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Elementary Teachers' Mental Models of Engineering Design Processes: A Comparison of Two Communities of Practice

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ELEMENTARY TEACHERS' MENTAL MODELS OF ENGINEERING DESIGN PROCESSES: A COMPARISON OF TWO COMMUNITIES OF PRACTICE

BY

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ABSTRACT

Educating K-12 students in the processes of design engineering is gaining popularity in public schools. Several states have adopted standards for engineering design despite the fact that no common agreement exists on what should be included in the K-12 engineering design process. Furthermore, little pre-service and in-service professional development exists that will prepare teachers to teach a design process that is fundamentally different from the science teaching process found in typical public schools. This study provides a glimpse into what teachers think happens in engineering design compared to articulated best practices in engineering design.

Wenger's communities of practice work and van Dijk's multidisciplinary theory of mental models provide the theoretical bases for comparing the mental models of two groups of elementary teachers (one group that teaches engineering and one that does not) to the mental models of design engineers (including this engineer/researcher/educator and professionals described elsewhere). The elementary school teachers and this engineer/researcher/educator observed the design engineering process enacted by professionals, then answered questions designed to elicit their mental models of the process they saw in terms of how they would teach it to elementary students.

The key finding is this: Both groups of teachers embedded the cognitive steps of the design process into the matrix of the social and emotional roles and skills of students. Conversely, the engineers embedded the social and emotional aspects of the design process into the matrix of the cognitive steps of the design process. In other words, teachers' mental models show that they perceive that students' social and emotional communicative roles and skills in the classroom drive their cognitive understandings of the engineering process, while the mental models of this engineer/researcher/educator and the engineers in the video show that we perceive that cognitive understandings of the engineering process drive the social and emotional roles and skills used in that process. This comparison of mental models with the process that professional designers use defines a problem space for future studies that investigate how to incorporate engineering practices into elementary classrooms. Recommendations for engineering curriculum development and teacher professional development based on this study are presented.

DEDICATION

To my husband, Tim McMahon. I met you on my first day as a co-op engineer. You are the engineer mentor I write about in Chapter 2. We married the next year while I was still an undergraduate engineering student. Together we have designed and built what is most important in life – a loving marriage and a happy family. Thirty years later, we are both thrilled that I've finished college at last.

To our sons, Bryan and Scott. You have been the motivational wind beneath my wings as I migrated from a career in aerospace engineering to one in science and engineering education. Rediscovering the natural and human-made world through your eyes continues to be a joy. Thank you for inspiring and indulging decades of family vacations planned around astronomical events and engineered marvels.

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I have been fortunate to learn from experts in several communities of practice. My researcher's point of view is synthesized from these experiences and perspectives. Thank you to my friends, colleagues and mentors from the following communities of practice:

School of Engineering & Applied Science, Washington University in St. Louis	K-12 Schools and School Districts throughout Missouri
College of Education, University of Missouri – St. Louis	Center for Inquiry in Science Teaching and Learning (*CISTL*), Ph.D. Cadre I
Center for Engineering Education and Outreach, Tufts University	Science Outreach, Washington University in St. Louis
National Science Resources Center's National Faculty for Leadership Assistance for Science Education Reform (LASER)	Visual Communications Research Studio, Sam Fox School of Design and Visual Arts, Washington University in St. Louis
Psychodynamic Research Training Program, Anna Freud Child Study Center, Yale University	Social System Design Lab, Washington University in St. Louis
Saint Louis Zoo	Saint Louis Science Center
Missouri Botanical Garden	WestEd
d.school, Hasso Plattner School of Design, Stanford University	McDonnell Douglas Corporation (now The Boeing Company)
McCare and University City Children's Center	Saint Louis Psychoanalytic Institute

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CHAPTER 1: Introduction

Mental Models in the Design Disciplines and K-12 Education

In 1943, Craik introduced the idea that people use mental models to make sense of and operate on the world. These small scale internal representations are functional rather than veridical, and underlie our perceptual, interpretive, predictive and explanatory interactions with the world (Craik, 1943). Merrill (2000) defines a mental model as a schema or mental representation combined with a process for manipulating the information in the schema (Merrill, 2000, p. 17). People might be aware of some of the mental models they use, and some remain outside of conscious awareness. Researchers in many disciplines, including education, psychology, artificial intelligence, economics and the design disciplines (i.e., engineering, architecture, and urban planning), have explored theories that address adaptive and maladaptive representations of the world using mental models, drawing on Craik's work (Bond & Ricci, 1991; Bransford, Brown, & Cocking, 2000; Coll, France, & Taylor, 2005; Donovan, Bransford, & Pellegrino, 1999; Driver, 1994; Fonagy, 2002; Hmelo-Silver & Pfeffer, 2004; Merrill, 2000; Schön, 1983, 1987, 1992).

In the design disciplines, the collaborative nature of design work requires that designers[1] not only disclose their mental models, but represent them in a variety of modalities as well. This allows a design team to operate from a shared model of reality, to systematically test their shared model against reality, and to revise the shared model *and*

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[1] In this document, the words "engineering" and "design", as well as "engineer" and "designer," will be used interchangeably.

their personal mental models as a result. For designers, what is learned *and* what is implemented is mediated by mental models that have been made explicit, which in turn leads to the revision of both the co-created design and the designers' implicit mental models (Bucciarelli, 1994; Cross, 2001; Eastman, McCracken, & Newstetter, 2001; Rittel & Webber, 1973; Schön, 1992; Vincenti, 1990). In the design communities of practice, mental model(s) lead to mathematical, narrative, and graphical model(s), which lead to the final product – the design and its physical embodiment. In 2005, the Design Council conducted a large-scale study of the design process in eleven different companies and created a general description of the process (Design Council, 2005). Furthermore, the design process was demonstrated by a design and innovation consulting firm called IDEO for the ABC news show *Nightline* in a story that aired on July 13, 1999 (ABC *Nightline*, 1999). The design process shown in the IDEO story, called The Deep Dive, represents best practices in design and will be revisited later.

Implicit in a teacher's performance in the classroom are mental models of the content knowledge being taught, its enactment in the real world, and how that enactment might be framed for teaching (pedagogical content knowledge, metastrategic knowledge, and pedagogical design capacity) (Brown & Edelson, 2003; Kennedy, 1997; Shulman, 1987; Zohar, 2006). While a teacher is obligated to provide a set of experiences that lead students to key understandings and skills associated with a given curriculum, the teacher is not obligated to articulate for herself or disclose to others the mental model(s) that led to her particular enactment of curriculum in the classroom. Indeed, the teacher might not be aware of the mental model(s) that underpin her assumptions about content and procedural choices made in learning and teaching a curriculum.

In K-12 engineering education, the classroom teacher must meld content knowledge and pedagogical content knowledge as she teaches a curriculum. A study by the National Academy of Engineering and the National Research Council revealed that "based on reviews of the research literature and curricular materials, the committee finds no widely accepted vision of the nature of K–12 engineering education" (Katehi, Pearson, & Feder, 2009, p. 155). Katehi et al's findings also indicate that the field of K-12 engineering education lacks key research in the area of teacher professional development. I claim that understanding elementary school teachers' mental models of the engineering design process is an important step in designing appropriate curriculum and professional development for engineering education. I consider professional development as a design activity and will describe the mental model(s) teachers hold of the engineering process. These teacher mental model(s) represent a problem space and a starting point for possible design studies that address curriculum, professional development, and instructional support systems (Edelson, 2002).

Researchers now have described the engineering design process used by professionals in enough detail that some states have incorporated the engineering design process into their state education standards. This study will reference the Massachusetts Science and Technology/Engineering Curriculum Framework (Massachusetts DOE, 2006). There are three reasons for using the Massachusetts Framework: 1) the state in which the study will be conducted, Missouri, does not yet incorporate the engineering design process into its state standards, 2) the engineering design process steps articulated in the Massachusetts Science and Technology/Engineering Curriculum Framework can be identified clearly in the *Nightline* story about The Deep Dive, IDEO's design process, and 3) the Massachusetts Framework was used in the creation of elementary engineering curriculum units that were used by some participants in this study (Massachusetts DOE, 2006). Furthermore, the engineering design process in the Massachusetts Framework is identical to the engineering design process that has been incorporated into the recently released *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (National Research Council, 2011).*

The theoretical basis for this study is the work of Wenger (1998) and Lave and Wenger (1991) on communities of practice as well as that of discourse analyst van Dijk (2008) on context models, which he equates to mental models. Lave and Wenger maintain that the development of expertise is socially mediated. Participants in a group of practitioners of a domain acquire identification with the practice embodied in the domain as they master peripheral roles at first, then progress to more central roles as ability and competence develop (Lave & Wenger, 1991; Wenger, 1998). The enduring nature of a *community of practice* comes from three characteristics of both community and practice: "mutual engagement, a joint enterprise, and a shared repertoire of ways of doing things." (Wenger, 1998, p. 49) Mental models are more malleable, yet what makes them adaptive and effective in interactions within a community of practice is that they are strategically simple within a particular epistemic community. Practitioners' mental models influence their discourse along a few properties relevant to most communicative interactions within a community of practice: "the setting, the ongoing action and the participants (and their identities, roles, relations, goals and knowledge)." (van Dijk, 2008, p. 220)

This is a study of how teachers perceive the engineering design process and communities of practice (in which they do not participate) from the perspective of a community of practice in which they do participate – elementary school teaching. The goal of the study is to articulate a foundation that can be used to inform and create curriculum and professional development about the engineering design process for elementary school teachers. This foundation rests on the assumption that the cyclic engineering design process (that includes Wenger's shared repertoire of ways of doing things) differs from the way science and mathematics (which are the school subjects most closely related to engineering design) are taught in most elementary school settings. Therefore, teachers will perceive what happens in an engineering design community of practice differently than the designers do. How teachers operationalize for classroom teaching what they see happening in an authentic engineering design event – their mental models of it – offers a starting point from which a curricular and professional development bridge can be built that connects engineering design communities of practice to classroom teaching communities of practice.

Research Questions

This study will elicit and compare the mental models of the design process held by two groups of six elementary school teachers. Their mental models will be elicited and analyzed vis-à-vis a videotaped example of best practices in design engineering. The research questions to be addressed are:

1) **What are teachers' mental models of the design process?**
   a) **What features do they contain?**
      i) **What features are common among the teachers?**
      ii) **What features are unique to each teacher?**

2) **How does each teacher's mental model compare to the design process represented by professionals at IDEO?**
3) **What are the within group and between group similarities and differences in mental models?**
4) **What implications do these mental models have for designing curriculum and professional development in elementary engineering education?**

Delimitations

Tufts University Center for Engineering and Education Outreach (CEEO) collaborated with me to recruit teacher participants for this study who have received professional development in and taught one of four LEGO-based engineering units in their classrooms. The LEGO engineering design units were developed by Tufts CEEO. They have been field tested with self-selected teachers in the Boston area public schools, and the resulting data has been used in doctoral dissertations written by the CEEO staff.

As a former member of Washington University's Science Outreach (WUSO) group, I have consulted with local schools and districts about professional development, curriculum and materials management for their science education programs. Before joining WUSO, I served for eight years as the K–12 science coordinator for a school district in suburban St. Louis. During that time, I directed a National Science Foundation grant to reform the district's K-12 science education program by providing inquiry-based science curriculum, professional development, instructional materials support, assessment strategies, and community and administrative support to teachers. I hold degrees in mechanical engineering and worked as a laser communications satellite engineer for a large aerospace company for 10 years prior to my career in science education. In that role, I interviewed manufacturing engineers, observed their practice, then designed and wrote artificial intelligence (expert systems) computer programs that automated how these practitioners determined the manufacturing process sequences for sheet metal parts and placement of components on printed circuit boards. I participated in the satellite design process in roles that include an electronics packaging designer, an aerodynamicist, and a thermodynamicist.

My background positions me as an observer who has experiential knowledge of both communities of practice. My experience as a design engineer and advocate of inquiry- and project-based science education biases me toward design-based reflective practice espoused by Donald Schön (Schön, 1987, 1992) and enacted in engineering communities of practice. My work in engineering and education has taught me that solutions emerge most readily from a clear and thorough definition of the problem space. For this study, I take the position of legitimate liminal participant (Penuel & O'Connor, 2010) – one who resides between engineering and education communities of practice, drawing on my experiences as a legitimate participant within both.

Definition of Terms

Design process. The cyclic design process used in this dissertation is represented by the following graphic:

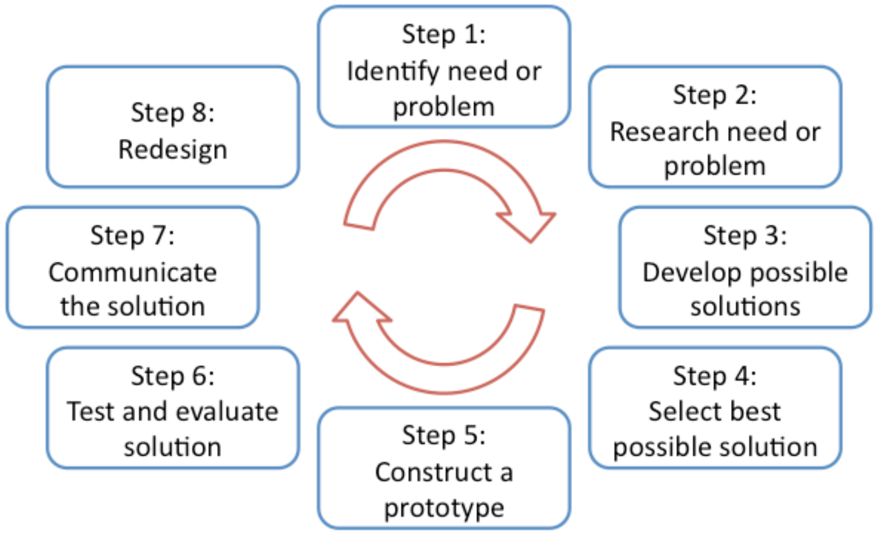

Figure 1. The Engineering Design Process (Massachusetts DOE, 2006)

Mental model. The definition of mental model articulated by Merrill (2000) will be used for this dissertation. "Mental-models combine a schema or mental representation with a process for manipulating the information in the schema." (p. 17) The components of the mental models used for representation are drawn from van Dijk's (2008) elements of context models and are presented in Chapter 3. The frequency of occurrence of van Dijk's elements in each participant's discourse provides indirect evidence of a flexible *interface* between a participant's internalization of her cumulative life experiences and her experience of an event in a community of practice. Van Dijk theorizes that this interface – the mental model – controls the production of discourse. Throughout this dissertation, I attribute mental models to participants, myself, and designers in The Deep Dive. I use the term mental model in the context of this dissertation to mean the interface I constructed from an analysis of the discursive evidence vis-à-vis van Dijk's theoretical components. The term is not meant to define an enduring characteristic of the individual to whom it is ascribed.

