I was thinking about, "What if this is wrong? What if that's wrong?" My brains gets all jumbled up and makes me *tired*.
>
> Interviewer: So, it's thinking about all the different pieces and trying to make it work?
>
> Mina: Yeah.
>
> Interviewer: And trying to figure out how—worrying about whether or not it's going to do what you wanted to do?
>
> Mina: Yeah, like a jigsaw puzzle like you're not sure if this piece goes over there or this piece goes over there and jumbled up … (Landon student interview, lines 112-121)

Mina's level of worry about her own performances may be attributed to her AIG status and her desire to want to maintain her perceived level of competence in the classroom during this new and unfamiliar, open-ended engineering-based challenge. Striving for perfectionism and over concern about making mistakes can present classroom challenges for gifted students (Fletcher & Speirs Neumeister, 2012).

Overall, despite these few negative characterizations students mostly experienced the unit as creative, social, emotionally positive individuals who perceive themselves with a high level of competence and ability.

Students' Perceived Level of Engineering Competence

Students navigated Wenger's *nexus of multi-membership* (refer to Table 7.1) as they negotiated a place for themselves in an engineering-centered classroom, moving across boundaries of practice. Students were held accountable to certain practices as indicated in previous chapters, but also chose the top three practices they felt were necessary to be successful during the unit (see Figure 7.2).

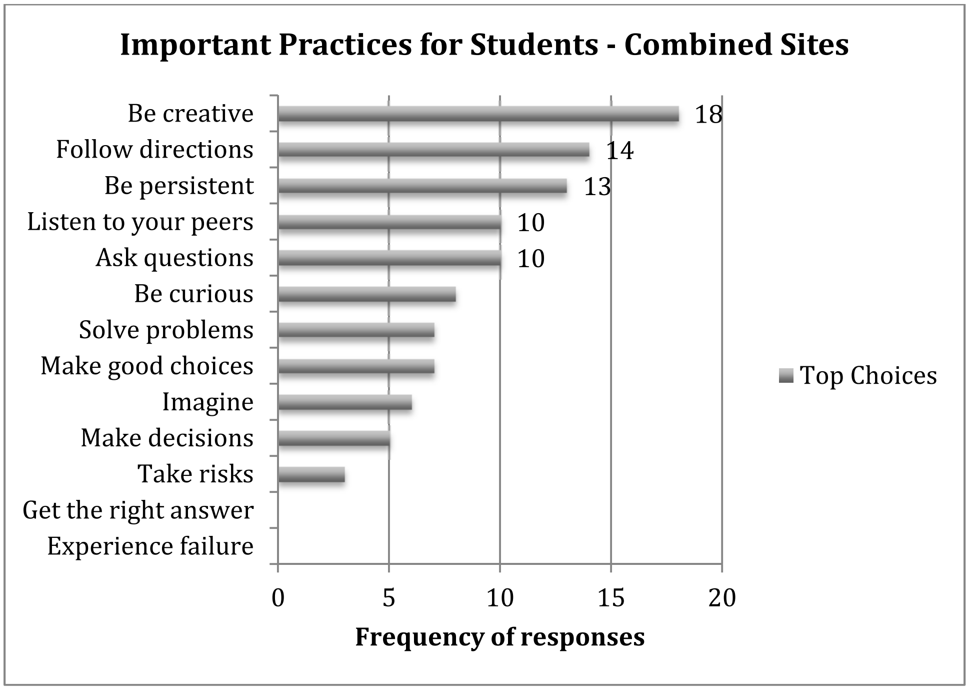


Figure 7.2 Important Practices for Students from Combined Sites

The most frequent card sort items are highlighted in Figure 7.2 to reflect that students prized creativity, following directions, persistence, listening to their peers, and asking questions.

During the interview, we also asked students to identify “smart engineer” students in their class and to provide qualities they possessed. Next, we asked students to identify “smart students” in general in their class as a point of comparison. This information provided insight into students’ perceived levels of competence and their affiliation with these qualities.

“Smart Engineer” Students

Most students described smart engineers as individuals who insulated their solar ovens well and made good choices about materials and resources to use during the design process. For example, Bruce (from Monroe) stated that being a smart engineer meant, “know[ing] which resources they're supposed to use, and they know that it's not harming the environment or anything.” Bruce included his partner (Charis) and others as smart engineers.

> Charis, and me...because we both used tin foil and we used foam. That kept our oven hot for the longest. (Monroe student interview, lines 43-44)

> I chose Isaac because his oven ... it got hotter than mine, but it lost more energy faster. It lost more heat faster. (Monroe student interview, lines 57-58)

> Yeah, Calvin...he decided to fix the tin foil reflecting to the food he was cooking, and his soup cooked the fastest. (Monroe student interview, lines 62-63)

Confidence and persistence (as in the card sort top choices) also emerged in students' descriptions of smart qualities. Jabari commended his classmates for these smart qualities.

> I say Jordan is a good engineer because with Jordan when we did our project...The first time we did it and [it didn't] work. He didn't give up on himself. He kept on going and made his solar oven better. (Monroe student interview, lines 8-10)

> I chose Jenna because when she does things, she knows that she's going to do good on it and I don't know…and when she does it, she actually knows that she's trying to do good on it and she will never go down on herself. (lines 14-17)

> Kayla, when she took things to she's creative and she know how to do a lot of things. Say she was doing a project and someone was telling her that she would not be able to do it, she still do it. (lines 28-30)

Among the Monroe students, 50% of the students listed themselves as smart engineers however, 90% affiliated with smart engineer qualities (see Table 7.3).

Table 7.3 Students' Affiliation with "Smart"

School Site	Self as "Smart Engineer"	Affiliation with "Smart Engineer" Qualities	Self as "Smart Student"
Landon	5 (31%)	11 (69%)	2 (12.5%)
Monroe	10 (50%)	18 (90%)	8 (40%)

At Landon, students reflected on smart engineer qualities in similar ways as at Monroe. They also mentioned smart qualities included "good ideas" and using shredded materials as insulators (see Figure 7.3 for sample solar oven using shredded materials). Callie described the following qualities in her classmates,

> Well, Megan, she had a great idea of covering the bowl with cotton balls. (Landon student interview, line 37)

> Eli because he had a great idea of how we could put shredded paper and fill up the box with it and I had the idea of putting cotton balls on the wall and covering up with foam, and cotton balls on the floor and covering that up with felt and then shredded paper all the way up. (lines 45-48)

> Then on the top [Eli] put plastic, like a plastic bag that was black. He kind of recycled and ... Yeah. Eli had the idea of just using scraps of other people's foam, shredded paper, anything that they didn't use. (lines 57-59)

> Tommy, he said ... We had an idea with the cotton balls. He looked at it and he said "Oh my God! That's such a good idea!" (lines 62-63)

Figure 7.3 Sample Solar Ovens with Shredded Materials

Raul discussed the use of shredded materials as a smart engineer quality. This was a point that Ms. Collins was trying to make with students during the testing and design phases of the unit. Earlier, Ms. Collins expressed her disappointment that many students did not realize that the increased surface area of shredded materials could help in insulating their ovens (see Chapter V). Raul was able to make this connection. For example,

> Raul: I don't really know who to choose but I guess it was the ones who chose like shredded stuff because I forgot that shredded stuff could let less air come in[8].
>
> Interviewer: If they chose the shredded then that worked?
>
> Raul: That's what I think.
>
> Interviewer: Do you know anybody in particular that seemed to really know what they were doing?
>
> Raul: I think it was Jane and her partner and maybe Faye and Russell. (Landon student interview, lines 31-38)

In comparison to Monroe, Landon students affiliated with smart engineer students 69% of the time and only 31% of students named themselves as smart engineers. While not completely transparent, the lower percentages of affiliation in Landon as compared to Monroe could have been the result of the composite of students in that class and/or the classroom culture that had been established by the students and the teacher.

"Smart Students" in School

Students described smart students in school in more prototypical ways. Students who were smart in school "get good grades", "answer a lot of questions", and are good at

---

[8] This is a misconception about how the shredded materials perform as insulators. The shredded materials take up space in the oven, reducing circulation of air. They do not necessarily block air flow into the oven.

other subjects like reading and math. They described smart students in school as well behaved, focused, and paying attention.

In Landon, “showing your work” appeared in students’ descriptions of “smart student.” This quality must have been emphasized in class and taken up by students as an accepted practice. For example,

> Interviewer: What kinds of qualities do they have that make them smart?
>
> Russell: The *pay attention* really, really well and they *show all their work* on like their math problems and stuff, so I think they would be the best three.
>
> Interviewer: Okay. Do you share those sort of qualities? Do you pay attention and show all your work on your math stuff?
>
> Russell: Well, not all the time. (Landon student interview, lines 35-40)

Sasha also commented on “showing work” as a smart quality in the classroom.

> Interviewer: How come? Why did you pick you as one of the smartest?
>
> Sasha: Because I like to be smart.
>
> Interviewer: What do you do that makes you smart?
>
> Sasha: *Show my work.*
>
> Interviewer: What about Jane? What does she do?
>
> Sasha: *Shows her work.*
>
> Interviewer: What about Meagan?
>
> Sasha: *Shows her work.* (Landon student interview, lines 73-87)

At Monroe, students referenced AIG status and the precursor to AIG status—TD or "talent development", good grades, and answering questions as smart qualities in the classroom in general. Jenna described smart students and classroom academic status as follows,

> Interviewer: Who would you list?
>
> Jenna: Kayla, Leah and me. I'm in AIG and Kayla and Leah are in TD.
>
> Interviewer: What's that?
>
> Jenna: TD is Talent Development. That's where they're starting to become familiar with AIG, but they're not quite there. When I got to 3rd Grade I started AIG.
>
> Interviewer: Okay. What qualities do you guys have that make you AIG and TD students and smart kids?
>
> Jenna: For AIG, it means that you have a higher average score, you're higher than average. You know more than you usually know, and so the teachers they try to keep you challenged but sometimes regular teachers, they're not AIG or TD teachers, they don't keep you as challenged so you get bored in class. (Monroe student interview, lines 79-89)

Answering questions, getting good grades, and being focused also gave students smart status in class. Kayla explained,

> Kayla: They're always *answering questions* correct, focusing on what they're learning.
>
> Interviewer: Okay, answering questions and focusing. Okay. Cool. Do you share any of those qualities with those students?
>
> Kayla: Yes.
>
> Interviewer: Yeah? Which ones do you feel like you share?

> Kayla: I *focus* in all the classes and I get *good grades*. (Monroe student interview, lines 52-59)

In contrast to the stronger affiliation with smart engineer qualities, only two students (12.5%) from Landon self-identified as smart students in general. At Monroe, eight students (40%) listed themselves as smart students. Additionally, smart qualities in general tended to carry narrow meanings of "smart" that are typical of most classrooms. It was encouraging that students felt recognized during the engineering unit for their unique performances by moving away from traditional conceptions of "smart" toward broader notion of competence.

Positioning: Teachers' Perceptions of Competence and Student Performances

In this section, I will address the teacher's perceptions of students' performances before and after the unit as well as the ways in which students negotiated their experiences during the unit. This information provided additional insight into students' identity trajectories and whether the context of engineering provided unique opportunities for students to engage and perform themselves in new ways.

As mentioned previously in Chapter III, six teachers took part in a EiE Seed Leadership project led by our research team in the summer of 2013 before the initiation of my student-based study. Our research team held a one-week summer professional development (PD) session with teachers prior to their fall implementation. Shortly into the fall semester but prior to implementation, our team interviewed teachers to ask them to identify two students they felt would be successful during the unit, two students who might struggle, and two students about whom they were unsure. After the unit was completed, our team interviewed teachers a second time to ask them to reflect on students' performances and indicate any surprises during the unit. Here, I reflect on the teachers' positioning of students based on their pre-conceived notions about what it meant to be a "competent" participant.

Successful, Struggling, and Unsure: Ms. Collins' Class

Prior to implementing the unit in her classroom, Ms. Collins reflected on students she believed would be successful and those she believed would struggle during their new and unfamiliar experiences with engineering (see Table 7.4). Ms. Collins provided two names for each category. All students with IRB approval were listed in Table 7.4 along with their general academic status, gender, and representative ethnicities (as described by the teachers).

Table 7.4 Ms. Collins' Pre-Implementation Predictions of Students' Potential

School: Landon Predictions	Student(s)	Academic Status	Demographics
Successful	**Tommy***	Above	White, male
	Jane	Above	White, female
Struggling	Sasha	Below	White, female
	Sarina*	Below	Biracial
Unsure	**Joel** *	At grade (reading)/ Above (math)	Hispanic, male

*Indicates students of focus in results section

I examined the experiences of students indicated by an asterisk (Tommy, Sarina, and Joel) as a part of this inquiry into students' identity trajectories and identities in practice during the engineering unit. According to Wenger's (1998) work highlighted in the conceptual framework chapter, students' trajectories *allow for students to draw from their collective life experiences to make sense of a new phenomenon, connecting the past, present, and future*. Wenger explained, "we define who we are by where we have been and where we are going" (p. 149). This acknowledges that students come to school with prior knowledge and life experience that plays a role in their identity work in engineering. During the EiE unit, novel experiences with engineering provided opportunities for students to perform themselves in new and different ways or identity trajectories. Teachers' perceptions of student competence can be potentially colored, often unintentionally, by sorting criteria such as gender, academic status, or ethnicity (Carlone et al, 2011). In the following sections, I look to explore each teacher's characterization of students from interview data and students' identity performances, based on my field note data, during their engineering unit.

Tommy: Successful student status. Ms. Collins believed that Tommy would be successful during the engineering unit. She indicated that his engagement during regular science class time and his above-grade-level status were markers for success (Ms. Collins pre-implementation interview, 9/27/13). Tommy's successful qualities included his ability to "put the pieces together very well", "see connections", and his penchant for "analytical thinking" putting him at the top of her list.

One of the first group activities in Ms. Collins class was the Tower Power activity (9/26/13), which consisted of a design challenge to support an object on a pedestal for a designated period of time. Tommy was partnered with two African American males during the challenge. He dominated the group by making one-sided decisions to control the outcome of the activity with the goal of competitively building the tallest structure possible. Such behaviors are not surprising among gifted students who sometimes struggle with emotions during academic challenges and social interaction (Clark, 2012). My reflections after the lesson indicated how Tommy responded to the early collapse of their tower.

> Tommy (an AIG student) was in tears because his tower fell. He was dominating his two teammates, edging them out. He seemed sure that his tower would be the best because it was so tall – it ended up falling. He was in tears. Ms. Collins had to pull him aside to talk with him and have him attempt to rebuild a smaller structure. He did, and it worked. He seemed consoled. (Field notes, 9/26/13)

My reflections mirrored Ms. Collins' reflections about Tommy's competitive spirit during her post-implementation interview.

> When Tommy worked in his first group, he's a little competitive guy. His was a group of three. He took over, took charge and did it his way and did not really respond to his [partners] very well. They sort of watched him. So, I was a little anxious about who I could put him with when he had to work with a partner on the solar oven. (Audio recording, 10/30/13)

Tommy's group had made the tallest tower in class; before it fell prematurely (see Figure 7.4). The tower was tall enough to reach the height of nearby bookshelves.