Significance of the Study

In the last fifteen years, enacting engineering education in K-12 schools has become prominent in the national conversation about science, technology, engineering and mathematics (STEM) education (Committee on Prospering in the Global Economy of the 21st Century & Committee on Science, 2007). However, few K-12 engineering education programs exist and very little research exists on how to prepare teachers to teach engineering in the K-12 classroom (Katehi, et al., 2009). This study provides a foundation upon which future studies about curriculum and professional development for engineering education can be based – a glimpse into what teachers think happens in engineering design compared to articulated best practices in engineering design.

CHAPTER 2: Literature Review

The Complexity of Teaching

Kennedy (1997) summarizes the demands of teaching mathematics and science as follows:

> Reform commentaries include numerous ideas about the qualities of knowledge, beliefs, and attitudes that teachers need in order to teach mathematics and science in the way reformers want these subjects taught. These qualities include a sense of size and proportion, an understanding of the central ideas in the discipline, an understanding of how these ideas are related to one another, knowledge of a variety of details that accompany these big ideas, an ability to reason, analyze, and solve problems within the discipline, an ability to generate metaphors and other representations of these ideas, an understanding of the nature of work in the disciplines, and an attitude of respect for the processes by which knowledge is generated through these disciplines. (p.12)

An elementary teacher's job is daunting. Most are not only responsible for teaching mathematics and science, but other subjects as well. The addition of engineering education is a topic that is now established in the national education conversation. Many believe engineering education can integrate the siloed subject areas of mathematics, science, social studies, technology and communication arts. The recently released *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Research Council, 2011) features engineering and technology as one of its disciplinary core ideas. Indeed, interdisciplinary teams have always been the norm in engineering practice, and globalization has rendered engineering teams international as well. In order for students of today to compete in the innovation-oriented world of tomorrow, they will need not only an understanding of science, technology, engineering and mathematics (STEM), but experience with engineering design communities of practice. There are some key values, norms and practices in education communities of practice and design communities of practice that appear diametrically opposed – for example, how each community of practice regards and deals with uncertainty and ambiguity. It is unreasonable to expect that teachers already possess in the domain of engineering design the qualities Kennedy describes. It is necessary to understand teachers' mental models of the engineering design process in order to determine what scaffolding they might need in order to be able to provide authentic engineering education experiences to their students. The literature about how teachers interact with instructional materials and how engineers design provides a basis for bringing both communities of practice together around mental models.

Building Mental Models for Science Teaching and Learning: Metacognitive Processes

Reflection is key to building expertise and achieving insights, understandings and change for professionals in education. Sawyer equates reflection with metacognition and defines it as "thinking about the process of learning and thinking about knowledge." He states that "one of the most central topics in learning sciences research is how to support students in educationally beneficial reflection" (Sawyer, 2006) (p. 12). This statement also applies to research on science teachers as learners. Research in science education includes a variety of cognitive and affective aspects of reflection. Three key findings emerged from a cognition-based study of how people learn, and are prominent in science education research: 1) people's prior knowledge must be engaged if lasting conceptual change is to occur, 2) people must learn facts and processes as part of a conceptual framework to achieve deep understanding and facilitate retrieval (schematization), and 3) people must develop metacognitive strategies for monitoring their learning (Bransford, et al., 2000; Donovan, et al., 1999, pp. 11-13). This kind of reflection is described by

Donovan and Bransford (2007) as an internal conversation that results in adaptive expertise characterized by schematized skills and knowledge. In an editorial on teaching future engineers, Bransford argues for expanding the unit of analysis in research on adaptive expertise to systems that encompass the sociocultural context of the expertise (Bransford, 2007). Bransford's statement is consistent with the theoretical stance that Wenger and Lave take in their investigations of communities of practice as units of analysis.

In 1987, Shulman introduced the distinct and interdependent concepts of teacher pedagogical content knowledge (PCK), subject matter knowledge (SMK), and pedagogical knowledge (PK) (Shulman, 1987). Shulman's work has organized a great deal of educational research about teacher knowledge, practice and professional development since then. Shulman's model of teacher science knowledge has been modified by others who have added components to PCK, PK and SMK. In examining the components of each kind of knowledge, it is apparent that some are subject matter specific (i.e. science syntactic knowledge that is different for life sciences and physical sciences), and some are generic (i.e. knowledge of instructional strategies in science). PCK, PK, and SMK all have metacognitive components.

There is much interest but little consensus in the research on exactly where subject matter specific and generic lines are drawn regarding PCK, as this integration of PK, SMK and PCK is the embodiment of science teaching. However, there is agreement that metacognitive skills are a necessary part of science instruction to which the awareness of the learner (of any age) must be drawn. Zohar (2006), in work with secondary science teachers about higher order thinking strategies in science, investigates thinking structures, or schemata, necessary for teachers to be able to move adaptively between procedural and metacognitive knowledge in classroom practice. Zohar uses the term metastrategic knowledge (MSK) to encompass the terms metacognition, metacognitive declarative knowledge, conditional knowledge, and explicit knowledge. Zohar defines it as follows:

> MSK is general, explicit knowledge about the cognitive procedures that are being manipulated. The cognitive procedures are comprised of higher order thinking skills and strategies. The pertinent metacognitive knowledge is an explicit awareness of the type of cognitive procedures being used in specific instances. It consists of the following abilities (Kuhn, 2000, 2001; Kuhn, Katz, & Dean, 2004): making generalizations and drawing rules regarding a thinking strategy; naming the thinking strategy; explaining when, why, and how such a thinking strategy should be used, when it should not be used, what the disadvantages are of not using appropriate strategies, and what task characteristics call for the use of the strategy. (p. 336)

Zohar concludes that MSK of teachers must be explicit in order for them to have intentional access to it in practice, and that teachers must value such thinking activities in their classrooms for all students. He cites much empirical research in education to support the use of metacognitive instruction for all students across subject areas, especially for low-achieving students. These findings indicate that low-achieving students need more help with practicing metarepresentation for regulation of thinking than do their higher-achieving peers.

> This type of knowledge seems to have a regulative significance for our thinking because it may give us regulative advice about how to apply correct cognitive processes to specific, contextually rich situations that are often "messy" in terms of their underlying structures. This knowledge may do so by directing our attention to the general structures that are embedded in specific situations and contexts. Therefore, an underlying assumption of this study was that although knowledge acquisition is content and context specific, general aspects of thinking also exist and have important significance for learning to think (Perkins & Salomon, 1989). (p. 337)

Teachers are adaptive designers of "messy" student learning environments; therefore, teachers' metacognitive strategies schematized with their CK, PCK, and beliefs and attitudes toward learning – their mental models – are important factors that can support or impede their own and their students' generative learning.

Jones and Carter echo Bransford's call for systems-level units of analysis and add an affective component to the key cognitive findings. In their summary of research on attitudes and beliefs of science teachers, they define attitudes as affective constructs and beliefs as cognitive constructs that influence individual teaching and systemic education reform efforts. They state that

> our definitions of ourselves as science teachers (and learners) is bound to our belief systems, epistemologies, prior experiences, motivation, knowledge, and skills. These factors are all linked to each other with reciprocal influence and are embedded in the larger sociocultural environment. Only through further research that can take a systems view of attitudes and beliefs can we truly understand how attitudes and beliefs shape instructional practice and use this knowledge to achieve reform (Jones & Carter, 2007, p. 1096).

Borko (2004) puts forth an agenda for research on teacher learning and its transformation into classroom practice. She acknowledges the interactive nature of the teacher's interpretation and enactment of the written curriculum in the same way Schön acknowledges the interaction of the designer with the materials of the design situation (Schön, 1992). She cites the need for new research methodologies and tools to accomplish this (Borko, 2004). The investigative emphases of Zohar, Jones and Carter, and Borko support the examination of teacher change within a community of practice.

Brown and Edelson (2003) explored the ways in which teachers interact with curriculum in order to design instructional materials that scaffold change in teacher practice. They found that teachers use instructional materials in three ways: they adapt materials to current circumstances; they teach directly from the materials with fidelity, a process Brown and Edelson call offloading; and they use the materials as inspiration for improvising instruction to meet curricular goals (Brown & Edelson, 2003). Brown and Edelson, like Schön, frame teaching as a creative design process and assert that methods for designing instructional resources and support (professional development, administrative support, assessment) must change as a result. They coin the term "pedagogical design capacity (PDC)" to describe a teacher's "ability to perceive and mobilize existing resources in order to craft instructional contexts." (p. 6) Brown and Edelson's PDC seems to share some characteristics with Zohar's MSK in that both are metacognitive processes that teachers must be able to use adaptively in a wide variety of instructional circumstances. Furthermore, a teacher's PCK, PDC and MSK depend on the teacher's mastery of and comfort with content knowledge.

Why Investigate Mental Models?

Researchers have studied mental models in a variety of contexts and to varying levels of complexity. All of the mental model research stems from Craik's foundational work. The literature on mental models includes Hmelo-Silver's work with mental models in the context of novice-expert structuring of knowledge. Hmelo-Silver & Pfeffer (2004) used a structure-behavior-function (SBF) paradigm to investigate novice and expert mental models of an aquatic system. She discussed the difference between how novices and experts think about the elements of an aquatic system and the complexity of what they do. Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers (2000) used an input-process-outcome (IPO) paradigm to investigate how the alignment of individuals' mental models affects team effectiveness. Singh, Dong, & Gero (2009) used agent based modeling techniques and proposed an entire research agenda to investigate how social learning occurs in teams. Johnson-Laird (2001) investigated how the quality and quantity of the mental models people hold regarding a given premise affect their ability to reason deductively. Barrouillet & Lecas (1999) investigated how the number of mental models used in conditional reasoning relates to the number of instances of an occurrence that are held in working memory. Byrne (2002) investigated how counterfactual thoughts affect mental models in the context of ascribing causality. Horowitz (2002) developed an instrument to diagram a person's mental model of self in relationship with another in order to facilitate psychotherapeutic interventions. Merrill (2000) studied how to facilitate the construction of mental models to facilitate teaching and learning of specific concepts.

Each of these studies represents a point on separate lines of research on mental models. Each line of research uses a different methodological lens and addresses different units of analysis (from individuals to dyads to groups of novices/experts to work teams). It is clear from the wide variety of research on mental models that they exist, can be elicited in a variety of ways, can be analyzed and shared, and that they influence the behavior and performance of individuals and teams. Each of these studies presupposed that the study participants had tacit and/or explicit experience in the context for which their mental models were elicited. This study does not presuppose that participants have any knowledge or experience of the best practices enacted by engineering professionals. This study documents what teachers notice and value about a process they observe, do not engage in on a professional level, and must transform to their classroom practice.

Elementary teachers, who are often generalists, must perform these transformations for the variety of subjects they are required to teach. For example, many must teach "the scientific method" and science inquiry even though they have never engaged in it as professional scientists do. It is not always appropriate or practical to directly import professional scientists' investigative processes into the classroom; they must transform authentic practice to classroom practice using PCK, MSK, and PDC. Even the participants in this study who have taught an engineering unit have been exposed only to the *pedagogical transformation* of the engineering design process to the classroom curriculum they taught. Will those teachers notice and value different things in the professional engineers' enactments than teachers who have had no exposure to the engineering design process? The engineering design process demands that the practitioners share their mental models and operate on them as a collaborative group. The teaching process does not. There are isolated action research projects in which multiple teachers collaborate as action researchers to systematically study and redesign their own teaching processes (Baird & Hagglund, 1994). However, this is the exception rather than the rule in K-12 education communities of practice in the United States at the time of this study. How can we know whether teachers recognize and value the mental model sharing that happens in the engineering design process unless we understand their mental models of it? This study is foundational to the K-12 engineering education field. It provides a baseline assessment of where a sample of teachers' understandings about the design engineering process begin, which provides an indicator of where they would need scaffolding and organizational support for transforming the engineering design process into meaningful and effective classroom practice – CK, PCK, MSK and PDC specifically for engineering education. This study creates the beginning of a taxonomy of mental models that can inform future design studies of curriculum and professional development in K-12 engineering education.

The research reviewed above shows that teachers must identify with the subject matter they teach if they are to make it part of their mental models and enact it effectively; therefore, teachers must be exposed to engineering design communities of practice in a way that shapes their identities and mental models as teachers of engineering. Designing professional development for this purpose requires understanding how teachers perceive the design process and how they perceive it fits into the teaching process with which they currently identify.

The Complexity of Designing

The literature on engineering and design contains positivist threads in which researchers view the design process as solving well-defined problems systematically (Bond & Ricci, 1991) and constructivist threads in which researchers view the design process as the creative act of solving ill-defined problems that relies on the designer's judgment and intuition informed by scientific knowledge (Cross, 2001). Constructivist researchers and theorists such as Cross and Schön offer a broad definition of the design process that includes variations on four steps that are combined in a repeating cycle: analysis, synthesis, simulation and evaluation (Cross, 1992; Schön, 1992). It is important to realize that the design process is different from the scientific inquiry process in that designers focus on creating what does *not* yet exist, while science is focused on investigating and understanding what *does* exist. This means that designers' habits of mind are necessarily different from scientists' habits of mind, although most designers use the scientific method at different stages in their design process (Cross, 2001). Iteration using the four steps listed above is a design norm, as is the acceptance of and ability to tolerate uncertainty and ambiguity throughout the process. The designer seldom works alone; her identity within a design community of practice is most often as a member of a team focused on solving a problem or addressing a need. Katehi et al summarize the design process in two of their three general principles for K-12 engineering education as follows:

> **Principle 1: K-12 engineering education should emphasize engineering design.**
> The design process, the engineering approach to identifying and solving problems, is (1) highly iterative; (2) open to the idea that a problem may have many possible solutions; (3) a meaningful context for learning scientific, mathematical and technological concepts; and (4) a stimulus to systems thinking, modeling, and analysis. In all of these ways, engineering design is a potentially useful pedagogical strategy. (p. 4)
>
> **Principle 3: K-12 engineering education should promote engineering habits of mind.** Engineering "habits of mind" align with what many believe are essential skills for citizens in the 21st century. These include (1) systems thinking, (2) creativity, (3) optimism, (4) collaboration, (5) communication, and (6) attention to ethical considerations. (p. 5)

Design ethnographer Bucciarelli highlights the designer's habits of mind in his rich, book-length case studies of engineering designers. Bucciarelli's transcripts and analysis show individual identities as stable by role within the subculture of the design firm – e.g. George from Production, or Fritz the chemist. As the participants come together to define the problem and potential solutions, their work identities – Bucciarelli refers to them as differing interests – are socially renegotiated as they define their relationship to the problem and its solution. These work identities meld into a collective identity – e.g. Sergio's team working on the photoprint problem – defined by their collaboration around the object of interest. Individual work identities and the expertise and creativity they bring are important in doing the work of designing, but become backgrounded to the problem and its solution – a key norm within design communities of practice. Bucciarelli also describes how uncertainty and ambiguity pervade the process. Indeed, the norm in this community of practice is to deal with uncertainty and ambiguity openly and as a team by negotiating the definition of the system, problem, and potential solutions. They share the information they have and request further study to generate information that is lacking. In the following excerpt, Bucciarelli interprets how Sergio's team approaches "the dropout problem." Dropout is a problem that occurs in commercial photograph printers when the machine does not deposit ink in places where ink should be, leaving white spaces in the photograph. Sergio has been tasked with assembling a group of engineers from a variety of disciplines and roles (Bucciarelli calls them object worlds) to fix the dropout problem with a chemical process, a mechanical process, or a combination of the two. The team consists of two chemists, two hardware design engineers, and a production engineer. Sergio, the team leader, has a mechanical background. In their initial meeting, the members of the team engage in a discussion of the dropout problem, each interpreting the problem from his own perspective and responding to the interpretations of others. The atmosphere is tense as participants struggle to define the problem with the information they have. The meeting ends with a lack of consensus on how to proceed because the team cannot reduce the uncertainty and ambiguity in their definition of the problem enough to determine whether the problem requires a chemical or mechanical solution. Frustrated, Sergio leaves the meeting knowing he must reconvene the group for another brainstorming session once they gather more information. He feels that the meeting was a failure despite the fact that the team members identified the information they need to proceed and are going about obtaining it. Sergio had hoped that the team had enough information among them to frame the problem for brainstorming possible solutions – the next step in towards fixing the problem.

> This is not to say that what participants see, define, fabricate, and do on their way to a solution is irrelevant or that one problem definition is as good as any other. For, while the uncertainty and ambiguity that prevail in design allow the sort of indeterminacy advocated here, there are constraints, of tradition as much as of science, on the visions, conjectures, and refutations of participants. What matters is that participants gain and remain in control of what they construe as the problem, working both across and within their respective object worlds [subdisciplines within engineering].
>
> If we take the perspective that designing is a process of negotiation and exchange across different interests, object worlds, and disciplines and that participants must work to establish and maintain both the problem and norms to be engaged in judging their contributions to the design task, then we can see Sergio's meeting was not a failure but as a first engagement on the road to the design of a fix of the (of a) dropout problem – albeit a rough and tense first step. (p. 163)

Bucciarelli shows that the mental models that different designers use in their communities of practice allow for each individual's identity to meld into the team's identity and embrace ambiguity and uncertainty as necessary steps along the way to a socially negotiated solution.

A Personal Reflection on Learning in an Engineering Design Community of Practice

I offer a reflection on my participation as an engineer on multiple projects over ten years in order to illuminate how one large aerospace engineering corporation's community of practice embodied socially mediated learning consistent with Bucciarelli's description and Lave and Wenger's community of practice theory.

My legitimate peripheral participation (Lave & Wenger, 1991) in an engineering community of practice began when I became a co-op engineer during my undergraduate years. I was studying mechanical engineering, a sub-discipline of engineering that appealed to me because the course of study was broader than the other disciplines in the engineering school. I was and still am interested in complex systems engineering. A degree in mechanical engineering meant that I would be qualified to work on any kind of complex hardware system. As an undergraduate engineering student in my university's cooperative education program, I worked at a local aerospace engineering company for four three-month periods that alternated with semesters in school. I was assigned to a different department within the company each time. By the time I graduated with my bachelor of science degree and joined the company as a full-time engineer, I had experience in structural aircraft design, user support for computer-aided design (CAD) of missiles, analysis of structural aircraft designs for mechanical strength properties, the development and testing of innovative bonding processes for metals, and graphic modeling of the plasma field in a nuclear fusion reactor. I call my experience as a co-op engineer legitimate *peripheral* participation because during each work period I began as a novice in a new sub-community of practice mentored by one or more experts.

On my first day of my first work period at the company, I was given two three-inch thick books to read – The Design Handbook and the Standard Parts Manual – both published by the corporation and issued to every designer. I was told these books defined "the company way" of designing things and would guide my design choices. These books, along with the formal documentation of every object the company produced (design drawings, models, prototypes, test results, addenda to design drawings, etc.), comprised the company's written institutional memory. They regulated design practices and were updated regularly as technology, resources, and practices changed.

I began my first assignment – designing a test fixture for an aircraft part. I learned how to interact with both books and my drafting materials by interacting with my mentor. We studied the part and determined what the fixture needed to do: we established the problem space. Then he narrowed my design options by explaining what metals were inexpensive, readily available in the machine shop on site, easy to work with, and had physical properties appropriate to support the weight of the part the fixture would hold. Armed with that information, I drafted what I thought was a creative, simple and functional fixture. During my design process, my mentor asked me questions such as why I chose a certain fastener to join the sheet metal pieces. It was one of the wide variety of available fasteners I found in the Standard Parts Manual. He told me that if I designed the holes in each piece with diameters within a certain range, I could reduce the cost of my fixture by using a different fastener that the company buys in large quantities for multiple airplanes. I had read about this kind of cost optimization in the Design Handbook, but I did not yet have the institutional knowledge that could help me apply what I knew. My mentor helped me gather information from the constraints of the problem, the materials available to me, and the institutional memory from the books and from his experience so that we could construct new institutional memory together within the context of our specific design problem. With my very first professional engineering drawing in hand, my mentor led me to the machine shop, introduced me to the operators there, and left me to work with them to build what I had designed.

Lucky for me, the machine shop operators were very kind as we struggled to cut and bend sheet metal, drill holes in each sheet metal part, then fasten them together to my exact and *unreasonably rigorous* specifications. In my naïve zeal, I had followed the company way to the letter, but created a part that was so difficult to build that its cost in time and effort – not to mention the patience and good will of the machine shop operators – was exorbitant. I redesigned and rebuilt that test fixture using the hard-won lessons about producibility that remain with me still. That single experience moved me from the periphery of participation into the creative, collaborative and ***systems-aware*** conversations of that group of engineers. I could tell similar stories that define my initiation into each sub-community of practice in which I worked as a co-op at that company.

My experiences after I graduated and joined the company were consistent with the literature already cited about how engineers function in their communities of practice. As Eastman et al, Bucciaralli, Vincenti, Cross, and Bond et al state, engineers work in interdisciplinary teams on complex systems using iterative design processes. I gained valuable systems thinking skills from the variety of co-op experiences I had as a student. As a graduate engineer, I wanted to continue gaining a systems-level big picture of what the company did so I set out to learn several sub-disciplines of engineering. For the next several years, I worked in an engineering sub-discipline until I became a competent practitioner, then transferred to a sub-discipline new to me. I became a competent practitioner of electronics packaging design, CAD/CAM software engineering and support, design support for manufacturing, aerodynamic and thermodynamic analysis of laser communication satellite systems, and software development of expert systems for manufacturing applications. With each new role, I became more adept at quickly moving inward from Lave and Wenger's periphery of situated learning to be able to provide expertise for a wide variety of engineering design teams. I realize now that I was able to do this easily because I had a mental model of the engineering design process I drew upon as I changed roles. My own narrative mental model of the engineering process follows. It synthesizes and is consistent with both the literature on engineering design processes and the literature on communities of practice.

Engineers use a systematic and rigorous process for considering possible options and solutions to a design problem or need. They consider the constraints, design specifications and performance requirements associated with the problem or design challenge. They consider prior knowledge (both written and socially constructed from experiences that are shared by design team members) of design processes and options used to solve similar problems. They consider advances in materials and technology that already exist for incorporation as well as advances that an innovative solution to this particular problem or need might create. They draw on all of these to formulate preliminary options for solutions. Engineers often evaluate several options computationally before constructing virtual and/or physical models of a subset of all solutions generated. This subset is reduced further to one or more designs for which prototypes are constructed. Physical prototypes are built and subjected to rigorous tests to assess performance of the design(s). The scientific method is used often in this stage of design to gather data about design elements. Performance characteristics are not the only determiners of whether a design goes into mass production. Producibility, maintainability, cost, and potential profit get factored into the equation. Sometimes the best performing design is rejected in favor of one that is more profitable. Once a prototype design has been selected to go into mass production, economies of producing it to scale are explored in greater depth, and the design might be revised again.

Throughout the process, the design team members representing different engineering sub-disciplines are analyzing the design and presenting revisions to the design that meet the industry standards and the requirements that regulate their particular sub-discipline. One or more design engineers are usually responsible for generating the design documents that will guide production. These engineers must incorporate all feedback from team members into the final design. Often, compromises must be made as engineers from each sub-discipline advocate for changes that optimize the design from their perspective but conflict with recommendations from another sub-discipline. Figure 2 is a humorous but not inaccurate depiction of how that process can seem to the team. Notice the sturdiness of the fuselage engineer's design, the simplicity of the production engineer's design, the sleekness of the aerodynamic engineer's design, and the prominence of the wing in the wing group's design. Each engineer brings these disparate expectations to the design team to be integrated and optimized. The designed object is the focus of the social interactions that take place to exchange the cognitive information that results in an integrated and optimized the design.

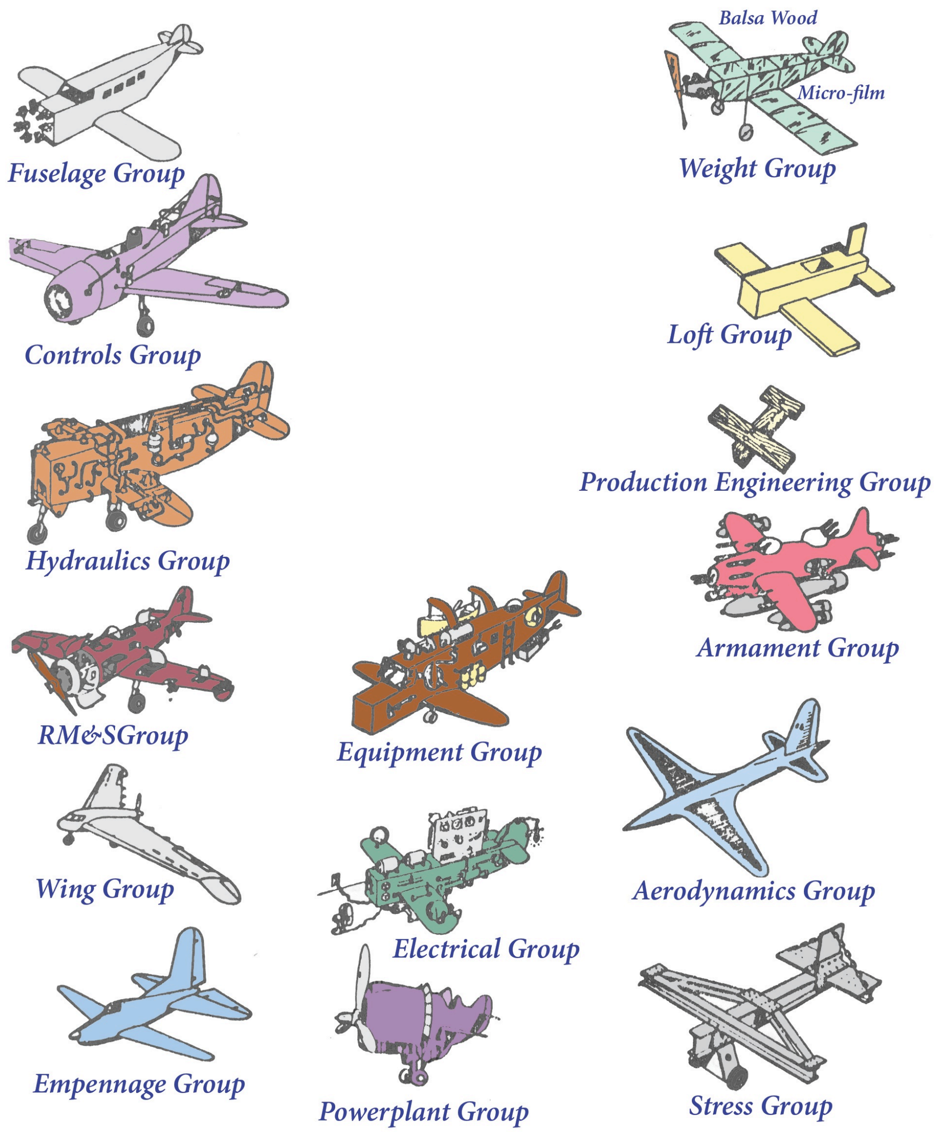

Figure 2. Dream Airplanes by C.W. Miller. Optimal airplane design from the perspective of engineers of different specialties. From *Fundamentals of Aircraft and Airship Design: Volume I – Aircraft Design (p. 4)*, by L. M. Nicolai and G. E. Carichner, 2010, Reston, VA: American Institute of Aeronautics and Astronautics. Copyright 2010 by L. M. Nicolai and G. E. Carichner. Reprinted with permission.

This collaborative design process allows for creativity and innovation while regulating the evolving design to meet industry and/or company standards. This evaluative and regulatory process constitutes ongoing formative assessment of the design. Formative assessment procedures such as multiple critical design reviews, in which the customer and others not on the design team critique the design, lead to successive iterations of the design. Each design team member must sign off on the final iteration of the design before it can go into production. These formative procedures ensure that requirements and performance specifications are met. The summative assessment of the design is how well it meets requirements, performance specifications, cost requirements, and production requirements. Even with formative design procedures in place, the final released design constitutes compromise on several levels as described above. An old engineering adage says that for every project, designers must balance production time, production cost, and quality of the produced object. The adage says that only two of the three can be controlled, and those two will drive the third. Put less formally, teams often ask "Do you want it fast, cheap, or right?"