Figure 7.4 Tower Power Challenge Structure

Ms. Collins later remarked about Tommy's struggles with group work and his competitiveness in her post-implementation interview.

> Again, building the [tower], my little Tommy was going berserk (*laughs*) because he wasn't winning! His was falling apart. He was very upset. He just...that really bothered him a lot. And, a few of my less academically successful kids, their [tower] was still standing the next day and [Tommy] was just beside himself with that, you know? I think a lot of this leveled the playing field. (Audio recording, 10/30/13)

Tommy was used to being successful in class. Initially, the open-ended nature of the challenge and the opportunity for multiple possible solutions was not something he was used to in science class. It is not uncommon for gifted students to become insecure when presented with an open-ended problem to solve with the potential for multiple solutions, because they are used to being "right" (Stepanek, 1999).

Ms. Collins expressed that she was anxious about whom to pair Tommy with during the solar-oven building phase of the EDP because of his previous encounter with group work. However, Ms. Collins indicated, "he did a much better job with his partner

[Sarina] on the solar oven, communicating and working together." Ms. Collins revealed that she had a talk with the class about how to work together effectively after Tommy's difficult first start.

In his interview, Tommy reflected about his work with his partner and the role he assumed in his group. He responded favorably about his partner Sarina, indicating that she was "a really good artist…and that helped a lot." Tommy discussed his role as a "planner."

> Tommy: I usually did the cutting stuff and the, you know, planning.
>
> Interviewer: Planning, ok.
>
> Tommy: Some of the planning—not the whole thing.
>
> Interviewer: So, what was involved kind of in planning, would you say? Like, if that was your role, what did you have to do?
>
> Tommy: Like thinking where stuff like other stuff would go like if this piece of a bag would go and foil would go there.
>
> Interviewer: Ok, so making decisions about where stuff goes, cool. So, your role in your group, in your engineering group, would that be the same as a role you would normally take on in your group working class like in other areas? Like what you do?
>
> Tommy: Yeah.
>
> Interviewer: Yeah, ok. So, you're a good planner and stuff like that?
>
> Tommy: I guess you could say that. (Landon student interview, lines 79-92)

Tommy displayed a high level of confidence and self-assuredness during the EiE unit in his reflections on his role in the EDP as displayed here in this excerpt from his interview.

Other times, he was insecure, unusually sensitive, and somewhat domineering (during Tower Power), characteristics not uncommon to gifted students (Clark, 2012).

Tommy's above-average academic status placed him cursorily in the successful category of students. It appeared that Tommy was able to modify his earlier bouts with competitiveness to work productively with his partner. While sometimes "bossy", gifted students also tend to be emotionally sensitive to criticism and perhaps this quality allowed Tommy to seek the acceptance of his teacher and peers by performing better as a partner during the design phase of the unit (Clark, 2012). He was also able to overcome his initial difficulty with ill-structured problems. Ms. Collins believed that her initial projections of Tommy's success during the unit were supported by his positive group experiences with Sarina and their solar oven effectiveness. Tommy identified making decisions, being persistent, and asking questions as critical practices to being successful during the unit.

Tommy was considered an "insider" even before he performed himself during the unit because of his above-grade level status. However, this *insider trajectory* (Wenger, 1998) required some negotiation and variable positioning within groups during the engineering unit to lead to successful outcomes. For Tommy, his new experiences with the open-ended nature of engineering problems required an evolution of practice that demanded he adjust his position and roles within groups to achieve desirable outcomes. Even though Ms. Collins predicted Tommy's initial success based on his established classroom status, he was challenged by the social negotiation required and the fluid, sometimes unstructured nature of the engineering design process.

Sarina: Struggling student status. Initially, Ms. Collins predicted that a student other than Sarina would struggle during the engineering unit. This female student was frequently pulled from class in the afternoons for special resource services, interrupting her ability to consistently engage with the unit and her peers, putting her at a disadvantage. Ms. Collins had attempted to arrange for the pullout sessions to occur at times that would not interfere with science and language arts time, but some of the student's services were not able to be rescheduled easily. For this reason, I decided instead to examine Sarina's (Tommy's partner) experiences with the engineering unit. Although Ms. Collins did not identify Sarina as a student who might struggle in her interview, I chose her as a case study student because Ms. Collins positioned Sarina as a below-grade-level student in class and someone who suffered from a hearing impairment. These were similar qualities described in the originally targeted student. Fortunately, Sarina experienced less frequent resource pullouts from class.

Sarina came to class each day with an aide by her side. She wore an audio device on a lanyard around her neck to amplify sound. As early as the second day of the EiE unit, Sarina asked to move her seat closer to the front of the room to be able to participate in the class discussion about the storybook. She raised her hand often during the reading, answering Ms. Collins' request for someone to revoice the main character's problem. During the discussion, Ms. Collins attempted to get students to understand the environmental concern that building homes requires cutting down trees. Sarina shared her understanding of this by stating, "When we cut down trees we lose air" (Field notes, 9/27/13). Sarina carefully reviewed the story with her aide while Ms. Collins' read aloud to class. Ms. Collins asked students why the characters in the story must cut down trees. Sarina answered, “They need to collect firewood, because that is how they cook their food” (Field notes, 9/30/14). Sarina was clearly able to follow the story line despite her aforementioned learning challenges.

Sarina described her role in working with Tommy during the engineering unit as both a supportive partner and someone who takes action.

> Interviewer: Describe your role that you took on in the unit. With you and Tommy, what was your role in the group?
>
> Sarina: To participate in, to make sure everything is right and correct, not messy or anything.
>
> Interviewer: Okay, so you were following instructions and participating?
>
> Sarina: Yeah.
>
> Interviewer: Okay. Is that your main role?
>
> Sarina: Yeah, I want to make sure that everything works perfect. I help cut the things and glue them and told Tommy where should we put it. (Landon student interview, lines 75-83)

Sarina described her role as one of compliance (following instructions, participating, not being messy) but also one where she took some initiative in making decisions about where to place materials in the solar oven.

Sarina described herself during the engineering unit stating, “I have knowledge”, “I participate[d]”, and “I was helpful.” Although she did not identify herself as a “smart engineer”, she indicated that she and her partner, Tommy conferred with other “smart engineer” groups and implemented their advice about what materials to include in their solar ovens. She described students who are “smart in school” as people who have “some great ideas.” Again, she did not identify herself in this category.

Sarina found learning about green engineering and the life cycle of paper (part two of the unit) difficult and confusing. Fortunately, she had the support of her partner to help her through these difficult phases. Sarina reflected during her interview,

> Sarina: [Part two] was not really great. I didn’t understand it a lot.
>
> Interviewer: Okay.
>
> Sarina: I had to get Tommy to help me with it a little bit.
>
> Interviewer: Okay. Like understanding what green engineers do and stuff?
>
> Sarina: Yeah.
>
> Interviewer: Okay.
>
> Sarina: It kind of got confusing. (Landon student interview, lines 119-125)

Although part two of the unit challenged her, Sarina noted that her favorite part of the unit was the design challenge. Participating in the EDP and creating the solar oven were her favorite parts of the unit.

> Sarina: I really like the part when we had to make a solar oven. We had to design it. I love the part where we had to plan it and then create it. The first time it didn’t work, I like the part when we had to fix it again the second time. (Landon student interview, lines 107-109)

Not succeeding in the challenge the first time, but being provided an opportunity to improve was something that spurred Sarina’s interest. She also commented on what it meant to work as part of an engineering team, including taking risks.

> Interviewer: What did it mean to you to take risks?
>
> Sarina: To understand and like…step up and join in and understand what they're doing. Don't just be left behind and stuff.
>
> Interviewer: Okay. Take an active role and give it a try?
>
> Sarina:Yeah. (Landon student interview, lines 192-197)

Sarina described herself previously as "participating" during the unit, which she elaborated on here to mean "step[ping] up" and not being "left behind." Sarina also mentioned that being creative involved team compromise.

> Sarina: Being creative is imagining what your work want to be. You can just think about it and then when you think about it you can show them and then your partner will say yes or no. That person will say I like it but that partner will say that I don't like it. We just change half of that for the partner and draw that one out and I can keep the other half the way it is.
>
> Interviewer: Ah, so you did some compromise.
>
> Sarina: Yeah. (Landon student interview, lines 272-278)

Sarina emphasized that listening to your peers was an important part of teamwork during the unit. She stated, "you can't just listen to your own ideas" to be successful during the unit, rather groups share ideas and make decisions as a team.

Despite Sarina's below-grade-level classroom status and physical disability, she performed herself as a competent member of her engineering team as characterized by an *inbound trajectory* (Wenger, 1998). As a newcomer to engineering, she struggled at times with certain aspects of the unit. However, she approached her role with an academically strong partner with confidence and compromise. She let her voice be heard in whole-class discussions and in the sharing of ideas with her partner and other groups. At times, Sarina described herself as a compliant student, while in others she positioned herself as a capable designer seemingly unfazed by the complexities of engineering design. These performances left Sarina open for future successful performances in engineering design.

Joel: An uncertain trajectory. It was September, early in the academic year and Joel, a Hispanic male, was new to the Landon school. Ms. Collins did not know much about Joel and his academic capabilities and potential. Ms. Collins indicated that he was at-grade level in reading and above-grade in math. She considered him a "very quiet" student and she was unsure of his potential in class or the new engineering unit. Ms. Collins discussed her early perceptions of Joel as follows,

> I am still trying to determine if he is attentive or not at different times. He doesn't volunteer or raise his raise hand or get involved very much. It takes quite a bit to light a fire under him; to appear to be interested in what is going on. I am still trying to determine if he has that ability make connections from what is presented and understand why an activity happens, to be able to use that information in another setting. I'm just not sure about him right now. (Audio recording, 9/27/13)

Even though Ms. Collins was unsure of Jason's trajectory during the unit, she described him as "in the game."

Joel made a point of answering questions during the teacher-led, whole-group discussions. He shared his ideas about how to contribute to the stability of the towers. He contributed his knowledge about the thatch and mud huts (rondavels) the characters lived in, as well as the features and function of the control solar oven used during testing. Joel had a voice in the classroom when he decided to be heard, but otherwise was mostly reserved and kept to himself. He had an African American, female partner who was also designated a student of “uncertainty” by Ms. Collins.

Joel described his role during the unit and in his regular science classroom during his interview.

> Interviewer: What role did you take in your group? What role do you think you took on when you were with your partner, what was your job?
>
> Joel: To do the materials and put stuff inside and think about ideas.
>
> Interviewer: Think of ideas and put stuff inside the box?
>
> Joel: And get the materials.
>
> Interviewer: And get the materials? Ok. So the role that you took in your engineering project, was that the same as the role that you take when you're doing other subjects in the classroom or other group projects? Do you usually take those kinds of roles, like materials gatherer, idea person?
>
> Joel: Sometimes we use material but sometimes we don't.
>
> Interviewer: Ok. So, how might your role be different in another group? Are you the leader guy, or the person that tells people what to do or…?
>
> Joel: Helper.
>
> Interviewer: You're a helper? Ok, nice. Did you feel like you were a helper with engineering unit as well? Yeah?
>
> Joel: Helping the environment.
>
> Interviewer: What's that?
>
> Joel: [affirmative] Helping the environment. (Landon student interview, lines 57-77)

Joel continued with his concern for the environment when he described how students were held accountable to solving problems during the unit. He explained that the goal was to determine which material “would hurt more of the environment” or “be more harmful” when deciding what to use to insulate their oven. In addition to ethical considerations, Joel identified making good choices, being persistent and listening to your peers as important practices for being successful during the unit.

Ms. Collins reflected on Joel’s experiences with engineering. She explained he was “engaged” and “answered questions” during the unit as compared to the beginning of the school year when he was “very shy and reticent.” Ms. Collins believed he was “getting more comfortable” and “coming out of himself a little bit more naturally” as the year progressed. She felt he really “liked this unit a lot” (Audio recording, post-implementation interview, 10/30/13).

The following descriptions of Joel’s participation during the engineering unit can be characterized as an *inbound trajectory* (Wenger, 1998). He was clearly a newcomer to the school and to the context of engineering. Ms. Collins characterized Joel as both “very quiet” and “in the game.” Joel was finding a place for himself in the classroom as well as a role that suited him best. He discovered new concerns for the environment as he learned about green engineering indicating his investment and potential for future participation. Joel remained mostly along the periphery in the classroom during the unit, with the potential for more full participation in time.

Successful, Struggling, and Unsure: Ms. Warner’s Class

Ms. Warner provided a detailed list of students and their potential in the context of engineering as indicated in Table 7.5. She was able to reflect more thoroughly in her pre-evaluation of students because her implementation occurred later along in the school year. Bruce, Charis, and Leah are the focus students in this section.

Bruce: Successful student status. Similar to Ms. Collins, Ms. Warner highlighted students with above-grade level academic status as potentially successful. Bruce was placed into the successful category because his peers recognized him as a "smart science kid." Ms. Warner indicated students in her class looked to Bruce and the others on her successful list as role models and tended to "lean towards what they are saying" in class. She described Bruce as someone whom others looked up to in class. For example,

> Especially Bruce because Bruce, I guess he's more of a National Geographic kid and he always watches all that stuff and he's always like "Oh yeah, I think that has something to do with blah blah blah" some obscure fact that you're like "Wow, this kid really watches this stuff!" (Post-implementation interview, 11/22/13)

Bruce frequently engaged in the whole-group discussion sessions that took place during the engineering unit. He appeared to be "getting it" by the depth of his thinking and insight in his responses. For example, during the first lesson the class was discussing what qualified as technology. Ms. Warner called students up to the board to place items in either a "technology" or "not technology" category. Franco went up to the board and placed scissors in the "not technology" category. Bruce responded confidently in disagreement as revealed in the field notes.

> Scissors—Franco puts “not technology”—students disagree. Bruce says they are man-made and helps you cut things, solves a problem; A boy says, “but it doesn’t use energy”; Bruce explains it “uses the energy from your hand.” (Field notes, 10/29/13)

Table 7.5 Ms. Warner’s Pre-Implementation Predictions of Students’ Potential

School: Monroe Predictions	Student(s)	Academic Status	Demographics
Successful	**Bruce***	Above	African American, male
	Dwayne	Above	Biracial, male
	Jenna	Above	White, female
Struggling	**Charis***	Below	African American, female
	Jake	Below	African American, male
Unsure	**Leah***	Above	African American, female
	Jordan	At grade	African American, male

*Indicates students of focus in results section

In the next lesson, Ms. Warner commended Bruce for his “imaginative ideas.” Ms. Warner was reviewing the technology lesson from the previous day, using a spoon as an example of technology. Bruce raised his hand to add a thought about pelicans and how they scoop up things (like a spoon) in their beaks. Bruce often had his hand raised during class discussion stating, “I have a connection.”

Bruce regularly connected his life experiences into what they were learning about green engineering. This included witnessing smoke spewing factories he passed while in the car with his father and reports of ground-contaminating landfills. He also shared insights from his travels to Nigeria (where he has family) and reported on the climate there when the class discussed the context of the story in Botswana.

During materials testing, Bruce also was one of the few students to grasp that shredded materials provided better insulating properties. Additionally, when Ms. Warner asked students how they might improve their findings she inquired, “What would an engineer do?” Bruce indicated that they could calculate and reconfirm the results (*improve*) through repeated testing as part of the iterative EDP.