This regulative, collaborative process facilitates both individual and team learning in engineering communities of practice. When engineers of different disciplines and experience levels collaborate, they pool their creative and problem solving abilities and their experience bases. Individuals on the team who are less experienced gain institutional knowledge from more senior members of the team regardless of team roles. The design review process and the day-to-day collaborative process scaffold the learning process of the less experienced engineer by requiring her to work with others to contribute to the design and to justify her contributions. Since there are usually multiple design reviews by experts on and off the team, the inexperienced engineer must explain her model of the design multiple times. Each design review generates feedback that informs successive iterations of her model of the design. It is also common for engineers in each sub-discipline to consult with role-alike others working on different design teams. This provides opportunities to hone sub-discipline-specific skills, which then benefits each interdisciplinary design team. Conversely, team learning is scaffolded by the knowledge networks each team member brings to the design team. A design team coalesces around a design problem. Each team member brings not only her own personal knowledge, skills, and experience but her network of role-alike others with whom she can consult. Furthermore, engineers often think laterally to generate creative solutions that are inspired by work done on other projects.

Transforming Engineering Norms and Process into Education

The synthesis of literature and personal experience above conveys implicit and explicit norms and levels of participation that are characteristic of engineering communities of practice. The complexity of this engineering design process has been transformed into state education standards as shown in Figure 1, repeated below (Massachusetts DOE, 2006):

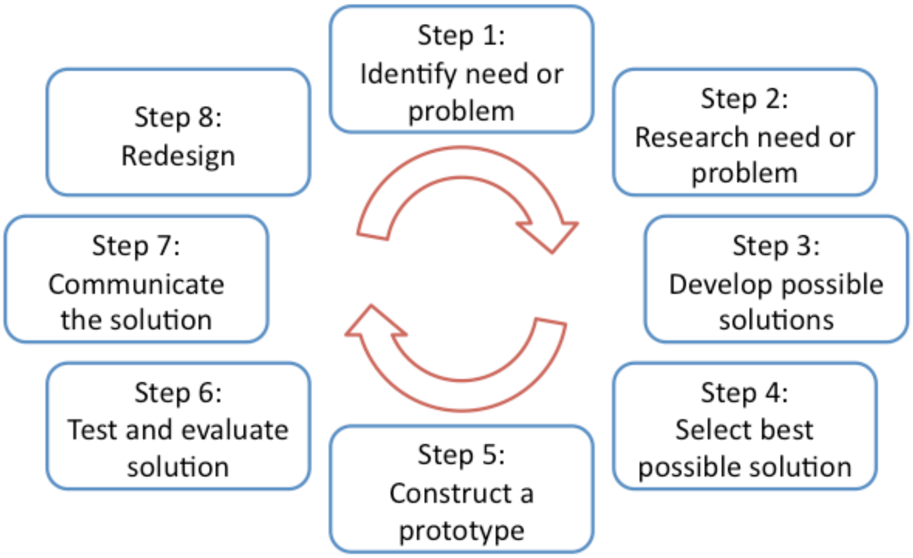

Figure 1. The Engineering Design Process (Massachusetts DOE, 2006). Graphic representation of the engineering design cycle in the Massachusetts Science and Technology/Engineering Curriculum Framework.

Educators are faced with the challenge of integrating this iterative, constructivist and open-ended cycle used in design communities of practice into an increasingly positivist, assessment-driven, public school community of practice. What do teachers notice about what happens in a real-life design process and what do they deem important enough to enact in the classroom? How do they envision enacting what they notice within the constraints of the school setting? There are no easy answers to these messy questions. The possibilities are complicated and depend on who does the noticing, their mental models of the process and its enactment, and how they approach the challenge in a given set of circumstances.

Engineering and Education as Wicked Problems

The study of education and engineering in their complex representations contains what Rittel and Webber refer to as "tame" and "wicked" problems (Rittel & Webber, 1973). Tame problems can be well-defined, and one can determine clearly when they have been solved. Determining the scope and sequence of a K-12 science curriculum or the course of study for undergraduate engineering students are examples of tame problems. In contrast, Rittel and Webber list the following ten characteristics of wicked problems:

1. There is no definitive formulation of a wicked problem.
2. Wicked problems have no stopping rule. [One never finishes solving a wicked problem; they are continually re-solved as consequences of implemented solutions create new problems.]
3. Solutions to wicked problems are not true-or-false, but good-or-bad.
4. There is no immediate and no ultimate test of a solution to a wicked problem.
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly [and has immediate and delayed consequences for people's lives].
6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
7. Every wicked problem is essentially unique [just like every student is unique].
8. Every wicked problem can be considered to be a symptom of another problem.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.
10. The planner [practitioner] has no right to be wrong [because the practitioner's decisions will affect people's lives for a long time]. (pp. 161-166)

To practice education and engineering involves addressing wicked problems in complex and interdependent systems. Wicked problems can be studied systematically if boundaries and conditions of the unit of analysis are clearly – even if artificially – drawn, and the affordances and constraints of the methodologies and limitations of the results are reported. Despite this, the definition of the system to be studied and the isolation of the variables under study within it remains a wicked process as defined above.

Schön includes the professions of engineering and education as design domains in his characterization of "designing as a reflective conversation with the materials of a design situation p. 3" (Schön, 1992, p. 3). In this sense, therefore, educators can be considered designers of experiences with and for their students who are – with themselves – the objects of their design situation. Because all students and teachers are different, as are the dynamics in each classroom, teaching is a wicked process. The same can be said of engineering – each problem has a unique set of circumstances addressed by a design team formed for the purpose of finding a solution. Sets of "best practices" based on research can be written and followed by practitioners. The variety of possible actions available to the practitioner is a function of the totality of the practitioner's experiences in transaction with the situation at hand – mental models. Even when practitioners are striving to follow a set of best practices, the enacted practices in complex situations are iterative, responsive, and can be influenced by reflection in action, on action and for action to produce wicked re-solutions of wicked problems (Custers & Aarts, 2010; Schön, 1983).

Brown and Edelson's pragmatic approach builds on Schön's work and conceptualizes teaching as a design activity that is approached appropriately as a design problem. As mentioned earlier, they investigated how teachers interact with instructional materials when teaching. They identified three ways in which teachers use instructional materials: 1) they adapt the materials to their immediate circumstances, 2) they offload instructional responsibility to the materials and follow it with fidelity, and 3) they use the materials as inspiration to improvise instruction. Each of these uses presupposes a different level of teacher knowledge, or pedagogical design capacity (PDC), to solve the same wicked problem – what to do moment-to-moment in the classroom setting (Brown & Edelson, 2003). Lines of research in engineering, education, and mental models converge around the production of mental models as schematizations combined with a heuristic process that informs action within the design transaction (Bransford, 2007; Bransford, et al., 2000; Eastman, et al., 2001; Merrill, 2000). These schemata or mental models have been examined through different operational definitions in the research summarized here (e.g. cognitive, affective, or combinations of the two; relational; attitudinal; problem-solving).

Edelson (2002) argues that conducting educational research with a design paradigm has several advantages. First, the design paradigm facilitates clarity and specificity in theory development. Second, the products of design research in education are tied to practice and are more likely to be useful and implementable. Finally, he argues that it places the researcher into the research context in a more pragmatic way than has historically occurred (Edelson, 2002). I add one more reason: conducting research with the design paradigm requires practitioners and researchers to make their mental models explicit and to share them in the search for workable solutions to wicked problems in education. My work with mental models defines a problem space that is expected to illuminate next steps in the research to integrate the engineering design process into elementary educational practice.

Bringing Together Two Communities of Practice in the Classroom: What Do Teachers Need?

Research on professional development for science and mathematics shows that coherent, sustained professional development that is tied to teacher practice are key features of effective professional development (Loucks-Horsley, 2003). How can the engineering design process be practiced in the K-12 classroom, and what preparation do teachers need in order to implement it with fidelity and efficacy? Katehi et al (2009) reviewed the existing literature in K-12 engineering education as well as many K-12 engineering curricula and determined that there is no consensus on what engineering design education in the K-12 classroom should include and how teachers should be prepared to teach engineering design in their classrooms. They found the following:

> Finding 2. There is considerable potential value, related to student motivation and achievement, in increasing the presence of technology and, especially, engineering in STEM education in the United States in ways that address the current lack of integration in STEM teaching and learning. (p.150)
>
> Finding 3. K–12 engineering education in the United States is supported by a relatively small number of curricular and teacher professional development initiatives. (p.153)
>
> Finding 4. Even though engineering education is a small slice of the K–12 educational pie, activity in this arena has increased significantly, from almost no curricula or programs 15 years ago to several dozen today. (p.153)
>
> Finding 5. While having considerable inherent value, the most intriguing possible benefit of K–12 engineering education relates to improved student learning and achievement in mathematics and science and enhanced interest in these subjects because of their relevance to real-world problem solving. However, the limited amount of reliable data does not provide a basis for unqualified claims of impact. (p.154)
>
> Finding 6. Based on reviews of the research literature and curricular materials, the committee finds no widely accepted vision of the nature of K–12 engineering education. (p.155)
>
> Finding 9. As reflected in the near absence of pre-service education as well as the small number of teachers who have experienced in-service professional development, teacher preparation for K–12 engineering is far less developed than for other STEM subjects.
> (p.159)

Wenger (1998) states that communities of practice are sources of knowledge and experiential resources to their self-selected members that they cannot get from the organizational structure in which they find themselves. Wenger and engineering ethnographers Bucciarelli (1994), Vincenti (1990), and Eastman et al (2001) agree that engineers transform their individual and group identities when they bring into existence a new object that meets a need or solves a problem. In his final chapter, Wenger asserts that transformational learning in schools can occur through intergenerational learning situated in circumstances authentic enough to engage learners, complex enough to allow learners to explore new competencies, and important enough to allow learners to imagine new identities for themselves (pp. 270-277). I agree. As an engineer, my knowledge and identity have been transformed by conversing with the natural world, the human-made world and my colleagues in order to create something useful that did not previously exist. As a science educator, I have witnessed how elementary students' purposeful interactions with objects and phenomena and each other in the elementary science classroom have changed how they perceive themselves as learners. Engineering education can offer students generative opportunities to construct different identities for themselves as learners and future professionals, but only if teachers are able to provide them the appropriate conditions.

The act of designing – bringing into existence something that did not yet exist in order to meet a need or solve a problem – is fundamentally different than systematically investigating something that already exists (although designers incorporate scientific, systematic investigation of what exists into the design process). As Rittel and Weber (1973) have shown, how designers solve a problem or meet a need depends largely on how the problem is framed. How a problem is framed is a product of how the design team reduces the uncertainty and ambiguity in the initial conditions of the situation. No two design teams will frame or solve a problem in exactly the same way. This presents a challenge in educational communities of practice that privilege all students learning the same thing at the same time. Furthermore, school science emphasizes the systematic investigation of existing objects and phenomena in order to acquire knowledge that has already been generated.

Most teachers have not experienced the engineering design process authentically or as a pedagogical transformation. The transformative value, according to Wenger, in K-12 engineering education lies in students' interactions with each other, knowledgeable adults, and the natural and human-made world. In these interactions, students have the opportunity to reconstruct their identities as learners in ways that can allow them to try on new identities beyond their school identities. By contrast, Wenger's case study of the insurance claims processing industry shows that claims processors perceived and acted within their work culture very much like they perceived and acted within their high school social culture – they maintained their school identities and their organizational work culture facilitated that. Teachers must learn how to facilitate these potentially transformative experiences for students while meeting institutional learning requirements. I expect that acquiring the knowledge and skills to provide transformative engineering education experiences to elementary students might be a transformative learning experience for many elementary teachers if they are steeped in a community of practice that tends to focus on understanding what is rather than creating what does not yet exist. For example, teachers practicing in states that have not yet incorporated engineering design into their standards might be constrained to teach only the science that is included in the standards and tested on high stakes tests. Therefore, they might not have the experience, opportunity or support to incorporate transformative design learning experiences into the curriculum. How this transformative learning experience (in the form of professional development, curriculum and materials support) for teachers is operationalized depends on how the challenge is framed. This study defines the gap between what exists in elementary teachers' minds about engineering education and the best practices embodied by engineering designers. Upon this frame of reference, K-12 engineering education researchers can build pedagogical experiences for teachers that bridge the engineering and education communities of practice and help them provide their students with conditions for the potentially transformational learning Wenger theorizes.

CHAPTER 3: Methods

Research Design

This dissertation is a qualitative study that defines a problem space for future design studies of engineering education in the elementary school grades. The study applies discourse analysis methods to trace mental models of an engineering community of practice as they are transformed by educators and an educator/engineer to an education community of practice. In his "multidisciplinary theory of context", discourse analyst van Dijk (2008) equates mental models with contexts and uses the term *context model* interchangeably with the term *mental model*. Van Dijk claims that these mental models incorporate key features of the communicator's environment and govern what is communicated, how it is communicated, and what the communicator understands about it. His definition captures the dynamic nature of a mental model that is consistent with my stated definition of a mental model as a combination of a schema or mental representation with a process for manipulating the information in the schema.

Van Dijk's discourse analysis method works particularly well for this study because it incorporates the many components of communication within a community of practice (participant engagement around a common purpose using shared ways of doing things) into his definition of a mental model, rendering it a dynamic, situated, and cognitive construct. Van Dijk's method encompasses and expands upon the work of other discourse analysts whose treatment of discourse ranges from small units of meaning to large units of meaning: such as Halliday's (1978) and Martin's (1992) definitions of context in systemic functional linguistics as "field" (what is happening), "tenor" (who is participating), and "mode" (how language is used), Gee's (1999) assertion that overarching patterns of communicating are symbols of identity and belonging within a particular community of practice (Discourse with a capital D), Lemke's (1990) assertion that science teaching and learning take place within larger discourses about social values and conflicts, and Roth's (2005) assertion that science learning occurs multimodally, with competence in some modalities leading or lagging competence in other modalities. Van Dijk's treatment of a mental model as a context model with specific components allows the construction of a cognitive heuristic for each participant that can be analyzed and interpreted at several levels of meaning. I used van Dijk's mental model framework of discourse analysis to code and analyze interview and survey data collected from participants. The interview protocol and survey instrument are described below.

Participants

I am a participant in this study and had someone use my interview protocol for elementary teachers to probe my own beliefs about engineering design. My background positions me as a legitimate liminal participant in both communities of practice, as described in Chapter 1. The designers in the Deep Dive video are represented as participants in an engineering design community of practice by editors at ABC's *Nightline* program where it aired. This engineering design community of practice, shown in the Deep Dive video, is consistent with the research on engineering design summarized in Chapter 2. That is why I chose this video as a referent to show to the teacher participants. I constructed a composite mental model of the Deep Dive designers' process to compare to my mental model and to those of the teacher participants. Any reference in this study to the mental model of the Deep Dive designers signifies my composite representation of the engineering design process represented in the video.