However, Bruce was not always in command during the unit. He experienced difficulty correctly reading his thermometer during the outside solar-oven testing phase. Several students tried to pull the thermometer out of the oven to read it, causing the temperatures to drop significantly. Bruce could be heard loudly shouting out his temperatures. He proudly called out, “62!” I was assisting students with their temperature readings and looked over at Bruce and his partner, Charis’ thermometer. It was well below 62 degrees.

> Interviewer: Uh, it looks like it is below 60. Sixty is right here (*pointing to the gradations on the thermometer*). So…
>
> Bruce: Oh, oh yeah!
>
> Interviewer: Yeah, so read again.
>
> Bruce: Um, 57? (*He appears to be guessing here.*)
>
> Interviewer: Um, 50 is right here (*pointing to the marks again*). So, it’s like one notch above 50.
>
> Bruce: Um, yeah 51.
>
> Interviewer: Yeah, sometimes it’s hard to read, right?

> Bruce: Yeah, thank you. (Audio recording, 11/13/13)

Bruce willingly accepted help with reading temperatures and politely responded afterward.

Bruce was absent during the improvement phase (11/14/13) of the unit, leaving his partner to take over the re-structuring improvements of their solar oven. Ms. Warner shared that his brief absence and Jenna's (another "successful" student) more extended absence allowed space for other students to rise to "being scientists" and have a voice in class.

Bruce indicated that he and his partner, Charis were "smart engineers" during the unit because "we both used tin foil and we used foam. That kept our oven hot for the longest" (lines 43-44). He was connecting being a smart engineer to understanding the insulating properties of materials, which was a fairly sophisticated notion. Bruce also listed Isaac and Calvin as "smart engineers" during his interview.

> Interviewer: What qualities do they have to make them smart?
>
> Bruce: They know which resources they're supposed to use, and they know that it's not harming the environment or anything.
>
> Interviewer: Do you share these qualities?
>
> Bruce: Yes. A little bit because I know what resources to use, and I know the direction to point the solar oven into the sun. (lines 64-69)

Bruce's characterizations of himself during the engineering unit highlight his confidence in himself and his ability to recognize smart engineering qualities in his peers, regardless of their academic status. However, Bruce continued to see himself as smart in prototypical ways. He stated that he received the highest scores on the reading benchmark tests the previous school year. Bruce also listed Dwayne and Leah as smart in school.

> Bruce: Oh. I chose Dwayne and Leah because last year me, Dwayne, and Leah...We would use to answer lots of questions that was confusing to other students.
>
> Interviewer: Okay. Do you know what subject this was? Were all 3 of you...
>
> Bruce: Reading, language, and history. (lines 89-92)

Bruce seemed to like his status as a recognized smart student in class. He celebrated moments to exhibit his abilities while also sharing the success with his partner. When asked how he felt about the product that he and Charis created he remarked, “I feel like we deserved the smartest because we did hard work and we made a successful solar oven.” Bruce identified making good choices, following directions, and solving problems as the top three practices he believed were necessary to be successful during the engineering unit.

Bruce successfully traversed the *boundary trajectories* (Wenger, 1998) of smart student in school and smart engineer, sustaining that identity work during his participation in both contexts. His teacher and peers recognized him as an influential class leader both socially and academically. Bruce drew from his life experiences to share and contribute his ideas with others. He willingly accepted his peers as “smart” student participants despite their varied academic status. Bruce engaged in polite exchanges with adults and peers and humbly accepted when he needed guidance. His positive interactions with his partner, Charis provided additional insight into his flexibility in working with others.

Charis: Struggling student status. Ms. Warner indicated that Charis would struggle during the engineering unit due to her below-grade level academic status. Ms. Warner elaborated on her concerns for Charis' (and Jake's) success in engineering in her pre-implementation interview.

> They have a difficult time um, processing the information. Anything that might be abstract, has to be really broken down for them—a lot of visual with both of them. So, I think if anything, they really need to understand the content. (Pre-implementation interview, 10/9/13)

Unlike Bruce's outgoing nature in the classroom, Charis rarely spoke out among her peers, and seldom if ever, raised her hand to speak. Her reluctance to contribute to discussion was so marked that I had not heard her voice until day 10 of the unit (11/15/13) when she had to share her improvements on the solar oven in Bruce's absence. I was surprised to hear the deep, powerful tone of her voice. Below is an excerpt from the field notes and parts of the audio recording from the lesson on November 15th.

> Charis and Candace—(both of their partners are absent) Charis tells what she did (her voice is bigger than I thought! – she is normally SO quiet and just smiles) – talks about the improvements she made. (Field notes, 11/15/13)

When Ms. Warner believed that all groups had shared their improvements, she made one final call for groups to share.

> Ms. Warner: Um, who else didn't I call? Everybody went? Yes, Candace and Charis! Did you guys make improvements on your designs? Yes? What did you

> do? (*Charis reluctantly makes her way to the front of the room holding her solar oven.*)
>
> Ms. Warner: You guys, when I asked, 'Did everybody go, you were like, Mm hmm.' Please don't look at me, please don't look at me. (*Playfully joking with the two girls and their attempts to not be called upon.*)
>
> Charis: What I did, I used aluminum foil for the bottom of it (inaudible)…and I think cotton balls. (*Students are moving about in their desks making it difficult to hear her clearly now.*) I did the foam, I did the foam on the outside. (*She starts to mumble here looking down at her project while she talks.*)
>
> Ms. Warner: Cool. Did you change your lid at all?
>
> Charis: Over here, I tried to glue to newspaper on the sides, but it didn't work so…(*mumbling softly again*)
>
> Ms. Warner: Ok. Charis was working by herself because her partner [was absent]. Ok, good job Charis. (Audio recording, 11/15/13)

Charis was clearly uncomfortable being at the front of the room presenting her solar oven improvements to the class. She tried to remain below the radar of Ms. Warner's attention and not be called upon rather than speak in front of her peers without the comfort of a partner. It was obvious that her classmates were losing their patience, as she and Candace were the last to present. Charis did not command the same level of respect as some of her peers with classroom status, as indicated by her peers' elevated noise level (shuffling seats and loud coughing).

Charis was more comfortable one-on-one during her interview, opening up about her experiences with engineering. She identified herself as having the "smart engineer" qualities she characterized in Franco and Kayla. Charis shared that she, "take[s] a little bit of notes, too, and I figure out what to put in the solar oven." Charis used the words "smart" and "caring" about the environment to describe herself during the unit. She indicated that it was a challenge to not waste resources when she worked on her improvements.

Toward the end of the interview, Charis shared her thoughts about what she and her partner accomplished with their product.

> Interviewer: How do you feel about your project?
>
> Charis: I feel good.
>
> Interviewer: Yeah? Is there anything you want to share with me, at all, about your experience, or anything you want to tell me?
>
> Charis: I experienced independence.
>
> Interviewer: You did, too, because you were on your own for a while. How did that feel?
>
> Charis: It [felt] challenging, because she said we were kind of out of time.
>
> Interviewer: Yeah, you were kind of in a hurry there. You smile when you say independence. Are you proud of what you did?
>
> Charis: Yes. (lines 243-252)

Although working alone for part of the unit was challenging for Charis, she felt “good” about her newfound “independence.” During her post-implementation interview, Ms. Warner continued to express concern for her struggling students and whether or not they “really grasped the concepts.” Charis was however, able to make some independent decisions and speak in front of her peers about her design. These were practices that might otherwise have been routinely avoided on her part. Similar to Bruce, Charis identified making good choices about materials as a critical element to successful engineering. Also, she listed following directions (a more prototypical practice), being curious, and asking questions as important to the EDP.

Charis protectively functioned along a *peripheral trajectory*. Her below-grade level status carried with it certain expected performances that kept her at a distance from full, meaningful participation. Charis' partner Bruce respectfully engaged with her but Charis took a secondary role in his presence. His absences allowed her to take a small step forward toward independence, which appeared to boost her confidence. Her self-identified "smart" student status provided a glimpse into her budding classroom confidence.

Leah: An uncertain trajectory. Ms. Warner was initially unsure about how Leah would perform during the engineering unit. Leah was labeled as an above-grade level student who was currently enrolled in the "talent development" program at the school, an initial step towards "gifted" status. In her pre-implementation interview, Ms. Warner stated, "she gets it, but I think every once and a while it just takes a little bit more of an explanation for her to say, 'Oh, ok, I get it!'" Leah's performances during the unit and her successes with her partner, Franco revealed that she was in fact "getting it."

Ms. Warner believed that Leah was a "smart" student who sometimes "holds back" in class. Leah's classroom performances revealed that she "gets it" during class, but is not necessarily a prominent voice in the classroom.

During the life cycle of paper session (11/1/13), Leah was called upon on two occasions to explain what "reuse" meant in terms of recycling. Initially, Leah responded that she did not know the answer. Calvin and Bruce were subsequently called upon to elaborate on the definition of “reuse.” Ms. Warner returned to Leah, but she was still unable to voice her own definition with clarity.

Students tested their solar ovens outside in the sun first for 30 minutes, and then in the shade. Leah and Franco talked about their solar oven with one of the members of the research team as they recorded temperatures in the sun. Leah spoke excitedly at first about their rising temperatures, but Franco soon took over the bulk of the conversation leaving Leah to record the temperatures and monitor the solar oven. Leah proudly reported, “we started out with 82 and now it’s all the way to 112!” As they continued to talk, the temperature rose to 114 degrees, which was high for a cold November day. The conversation continued as Leah made predictions about what would happen when they moved the solar oven to the shade.

> Interviewer: What do you think will happen when you put your [oven] in the shade? What will happen to the temperature?
>
> Leah: I think it would drop.
>
> Interviewer: A lot?
>
> Leah: Yeah…well…
>
> Interviewer: Quickly or slowly?
>
> Leah: I would think, like kind of slowly. It’s like a hot temperature right now, so I don’t think it would drop that far. (*They continue to talk about the falling temperature of the oven. The interviewer commented on the structure of the solar oven to get them to discuss their design.*)
>
> Interviewer: One of the things I see that’s different about your oven than some of the others, is that you seem to have more stuff in there.

> Leah: Yeah, because Franco had brought some extra newspapers and he brought some cotton balls, so we just stuffed all of that in. (*They continued on to discuss the role of the cotton balls as an insulator in the oven.*)
>
> Interviewer: What is it about cotton that makes it work well, as an insulator?
>
> Franco: Well, cotton…
>
> Leah: It warms it up, like a lot. (*Ms. Warner gives instructions to move to the ovens into the shade.*) (Audio recording, 11/13/13)

Leah confidently shared her ideas about their solar oven and its insulating properties. Franco also had a lot to contribute during this inquiry. Leah willingly shared her insights but waited patiently for her turn to speak.

In the shade, Leah responded to questions about the expected rate of cooling she predicted for their solar oven.

> Leah: I would think that our solar oven [temperature] wouldn't drop quickly. But, it's like, I think ours is a bad one now because it's dropping so quickly.
>
> Interviewer: Well, it's not a *bad* one.
>
> Leah: Well, not a bad one…(*Interviewer points out to Leah that the oven can be improved*)
>
> Interviewer: Why does a good solar oven drop slowly? What's going on?
>
> Leah: Because it's like…a good solar oven would drop slowly because it's holding in all the heat and stuff. A not-so-good solar oven would like, the heat would just flow out. (*Ms. Warner calls out that it is time to take the shade temperatures. Leah moves into action as Franco takes over the remainder of the conversation. Leah records.*) (Audio recording, 11/13/13)

The interviewer's probes drew Leah out and gave insight into her understanding of the purpose of the testing. Leah appeared to be clear about what was supposed to happen and exhibited some worry about whether the oven results would be “good” or “bad.” Leah did not initiate or drive the inquiry as Franco did, but she confidently and thoughtfully responded to the interviewer’s questions about the solar oven testing process and goals.

In the post-implementation interview (11/22/13), Ms. Warner shared her beliefs that Leah and Franco were really understanding the concepts and “getting it.” Ms. Warner remarked, “they both were really excited about it and they were able to really explain it and they knew what was happening.”

Leah listed her partner, Franco as one of the smart engineers in class because he came up with the idea to use the cotton balls as insulators. Leah also listed Elise as a smart engineer because of her materials choices and steady temperatures in the shade. Lastly, almost as an afterthought, Leah listed herself as a smart engineer, revealing that she was the one that had the idea to insulate the lid of the oven.

> Leah: Actually, I would kind of include myself because I was the one that like, I thought of the idea to like, the top of the thing.
>
> Interviewer: Oh, your lid?
>
> Leah: Yes, I had put like, tinfoil around the top part so that most sun could reflect in there, and like, newspaper like all around the edges.
>
> Interviewer: Yeah, were you the only ones that did that, with your lid?
>
> Leah: I think so. (lines 45-51)

This was an important declaration for Leah to make because insulating the lid was the creative idea later emulated by many of the groups during the improvement phase of the unit. Leah humbly shared this information.

Teamwork was also a vital component in Leah and Franco's solar oven design and testing. Leah commented on the importance of "listening to your peers" during the card sort portion of the interview.

> Interviewer: Your classmates, were you expected to listen to each other?
>
> Leah: Yes.
>
> Interviewer: Okay. Tell me why that was an important thing.
>
> Leah: It was important because we had to listen to each other to find out if we both agreed like, what's supposed to go in there and how much and if we thought we were going to get enough sun, and where to put it, and like, which one of us was going to like you know keep the track of it with the thermometer and write it down. (lines 260-268)

In addition to teamwork, Leah chose following directions, being persistent, and solving problems as critical practices to be successful during the unit.

Leah and Franco's solar oven was deemed successful by the students in their classroom because of the creativity in design and effective insulating properties (see Figure 7.5). Many students attempted to incorporate Leah's creative idea to insulate the lid of the oven during the improve phase. Their peers elevated Leah and Franco's design team to a position of status in the classroom. Many students looked to Leah and her partner as smart engineers because of their innovation and successful outcomes.

Figure 7.5 Leah and Franco’s Solar Oven and Replicated Lid Design.

Leah’s engagement during the unit reflected an *inbound trajectory* (Wenger, 1998). She was a newcomer to engineering and the design process, but actively took up the creative and collaborative practices necessary to negotiate a complex design solution. Leah appeared to have a firm grasp of the science concepts involved and began to be recognized for her successful engineering performances. Perhaps with continued exposure to the engineering design process, Leah could continue to work to develop her level of participation and identity as a “smart engineer.”

Summary: Students’ Identity Work as Engineers

Whether students held a position of above-grade or below-grade academic status in the classroom, many were able to negotiate a space for themselves to be successful, productive members of the classroom community during the engineering unit.

Above-grade level students (i.e., Tommy and Bruce) began their experiences in the unit from a position of status, power, and control. However, the complexity of solving novel, open-ended problems with a new skill set challenged these positions and meant that typical practices that held status in the classroom might be contested. Tommy and

Bruce had to work to negotiate a new space for themselves, which was not always aligned with their typical classroom performances. The vital role of collaborative team member became a crucial element to success during the unit. Individual success did not guarantee the design challenge would be fruitful.

Below-grade level students were challenged the most during the unit because they were required to overcome the daily obstacles of resource pullouts, enduring perceptions of their potential competence, and established classroom hierarchies. However, Sarina and Charis were able to establish a space for themselves in the engineering classroom, each in their own way. Being a member of a design team allowed both Sarina and Charis to step out of their typical roles. Charis tested her creative ideas and collaborative propensity during the design process by solving problems and making material design decisions. Charis even had the opportunity to develop her voice when her partner was absent and she was compelled improvise as the decision maker for her team. Charis felt confident enough about their performances to characterize herself as "smart engineer." Sarina struggled grasping the content in part two of the unit, although she was not afraid to ask for help. She managed to hold her position in her design team as a competent member, despite having a strongly opinioned partner. Sarina managed to grow as a result her work on the team and found that communication and compromise were valuable skills developed during the unit.

Students who the teachers were unsure about (i.e., Joel and Leah) were also able to establish a position of status and competence during the engineering unit. Leah was elevated to a position of "resident expert" along with her partner, Franco, because she took a risk to develop her creative idea to insulate the solar oven lid. Taking this risk paid off for her team as they achieved the highest temperatures in their solar oven. Subsequently, other teams adopted their practices and experienced similar results. Joel experienced similar successes with teamwork and productive decision-making. He considered himself a “helper” in terms of working well with his classmates and in protecting the environment. Joel was able to move from being the shy, reticent student to one who was driven by ethical considerations, solving problems, and teamwork.

Overall, the engineering unit provided opportunities for students of all abilities to “try on” new engineering identities in the classroom through new experiences with design, problem-solving, and productive collaboration. Students were able to negotiate the complexity of their established classroom science identities by thinking creatively, discovering the ethical considerations of design, and engaging collaboratively in engineering-based teams.

CHAPTER VIII

CONCLUSIONS AND IMPLICATIONS

For decades, science educators have struggled to address the lingering achievement gap among students in underrepresented groups and their middle and upper class, White peers (Lee, 2012). While progress has been made, the disparity in academic performance persists despite our best reform efforts. In the meantime, our society continues to grow more culturally, ethnically, and socioeconomically diverse (U.S. Census Bureau, n.d.). These concerns for equity are not likely to be resolved without major changes in the way we frame and conceptualize science education for students and teachers in our rapidly changing global landscape. The recent incorporation of engineering practices in the *Next Generation Science Standards* (NGSS Lead States, 2013) was a bold move toward a re-conceptualized vision of science education in the 21st century. STEM (Science, Technology, Engineering, and Mathematics) education has moved to the forefront of our educational efforts. As with every new reform effort, we are often left with more questions than answers. What are the educational implications of the shifting emphasis on the integration of the STEM disciplines? How does the integration of science and engineering practices in the new standards help or hinder our equity problem? Considering the gatekeeping history science and engineering both carry as their legacies, concerns linger as to whether or not the recent STEM trend will benefit students' academic trajectories or further add to their complicated sociohistorical legacies and equity problems.

In addition to the equity problem, a creativity problem also challenges our future. Reports of a *creativity crisis* have been widely reported in the media, as our need for a STEM-capable workforce becomes an ever-growing concern (Florida, 2004; Moritz, 2012; NSB, 2010; Strutz et al., 2011; Williams, 2014). Creative and innovative skill sets are more critical than ever in our globally competitive, rapidly evolving society. Socially just educational contexts that support STEM literacy have the potential to put students in a position of control about decisions that affect their personal lives and their communities (Calabrese Barton & Tan, 2010; Katehi et al., 2009). No longer can we just give lip service to the often-mentioned twenty-first century skills (i.e., creativity, collaboration, communication, and critical thinking) (P21, 2009). Now, it is critical to explicitly address the cultivation and recognition of these necessary skills in our students. The introduction of engineering education as part of the science curriculum as early as elementary school is a visionary step toward addressing these issues.

The purpose of my study therefore, was to understand the ways in which engineering education has the potential to promote creativity and academic competence in elementary science classrooms, thereby contributing to creative development and untapped potential in youth. Findings from my study shed light on the implications of introducing engineering practices as early as elementary school and what that means for our equity problem. Additionally, I explored three specific engineering habits of mind (creativity, collaboration, and attention to ethical considerations) as students engaged in a green engineering solar energy unit to better understand how each emerges in practice in elementary school.

In the following sections, I begin with my reflections on the Engineering is Elementary (EiE) curriculum that was the focus of this study and implications for instructional practice. Next, I turn to address the implications for equity in engineering (and science) education. I address the complementarity of science and engineering and make recommendations for the future of science education in these mutually reinforcing disciplines. I continue by making recommendations for pre-service teacher engineering education and the vital role teachers can play in its successful implementation. Finally, I present an agenda for future research and share my final thoughts about the outcomes and lessons learned during the course of my study.

The EiE Curriculum: Reflections

Katehi et al. (2009) highlight EiE and other engineering curriculum packages, workshops, and courses geared toward elementary students in their report on K-12 Engineering Education to include: *City Technology* (City College of New York); *Children Designing and Engineering* (course held at George Mason University); *Engineering Our Future New Jersey* (Staff at the Stevens Institute of Technology, New Jersey); *INSPIRES* (workshops by technology teachers in Maryland); and *World in Motion* (kits and workshops). I chose to study the EiE curriculum because of its focus on equity; careful integration of science, engineering, and technology; and research-based design principles (Museum of Science Boston, 2014).

The unique four-part design of the EiE curriculum provides a comprehensive way for students to engage in: 1) a multicultural engineering-based story; 2) the broader view of a field of engineering (in this case, green engineering); 3) how scientific data inform engineering; and 4) an engineering design challenge. During implementation, the fifth-grade students in my study indicated that they felt most creative during part four, the design challenge. Students had opportunities to engage in the engineering design process throughout the unit and reflected that they enjoyed designing, improving, and making decisions about their solar ovens the most. For example, Leah reflected,

> Leah: I have to say designing the solar oven
>
> Interviewer: This part? Part 4?
>
> Leah: Yes, because we got to rip up paper, and we got to keep adding cotton balls, and it's like, we just got to do so much things, we got to rip up the aluminum foil too, and put it around.
>
> Interviewer: I get a feeling you liked that.
>
> Lauren: Yeah. And we got to see what it was like to cook with the solar oven and cook outside.
>
> Interviewer: Yeah, because you read the story, and then you actually got to do it, that's pretty cool.
>
> Leah: I was amazed that they let us like, eat something out of it. (Monroe student interview, lines 97-107)

Sarina commented similarly in the previous chapter on how she also enjoyed aspects of the engineering design process in her reflection on the unit.

> Sarina: I really like the part when we had to make a solar oven. We had to design it. I love the part where we had to plan it and then create it. The first time it didn't work, I like the part when we had to fix it again the second time.
>
> Interviewer: You liked improving?
>
> Sarina: Yeah. (Landon student interview, lines 107-111).

These positive emotional reflections about the unit and the engineering design process were not uncommon among participants in the study.

The developers of EiE state that their units promote classroom equity by introducing failure as part of the problem-solving process (Cunningham & Lachapelle, 2014). They also report that the opportunity to seek multiple solutions serves to promote equity among students, where there is not one right answer as is traditionally seen in school science classrooms (MOS, 2014). I found many of the developers' claims to have merit as I witnessed successful students (Bruce and Tommy), struggling students (Sarina and Charis), and students with uncertain trajectories (Joel and Leah) establish themselves as competent and efficacious engineers.

The carefully researched and designed EiE curriculum contains necessary elements for promoting equity, stimulating student interest and engagement, developing creative and innovative problem-solving skills and engineering habits of mind. However, while the curriculum addresses these important elements in its design features, the ultimate effectiveness of the units to deliver on these promises relies on the proficiency of the teacher who implements the curriculum (Orlich et al., 2013; Schneider & Plasman, 2011; The Center for Public Education, 2005). In the next section, I highlight three areas I believe should be explicitly emphasized as part of teacher professional learning experiences for EiE implementation: brainstorming best practices; teaching for failure; and the social value of engineering design.

Implications for Instructional Practice

EiE introduces *imagine* as one of the five parts of the engineering design process (EDP). *Imagine* as part of the EDP is first introduced in the storybook, *Lerato Cooks Up a Plan.* The characters in the story imagined different kinds of materials (mud, plastic bags, palm fronds) that might be used as insulators in their solar ovens. In lesson two, *The Good Life,* students learned about the life cycle of paper and the environmental impact of its use. Ms. Collins from Landon capitalized on an opportunity to use brainstorming in this lesson when she held a brief (1.5 minute) brainstorming session about the many uses for paper. In lesson four, *Designing a Solar Oven*, students utilized information from their controlled experiments on the insulating properties of materials in lesson three to imagine (first individually and then in small groups) different ways to insulate their solar ovens. The EiE instructions for brainstorming involve coming up with at least two ideas individually, then group members come together, share ideas, and decide on one idea to formulate a plan for design.

The search for multiple answers/solutions/ideas (maxim 4) is a critical part of the creative process (Kazeronian & Foley, 2007). Properly facilitated brainstorming strategies allow for creativity to emerge as students become more fluent and flexible thinkers in carefully facilitated collaborative groups (Isaksen & Gaulin, 2005). Teachers can function as facilitators to help guide collaborative groups through brainstorming sessions. Facilitated brainstorming groups produce more non-redundant ideas than in individual sessions. It is important that students are primed beforehand, facilitated during, and engaged in a period of reflection after a brainstorming session to achieve maximum benefit (Isaksen & Gaulin, 2005; Osborne, 1953). Groups must also be judiciously comprised for defined roles and responsibilities, guidelines about judgment and criticism, and establishment of equitable member status/power/rank. If these idea-generating group dynamics are adequately cultivated in advance (perhaps in science and in other subject areas) maximum benefit from brainstorming sessions can be achieved. Brainstorming guidelines for teachers may benefit the collaborative and creative outcomes of the *imagine* part of the EDP.

Additionally, explicitly teaching for multiple solutions over the traditional one-right-answer mentality presents opportunities for students to seek alternative sources for inspiration rather than turning to the teacher as the ultimate authority figure. Over half of the students in my study indicated that getting the right answer was not expected of them during the unit. This productive practice also allowed for students to look for communal sources of inspiration (their peers) in addition to looking within themselves for unique ideas to contribute to the design challenge. Although, it was difficult for some students to release themselves from traditional conceptions of “being right” others began to see the possibilities in “being right” with multiple solutions. Explicitly teaching to break down the traditional barriers of unilateral, narrowly focused thinking, is one way to welcome and encourage the possibility of multiple creative solutions.

Experiencing productive failure as a positive outcome of engineering education represents a cultural shift from how failure has traditionally been perceived in the context of education (Lottero-Perdue & Parry, 2014). Developers of EiE suggest that experiencing failure as part of the problem-solving process has the potential to promote classroom equity. Experiencing failure and taking risks were practices I was certain I would observe during the EiE unit. However, I was surprised by the inconsistency in my findings. It was difficult for students to let go of enduring histories of prototypical school science associated with good grades as typical motivators. The term "fail" is associated with negative experiences in school (i.e., poor grades) and therefore difficult to negotiate. Two thirds of the students responded *maybe* or *no* to the card sort item, *experience failure*. Some even saw the teacher as someone who buffered or protected them from failure. Only about a third of the students responded *yes,* they were expected to experience failure during the engineering unit. It is these students' experiences that need to be capitalized upon moving forward. This small faction of students experienced failure optimistically as an opportunity to learn as part of the *improve* part of the EDP. I believe that we should take advantage of opportunities for students to take risks and experience failure as part of engineering by explicitly teaching for these practices. Perhaps the term "failure" carries too much of a negative history, instead we should teach about product *malfunctions* or *glitches* in the process or products of engineering, exploiting the fact that experiences with failure can lead to better solutions and opportunities to learn. Either we work toward desensitizing students to the term *failure* or we use more student-friendly language to convey to students that it is okay to not get it right the first time or even assume there is one right answer.

Furthermore in my study, one of the engineering-habit-of-mind themes that emerged in practice was creativity as social value (see Figure 4.2). As a part of this theme, students described creativity as the ability to produce original products that held some value for the social group (Sawyer, 2012). For instance, Franco and Leah's original solar oven with its unique lid design was highly regarded among students in the class. Students also added value to their designs by drawing from life experiences as they constructed solar ovens simulating insulation in the walls of a home or coloring the inside of the solar oven black like their ovens at home. Only a small portion (approximately 14%) of students described creativity aesthetically. This represented a more typical approach to creativity constituting artistic ability or visual appeal, which is often associated with surface level significance rather than a socially meaningful practical application. During the course of my research, I discovered that this typical stance was not a superfluous one. There are aesthetic implications to engineers' work, as perceptions of artistic quality remain important in design (Faste, 1995). It is important for students to understand particular elements of creativity that are part of the EDP. For instance, during this engineering unit creativity emerged to include: idea generation, design and innovation, gumption/resourcefulness, and social value. Students encountered many aspects of creativity during the EDP that requires attention and intentional cultivation to be fully realized.

Implications for Equity in Engineering Education

Equity concerns continue amidst slow-paced change in the achievement gap and diverse students' affiliation with STEM disciplines. However, each new step for reform (e.g., the incorporation of engineering into the *NGSS*) provides opportunities for students to connect with the STEM disciplines in progressive and innovative ways. The recent research report released by the Committee for STEM-Integration in K-12 Education indicated that students' engagement with integrated STEM disciplines has possibilities for transforming STEM-related identities (Honey, Pearson, & Schweingruber, 2014).

In my study, students were able to showcase their creative abilities as their design thinking skills were challenged during the engineering unit. Additionally, students experienced working collaboratively on engineering design teams, productively sharing their knowledge, prior experience, and innovative ideas with one another. Unexpectedly, but equally as encouraging, students connected with the plight of the characters in the engineering storybook. Students became invested in developing environmentally friendly solutions to the problem of finding alternative energy sources for cooking food with the goal protecting our natural resources. These positive outcomes associated with engagement in engineering practices were stimulated by the real-life context and open-ended nature of the engineering design challenge. These findings present encouraging outcomes cast against documented studies that indicate traditional K-12 classrooms and prototypical school practices can discourage underrepresented groups from STEM (Honey et al., 2014). The potential for engineering education to open up new gateways for students to showcase their creative skills and talents (e.g., idea generation, design and innovation, gumption) and excel with new competencies (e.g., collaboration skills and attention to ethical considerations) presents exciting implications for the future of STEM education.

Struggling students and students with uncertain trajectories in my study surprised the teachers with their efficacious performances during the engineering unit. Thirty-one percent of students in Landon and 50 percent from Monroe identified themselves as "smart engineers." Additionally, many more students (69% from Landon and 90% from Monroe) affiliated with characteristics they used to describe "smart engineers" in their classrooms. These qualities included careful use of resources; making good decisions about insulating materials to include in the solar oven; creative design solutions; confidence; and persistence during the design process. Students' perceived levels of engineering competence also appeared to influence their positions in their collaborative teams, providing possibilities for disruption of classroom status and hierarchies. Students who typically excelled in science class and had established a place for themselves as leaders (e.g., Tommy and Bruce) found themselves struggling with certain aspects of the design process. They discovered the necessity of teamwork and the need to rely on the support and ideas of their team members to be successful. Struggling students who did not typically have a voice in the classroom (e.g., Charis) found their voices, presenting their ideas to the class and making instrumental design decisions. Students who presented to the teacher as having uncertain trajectories (e.g., Leah) made a place for themselves as innovative roles models for product design.