Additionally two groups of six elementary school teachers participated in my study. One group of six teachers came from schools in the St. Louis, Missouri, area. The St. Louis group teaches textbook-based or kit-based science (i.e., Full Option Science System (FOSS), or Science & Technology for Children (STC)); they have taught at least one unit that contains an engineering-type "design challenge." The second group of teachers came from the greater Boston, Massachusetts, area. These teachers have taught at least one engineering-based unit developed by Tufts University Center for Engineering and Education Outreach (CEEO). Since the Tufts group of teachers was the only group with experience teaching actual engineering-based units, the demographics of that group (grade taught, years of teaching experience, public or faith-based school) drove the selection of the other group so that the two groups would be similar in as many ways as possible. The Tufts teachers teach 3rd or 4th grade and are self-selected from public, faith-based, and charter schools. These teachers are motivated and had the support of principals for implementing the engineering units. I recruited six 3rd, 4th, and 5th grade teachers in the St. Louis area who are highly regarded by science leaders in their district and/or the head of school. They were supported by their principals in the implementation of their curriculum units. The group from St. Louis included two teachers from faith-based schools, two from schools in low achieving districts, and two from school in high achieving districts as defined by the Annual Performance Reports on the Missouri Department of Elementary and Secondary Education's website. The categories of curriculum taught represent the two most likely types of science curriculum taught in Missouri as well as the engineering curriculum that is already in use in the Boston area and likely to become available in Missouri in the coming school years. For example, most textbook publishers now include supplemental hands-on science materials in their textbook series; all kit-based science publishers include materials and teacher guides. While there are fewer engineering curricula available for adoption, these curricula resemble either the textbook-with-supplemental materials format or the kit-based material with teacher guide format. These teachers represent a purposive sample of elementary school teachers that have varying exposure to engineering education curriculum by virtue of their state's requirements to teach the engineering process, and its availability in their teaching context.

The professional experience data collected from each participant group is shown in the surveys in Appendices A and B. The data are summarized in the narrative descriptions of each teacher below and in Table 1. These surveys are adapted with permission from those used by Tufts CEEO (Bethke, Rogers, Jarvin, & Barnett, 2006). Teacher participant names are randomly generated pseudonyms. In the references to and excerpts from participants that follow, the abbreviation for the state in which each teacher practices (MO or MA) will appear next to her name.

Teacher Participant Profiles

Renee (MO) is a third grade teacher in a public elementary school that is struggling to meet state mandated academic performance requirements. At the time of her interview, Renee has been teaching for 13 years total, with 11 years teaching third grade. She uses four FOSS kits per year to teach science for four hours each week. She states that she values the FOSS curriculum because she receives a user-friendly teacher guide and professional development for each unit she teaches, as well as all the hands-on materials her students need for each lesson. Renee reports that after teaching each unit two or three times, she feels confident to adapt the units to her teaching style and to the needs of her students. The Water unit has a design investigation in which students design a water wheel. Renee reports that as she gained experience teaching her students this investigation, she has been able to allow her students more freedom to experience the water wheel design task in a less teacher-directed way. Her students look forward to science time and participate eagerly. Each of her students keeps a science notebook, which Renee uses for both formative (ongoing) and summative (end-of-unit) assessment purposes. She regrets that science time sometimes gets sacrificed in favor of the mandated math and language arts time blocks when special events happen at her school. She wishes she had more time to teach science because her students are so engaged by it and many lessons take longer to complete than the science time she is allowed.

Sandra (MO) describes herself as her school's science advocate. She teaches fourth grade in a public elementary school that is meeting state mandated academic performance requirements. At the time of her interview, she has been teaching for 17 years and has graduate certificates in instructional technology and science education. Sandra would teach science all day if she could, rather than the 45 minutes per day she has in her schedule. She enthusiastically claims that science is a perfect context in which to teach language arts, math, and social studies. Her administrators prefer that the teachers focus on language arts and math, but Sandra says they allow her to emphasize science in her classroom. Sandra attributes this to the fact that she communicates often and emphatically how science fosters math and language arts skills, and that students in her school perform well on the high-stakes state tests. She teaches from a variety of kit-based programs published by the Missouri Department of Conservation, FOSS, and Delta

Education. She takes advantage of the science professional development and outreach offered through her school district, area universities, and local STEM businesses. Science materials are included in her school's budget, and Sandra can rely on parents to donate special materials she might need. The electricity unit Sandra teaches includes a design challenge in which students figure out how to wire a house. Sandra believes that students learn best when instruction is hands-on.

Lillian (MO) teaches fifth grade in a faith-based elementary school. Her school has developed a curriculum that follows the Missouri state standards, but students are not required to take the state's high stakes exams. Lillian describes her pedagogy as constructivist, and she uses a mixture of FOSS and STC kits as her instructional base. Lillian says she adapts and adds to the units she teaches in response to her students' interests and needs, and she adapts accordingly the amount of time per day she spends teaching science. She teaches a kit-based unit called Motion and Design, which has students create and test vehicles that meet performance criteria. Her students used this as a springboard to explore how bridges are built. They designed, constructed and tested different bridges to determine how they performed. A teacher for 37 years at the time of her interview, Lillian states that she works at finding multimedia and community resources to support her students' science interests. Her school provides science kit materials and accompanying professional development, and she relies on parents and other community members to contribute special materials and expertise. She says that the head of the school supports her science teaching with additional materials when she needs them as well as with flexibility in the amount of time Lillian has to teach science. Lillian loves teaching the adopted science units as well as the impromptu units her students inspire. She incorporates math, language arts, and social studies into science whenever possible.

Valerie (MO) comes to teaching fourth grade after teaching fourth and fifth grade science as a science specialist in her school district. At the time of her interview, she has been teaching for six years at a public elementary school that is struggling to meet state mandated academic performance requirements. Valerie describes her pedagogy as inquiry-based, and she teaches from a scope and sequence provided by the district. She states that she has some flexibility in her 50 minute per day science schedule, but she must teach science topics in a designated order because her students must take common, district-wide assessments at specific times throughout the school year. Her instructional materials are derived from kit-based science units and a textbook the district adopted but Valerie says she seldom uses. The district has a collection of science materials that Valerie can use in her classroom. She supplements these materials with ones that she purchases out-of-pocket. She teaches as much hands-on science as is possible, and she says she has her students keep detailed science notebooks, which she uses as one form of assessment. Valerie finds it challenging that her district has cut funding for science instructional materials, but she feels supported by the district's science facilitator, who attempts to provide Valerie with the teaching materials she needs.

Nancy (MO) teaches fourth grade at a faith-based elementary school. Nancy describes her teaching as inquiry-based with a strong vocabulary base. A teacher for 34 years at the time of her interview, Nancy says she has the flexibility in her schedule to expand or contract her science teaching times according to the unit she is teaching. She likes to keep students guessing about what comes next, so she mixes science into her schedule differently each week. Nancy has designated units she must teach each year, and she states that she uses a mixture of kit-based and textbook instructional materials. Her school provides some of the hands-on materials, and she relies on donations for others. Each year, Nancy teaches a unit in which students must design a snowman. The snowman must have a function and must meet specified criteria and constraints for performance, size, cost and appeal. Nancy says she has her students work in teams to accomplish this design task. They keep notebooks and present their prototypes to the school community at the end of the unit. Her students do not take the state's high stakes exams.

Ashley (MO) teaches third grade at a public elementary school that is struggling to meet state mandated academic performance requirements. A teacher for nine years at the time of her interview, Ashley reports that she follows her school district's scope and sequence of topics for her grade that are tied to the state standards. She states that she uses a textbook with supplementary hands-on materials that are provided by her district. She teaches science for 30 to 40 minutes per day in three-week blocks that alternate with other subjects, and she claims that it is difficult to accomplish many of the hands-on science activities within this time constraint. Ashley has participated in professional development through her district and through the Missouri Department of Conservation. Ashley assesses her students in science and other subjects using a portfolio system in which students produce their notebook entries, PowerPoint presentations, and other works on laptop computers. She says she feels pressured to teach only the science that is district-mandated so that students will be prepared to perform well on the high-stakes state science test that is administered in fifth grade. Ashley also feels pressured by her administration to emphasize math and language arts so that students will perform well on annual high-stakes state language arts and math exams.

Lenora (MA) teaches third grade at a public elementary school that is struggling to meet state mandated academic performance requirements. At the time of her interview, Lenora has been teaching for 36 years. She claims that her school district's science curriculum is tied to state standards, and she teaches from two STC kits per year. Lenora reports that the district requires her to teach a 90 minute block of language arts and a 90 minute block of math daily, so she condenses the science units to do multiple one-hour lessons in her one weekly science hour. Because she teaches an accelerated third grade class, she has been granted some flexibility to increase her science time when she teaches her LEGO robotics unit each spring. She states that parents of her students helped secure this flexibility by talking to her school administrators. Lenora claims it was necessary for her to get a formal waiver to do this because administrators visit classrooms periodically to ensure that teachers follow the district's strict pacing guide for math and language arts instruction; teachers who fall behind on the pacing guide experience negative career consequences. Lenora has taken advantage of the LEGO curriculum, professional development, and equipment offered by the Tufts University Center for Engineering Education and Outreach. She reports that she and her students enjoy the LEGO robotics unit she teaches each year. She wishes she had more time to teach science, but does not anticipate that happening soon because science and social studies take a back seat to math and language arts in order to increase the likelihood that students will perform well on the high-stakes state exams.

Ruth (MA) has been using LEGOs in the classroom since 1998. She has been teaching for 27 years, and currently teaches LEGO engineering units as a kindergarten through sixth grade specialist in a faith-based school. She teaches one six-week long LEGO design unit to each grade once per year. Students come to her for one hour each week, when they work in pairs designated by their homeroom teacher. Ruth has been asked to follow the Massachusetts curriculum frameworks for science and technology, which include engineering, and her principal has been very supportive of her work. She has been given "free reign" to conduct her program as she wishes, so she takes advantage of the LEGO curriculum, professional development, and equipment offered by the Tufts University Center for Engineering Education and Outreach. Whatever materials she needs besides those provided by Tufts are donated or purchased by her school. Ruth begins teaching students when they enter kindergarten, so they learn her norms and expectations year by year. She says that students of all grades look forward to their LEGO unit, and by fifth and sixth grade, Ruth incorporates the design of a whole-class system into her curriculum. Fifth and sixth grade students work in teams to construct a system that is made up of different devices that share space and resources. Her sixth grade class had just completed their systems engineering challenge of designing an amusement park at the time of her interview. Ruth does not do formal assessments of her students for their homeroom teachers' grade reports; however, students display and present their work to other classes and to the wider school community.

Elizabeth (MA) teaches a mixed third and fourth grade class at a faith-based elementary school. She describes her science teaching as constructivist and project based. A teacher for nine years at the time of her interview, Elizabeth brings her students to a designated science room and a science specialist twice per week for 45 minutes each time. She reports that she and the science specialist co-teach from STC kit-based science units. When she teaches a LEGO unit, the science specialist comes to her classroom and assists with two to three one-hour lessons per week. Tufts Center for Engineering Education and Outreach provided her with professional development and the LEGO equipment; her school provides the STC materials, and Elizabeth says she feels fortunate that her school purchases other materials she needs. Elizabeth says she can structure her science teaching time flexibly. Because her teaching is project based, she emphasizes the processes – the scientific method and the engineering design process. Her assessment methods include science notebooks and a group presentation of projects to the school community.

Jody (MA) has been teaching a mixed third and fourth grade class for five years at a public elementary school that is struggling to meet state mandated academic performance requirements. She came to teaching five years ago at the time of her interview right after graduation from college as an English major. Jody reports that she was given the third-grade STC kit-based science units with hands-on materials to teach without any professional development or help from a more experienced teacher. In Jody's first year of teaching, the researchers from Tufts Center for Engineering Education and Outreach visited her school to recruit teachers for their LEGO engineering project. Jody says she eagerly volunteered for the study and received materials and professional development. She credits the support she received from CEEO with helping her learn how to teach both engineering and science process skills and to assess using notebooks. Jody and her partner teacher alternate six-week blocks of science instruction with social studies instruction. This allows them to teach two or three two-hour science blocks per week. Jody reports that their students become immersed in the topic and the schedule allows adequate time to complete each lesson.

Ellen (MA) teaches a third grade class at a public elementary school that is meeting state mandated academic performance requirements. At the time of her interview, Ellen has been teaching for 36 years. She reports that she teaches from STC kit-based units and from Tufts' LEGO units. Ellen says she must teach 90-minute blocks of language arts and mathematics each day, but she prefers to teach science. She has structured her schedule to alternate science and social studies units so that she can teach science or engineering one hour per day for four to five days per week. Ellen states that she values the professional development and materials she received from Tufts Center for Engineering Education and Outreach. She receives science kit materials from her school. Ellen likes the LEGO units because they allow students who are better at building things than at traditional learning to become class leaders. She says she capitalizes on the strengths of her students by pairing them to maximize peer teaching and learning.

Jill (MA) teaches third grade at a public school that is struggling to meet state mandated academic performance requirements. Jill has been teaching for five years at the time of her interview after previous careers in corporate accounting and theater management. Jill says she received professional development and LEGO materials from Tufts Center for Engineering Education and Outreach; she receives hands-on materials from her district for STC units and units created by the Boston Museum of Science. Jill reports that she and her partner teacher alternate teaching science and social studies by weeks. Jill says she teaches both classes science one hour per day during one week; her partner teaches both classes social studies one hour per day during alternate weeks. Jill laments that science class gets canceled whenever there is a change in school schedule, such as an assembly, field trip, or snow day. Jill marvels at the creativity her students display during the LEGO engineering units. When she teaches engineering, Jill says she regularly refers to the poster of the cyclic engineering process that Tufts provided her. Jill claims that this keeps her and her students aware of the process they need to follow and helps students frame what they write in their notebooks.

Table 1 summarizes the demographic data and school information for the twelve teachers who participated in the study.