Finally, the implications of early exposure cannot be ignored as a critical element in engaging diverse students in engineering and the STEM disciplines. The more exposure students have early in school to possible careers in engineering (i.e., the 20 different fields of engineering introduced in the EiE units) and the design thinking skills that seldom get developed as part of a typical classroom experience, the more likely students are to develop interest and affiliation that may carry on in later years. Dispelling myths of engineering education (and of science) as a profession only attainable by White males is an important first step. Women and individuals from underrepresented groups have much to offer the field. Ms. Warner shrewdly introduced students to a Hispanic male aerospace engineer in a video in part two of the EiE lesson. Websites like *Engineer Girl* (NAE, n.d.) also provide an avenue for girls to learn about and initiate discourse with women in engineering. Opportunities for early exposure to engineering are necessary as we move forward to spark interest and open up possibilities for more diverse affiliation and membership in the field.

Science and Engineering: Capitalizing on Complementarity

In Chapter I, I mapped out an argument for the introduction of engineering as early as elementary school as a way to provide students with opportunities to engage their creativity and promote a level of academic competence that has not been easily achieved within the current structure of traditional science classrooms. I proposed partnering progressive inquiry-based science education with engineering education as a way to achieve those goals. The structure of the EiE curriculum provides a way to productively infuse elements of scientific inquiry into the engineering curriculum (i.e., Part 3 – How scientific data inform engineering) opening up the potential for integration by providing opportunities to capitalize on the complementarity of each discipline.

The shared conceptual landscape of science and engineering and their overlapping, but not identical, practices and habits of mind make for interesting opportunities to study science learning in the context of engineering and engineering learning in the context of science (Cunningham & Carlsen, 2014). When integrating subjects in STEM education, one subject tends to take a dominant role, carrying either an explicit or implicit focus (Honey et al. 2014). The purpose of integration is to have supporting subjects strengthen or deepen conceptual understanding of the dominant, focal subject. In my study, engineering assumed the dominant role and science, in addition to fundamentals of technology, served to deepen and enrich students' learning experiences. Such can be the case in a carefully constructed science inquiry unit or lesson where science assumes the dominant role while other STEM subjects take on supporting positions. It is not logical or practical to assume that subjects can be effectively taught in isolation or that one is hierarchically superior to another, especially in our current educational climate.

To capitalize on the complementarity of science and engineering and their mutually reinforcing nature, I propose four areas I believe can be better promoted in both disciplines as the result of my work in this engineering-based study. I recommend teachers explicitly teach to recognize and cultivate: creativity; team-based learning/collaboration; and socio-scientific issues/ethical considerations, which are relevant to both engineering and science, as these were found to be an important part of the learning experience for students in this study.

Creativity in Science and Engineering

The cultural production of creativity during the engineering unit gave insight into the meanings students made of creativity as part of the engineering design process. In this context, engineering emerged as idea generation, design and innovation, gumption/resourcefulness, and social value. Elements of creativity as outlined in Kazerounian and Foley's (2007) ten maxims emerged through out the unit, threaded throughout each of the four themes, highlighting the relevance of creativity in practice. Specifically intriguing with implications for science education, were: providing space for imagination (maxim 1); tolerance for ambiguity (maxim 2); and ownership of learning (maxim 10).

Students reported that they felt comfortable imagining during the engineering unit due to the lack of rigid structure or step-by-step guidelines that are often present in procedurally oriented science lessons. Students indicated opportunities to think ahead and develop creative visions (e.g., "create pictures in their head"). The lack of firmly established rules and procedures during the design challenge allowed for students to keep an open mind, see things in a new light, and pay attention to the unexpected (maxim 1).

Students had to learn to become comfortable with unexpected outcomes during the engineering unit. Solutions to problems were not always readily available as teachers in addition to students were confronted with the possibility that there could be more than one right answer to solving the problem. Opportunities to *improve* allowed a safe space for students to test new ideas and develop tolerance with ambiguity (maxim 2). The *improve* phase of the EDP therefore became a critical component of the unit and one that could be easily adapted to science-inquiry lessons.

Additionally, ownership of learning (maxim 10) emerged as positive outcome of engaging in the engineering design process. Students were able to make decisions about the design and materials to use in their solar ovens giving them control over the outcomes of their designs. Students became personally invested in their solar oven design outcomes. They were free to make decisions and take potential risks while balancing the tradeoffs of their design choices. The benefits of autonomous, agentic practice cannot be underrated and are not limited to engineering. Developing this form of agency, ownership of learning and decision-making can also be included as a regular goal of practice in science classrooms.

Team-Based Learning in Science and Engineering

The cultural production of collaboration during the engineering unit provided insight into how students negotiated space for themselves in their design teams and how teachers facilitated that collaborative process. The teachers used a mix of pedagogical strategies ranging from more structured teacher-led discussion to more autonomous small-group work. With each progressive stage of the four-part unit, students were provided increasing opportunities for autonomous practice (refer to Figures 5.1 and 5.2). As part of the group dynamic in each classroom, students negotiated spaces for collaboration through challenges of competition versus compromise; assumed versus assigned roles; management of verbal versus non-verbal communication; and shifts from teacher-as-authority-figure to peers as sources of knowledge and inspiration.

Earlier in Chapter I, Mann et al. (2011) highlighted the importance of integrating engineering education into the K-6 curriculum as a way to develop communication, teamwork, and leadership abilities in students. Smith et al. (2005) similarly emphasized teamwork skills as critical to engineering design teams. These skills included leadership, decision-making, trust-building, communication, and conflict-management skills. Also, Smith et al. indicated the focus on joint performance or “positive interdependence” as a critical component of effective design teams. Explicitly cultivating these team-based skills and the addressing the potential challenges faced by students in engineering design teams (as above) should be addressed across subject areas as a common practice in productive learning environments for students.

Ethical Considerations in Science and Engineering

The open-ended nature of the engineering design challenges provided an ideal context for broaching socio-scientific issues (SSIs) and attention to ethical considerations during the engineering unit. Teaching to promote attention to ethical considerations has proven problematic in school because it challenges students’ developing emotional and social skills (Lindhal et .al, 2011). During the EiE unit, students became emotionally invested in solving the central character’s problem of finding and alternative form of energy to cook food, while protecting natural resources.

Due to recent advances in science and engineering and the environmental challenges we face as a nation every day, opportunities to develop moral and ethical reasoning (Lewis & Leach, 2006) in our students is important now more than ever. It is also critical for students to understand the obligations of engineers (and scientists) to society. It is important to recognize that some failures in engineering have had devastating results on life and the economy (e.g., Quebec Bridge Collapse, 1907; Love Canal, 1980; Chernobyl disaster, 1986; and the Space Shuttle Challenger, 1986 and Columbia, 2003 disasters). Although learning occurred through failure with each devastating incident, ethically, engineers are obligated to protect human life and the environment. As a reminder of this obligation, Canadians (circa 1948) instituted the Iron Ring Ceremony, an iron ring to be worn as a reminder of ethical service, and an oath ("Obligation of the Calling of an Engineer") much like the Hippocratic oath taken by doctors in medicine (Petroski, 2012). By 1970, a similar ring ceremony was instituted in the United States along with an oath ("Order of the Engineer") as a reminder of ethical service to "foster a spirit of pride and responsibility in the profession, to bridge a gap between training and practice, and to present the public with a visible symbol identifying the engineer" (p. 189).

Opportunities to initiate discussion about ethics and moral reasoning in socio-scientific issues is easily possible as part of engineering curricular units. It is equally as important to broach these issues in science classrooms. Educators should make it a priority to engage in these dialogues, making students aware of the responsibilities and obligations professionals in the disciplines of engineering and science face as a regular part of their daily practice.

Recommendations for Pre-Service Teacher Initiatives

Currently, no established pre-service initiatives exist with specified K-12 qualifications for engineering educators (Katehi, 2009). This points to a key area in need of development if engineering is to be introduced successfully at the elementary school level. In-service elementary school teachers are already struggling to lobby for space and time in the curriculum to teach science effectively with the demands on prioritizing reading and mathematics in our high-stakes testing environment. These limitations clearly call for attention to be focused on the development of pre-service teacher programs that adequately prepare teachers to meet the increasing demands of teaching science and engineering in our current educational climate. The advantage of initiating pre-service engineering education in favor of waiting for in-service professional development opportunities is pre-service teachers are able to engage in longer periods of exposure to develop concepts and skills necessary to teach engineering as part of their professional development programs (Katehi et al., 2009).

According to the findings and implications for practice I have highlighted in this chapter as a result of my engineering-based study, I propose a series of recommendations for pre-service teacher education programs to strengthen qualifications for teaching engineering (and other STEM disciplines) in the elementary school.

- Recommendation 1—*Explicitly teach for creativity*. Teachers need to understand how to recognize and cultivate creativity in their students. Design thinking skills can be emphasized to include opportunities for idea generation through carefully constructed and facilitated brainstorming sessions; understanding the structural and functional aspects of design and innovation; developing *gumption* through experiences with failure, risk-taking, and optimistically created design solutions; and appreciation of the practical, aesthetic, and social value of design products.
- Recommendation 2—*Promote equity by broadening exposure and affiliation*. Pre-service teachers should be made aware of the many fields of engineering to be able to provide broad exposure to students. The history of engineering can be explored to highlight the accomplishments of women and other underrepresented

groups. A strong team-based collaborative culture should be cultivated to allow for development of leadership, decision-making, trust-building, communication, and conflict-management skills. Groups need to be deftly nurtured to shift students from a mindset of teacher-as-authority figure toward more communal sources of inspiration with the goal of efficacious practice among all students.

- Recommendation 3—*Mindfully integrate STEM subjects*. Students' engagement with integrated STEM disciplines has been determined to have a positive effect on interest, identity, learning and achievement (Honey et al., 2014). The mutually reinforcing nature of science and engineering presents prime opportunities to teach these two subjects in concert instead of as silo-ed subjects (Katehi, 2009). Engaging experiences with STEM subjects can help to promote STEM identities (Honey et al., 2014). Additionally, exposing pre-service teachers to effective strategies for integration can help to capitalize on time and efficiency in their teaching practices.
- Recommendation 4—*Teach to promote attention to ethical considerations*. Pre-service teachers should be exposed to the socio-scientific issues that surround science and engineering. Opportunities must be made available to address environmental concerns facing each discipline with an understanding of how to connect these concepts to students' lives. Attention should be aimed at both local and global concerns. Moral and ethical reasoning and the obligations STEM professionals face need to be part of the pre-service teacher curriculum. Helping

students become advocates for themselves and their communities must be a curricular focus.

Ultimately, it is important for teachers to recognize the important role they play in facilitating learning for students in the STEM disciplines. A carefully crafted curriculum is one piece of the puzzle. Teachers are the critical element necessary for successful implementation.

Future Research

The range of research studies focused on engineering education in elementary school remains sparse (Katehi et al., 2009). We are only beginning to understand the meaning that students (and teachers) are making of this newly introduced discipline and its associated practices and habits of mind. My study was focused on the implementation of a green engineering solar energy unit in two fifth-grade classrooms, with attention to specific engineering habits of mind (creativity, collaboration, and attention to ethical considerations) and students' identity work. While this is a good start, much more research needs to be done to determine how to best support the learning of students (and teachers) regarding engineering in the elementary school.

Here, I suggest potential areas for future research that might logically evolve from my experiences in studying engineering in two fifth-grade school classrooms.

- My study involved implementation of one unit in one specific grade level over the course of 10-12 lessons. Suggestions for future studies would involve studying across multiple grade levels (third through fifth) and with more than one engineering unit. For example, a comparative study could be conducted to examine the implementation of a particular EiE unit (e.g., *Just Passing Through: Designing Model Membranes*) in a third, fourth, and fifth grade classroom. This could provide insights into how students developmentally approach engineering practices and habits of mind. Alternatively, one could study a fifth-grade classroom over the course of an instructional school year and students' experiences with multiple engineering units. Examining how learning occurs, practices are taken up or resisted, and habits of mind are negotiated over time would provide interesting insights. A longer-term strategy could be to conduct a longitudinal study to examine how students' experiences with engineering emerge over the course of successive school years.

- Due to the inevitable comparisons between science and engineering, it might be prudent to design a study to examine the affordances and constraints of a well constructed, stand-alone science inquiry unit, an engineering unit, and a unit designed to integrate both science and engineering practices. A veteran teacher, who is well versed in teaching in the STEM disciplines, should deliver each unit. Student learning gains, interest, and identity work in each of these contexts could provide information about the design and implementation of these STEM-based units.
- Next, in a shift from student to teacher, I propose studying pre-service teachers' experiences with engineering education. This could involve implementing a STEM-focused pre-service teacher curriculum specifically focused on developing competency with engineering educational practices and habits of mind. The pre-

service teachers could initially be followed during the course of the semester and during their internship experiences and subsequently followed through their first year of teaching to determine their level of competency and comfort in delivering effective engineering instruction to students. This could provide insights into development of strong teacher preparation programs.

Final Thoughts

I would like to close by reflecting on lessons learned from my experiences introducing engineering curricula in elementary school. This study provided some unique insights and some unexpected surprises about the benefits and challenges of exploring new territory (engineering education) in a well-established domain (science education).

First, I begin with the challenges. The restriction of time available for teachers to teach science in elementary school is daunting. Therefore, the prospect of introducing engineering further complicated limitations on time. Despite a supportive administration, the teachers in my study had to overcome significant obstacles to be able to implement one complete engineering unit in their classrooms during regular science instructional time. Each teacher creatively managed their schedules to successfully implement the unit, but this was not an easy task. These rigid limits on instructional time for subjects like science, engineering, and technology shed light on the priorities of our educational system, limiting opportunities for growth and innovation. Teachers have become crafty negotiators of time, but these strict limitations on autonomous teaching weigh heavily on teachers' shoulders. This current educational climate does not bode well for a teacher's desire to incorporate new curricula and innovative teaching practices in their classrooms.

Perhaps, the poor projections for fulfilling our country's quotas for STEM-based professionals will be a catalyst for reform to eventually re-structure the current elementary school instructional day. On a more positive note, the teachers in this study were able to persevere through a difficult system and expressed their desire to continue teaching to promote engineering in the future.

The next challenge I faced was navigating the unexpected rift spurred by the introduction of engineering practices into the existing science standards as part of the *Next Generation Science Standards* (NGSS Lead States, 2013). Science has an established place of dominance and the introduction of engineering threatens its status. The "border disputes" between science education and the other STEM disciplines indicate the historical status each has established over time (Cunningham & Carlsen, 2014). For example, the status of each includes,

> …(Mathematics) that enjoys both societal status and security in the precollege curriculum, one (Engineering) that is characterized by high status but has an almost negligible presence in the precollege curriculum, and one (Technology) that, depending on the country of interest, varies widely around the world in status and curricular security (from ascendant to strong to threatened with extinction). (p. 756)

My pursuit to learn more about the affordances of engineering education was not to upend or find a replacement for science education. Rather, it was my desire to learn how to further enrich students' learning experiences and find ways to move forward and stay current in our field by learning how to enhance the complementarity of these disciplines. Cunningham and Carlsen (2014) suggested cycles of engineering design and scientific investigation to promote deeper learning experiences for students. I share in this vision.

A benefit of including engineering education as part of the elementary school curriculum is the opportunity to stimulate creative thinking in students. In this study, the open-ended nature of the engineering design challenge afforded unique opportunities for students to imagine and generate multiple, viable solutions to a problem. It allowed for space to collaborate in engineering teams to develop innovative design solutions. Students were provided freedom to experiment with and choose materials in original combinations. They had experiences with failure and were presented with opportunities to improve their designs. I found this mostly autonomous practice to be especially liberating for students used to the typically rigid structure of school. Students came to see themselves as “smart engineers” as they confidently produced design products that had a positive impact on the environment.

Due to the green engineering focus and literacy connections presented in this unit, students were able to connect with the plight of the main character and developed environmental awareness as they explored the central problem. This finding is encouraging for the prospect of productively teaching socio-scientific issues with the purpose of developing moral reasoning and addressing ethical considerations as a part of the science and engineering curriculum.

Of course, the findings from this study represent only a small glimpse into the possibilities and potential of introducing engineering in elementary school, but these initial findings are encouraging. The field is ripe and ready for continued research with the goal of producing capable, competent students ready to face the challenges of a rapidly changing, ever-demanding STEM-focused future.

REFERENCES

Alliance for Excellent Education. (2014). *Publications: Reports and fact sheets.* Retrieved from http://all4ed.org/publications/

Amabile, T. M. (1983). *The social psychology of creativity.* New York: Springer-Verlag.

Amabile, T. M. (1995). Attributions of creativity: What are the consequences? *Creativity Research Journal*, *8*(4), 423-426. doi:10.1207/s15326934crj0804_10

Amabile, T. M. (1996). *Creativity in context: Update to "The social psychology of creativity*." Boulder, CO: Westview Press.

American Association for the Advancement of Science [AAAS]. (1997). *Resources for science literacy: Professional development*. New York: Oxford University Press.

Armytage, W. H. G. (2003). *A social history of engineering* (2nd ed.). Cambridge, MA: The MIT Press.

Auyang, S. Y. (2004). *Engineering—An endless frontier.* Cambridge, MA: Harvard University Press.

Auyang, S. Y (2005, October 13). *Similarity and complementarity of science and engineering.* Paper presented at the Conference on the Philosophy of Technology, Copenhagen.

Auyang, S. Y. (n.d.). *Engineering the information age*. Retrieved from http://www.creatingtechnology.org/history3.htm

Barton, A. C., & Yang, K. (2000). The culture of power and science education: Learning from Miguel. *Journal of Research in Science Teaching*, *37*(8), 871-88

Basu, S. J., & Barton, A. C. (2007). Developing a sustained interest in science among urban minority youth. *Journal of Research in Science Teaching*, *44*(3), 466-489. doi: 10.1002/tea.20143

Bell, P., Lewenstein, B., Shouse, A. W., & Feder, M. A. (Eds.). (2009). *Learning science in informal environments: People, places, and pursuits*. Washington, DC: National Academies Press.

Besemer, S. P. & Treffinger, D. J. (1981). Analysis of creative products: Review and synthesis. *The Journal of Creative Behavior*, *15*(3), 158-177.

Bourdieu, P. (1977). *Outline of a theory of practice*. Cambridge, MA: Cambridge University Press.

Brickhouse, N. (1994). Bringing in the outsiders: Reshaping the sciences of the future. *Journal of Curriculum Studies*, *26*(4), 401-416. doi:10.1080/0022027940260404

Brickhouse, N. W., Lowery, P., & Schultz, K. (2000). What kind of a girl does science? The construction of school science identities. *Journal of Research in Science Teaching*, *37*(5), 441-458.

Brophy, S., Klein, S., Portsmore, M., & Rogers, C. (2008). Advancing engineering education in P-12 classrooms. *Journal of Engineering Education*, *97*(3), 369-387.

Buxton, C. A. (2001). Modeling science teaching on science practice? Painting a more accurate picture through an ethnographic lab study. *Journal of Research in Science Teaching*, *38*(4), 387-407.

Bybee, R. W. (2011). K-12 engineering education standards: Opportunities and barriers. *Technology & Engineering Teacher*, *70*(5), 21-29.

Calabrese Barton, A. (2007). Science learning in urban settings. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 319-343). London: Lawrence Erlbaum Associates.

Calabrese Barton, A. & Tan, E. (2009). Funds of knowledge and discourses and hybrid space. *Journal of Research in Science Teaching, 46*(1), 50-73.

Calabrese Barton, A. C. & Tan, E. (2010). We be burnin'! Agency, identity, and science learning. *Journal of the Learning Sciences*, *19*(2), 187–229.

Cardella, M. E. (2006). *Engineering mathematics: An investigation of students' mathematical thinking from a cognitive engineering perspective* (Doctoral dissertation). Retrieved from ProQuest.

Carlone, H. B. (2004). The cultural production of science in reform-based physics: Girls' access, participation, and resistance. *Journal of Research in Science Teaching*, *41*(4), 392-414.

Carlone, H. B. (2012). Methodological considerations for studying students' identities in school science: An anthropological approach. In M. Varelas (Ed). *Identity construction and science education research: Learning, teaching, and being in multiple contexts*, (pp. 9-26). Sense Publishers: Rotterdam, The Netherlands.

Carlone, H. B., Haun-Frank, J., & Webb, A. (2011). Assessing equity beyond knowledge- and skills-based outcomes: A comparative ethnography of two fourth-grade reform-based science classrooms. *Journal of Research in Science Teaching, 48*(5), 459-485.

Carlone, H.B**.**, Johnson, A., & Eisenhart, M.E. (2014). Cultural perspectives in science education. In S.K. Abell & N. Lederman (Eds.). *Handbook of Research in Science Education (2nd edition)* (pp. 2069-2135). New York: Routledge.

Carlsen, W. S. (1998). Engineering design in the classroom: Is it good science education or is it revolting?. *Research in Science Education*, *28*, 51-63.

Clark, B. (2012). *Growing up gifted: Developing the potential of children at school and at home.* Upper Saddle River, NJ: Pearson.

Cooper, M. (2012, December 12). Census officials, citing increasing diversity, say U.S. will be a ‘plurality nation’. *The New York Times.* Retrieved from http://www.nytimes.com/2012/12/13/us/us-will-have-no-ethnic-majority-census-finds.html?_r=0

Craft, A. (2001). An analysis of research and literature on creativity in education. *Qualifications and Curriculum Authority*, 1-37.

Craft, A. (2003). The limits to creativity in education: Dilemmas for the educator. *British Journal of Educational Studies*, *51*(2), 113-127.

Creswell, J. W. (2012). *Educational research: Planning, conducting, and evaluating quantitative and qualitative research.* Boston, MA: Pearson Education, Inc.

Cunningham, C. M. (2009). Engineering is elementary. *The Bridge*, *30*(3), 11-17.

Cunningham, C. M. & Carlsen, W. S. (2014). Precollege engineering education. In N. Lederman (Ed.), *Handbook of research on science education* (pp. 747-758). Mahweh, NJ: Lawrence Erlbaum Associates, Publishers.

Cunningham, C. M. & Lachapelle, C. P. (2014). Designing engineering experiences to engage all students. In S. Purzer, J. Strobel, & M. Cardella (Eds.), *Engineering in pre-college settings: Synthesizing research, policy, and practices* (pp. 117-142). Lafayette, IN: Purdue University Press.

Denzin, N. K., & Lincoln, Y. S. (2005). Introduction: The discipline and practice of qualitative research. In N. K. Denzin & Y. S. Lincoln (Eds.). *The Sage handbook of qualitative research* (3rd ed.) (pp. 1-32). Thousand Oaks, CA: Sage.

Dweck, C.S. (2008). *Mindset: The new psychology of success.* Ballantine Books: New York.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*(1), 103-120.

Eisenhart, M. (2001a). Educational ethnography past, present, and future: Ideas to think with. *Educational Researcher*, *30*(8), 16-27.

Eisenhart, M. (2001b). Changing conceptions of culture and ethnographic methodology: Recent thematic shifts and their implications for research on teaching. In V. Richardson (Ed). *Handbook of research on teaching* (4th ed.) (pp. 209-225). Washington, DC: American Educational Research Association.

Engineering is Elementary (2011). *Now you're cooking: Designing solar ovens*. Boston, MA: Museum of Science.

Faste, R. A. (1995). The role of aesthetics in engineering. *Japan Society of Mechanical Engineers*, *28*, 385-390.

Fleer, M. (1999). Children's alternative views: Alternative to what? *International Journal of Science Education, 21*(2), 119–35.

Fleer, M. (2000). Working technologically: Investigations into how young children design and make during technology education. *International Journal of Technology and Design Education, 10*(1), 43–59.

Fletcher, K. L., & Speirs Neumeister, K. L. (2012). Research on perfectionism and achievement motivation: Implications for gifted students. *Psychology in the Schools*, *49*(7), 668-677.

Florida, R. (2004, October). America's looming creativity crisis. *Harvard Business Review, 1-9.*

Foor, C. E., Walden, S. E., & Trytten, D. A. (2007). "I wish that I belonged more in this whole engineering group:" Achieving individual diversity. *Journal of Engineering Education*, *96*(2), 103-115.

Fortus, D., Dershimer, R. C., Krajcik, J. S., Marx, R. W., & Mamlok-Naaman, R. (2004). Design-based science and student learning. *Journal of Research in Science Teaching*, *41*(10), 1081–1110.

Friedman, T. L. (2014, February, 22). How to get a job at Google. *The New York Times.* Retrieved from http://www.nytimes.com/2014/02/23/opinion/sunday/friedman-how-to-get-a-job-at-google.html?_r=0

Gándara, P. (2005, December). Fragile futures: Risk and vulnerability among Latino high achievers. *Educational Testing Service Policy Information Report*. Retrieved from http://www.nea.org/home/20380.htm

Glesne, C. (2011). *Becoming qualitative researchers: An introduction* (4th ed.). Boston, MA: Pearson.

Gutierrez, K., & Rogoff, B. (2003). Cultural ways of learning: Individual traits or repertoires of practice. *Educational Researcher, 32*(5), 19-25.

Hammond, L., & Brandt, C. (2004). Science and cultural process: Defining an anthropological approach to science education. *Studies in Science Education, 40*(1), 1-47. doi:10.1080/03057260408560202

Hatt, B. (2012). Smartness as a cultural practice in schools. *American Educational Research Journal*, *49*(3), 438-460.

Hegedus, T., Carlone, H. B., & Carter, A. (2014). *Shifts in the cultural production of "smartness" through engineering in elementary classrooms*. Proceedings of the annual meeting of the American Society of Engineering Education. Indianapolis, IN.

Holland, D., & Lachicotte, J. W., Skinner, D., & Cain, C. (1998). *Identity and agency in cultural worlds*. Cambridge, MA: Harvard University Press.

Holland, D., & Lave, J. (2009). Social practice theory and the historical production of persons. *Actio: An International Journal of Human Activity Theory*, *2*, 1-15.

Honey, M., Pearson, G., & Schweingruber, H. (Eds.). (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. Washington, DC: National Academies Press.

Hung, D., Chen, V., & Lim, S. H. (2009). Unpacking the hidden efficacies of learning in productive failure. *Learning Inquiry*, *3*(1), 1-19.

Isaksen, S. G., & Gaulin, J. P. (2005). A reexamination of brainstorming research: Implications for research and practice. *Gifted Child Quarterly*, *49*(4), 315-329.

Johnsey, R. (1995). *The place of the process skill making in design and technology: Lessons from research into the way primary children design and make*. In Proceedings of the IDATER95: International Conference on Design and Technology Educational Research and Curriculum Development. Loughborough, UK: Loughborough University of Technology.

Jones, G. M., Jones, B. D., & Hargrove, T. (2003). *The unintended consequences of high-stakes testing*. Lanham, MD: Rowman & Littlefield Publishers.

Katehi, L. P. B. (2009, October 22). *Engineering in K-12 education*. In report before the Subcommittee on Research and Science Education, Committee on Science, U.S. House of Representatives (pp. 1-14). Washington, D.C.

Katehi, L., Pearson, G., & Feder, M. A. (2009). *Engineering in K-12 education: Understanding the status and improving the prospects*. Washington, DC: National Academies Press.

Kaufman, J. C., & Plucker, J. A. (2011). Intelligence and creativity. In R. J. Sternberg & S. B. Kaufman (Eds.), *The Cambridge handbook of intelligence* (pp. 771-783). New York, NY: Cambridge University Press.

Kazerounian, K., & Foley, S. (2007). Barriers to creativity in engineering education: A study of instructors and students perceptions. *Journal of Mechanical Design*, *129*, 761.

Kelly, G. J. (2010). Scientific literacy, discourse, and epistemic practices. In C. Linder, L. Ostman, D. A. Roberts, P. O. Wickman, G. Erickson, & A. MacKinnon (Eds.), *Exploring the landscape of scientific literacy* (pp. 61–73). New York: Routledge.

Kelly, G. J., Chen, C., & Crawford, T. (1998). Methodological considerations for studying science-in-the-making in educational settings. *Research in Science Education*, *28*(1), 23-49.

Kelly, G. J., & Duschl, R. A. (2002, April). *Toward a research agenda for epistemological studies in science education.* In the annual meeting of the National Association for Research in Science Teaching, New Orleans, LA.

Khatena, J., & Torrance, E. P. (1973). *Thinking creatively with sounds and words: Technical Manual* (Research Ed.). Lexington, MA: Personnel Press.

Knight, M., & Cunningham, C. M. (2004). *Draw an engineer test (DAET): Development of a tool to investigate students' ideas about engineers and engineering*. In paper presented at the ASEE Annual Conference and Exposition. Salt Lake City, UT.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., … Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting Learning by Design into practice. *Journal of the Learning Sciences*, *12*(4), 495–547.

Lachapelle, C. P. & Cunningham, C. M. (2014). Engineering in elementary schools. In S. Purzer, J. Strobel, & M. Cardella (Eds.), *Engineering in pre-college settings: Synthesizing research, policy, and practices* (pp.61-88). Lafayette, IN: Purdue University Press.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. New York: Cambridge University Press.

Lederman, N. G. (2010). A powerful way to learn. *Science and Children*, *48*(1), 8-9.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching*, *39*(6), 497-521.

Lee, O. (1997). Guest editorial: Scientific literacy for all: What is it, and how can we achieve it?. *Journal of Research in Science Teaching*, *34*(3), 219-222.

Lee, O. (2003). Equity for linguistically and culturally diverse students in science education: A research agenda. *Teachers College Record*, *105*(3), 465–489.

Lee, O. (2012, March 27). "*Diversity and equity in science education: A research agenda and role for NARST*." NARST Annual International Conference, JW Marriott, Indianapolis, IN. Keynote Address.

Lee, O. & Luykx, A. (2007). Science education and student diversity: Race/ethnicity, language, culture, and socioeconomic status. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 171-197). London: Lawrence Erlbaum Associates.