Table 1. Summary of Participant Demographic Data

Teacher Information	**Missouri**	**Massachusetts**
5-9 Years Teaching	Valerie, Ashley	Jody, Jill
10-20 Years Teaching	Renee, Sandra	Elizabeth
25+ Years Teaching	Lillian, Nancy	Lenora, Ruth, Ellen
Teach 3rd Grade	Renee, Ashley	Lenora, Ellen, Jill
Teach 3rd & 4th Grade Combined	0	Elizabeth, Jody
Teach 4th Grade	Sandra, Valerie, Nancy	0
Teach 5th Grade	Lillian	0
Teach LEGO Units as Tech Specialist	0	Ruth
School Information	**Missouri**	**Massachusetts**
Faith-based School	Lillian, Nancy	Ruth, Elizabeth
Public School	Renee, Sandra, Valerie, Ashley	Lenora, Jody, Ellen, Jill
School is meeting state mandated academic performance requirements	Sandra	Ellen

School is struggling to meet state mandated academic performance requirements	Ashley, Valerie, Renee	Jill, Lenora, Jody

Instrumentation and Data Collection Procedures

As stated in the Introduction, the *Nightline* segment The Deep Dive, about the design process used by IDEO, represents the best practices in engineering design and was used as the design scenario presented to teachers in the elicitation of their mental models of the design process. The steps professional designers take in the Deep Dive video map onto the engineering design cycle in the Massachusetts Science and Technology/Engineering Curriculum Framework, and they are consistent with the research reviewed in Chapter 2 about what engineers do and how they do it. These steps were included as axial coding subcategories for analyzing the mental models of the participants.

The mental model elicitation procedure is shown in Appendix C and consists of teachers watching the Deep Dive video, responding to four prompts, and explaining their responses in a semi-structured interview. Each prompt is designed to elicit different information that will be used to construct each teacher's mental model.

First, each teacher was told that she will be asked to think about what she sees in the video as something she would teach to her students. This is intended to prime her thinking about content knowledge (CK) and pedagogical content knowledge (PCK). What she notices and considers important enough to include in a lesson plan for students gives clues to what is available in her own CK and what she values enough to include in her pedagogy.

Second, teachers were asked what instructional materials they might need. Instruction materials can include written and/or multimedia materials, physical objects, and/or others in the classroom for instructional support. This question is designed to elicit clues about meta-strategic knowledge (MSK) and pedagogical design capacity (PDC). During the interview in which each teacher is asked to explain her answers, the researcher asked in what way(s) the teacher imagines each instructional material will be used. Analysis of the answers was expected to give clues to how a teacher is likely to interact with instructional materials (e.g., adapting, offloading, or improvising). This provides clues about each teacher's MSK and PDC.

Third, each teacher was asked to imagine formative (along the way, during the unit) assessment procedures. This prompt is designed to elicit each teacher's awareness of the steps in the process they saw in the video.

Fourth, each teacher was asked to imagine and describe summative (end of unit) assessment procedures. Taken together with the formative procedures, the answers to this question were expected to illuminate what teachers themselves know about designing based on what they noticed in the video, what they imagine is possible to enact in the classroom and the process through which it would be enacted successfully, and the overall value of the exercise. Participants' answers to these four prompts, combined with their explanations of their answers in a semi-structured interview yielded each teacher's mental model as defined by Merrill (2000) – a schema or mental representation combined with a process for manipulating the information in the schema – and represented by van Dijk's (2008) elements.

I also elicited my own mental model of the process, following the procedure in Appendix C, and incorporated it into the dissertation as the discourse analyst's context. I hypothesized that where my responses were more aligned with engineers' thinking than with teachers', I could illuminate potential gaps in teacher background knowledge about the engineering process and/or potential challenges in transforming engineering practices to classroom practices. This is important in formulating implications and recommendations for elementary engineering curriculum and professional development. This documented my researcher's perspective as a legitimate liminal participant between both communities of practice, seeking evidence to inform a bridge between two communities of practice.

Data Coding Procedures

I used the following elements in van Dijk's coding paradigm as initial coding categories for constructing and analyzing the mental models of (a) the Deep Dive designers represented in the video, (b) myself, and (c) my participants:

- Setting: Space and teaching environment, defined as institutional requirements and provisions (i.e. curriculum and pacing guides);
- Communicative roles (participation structures of Deep Dive designers, students, and teachers), defined as the combinations in which participants engaged with one another and the social norms that governed their interactions (i.e. small group work and deferring judgment of another's ideas);

- Social roles of Deep Dive designers and of teachers, defined as actions taken to provide the conditions for designing and learning, respectively (i.e. "leaders emerge as needed" in the Deep Dive and teachers provide feedback in formative assessments);
- Shared and social knowledge and beliefs associated with the IDEO design culture, school engineering, and school science, defined as implicit and explicit assumptions about how work is done (e.g. "fail often in order to succeed sooner", engineering is creative, and there are specific science topics taught at each grade);
- Intentions and goals of Deep Dive designers and of teachers, defined as the cognitive purpose of communications and actions (to reduce theft of shopping carts, and to facilitate students' mastery of science/engineering concepts);
- Communicative and other actions for engineering and for science, defined as the steps of the engineering process and the scientific method, respectively.

Van Dijk uses the term participation structure to represent how a defined 'Self' models personal episodic experiences in relation to other participants (e.g. as a contributor of ideas, a receiver of ideas, a turn-taker in a dialog). Subcategories of these initial categories emerged as the data was coded and will be discussed below. Table 2 shows how the data gathering instruments were structured to elicit these elements of mental models that van Dijk equates to context models (van Dijk, 2006; 2008). The communicative event for me and the participants is each individual's formulation and communication of a plan to teach their students the design process observed in the video. This teaching (lesson) plan was designed to illuminate participants' shared professional knowledge and beliefs (PCK) in the domain of teaching.

The eight steps of the design process represented in the Massachusetts Science and Technology/Engineering Curriculum are included as communicative actions for designing (CK). How each participant notices, names and deems these steps relevant (or not) to include in her plan, combined with the other information elicited (see Table 2) represented each participants' CK, PCK, and PDC within the complexity of each participants' teaching situation – her mental (context) model. Participants' responses were compared to my mental model and the inferred composite mental model of the Deep Dive designers shown in the video. These findings were used to address the stated research questions.

Table 2. Elements of Mental Models and the Components of the Instruments Used to Elicit Each Element.

Elements Of Mental Models **(These are documented in this study's findings for the designers in the IDEO video, Ann McMahon (the researcher), and each teacher participant)**	**Instrument Components Designed To Elicit Responses For Elements Of Mental Models**
Setting: Time/Period, Space/Place/Environment	*All survey questions* *Interview protocol questions* • *We would like to know about your particular school and how you teach science there.* • *Please describe your science teaching practice.* • *Please tell me about the affordances and constraints of teaching science in your school.*

	Additional probes as needed.
Communicative roles	*All survey questions* *Interview protocol questions* • *We would like to know about your particular school and how you teach science there.* • *Please describe your science teaching practice.* • *Please tell me about the affordances and constraints of teaching science in your school.* *Additional probes as needed.*
Social roles types, membership or identities	*All survey questions* *Interview protocol questions* • *We would like to know about your particular school and how you teach science there.* • *Please describe your science teaching practice.* • *Please tell me about the affordances and constraints of teaching science in your school.* *Additional probes as needed.*
Relations between participants	*All survey questions* *Interview protocol questions* • *We would like to know about your particular school and how you teach science there.* • *Please describe your science teaching practice.* • *Please tell me about the affordances and constraints of teaching science in your school.* *Additional probes as needed.*
Shared and social knowledge and beliefs about the design process shown in the video as well as shared and social knowledge and beliefs about how to teach the process shown in the video to participants' students	*Interview protocol questions* • *What did you notice happening in the video?* • *How would you teach your students to enact what you noticed people doing in the video?* • *What instructional materials would you need?* • *How would you assess whether your students were learning the relevant content and the process skills you*

	identified (formative assessment)? • *How would you evaluate their final results (summative assessment)?* • *How does your plan relate to what you already do in your science teaching practice?* *Additional probes as needed.*
Intentions and goals for teaching the process shown in the video to participants' students	*Interview protocol questions* • *What did you notice happening in the video?* • *How would you teach your students to enact what you noticed people doing in the video?* • *What instructional materials would you need?* • *How would you assess whether your students were learning the relevant content and the process skills you identified (formative assessment)?* • *How would you evaluate their final results (summative assessment)?* • *How does your plan relate to what you already do in your science teaching practice?* *Additional probes as needed*
Communicative and other Actions/Events **Participants' responses will be examined for evidence of the following:** ▪ **Identify need or problem** ▪ **Research need or problem** ▪ **Develop possible solutions** ▪ **Select best possible solution** ▪ **Construct a prototype** ▪ **Test and evaluate solution** ▪ **Communicate solution** ▪ **Redesign**	*Interview protocol questions* • *What did you notice happening in the video?* • *How would you teach your students to enact what you noticed people doing in the video?* • *What instructional materials would you need?* • *How would you assess whether your students were learning the relevant content and the process skills you identified (formative assessment)?* • *How would you evaluate their final results (summative assessment)?* • *How does your plan relate to what you already do in your science teaching practice?* *Additional probes as needed*

I conducted the data collection and analysis in the following sequence. During Fall 2010, I wrote and defended my dissertation proposal. I received approval from the Institutional Review Board to proceed; I then received approval from the graduate dean to proceed. I used my personal networks to recruit six St. Louis teachers and six Boston area teachers. My husband interviewed me using the protocol in Appendix C[2], so that I could experience the protocol in the same way as my teacher participants would. I met with each participant individually and in person – most often in her classroom – and obtained her informed consent. I elicited each participant's mental model using the Deep Dive video and the protocol in Appendix C. During each meeting, I audiotaped the interview and asked the participant to take notes as she wished using a LiveScribe Echo Smartpen and notebook. I assigned a randomly generated pseudonym to each participant after the interview. The audiotaped interviews were transcribed. I sent each participant her transcript and offered her the opportunity to add to or amend the text as a member check to increase trustworthiness of data. I received a correction to one participant's transcript and acknowledgement from nine other participants that they had read and approved their transcripts. Two did not reply after two follow-up attempts.

I coded and analyzed each participant's written and transcribed responses to the prompts. First, I used van Dijk's coding paradigm to establish the main coding categories as shown in Table 3 and defined above.

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[2] The Deep Dive video can be viewed on YouTube in three parts. A DVD of the uninterrupted story with the appropriate educational site license was purchased for use in the research.

Table 3. Fifteen Main Coding Categories that Define Mental Models, Based on van Dijk's Elements of Mental Models.

Communicative Actions for Engineering	Shared and Social Knowledge and Beliefs in The Deep Dive	Intentions of Designers in The Deep Dive
Communicative Actions for Science	Shared and Social Knowledge and Beliefs in School Engineering	Goals of Designers in The Deep Dive
Communicative Roles of Designers in The Deep Dive	Shared and Social Knowledge and Beliefs in School Science	Teacher Intentions
Communicative Roles of Students	Social Roles for Designers in The Deep Dive	Teacher Goals
Communicative Roles of Teachers	Social Roles for Teachers	School Setting

The generation of a participant's mental (context) model that represents the transformation of the event in the Deep Dive video to the participant's classroom implies the existence of stable referent(s) within the context of the design event and within the context of teaching elementary school. In order to construct participants' mental models of teaching vis-à-vis the design event, the discourse analysis must reveal a participant's connections between both contexts. In order to do this, I coded the design event in the Deep Dive video for elements of mental models in Table 3. A key affordance of using the Deep Dive video as a referent is that the *Nightline* editors and the Deep Dive designers make their practice explicit because that is what the designers and reporters are tasked to convey. The communicative actions for engineering, communicative roles, social roles, and shared knowledge and beliefs, goals and intentions of designers in the Deep Dive are stated clearly in the transcript. These became *in vivo* subcategories of van Dijk's main coding categories. These represent the composite mental (context) model of designers as represented by the *Nightline* editors for the referent community of practice. These subcategories are also found in published documentation of IDEO's design methodology (IDEO, 2009). The Deep Dive transcript was then coded axially. Each utterance had the potential to be coded in multiple categories and subcategories because of the synergy among categories and subcategories (Jenner, Meyer, Titscher, Vetter, & Wodak, 2000; Strauss, 1987; Strauss & Corbin, 1990).

Transcripts and written data were coded by participant utterance, which is a turn, or a unit of meaning. Where a single turn is lengthy and has multiple topics, it was divided at breaks in topic. A "1" was entered in the cell under each subcategory which was found in each utterance. If the utterance was not coded for a particular subcategory, the cell was left blank. In general, synonyms, metaphors and other lexical and syntactic variations that could mean the same as the subcategory statement were coded as a "1."

As I did with the Deep Dive transcript, I coded each participant's transcribed responses first by content that corresponds to the elements in Table 3. These elements include the referent categories as well as separate categories of van Dijk's coding paradigm that refer where appropriate to teachers, students, school science, and school engineering. *In vivo* subcategories of each school-related element emerged after the initial content coding. I performed a second-level analysis to code within and across the axes and emergent subcategories that address semantic and pragmatic meaning. Coding subcategories that are grouped under headings of steps in school engineering process and steps in school scientific method were taken from state standards for engineering (in

Massachusetts) and for science (in both Massachusetts and Missouri) (Massachusetts DOE, 2006; Missouri Department of Elementary and Secondary Education, 2008). All other subcategories emerged from recurring themes in participant responses. Many subcategories that emerged from participant responses paralleled the Deep Dive subcategories. The only differences were minor adaptations for use in the elementary classroom. The parallel themes noted by teacher participants naturally triangulated with those in the Deep Dive video. The remainder of the subcategories referred to constraints, affordances, and shared practices in the elementary school setting.

Because the Deep Dive context only refers to that professional context, the Deep Dive transcript was not coded in categories that refer to school, teachers or students – the education community of practice. As with utterances in the Deep Dive transcript, participants' utterances had the potential to be coded in multiple categories and subcategories because of the synergy among categories and subcategories. Appendix D contains the code book that was used for coding and organizing the combined transcripts and participant-written data. Representative examples for each coding category are included.

Data Analysis Procedures

A table of total utterances per category and subcategory was constructed. I noted the absence of codes in any subcategory for each participant for future interpretation. Totals for each category and subcategory were computed for each participant and percentage-based mental models were constructed for each participant from the total number of utterances in each of the 15 main categories.

I noted both the absence and preponderance of codes in subcategories for the professional designers, myself, and both teacher groups for a second-level analysis that I assumed would be lexical and syntactical. I found that pronounced distinctions occurred between designers' and teachers' mental models at a larger unit of analysis – across the subcategories themselves rather than in nuances within the subcategories. I concluded that a lexical and syntactic analysis within and across subcategories would not be meaningful without first analyzing the distinctions across subcategories. In the remainder of this section, I will describe the axial categorical coding based on subcategories that emerged from the discursive data. I will illustrate these subcategories with examples.