Levinson, B. A., Foley, D. E., & Holland, D. C. (1996). *The cultural production of the educated person: Critical ethnographies of schooling and local practice.* Albany, NY: State University of New York Press.

Lewis, C., & Moje, E. B. (2003). Sociocultural perspectives meet critical theories. *International Journal of Learning*, *10*, 1979-95.

Lewis, J., & Leach, J. (2006). Discussion of socio-scientific issues: The role of science knowledge. *International Journal of Science Education*, *28*(11), 1267-1287.

Lewis, T. (2006). Design and inquiry: Bases for an accommodation between science and technology education in the curriculum?. *Journal of Research in Science Teaching*, *43*(3), 255-281.

Lichtman, M. (2010). *Qualitative research in education: A user's guide* (2nd ed.). Washington, DC: Sage.

Locke, E. (2009). Proposed model for a streamlined, cohesive, and optimized K-12 STEM curriculum with a focus on engineering. *Journal of Technology Studies*, *35*(2) 23-35.

Lottero-Perdue, P. S., & Parry, E. A. (2014, June). *Perspectives on failure in the classroom by elementary teachers new to teaching engineering*. In paper presented at the 121st ASEE Annual Conference and Exposition, Indianapolis, IN. Paper ID# 9624.

Mann, E. L., Mann, R. L., Strutz, M. L., Duncan, D., & Yoon, S. Y. (2011). Integrating engineering into K-6 curriculum developing talent in the STEM disciplines. *Journal of Advanced Academics*, *22*(4), 639-658.

Maxwell, J. A. (2013). *Qualitative research design.* Thousand Oaks, CA: Sage Publications, Inc.

Mayer, R. E. (2011). Intelligence and achievement. In R. J. Sternberg & S. B. Kaufman (Eds.), *The Cambridge handbook of intelligence* (pp. 738-747). New York, NY: Cambridge University Press.

Mehalik, M. M., Doppelt, Y., & Schunn, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. *Journal of Engineering Education*, *97*(1), 71–71.

Merriam, S. B. (2002). *Qualitative research in practice: Examples for discussion and analysis.* San Francisco: Jossey-Bass.

Meyer, D. Z., & Avery, L. M. (2009). Excel as a qualitative data analysis tool. *Field Methods*, *21*(1), 91-112.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). Thousand Oaks, CA: Sage Publications, Inc.

Morales, J. F., & Coop, A. (2006, April). A people's history of science: An interview with Clifford Conner. *Natural Selections, 25,* 1-3.

Moritz, B. (2014, January 23). America's talent gap. *The Huffington Post.* Retrieved from http://www.huffingtonpost.com/bob-moritz/americas-talent-gap_b_2080162.html

Museum of Science, Boston [MOS]. (2014). *Engineering is elementary.* Retrieved from http://www.eie.org/

National Academy of Engineering [NAE]. (n.d.). *Engineer girl.* Retrieved from http://www.engineergirl.org

National Advisory Committee on Creative and Cultural Education [NACCCE]. (1999). *All our futures: Creativity, culture and education*. Department for Education and Employment, London.

National Center for Educational Statistics [NCES]. (2014, February 10). *National Assessment of Educational Progress: Technology and engineering literacy assessment.* Retrieved from http://nces.ed.gov/nationsreportcard/tel/

National Conference of State Legislatures [NCSL]. (n.d.). Science, technology, engineering, and math (STEM). Retrieved from http://www.ncsl.org/research/education/stem-overview.aspx

National Education Association [NEA]. (n.d.). *Students affected by achievement gaps.* Retrieved from http://www.nea.org/home/20380.htm

National Education Association [NEA]. (2007, December). *Hispanics – Special education and English language learners.* Retrieved from http://www.nea.org/home/20380.htm

National Education Association [NEA]. (2008, February). *News we lose: Black student gains*. Retrieved from http://www.nea.org/home/20380.htm

National Research Council [NRC]. (2010). *Standards for K-12 engineering education?* Washington, DC: The National Academies Press.

National Research Council [NRC]. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Committee on a conceptual framework for new K-12 science education standards. Board of Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

National Science Board [NSB]. (2008). *Science and engineering indicators 2008*. Arlington, VA: National Science Foundation (NSB-08-1).

National Science Board [NSB]. (2010). *Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital* (Report No. NSB 10-33). Arlington, VA: National Science Foundation.

National Science Foundation [NSF]. (2009). *Women, minorities, and persons with disabilities in science and engineering: 2009.* NSF 09-305. Division of Science Resources Statistics. Retrieved from http://www.nsf. gov/statistics/wmpd/

National Science Foundation [NSF]. (2014, February). *Science and engineering indicators 2014.* NSB 14-01. Retrieved from http://www.nsf.gov/statistics/seind14/index.cfm/chapter-2/c2h.htm

National Science Teachers Association. [NSTA]. (2000, July). *NSTA position statement: The nature of science*. Retrieved from http://www.nsta.org/about/positions/natureofscience.aspx

NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. Washington, DC: The National Academies Press.

Nichols, S. L., & Berliner, D. C. (2007). *Collateral damage: How high-stakes testing corrupts America's schools*. Cambridge, MA: Harvard Education Press.

North Carolina Department of Public Instruction [NCDPI]. (n.d.). *NC essential standards*. Retrieved from http://www.ncpublicschools.org/acre/standards/new-standards/

Oakley, B. A., Hanna, D. M., Kuzmyn, Z., & Felder, R. M. (2007). Best practices involving teamwork in the classroom: Results from a survey of 6435 engineering student respondents. *Education, IEEE Transactions on Education*, *50*(3), 266-272.

Orlich, D., Harder, R., Callahan, R., Trevisan, M., & Brown, A. (2013). *Teaching strategies: A guide to effective instruction* (10th ed.). Belmont, CA: Cengage Learning.

Orsak, G. C. (2003). Guest editorial K-12: Engineering's new frontier. *Education, IEEE Transactions on*, *46*(2), 209-210.

Osborne, A. F. (1953). *Applied imagination: Principles and procedures of creative thinking.* New York: Charles Scribner’s Sons.

Osborn, A. F. (1963). *Applied imagination: Principles and procedures of creative problem solving* (3rd Rev. ed.). New York: Charles Scribner's Sons.

Osborne, J., & Collins, S. (2001). Pupils' views of the role and value of the science curriculum: A focus-group study. *International Journal of Science Education, 23*(5), 441-467.

Oxford University Press. (2014). *Oxford dictionaries: Language matters*. Retrieved from http://www.oxforddictionaries.com/us/definition/american_english/gumption

Pandina Scot, T., Callahan, C. M., & Urquhart, J. (2008). Paint-by-number teachers and cookie-cutter students: The unintended effects of high-stakes testing on the education of gifted students. *Roeper Review*, *31*(1), 40-52.

Parsons, W. B., & Woodbury, R. S. (1976). *Engineers and engineering in the Renaissance* (2nd ed.). Cambridge, MA: The MIT Press.

Partnership for 21st Century Skills [P21]. (2009). Framework for 21st century learning. Retrieved from http://www.p21.org/overview/skills-framework

Patton, M. Q. (2002). Qualitative interviewing. In M. Q. Patton, *Qualitative research and evaluation methods* (3rd ed.) (pp. 339-427). Thousand Oaks, CA: Sage Publications, Inc.

Persad, U., & Athre, K. (2013). Experiences with teaching introductory product design to engineering undergraduates. *The West Indian Journal of Engineering, 36*(1), 66-78.

Peshkin, A. (October, 1988). In search of subjectivity – One's own. *Educational Researcher, 17*(7), *17-21.*

Petroski, H. (2011). *The essential engineer: Why science alone will not solve our global problems* (Audiobook version). Retrieved from Audible.com

Petroski, H. (2012). *To forgive design: Understanding failure*. Cambridge, MA: Harvard University Press.

Pinch, T. J. (1992). Opening black boxes: Science, technology and society. *Social studies of science*, *22*(3), 487-510.

Rhodes, M. (1961). An analysis of creativity, *Phi Delta Kappan, 42,* 305-310.

Robinson, K. (2006, February). *TED*: *Ken Robinson says schools kill creativity* [video]. Retrieved from http://www.ted.com/talks/ken_robinson_says_schools_kill_creativity.html?quote=85

Rockland, R., Bloom, D. S., Carpinelli, J., Burr-Alexander, L., Hirsch, L. S., & Kimmel, H. (2010). Advancing the "E" in K-12 STEM education. *The Journal of Technology Studies, 36*(1), 53-64.

Roden, C. (1999). How children's problem solving strategies develop at key stage 1. *The Journal of Design and Technology Education, 4*(1), 21–27.

Rogers, C., & Portsmore, M. (2004). Bringing engineering to elementary school. *Journal of STEM Education: Innovations & Research*, *5*(3-4), 17-28.

Rogoff, B. (1994). Developing understanding of the idea of communities of learners. *Mind, Culture, and Activity, 1*(4), 209-229.

Roth, W. M. (1996). Knowledge diffusion in a grade 4–5 classroom during a unit on civil engineering: An analysis of a classroom community in terms of its changing resources and practices. *Cognition and Instruction, 14*(2), 179–220.

Runco, M. A. (2005). Creative giftedness. In R. J. Sternberg & J. E. Davidson (Eds.), *Conceptions of giftedness* (2nd ed.) (pp. 295-311). New York, NY: Cambridge University Press.

Sadler, T. D. (2004). Informal reasoning regarding socioscientific issues: A critical review of research. *Journal of Research in Science Teaching*, *41*(5), 513-536.

Sadler, T. D. (2009). Situated learning in science education: Socio-scientific issues as contexts for practice. *Studies in Science Education*, *45*(1), 1-42.

Sawyer, R. K. (2012). *Explaining creativity: The science of human innovation* (2nd ed.). New York: Oxford University Press.

Sawyer, R. K., & DeZutter, S. (2009). Distributed creativity: How collective creations emerge from collaboration. *Psychology of Aesthetics, Creativity, and the Arts*, *3*(2), 81-92.

Schensul, S. L., Schensul, J. J., & Le Compte, M. D. (1999). *Essential ethnographic methods: Observations, interviews, and questionnaires* (Vol. 2). Lanham, MD: Rowman & Littlefield Publishers, Inc.

Schneider, R. M., & Plasman, K. (2011). Science teacher learning progressions: A review of science teachers' pedagogical content knowledge development. *Review of Educational Research*, *81*(4), 530-565.

Schram, T. H. (2006). *Conceptualizing and proposing qualitative research*. Upper Saddle River, NJ: Pearson Merrill Prentice Hall.

Schunn, C. D. (2009). How kids learn engineering: The cognitive science perspective. *The Bridge*, *39*(3), 32-37.

Shaheen, R. (2010). Creativity and education. *Creative Education*, *1*(03), 166-169.

Silk, E. M., Schunn, C. D., & Cary, M. S. (2009). The impact of an engineering design curriculum on science reasoning in an urban setting. *Journal of Science Education and Technology*, *18*(3), 209–223.

Smith, K. A. (1995, January). *Cooperative learning: Effective teamwork for engineering classrooms*. Proceedings of the Frontiers in Education Conference (Vol. 1, pp. 13-18). IEEE.

Smith, K. A., Sheppard, S. D., Johnson, D. W., & Johnson, R. T. (2005). Pedagogies of engagement: Classroom-based practices. *Journal of Engineering Education, 94*(1), 87-101.

Smith, M. K. (2009). Jean Lave, Etienne Wenger and communities of practice. *The encyclopedia of informal education*. Retrieved from www.infed.org/biblio/communities_of_practice.htm

Spradley, J. P. (1980). *Participant observation.* New York: Holt, Rinehart, and Winston.

Stepanek, J. (1999, December). *Meeting the needs of gifted students: Differentiating Mathematics and Science Instruction*. Portand, OR: Northwest Regional Educational Laboratory.

Sternberg, R. J. (1999). The theory of successful intelligence. *Review of General Psychology, 3*(4)*,* 292–316. doi: 10.1037/1089-2680.3.4.292

Sternberg, R. J. (2005). The theory of successful intelligence. *Revista Interamericana de Psicología/Interamerican Journal of Psychology, 39(*2), 189-202.

Sternberg, R. J. (2011). The theory of successful intelligence. In R. J. Sternberg & S. B. Kaufman (Eds.), *The Cambridge handbook of intelligence* (pp. 504-527). New York, NY: Cambridge University Press.

Stump, G. S., Hilpert, J. C., Husman, J., Chung, W. T., & Kim, W. (2011). Collaborative learning in engineering students: Gender and achievement. *Journal of Engineering Education*, *100*(3), 475-497.

Tan, E., & Barton, A. C. (2008). Unpacking science for all through the lens of identities-in-practice: The stories of Amelia and Ginny. *Cultural Studies of Science Education*, *3*(1), 43-71.

The Center for Public Education. (2005, November 1). *Teacher quality and student achievement: Research review*. Retrieved from http://www.centerforpubliceducation.org/Main-Menu/Staffingstudents/Teacher-quality-and-student-achievement-At-a-glance/Teacher-quality-and-student-achievement-Research-review.html

The White House. (n.d.). *Knowledge and skills for the jobs of the future: Educate to innovate*. Retrieved from http://www.whitehouse.gov/issues/education/k-12/educate-innovate

Tolbert, M. D. A., & Cardella, M. E. (2013, June). *Early work for the mathematics as a gatekeeper to engineering project: A review of informal learning, engineering and design thinking literature.* In paper presented at the 120th ASEE Annual Conference and Exposition, Atlanta, GA.

Tracy, S. J. (2010). Qualitative quality: Eight “big-tent” criteria for excellent qualitative research. *Qualitative inquiry*, *16*(10), 837-851.

Treffinger, D. J., Young, G. C., Selby, E. C., & Shepardson, C. (2002, December). *Assessing creativity: A guide for educators*. Storrs, CT: National Research Center on the Gifted and Talented.

U.S. Census Bureau. (n.d.). *United States census 2010: It’s in our hands*. Retrieved from https://www.census.gov/2010census/

Van Tassel-Baska, J., Quek, C., & Xuemei Feng, A. (2006). The development and use of a structured teacher observation scale to assess differentiated best practice. *Roeper Review, 29*(2), 84-92.

Verdugo, R. (2006). *A report on the status of Hispanics in education: Overcoming a history of neglect.* National Education Association. Retrieved from http://www.nea.org/home/20380.htm

Warner, S.A. (2003). Teaching design: Taking the first steps. *The Technology Teacher, 62*, 7–10.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity.* New York, NY: Cambridge University Press.

Wenger, E. (2006). Communities of practice: A brief introduction. Retrieved from http://wenger-trayner.com/theory/

Wicklein, R. C. (2006). Five good reasons for engineering as THE focus for technology education. *The Technology Teacher*, *65*(7), 25.

Williams, J. P. (2014, January 8). STEM roundup: Engineer jobs in high demand. *U.S. News and World Report.* Retrieved from http://www.usnews.com/news/stem-solutions/articles/2014/01/08/stem-roundup-engineering-jobs-in-high-demand

Willis, P. E. (1977). *Learning to labor: How working class kids get working class jobs*. Columbia University Press.

Willis, P. (1981). Cultural production is different from cultural reproduction is different from social reproduction is different from reproduction. *Interchange*, *12*(2-3), 48-67.