I constructed graphs of key categories and subcategories for second-level qualitative interpretation at this unit of analysis. See Tables 4 through 7 below for the key categories and subcategories. Appendix D contains representative examples of discourse from the referent video, this researcher, and teacher participants that were coded for each subcategory. These examples of discourse, shown side by side in Appendix D, partially illuminate the similarities and differences expanded upon in Chapter 4.

Table 4 below shows the shared knowledge and beliefs about school science and engineering about which participants spoke prior to viewing the video. These subcategories and the main category of shared knowledge and beliefs represent a common frame within the education community of practice. For example, when teachers talked about specific science topics per grade, they said things like "We have a scope and sequence that's laid out for us on the [name of school district] website that kind of tells us the curriculum," (Valerie, MO). A scope and sequence defines the curricular topics for a school or district. When they stated that the engineering topics must fit grade level science requirements, they said things like "…in 4^{th} grade we swapped out simple machines and the animal unit with the Lego kits, but we supplement the Lego kits with part of the NSRC kits…", (Jody, MA). The NSRC kits refer to science kits assigned to her grade level, and the LEGO kits were chosen to replace the simple machines and animal units that were originally in her science curriculum. Teachers said things like "…we had three conditions that they had to meet and then I added a couple of conditions as we went along," (Lenora, MA), and when they talked about assessment based on products meeting design criteria. They made statements such as "…Then we keep a science notebook with certain steps and requirements and so that's the other assessment piece…," Lenora (MA) when they talked about science notebooks being assessed against standards.

Table 4. Shared Knowledge and Beliefs in School Engineering and School Science prior to viewing the video

Shared and Social Knowledge and Beliefs in School Science	**Shared and Social Knowledge and Beliefs in School Engineering**
Specific science topics per grade	Engineering topics must fit grade level science requirements
Prescribed science activities implemented in classroom	Engineering is creative
Science vocabulary assessed against standards	Engineering engages students
Science process skills assessed against standards	Engineering includes scientific experimentation
Science notebooks assessed against standards	Assessment based on products meeting design criteria
Science engages students	

Table 5 displays communicative actions and roles side-by-side because the discourse revealed implicit links among these categories prior to participants watching the Deep Dive video and a different relationship among them after participants watched the video. These relationships and the discursive evidence for them are explained in Chapter 4. It is important to note that the communicative actions represent the cognitive aspects of learning and that the communicative roles represent the social and emotional aspects of learning. The precursive abilities students must have to demonstrate these actions and roles are called executive function skills (National Scientific Council on the Developing Child, 2011). Executive functioning is defined along three dimensions: working memory, inhibitory control, and cognitive or mental flexibility. The relationship among executive function skills and communicative actions and roles is developed in Chapter 4.

Examples of communicative actions for engineering and science include statements such as "…they went through their design process …" (Elizabeth, MA) for global reference to engineering process and "…following the steps of the scientific method…," (Valerie, MO) for global reference to scientific method. References to steps in each process included language such as "…they built the prototype and then they tested it…," (Jill, MA) for the subcategory of test and evaluate solution and "…what do you think is going to happen in some of those kinds of situations?" (Ashley, MO) for the subcategory of hypothesis.

Examples of the communicative roles of designers in the Deep Dive and for communicative roles of students included statements such as "…then they were put into groups," (Jody, MA) for participate in small group activities (Deep Dive) and "I would have them work in their groups…" (Sandra, MO) for participate in small group activities (students). Teachers used language such as "…respecting each other's opinions…"

(Renee, MO) for defer judgment (Deep Dive) and "no idea was ever put down," (Sandra, MO) for defer judgment (students).

Table 5. Communicative Actions and Roles for Engineering and for Science

Communicative Actions for Engineering	**Communicative Actions for Science**	**Communicative Roles of Designers in The Deep Dive**	**Communicative Roles of Students**
Global Reference to Engineering Process	Global Reference to Scientific Method	Participate in whole group activities	Participate in whole class activities
Identify need or problem	Question	Participate in small group activities	Participate in small group activities
Research need or problem	Hypothesis	Interact with experts outside the design group	Participate in pair activities
Develop possible solutions	Procedure	Build on the ideas of others	Contribute ideas to group product
Select best possible solution	Data Collection	One conversation at a time	Listen respectfully to others
Construct a prototype	Data Analysis	Defer judgment	Resolve conflicts within the group
Test and evaluate solution	Conclusion	Stay focused	Take turns
Communicate solution		Encourage wild ideas	Reach consensus
Redesign			Learn from the ideas and preferences of others
			Defer judgment
			Invest in another's idea instead of one's own when appropriate

Table 6 shows the social and communicative roles of teachers side-by-side in order to convey the ways in which teachers manage the social and emotional classroom environment through their social roles to facilitate students' cognitive learning through their communicative roles. These roles that teachers enact also develop students' executive functions. This will be discussed in Chapter 4.

Examples of the social roles of encouraging collaboration among students and dynamic student-to-student interactions influencing classroom instruction include statement such as "Our hope was it would be very collaborative and that both partners would be sharing the work, by and large I would say that was true…" (Elizabeth, MA) and "...I do different things depending on the children involved," (Ruth, MA), respectively. Examples of the communicative roles of direct instructional activities in the classroom and provide formal and informal feedback to students include statements such as "…the next week is when they would start working in their smaller groups. I think it would take a couple of days, probably 2 days for them to come up with their ideas…" (Renee, MO), and "…as you're floating around checking in with each group and working in, you know, maybe doing whole group check-ins…" (Jody, MA), respectively.

Table 6. Subcategories for Social and Communicative Roles of Teachers

Social Roles of Teachers	**Communicative Roles of Teachers**
Teacher makes judgments about the ability of students to enact social and communicative roles	Establish the instructional objectives of the unit
Teacher controls instructional activities in the classroom	Direct instructional activities in the classroom
Teacher mediates conflicts among students	Provide students with instructional materials
Teacher encourages collaboration among students	Facilitate student learning as needs emerge (reteaching, troubleshooting)
Teacher takes peer-to-peer dynamics into account when grouping students for activities	Facilitate student learning through sense-making events
Dynamic student-to-student interactions influence classroom instruction	Communicate criteria by which students will be assessed
	Ensure participation by all students
	Provide formal and informal feedback to students

The discursive evidence discussed in Chapter 4 shows that the shared knowledge and beliefs in the Deep Dive, the engineering community of practice, do not transform easily or directly to the classroom and the education community of practice. These subcategories are shown in Table 7 below. Teachers used language such as "…just try it…being playful is important… go ahead and try it and then you see why it does work or it doesn't work…" (Renee, MO) for enlightened trial and error succeeds over the planning of lone genius. For the subcategory of interviewing real world experts facilitates faster learning than the typical ways one learns on one's own, teachers made statements such as "…who could we ask, who, you know, who would be an expert in this, who could we call, who could we talk to, and of course they have their parents they could interview and then other people that we could get to come in…" (Lillian, MO). For the subcategory of fail often in order to succeed sooner, teachers used language such as "…don't be afraid to fail…" (Nancy, MO).

Table 7. Subcategories for Shared and Social Knowledge and Beliefs in the Deep Dive

Shared and social knowledge and beliefs in The Deep Dive
Enlightened trial and error succeeds over the planning of the lone genius
Status is conferred to those who come up with the best ideas
Interviewing real world experts facilitates faster learning than the typical ways one learns on one's own
Fresh ideas come faster in a fun place
Focused chaos produces innovation
Fail often in order to succeed sooner
Work under time constraints in order to force an end to the design process and get things done

Examination of the data after the second-level analysis revealed compelling differences between the mental models of Deep Dive designers and this researcher compared to the mental models of all teacher participants as a group. These differences occurred in the semantic macrostructures of discourse meaning, which are the subcategories each group dwelled upon or did not dwell upon, the granularity, or levels of completeness, of their treatments of the categories, and the presuppositions or entailments that the granularity indicates. According to van Dijk (2008), such differences could indicate crucial differences in identity shared or not shared by the participants. In other words, the control of meaning in a particular discourse context rests on some basic and shared referent. In this study, the Deep Dive design event served as the referent for discourse. The second-level analysis revealed that the contextual subcategories considered most relevant to the Deep Dive designers and Ann McMahon were not the same as the contextual subcategories the teachers considered most relevant, hence, the two sets of structurally similar mental models (designers and teachers) differed in compelling ways. With this lens on the data and my research questions in mind, I focused my discourse analysis at the semantic macrostructural, or subcategory, level. Specific findings that support this decision are presented in Chapter 4.

The small purposive sample limits the generalizability of results; however, it is expected that the insights gained through comparing the mental models of practitioners in an engineering community of practice with the mental models held by practitioners in an education community of practice will scaffold future research in K-12 engineering education development and serve as a bridge between practices that might inform one another in new ways.

In Chapter 4, I address the first three research questions. I describe the features of the mental models of the professional designers and of the participants and myself. Then I analyze the discursive data and compare the teachers' mental models with my own and the composite mental model of the professional designers. I describe overall and between group similarities and differences. I use the findings in Chapter 4 to address the fourth research question in Chapter 5. I articulate implications for curriculum developers and professional development providers of engineering education, and I reflect on my liminal participation in this study and provide suggestions for future research.

CHAPTER 4: Data Analysis

Introduction

As stated in Chapter 1, the purpose of this study is to elicit, construct and analyze the mental models of myself and two groups of six elementary school teachers. One group teaches design engineering units and the other does not. All mental models are compared to a referent mental model that is a composite of professional designers at IDEO, a design company. This composite mental model of designers at IDEO was generated by this researcher from a video representation of their practice that was produced by ABC for a segment on *Nightline*. This chapter will address the research questions posed in Chapter 1 and repeated here:

1) **What are teachers' mental models of the design process?**
   a) **What features do they contain?**
      i) **What features are common among the teachers?**
      ii) **What features are unique to each teacher?**
2) **How does each teacher's mental model compare to the design process represented by professionals at IDEO?**
3) **What are the within group and between group similarities and differences in mental models?**
4) **What implications do these mental models have for designing curriculum and professional development in elementary engineering education?**

First, I describe the features of the mental models of the professional designers and of the participants. Then I enter and analyze the narrative data through contrasts: What did teachers speak about at length or in detail that I did not? What did I speak about at length or in detail that teachers did not? I compare the teachers' mental models with my own and the professional designers and note overall and between group similarities and differences. I use these findings to address the fourth question.

Research Question 1: Constructing Mental Models

There were twelve teacher participants. Figure 3 shows a graphic representation of the mental models of designers in the referent video, myself, and two groups of six teachers. The referent mental model is the leftmost bar labeled Deep Dive. It represents a composite mental model of designers in the Deep Dive as depicted in the video used as a prompt for participant responses. My own mental model is to the right of Deep Dive. The teachers in the Missouri group appear as the first six names (Renee through Ashley) to the right of my name; the second six names (Lenora through Jill) are the Massachusetts teachers. Each color in the bar above a single name represents one mental model category as defined by van Dijk. There were 15 categories in all (see Table 3). As mentioned above, the coding categories are synergistic, with many utterances coded in more than one category; therefore, each mental model is more of a synergistic blend of categories than the separate color bars would indicate. The separation of categories allows me to enter the data to analyze it in parts, then produce findings that address the data as a systemic whole.

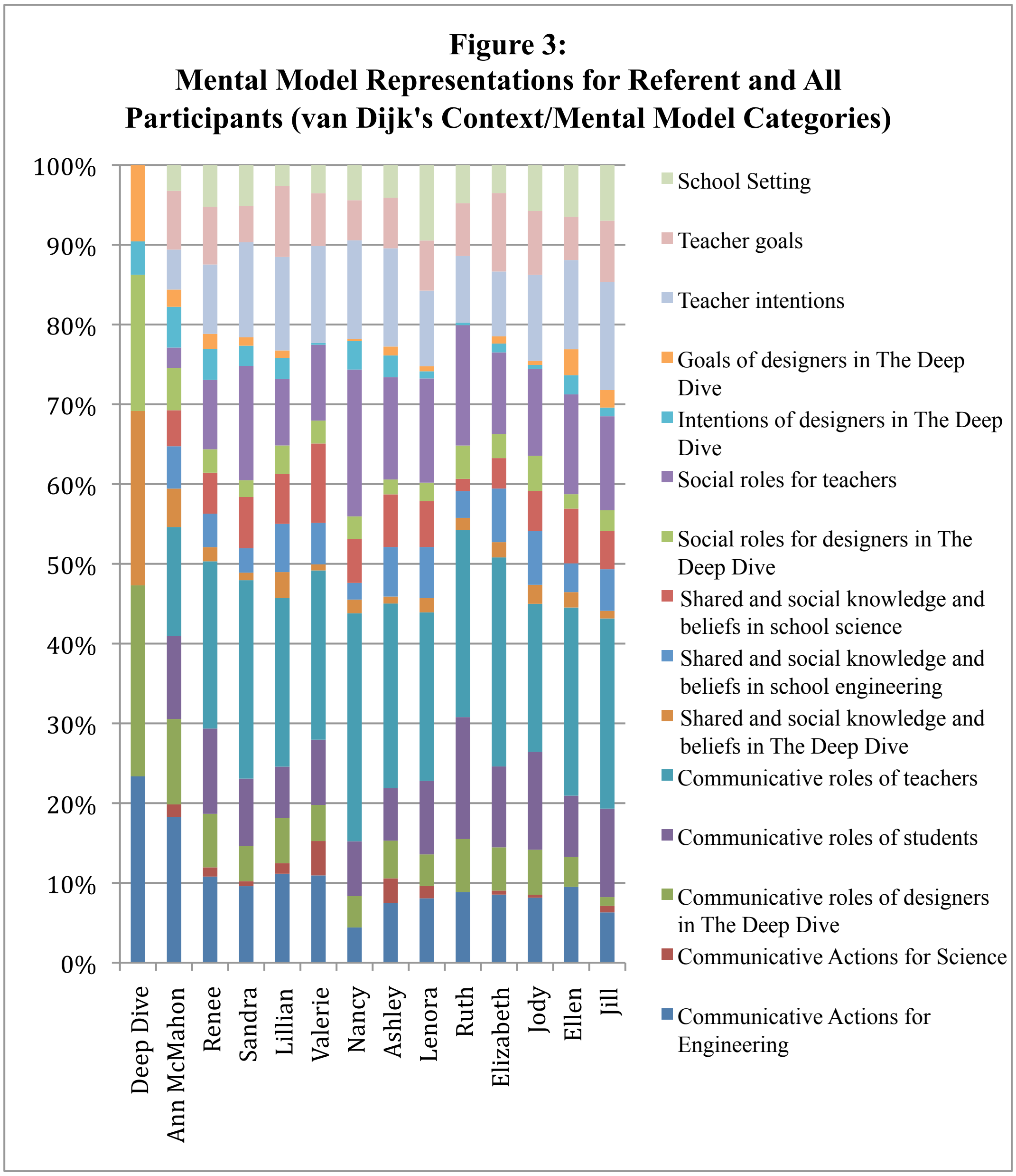

Figure 3. Mental Model Representation of Referent Designers and All Participants

The length of each color represents the percentage of codes assigned to that category for each participant based on the total utterances and written notes of each participant. Six of the categories refer specifically to the referent video, The Deep Dive; therefore, the transcript for The Deep Dive was only coded for those six categories and the composite mental model for designers contains only those elements.