Winkelman, P. (2009). Perceptions of mathematics in engineering. *European Journal of Engineering Education*, *34*(4), 305-316.

Woods, P. (1990). *Teacher skills and strategies*. Bristol, PA: Taylor & Francis, Inc.

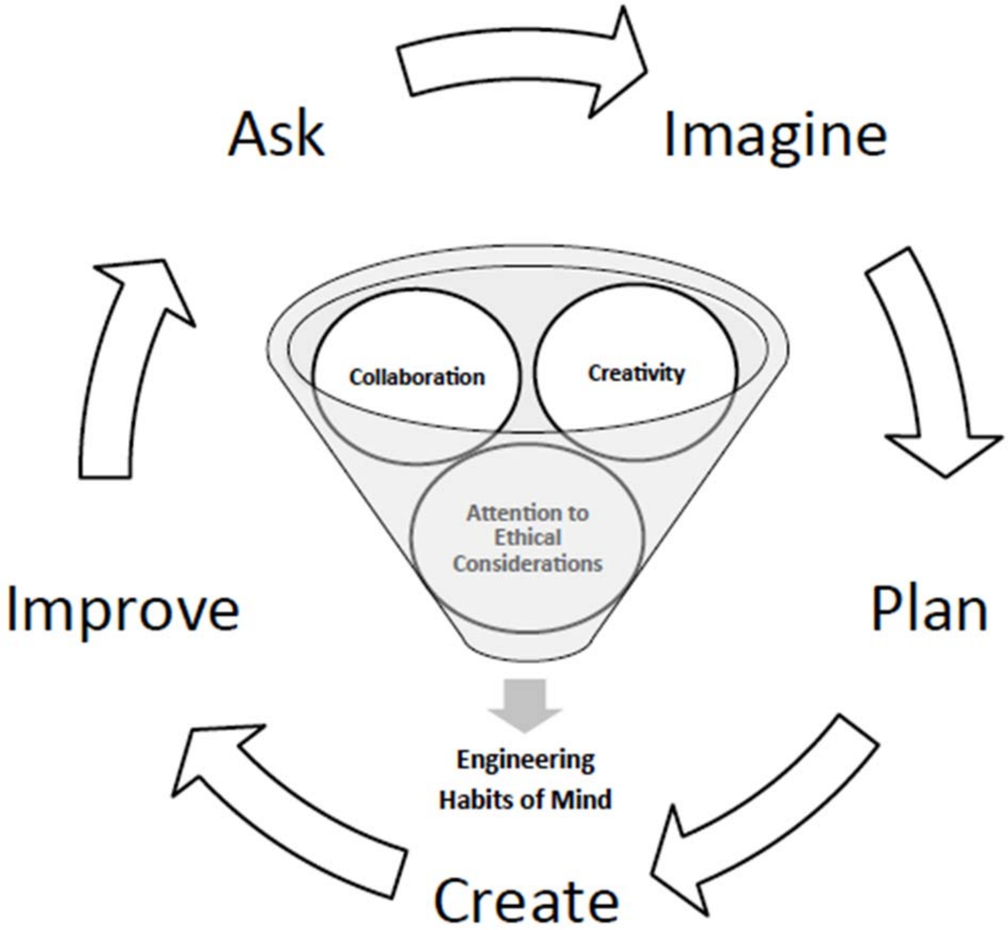
Woods, P. (1993). *Critical events in teaching and learning*. New York, NY: Routledge.

Woods, P. (1995). *Creative teachers in primary schools*. Buckingham, UK: Open University Press.

Wulf, W. A. (1998, June). *The urgency of engineering education reform*. Proceedings from the Conference on Realizing the New Paradigm for Engineering Education (pp. 28-30). Baltimore, MD: Engineering Foundation Conference.

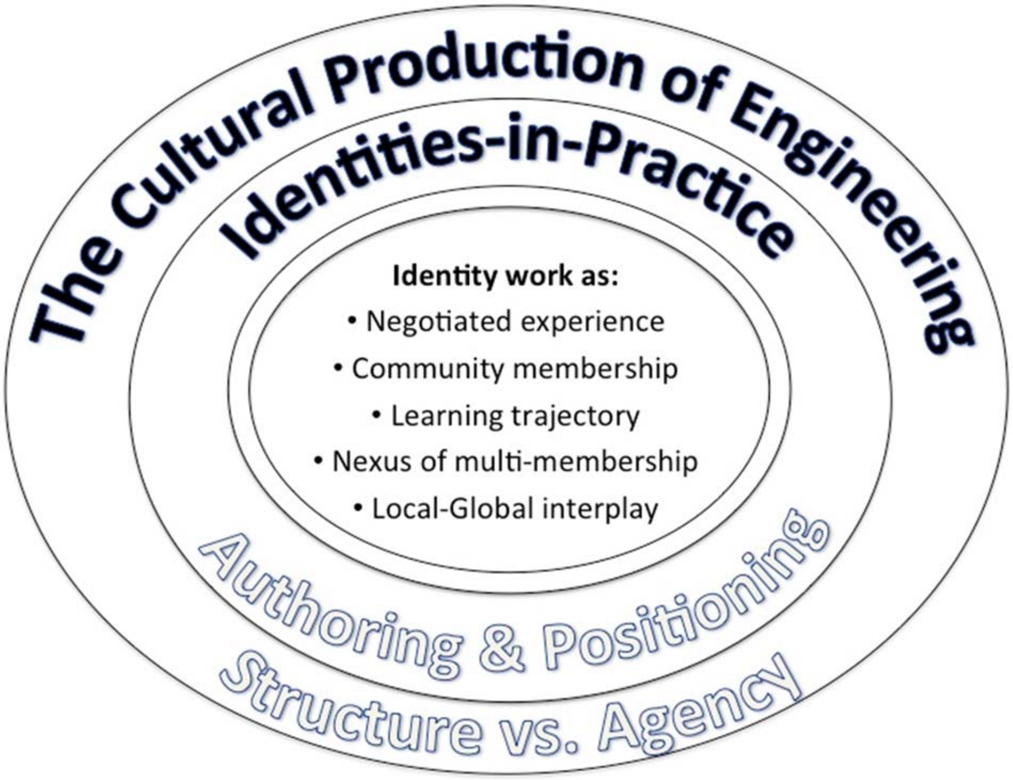
APPENDIX A

THE ENGINEERING DESIGN PROCESS AND FOCAL HABITS OF MIND



APPENDIX B

CULTURAL FRAMEWORK REPRESENTATION



APPENDIX C

EIE STUDENT STUDY OBSERVATION PROTOCOL

I. **Curriculum Implementation – Student experiences during the EiE Unit**

Looking for: What does it mean to be "good at science" or "good in engineering"?

- Investigative practices
  - observation, data collection, using tools, data analysis
- Communicative practices
  - question-asking, story-telling, using scientific/engineering vocabulary
- Epistemic practices
  - Justifying, legitimating, inferring, evaluating, scientific/engineering knowledge

Pay attention to:

- Power hierarchies, equity, and access
- Social practices and collaboration (peer-peer interaction; teacher-student interaction)

II. **Student Identity Work**

Looking for: What students are doing, saying, and producing? (Spradley, 1980)

Authoring of Self:

Scientific and/or engineering performances	Social performances	Displays of knowledge/skills
Affective displays	Bids for recognition	Question-asking
Holding the floor	Volunteering	Utilizing funds of knowledge
Acting like an engineer	Acting like a scientist	Authoring self as creative

Positioning by Others:

Others seek her/his help	Subtle ways to marginalize	Others avoid this person
Others look to person to take lead		

III. **<u>Engineering Habits of Mind</u>**

Looking for: *What does it mean to engineer? What are the values, attitudes, and thinking skills associated with engineering? How do students engage in the practices of engineering?*

According to Katehi et al. (2009), engineering habits of mind include: creativity, collaboration, communication, optimism, systems thinking, and attention to ethical considerations.

*Specific attention directed to the following habits of mind:

Creativity	**Collaboration**	**Attention to Ethical Considerations**
Taking risks	Leveraging group knowledge	Recognizing advantages in technologies/ designs
Tolerance for ambiguity	Sharing ideas	Recognizing disadvantages in technologies/ designs
Keeping an open mind	Collective brainstorming	Acknowledgement of environmental impact
Brainstorming (individual or group idea generation)	Taking another's perspective	Recognition of human impact
Searching for more than one answer	Working as a team	Voicing empathy for people, animals, or the environment

APPENDIX D

EIE STUDENT STUDY CONTACT SUMMARY FORM

Researchers complete this form after expanded field notes have been recorded.

Date of Observation:

Your name:

Teacher/School (research site):

Students in your group:

1. What was the unit, lesson, and topic/activity for this observation?

2. Briefly summarize the major parts of the activity and identify the estimated time intervals for each major part

3. Reveal insights about the cultural aspect of the class (i.e., the cultural production of engineering and engineering habits of mind):

4. Summarize inferences and **key** observations related to participants' identity work (authoring and positioning)

4. What are some seemingly emerging themes that need to be followed up on during the next contact? What questions do I have?

APPENDIX E

EIE STUDENT INTERVIEW PROTOCOL

Opening statement:
I would like to ask you a few questions about your experience with the engineering unit we just completed. Just to remind you about the stages of this engineering unit, we started with:
part one - the storybook; part two - learning about types of engineers; part three – materials testing; and part four – the design challenge.
Is it OK if I audio record our conversation?

Experiences with the EIE Curriculum: Guiding questions:
1. How do students experience the Engineering is Elementary (EiE) curriculum?
2. What are students expected to do and know as part of their participation in the EiE unit?
3. How do students take up the elements of the engineering design process (*ask, imagine, plan, create, and improve*)?

Part 1: Initial questions:

1. What does it mean to be an engineer?
2. Who are the three "smartest engineers" in class? (you may choose yourself)
    a. Why did you choose them?
    b. What qualities do they have that make them "smart"?
    c. Do you share these qualities?
    d. If I asked you to choose the three smartest kids in general, are these the same three kids you would choose? Why or why not?
3. Describe YOU in three words during this engineering unit.
4. Tell me everything you liked about the unit and everything that you didn't like about the unit.
    a. The hardest part of this unit was: ________________
    b. The easiest part of this unit was: ________________

5. During what stage of the engineering unit did you feel the most creative? Tell me about that time.
6. During what stage of the engineering unit did you feel the least creative? Tell me about that time.
7. Who would you say is the most creative person in your group and why?

Part 2: Card Sort Activity:

Read to the students: *These cards contain words that represent practices you may have experienced in the engineering unit. We would like to understand your meaning about each of these practices.*

Card Sort items:

Ask questions
Take risks (do something you are not sure will work; that you are not sure is correct)
Be curious
Make decisions
Imagine
Experience failure
Make good choices
Be persistent (don't give up easily)
Solve problems
Follow directions
Be creative
Get the right answer
Listen to your peers

Task 1: Students read the card and tell whether or not this was something they were held accountable (or expected) to do during the engineering unit. They will be instructed to place the cards in a 'yes', 'no', or 'maybe' pile.

Task 2: Students will be asked to describe what each practice in the 'yes' pile means to them (*"What did it mean to imagine during this unit?*") and to give an example of when and/or how they experienced this practice during the unit.

Task 3: Students will be asked to choose three cards that they felt they absolutely had to do to be successful during this unit.

Part 3: Design Products

Read to the students: *I have your design product (or a picture of the design product) that you and your group members created during part four of the EiE unit.*

5. Tell me about the process you and your group members went through to make this product.
6. What were the challenges in creating this product? What were the easy parts?
7. What else would you like me to know about your engineering design product?
8. How do you feel about what you and your group members created?

Final question: *Is there anything else you would like to share with me about the engineering unit that you have not had the opportunity to share before we complete the interview?*

APPENDIX F

VALIDITY MATRIX

What do I need to know?	Why I need to know this	What kind of data will answer the questions?	Analysis plans	Validity threats	Possible strategies for dealing with the validity threats	Rationale for strategies
RQ1: 1. What engineering habits of mind emerge as significant during students' engagement with an EiE green engineering, solar energy unit? a. How does creativity emerge during the engineering unit? b. In what ways do students collaborate during the engineering unit? c. In what ways do ethical considerations play a role in students' understanding of the engineering unit	Students come to school at many different levels of academic preparation, from diverse backgrounds and varied experiences. School science traditionally does not support the development of engineering habits of mind due to its recent incorporation into the standards and the current emphasis on standardization and accountability. I want to know how students from varied backgrounds take up or resist these practices when given the opportunity to engage in this manner. I am looking to better understand the meaning students make of engineering and how engineering is culturally produced in a 5th grade classroom.	-Classroom observation/field notes/ contact summary sheets -Audio of student cooperative learning groups -Semi-structured student interviews including a card sort interview -Student artifacts (pictures of students' design products and/or work samples)	-Field note/contact summary analysis of classroom observations [Spradley's method (1980)] -Review of audio data from student groups -Transcription of interviews; Dedoose software coding for themes -Quantizing/ frequency counts of data from card sort to look for patterns	-Researcher bias (the sole/primary observer) -Reactivity (the influence of the researcher on the setting or individuals studied) -Age of students (ability to convey meaning to researcher in interviews) -Existing teacher /school limiting structures	-Cross check coding with researcher peers/mentors -Open-ended interview questions to avoid leading student interview responses -Time spent in classroom setting should be as lengthy as possible	Maxwell (2013): -Triangulation; rich data (verbatim transcripts) -Time spent on site (sustained presence) as important validity checks -Asking others for feedback on my conclusions -Use of comparison groups -Numbers/ "quasi-statistics"

What do I need to know?	Why I need to know this	What kind of data will answer the questions?	Analysis plans	Validity threats	Possible strategies for dealing with the validity threats	Rationale for strategies
RQ2: 1. How do students author themselves and/or get positioned by others during the engineering unit?	The level of achievement, interaction, and performance during the engineering unit can be better understood by examining students' sense of agency and identity (identities in practice) and how others position them. Students from diverse backgrounds tend to get marginalized in traditional science settings. An emphasis on engineering practices may challenge the traditional hierarchies and sorting mechanisms that occur in classrooms that traditionally privilege primarily math and verbal abilities. To understand if students respond the same (as in a traditional classroom with traditional curriculum) or differently (disputing hierarchies and sorting mechanisms) to the challenges presented to them in an engineering curriculum	-Semi-structured interview questions and card sort -Classroom observation; field notes; contact summary sheets -Audio of student group work -Student artifacts: (design products; samples of student work) -Audio of group and individual interaction	-Excel thematic coding of interview transcripts (e.g., student descriptions of "smart" in engineering vs. "smart" in school from interview) -Review/ analysis of audio: roles/student positions taken up or resisted in the classroom setting; patterns/ differences among demographic groups or students from pre-determined ability levels (gifted, gen. ed, spec svcs.)	Data saturation – obtaining enough information from enough participants in order to reach saturation (number of participants) -Researcher bias -Reactivity (white, female, middle class researcher vs. diverse student participants)	-Sampling from two different classroom settings/groups at two different schools -Cross checking with researcher peers or mentors -Obtain teacher's interpretations as a cross reference	Merriam (2002): -Data saturation (use of multiple settings) -"Researcher's position" Maxwell (2013): -Triangulation (multiple sources of data/evidence) -Rich data from long-term involvement with participants at each site/context