A first-level examination of the mental models in Figure 3 reveals that two thirds of the teachers spoke about every category; therefore those elements are contained in their mental models. Four teachers (Nancy (MO), Ruth (MA), Jody (MA), and Ellen (MA)) did not speak about communicative actions in science (steps in the scientific method), but only spoke about communicative actions in engineering (steps in the engineering process). I was not surprised by this because Ruth (MA), Jody (MA), and Ellen (MA) teach engineering while Nancy (MO) spoke at length about a design unit she teaches every year. While the other eight teachers mixed comments about the scientific method with comments about the engineering process, these four spoke only about the engineering process. Since Nancy (MO), Ruth (MA), Jody (MA), and Ellen (MA) teach science in their classrooms and are regarded as competent, the absence of this category in their utterances and notes is likely due to my stated focus on their perceptions of what design engineers do rather than to any unfamiliarity with the scientific method.

Within the category of communicative actions for engineering, all twelve teachers noticed and articulated every step in the engineering design process. Two teachers, Valerie (MO) and Ruth (MA), did not write or speak about any of the four stated goals of the designers in the referent video. However, Valerie (MO) and Ruth (MA) did speak and/or write about identifying a need or problem in the communicative actions for engineering (steps in the engineering process) category. Thus, both groups of teachers have mental models that include this broader category even though they did not communicate specifically about its exemplars in the referent video.

In summary, the mental models were constructed from 15 coding categories that represent van Dijk's (2008) main elements of mental models. The composite mental model generated for the referent Deep Dive video contains only the six categories that pertain to professional engineering. Before coding, all participants' and my own mental models had the potential to contain all 15 main elements based on utterances and written notes in response to the referent video and interview questions. My mental model contains all 15 elements. Not all participant mental models contain all elements. The mental models of two Missouri teachers (Nancy and Valerie) and two Massachusetts teachers (Jody and Ellen) contain 14 of the 15 elements; one Massachusetts teacher's (Ruth) mental model contains 13 of the 15 elements. The mental models of the remaining four Missouri teachers and three Massachusetts teachers contain all 15 elements. It is important to note the commonality across groups for the engineering process steps: everyone included all the steps in the engineering process that were represented in the referent video and in the Massachusetts Science and Technology/Engineering Curriculum Framework; these were coded as communicative actions for engineering, in our mental models. The number of coded utterances and written notes for each category was unique to each teacher. This represents her unique emphasis for each element of her mental model and is indicated in Figure 3 by the length of each colored section above her name.

Research Questions 2 and 3

The answers to research questions 2 and 3,

2) **How does each teacher's mental model compare to the design process represented by professionals at IDEO?**
3) **What are the within group and between group similarities and differences in mental models?**

are intertwined and emerge from a content analysis of participants' discourse. I will present the analysis, then answer the research questions in a summary at the end of this chapter.

Participants' Teaching Practices: Topics and Pedagogical Approaches

In response to my introductory question to establish the context of their science teaching practice, all participants – including me – talked about the topics they teach and/or their pedagogical approach. Valerie, Nancy and I refer to guided inquiry as our pedagogical approach, while Elizabeth describes her pedagogical approach as constructivist and project based. We do not name topics or activities, which presupposes that any topic we teach is presented through guided inquiry or within the context of a project.

> Valerie (MO): One of the main things that we try to really make sure we do in our school district is that we have inquiry based science, so we want the kids to be doing as much as possible hands on, and we also add in with that an inquiry based notebook where they have to take notes and write things down. So, as much as possible we do hands on labs and experiments and things that we can do with the materials we have in the classroom.
>
> Nancy (MO): I predominately use guided inquiry, and guided inquiry with a heavy vocabulary base.
>
> Elizabeth (MA): I would say we're very constructivist in our science curriculum; everything's about creating the kid's understanding. It tends to be very project based.
>
> Ann McMahon: Well, I teach teachers. I teach kindergarten through 8^{th} grade teachers mostly, and the way I set up my courses is with an inquiry method, usually guided inquiry, which means that I have objectives in mind for my teacher-learners to achieve and I set up experiences with objects and phenomena that allow them to make observations of those objects and phenomena.

Renee, Ellen and Jill describe specific kits or kit publishers, topics, and strategies such as science notebooking. The kit-based curriculum publishers these teachers mention make their pedagogical approach explicit in the teacher guide that accompanies the kit, so these teachers might conflate the kit publisher or topic with a pedagogical approach such as guided inquiry.

> Renee (MO): Yes, we use the FOSS kits and we do science notebooking with that.
>
> Ellen (MA): Well, we have in our grade level and across our district we have certain units that we have to teach. In particular 3rd grade we have to teach a unit on the solar system, we have to teach sound, we need to teach simple machines, we need to teach a plant unit which really is on the bee's pollinating, you know, so it goes a little bit further, and we're supposed to teach also animal adaptations, so [those are] the units that we do.
>
> Jill (MA): Well, for teaching science we normally in the school district use the STC kits and also kits from the museum of science, and then a few years ago there was a collaboration with Tufts LEGO to use Tufts LEGO units to teach science in here, so a lot of teachers had jumped onboard and took advantage of that opportunity of learning another set of curriculum materials to use for teaching science.

Before viewing the IDEO video, participants mentioned students working in pairs or small groups in the context of managing their classroom. Four participants mentioned their student grouping strategies without prompting.

> Renee (MO): We usually, we don't do it [science] every day, it's pretty much every other day, the kids work in groups of four and I model what we're going to be doing or what the concept is…
>
> Valerie (MO): Well … you can see my room's set up in pods so we do a lot of group work, so even when we're not doing a lab they're doing a lot of things together. I do a lot of differentiation, so different groups may be doing different things depending on what level they're at.
>
> Elizabeth (MA): In terms of the setup we actually had 27 kids in one of our rooms, which are fairly small, so that logistically was a little bit more challenging to manage that number of kids in one room. We set them up with partners.
>
> Jill (MA): Well, … right now we're currently in the middle of the properties of materials LEGO unit, and they're working with partners.

Prior to viewing the designers at work, the participants and I spoke about our teaching practices from a cognitive and pedagogical perspective. Our comments reflected the coding categories in our shared knowledge and beliefs about school science, specifically that: 1) students should engage with prescribed topics and experiences through inquiry, 2) students should know vocabulary associated with each topic, and 3) students should be able to use that vocabulary to write about the processes they used to investigate objects and phenomena in science notebooks. The teachers who teach LEGO engineering units added to our shared knowledge and beliefs about science that students experiencing school engineering 1) engage in a creative process, 2) use the scientific method as part of creating objects that meet specified performance criteria, and 3) meet grade level science requirements through engineering units aligned with the science scope and sequence. The coding categories for shared knowledge and beliefs in school science and school engineering are shown in Table 4.

Participants' Teaching Practices: Group Norms for Student Collaboration

Our comments about students' communicative roles of enacting school science and engineering reflected logistical concerns about how the prescribed science and engineering activities and requirements would be managed in the classroom and, in some cases, pedagogical concerns about how instruction would be differentiated by student group. No participant mentioned group norms specifically for how students should communicate with one another in order to carry out their science or engineering tasks and consolidate their learning socially or individually. Participants spoke about grouping students in terms of managing activities. In the following excerpts, Ruth (MA) and Nancy (MO) do not articulate communicative norms that facilitate student collaboration, although it is clear that they want students to work together in their classrooms. Elizabeth (MA) elaborates on how collaboration would look in her classroom in terms of what she saw that impeded it.

> Ruth (MA) (the specialist who teaches engineering): Well, they come in pairs. I ask the teachers to set them up in pairs because the teachers know them a little bit better than I do…
>
> Nancy (MO): Sometimes it's individual; the cloud posters were individual endeavors. Other times we do collaborative learning and it turned out that the activity I gave them today, the water cycle poster, the cloud recipe, and researching different types of weather fronts, I broke, they were in groups of two, and so I needed six kids who wanted to work in a group and it turns out seven kids stood up, so, eight kids stood up, and then seven, and then there was one who was ambivalent so they rock-paper-scissor on who was going to be in and who's not going to be in and that's just the way we handle it…
>
> Elizabeth (MA): Our hope was it would be very collaborative and that both partners would be sharing the work, by and large I would say that was true, there were some partnerships we had to watch pretty carefully because one child tended to do most of the building [with LEGOs] or one child tended to come up with most of the ideas and they then would do more directing than we would have hoped, but by and large it was pretty collaborative and they did a good job with that.

This discourse indicates that all of us conflated van Dijk's communicative roles or participation structure of school science with the communicative actions of school science (See Table 5). The discourse before participants viewed the Deep Dive conflates communicative actions with communicative roles and content with pedagogy. In other words, all of us defaulted to foregrounding the communicative event (science or engineering activity) while minimizing the communicative roles – the students' participation structure.

Expected Similarities and Differences in Participant Discourse After Viewing The Deep Dive

After participants viewed the IDEO designers enacting the communicative actions of professional engineering in the Deep Dive, I expected their discourse to foreground the communicative actions of engineering – the steps of the engineering process – as they did in their comments prior to viewing the video of the Deep Dive. These communicative actions for engineering are the cognitive counterparts to the communicative actions of science – the steps of the scientific method (See Table 5). My hypothesis was that the answers to my second and third research questions would lie in teasing out differences in how the two groups of teachers perceived the cognitive aspects of the engineering process. Instead, all of the participants focused similarly and insistently on the communicative roles they saw in the Deep Dive and minimized the communicative actions – the process steps – of engineering (See Table 5). The teacher participants transformed the roles for designers the Deep Dive to classroom norms that made more sense for them. Participants transformed the Deep Dive role of one conversation at a time into the desired classroom norms of listen respectfully to others and take turns. They transformed the Deep Dive role of stay focused into the desired classroom norms of contribute ideas to a group product and reach consensus. I, on the other hand, continued to elaborate on the cognitive steps of the engineering process over the more social and emotional communicative roles within it. Here is where the mental models of the teachers and me – the engineer – show some differences.

Emergent Similarities and Differences in Participant Discourse: Communicative Actions vs. Communicative Roles

The difference between what I notice and what teacher participants notice begins to emerge in the first comments we make after viewing the designers at work. We responded to the prompt "What did you notice happening in the video?" I began speaking about the engineering process steps, as do Nancy (MO), Ashley (MO), Elizabeth (MA) and Ellen (MA).

> Ann McMahon: OK, I noticed that the designers took something that I've used lots and lots of times and they completely remade it.
>
> Nancy (MO): I do a lot like that in my classroom, which is what I'm doing right now, you know, when I gave them what they were going to do with the different parts of the weather, yeah, oh yeah, very cool.
>
> Ashley (MO): I guess I saw them working together and kind of problem solving and I guess kind of troubleshooting a lot of the way too, like and then as one got, you know they had one design and one had this design and one had that design they were trying to see well this is a good part of that design, that's something we could use here, or we could use that part here and kind of make it better as a whole.
>
> Elizabeth (MA): Problem solving. There's a problem and they went through their design process and came up with a solution.
>
> Ellen (MA): …I know that's part of the engineering process is the redesign, you know, if it doesn't work to go and redesign, and it is for to make things easier for human whatever it is…

The remaining teachers remark on the designers' participation structure first. The comments of Renee (MO), Sandra (MO), Lenora (MA) and Jody (MA) are all about the engineering team.

> Renee (MO): Well, I noticed that there were a lot of different kinds of people trying to come to a consensus on what would be the best way to redesign this product, and they were, I like their idea of this organized chaos that's focused because they all were focused on coming up with these new ideas, but there was a process to this, you know, I mean everybody gets to share their ideas and then it's

> narrowed down, it's voted on, and then you try it out, some things fail, and they kept working until they came up with the end product.
>
> Sandra (MO): Oh wow, that was fun. That was fun; I would love to be part of that team.

Lenora (MA) and Jody (MA) referred to different work cultures, one a Taylorist culture shown at the beginning of the video (Lenora (MA)) and another that Jody (MA) learned about from her friends and was similar to the ideal culture she saw in the Deep Dive. They relate those comments to their observation of teamwork in the Deep Dive.

> Lenora (MA): OK, everybody always had their hands on something and just were actively engaged in something, so I don't know what other things they were doing but that was also the case with the [shopping] cart. You know, so trying things out, building, I mean it was interesting how it [the video] started with the women at their stations at the beginning all in their little space at their desk just sitting there doing what they're supposed to do [a reference in the video to how other corporations operate]…and then all this freedom. I wonder how many companies really operate like that.
>
> Jody (MA): OK, so the biggest thing was just that it's that sort of culture that I think this was, I mean I wanted to know the date because this was in '99 and if you look at a lot of companies these days more so they've become a lot more I think like IDEO [the company featured in the Deep Dive video]…I've never worked in corporate, but talking to my friends who have gone into…corporate culture, have gone up to Silicon Valley that is the kind of environment that they're working in these days, the whole idea that you can show up to work in jeans and a shirt and you're all set and that you sit around and you actually generate ideas and you're not just, you're not working in a cubicle by yourself all the time I think is the big thing.

Lillian (MO), Valerie (MO), Ruth (MA) and Jill (MA) remark about the norms of the designers in the video and compare or relate it to what happens in their classrooms.

> Lillian (MO): OK, the first thing I thought of was this is exactly how I run my class, you know, it was so cool to watch it in adults rather than just me – crazy me and a bunch of crazy kids, you know? It was great, I mean that's how they came up with the bridge stuff [a unit on bridge construction she described earlier], that's how they, I mean it's wonderful, it's wonderful to see adults doing that and it makes it, and they said at some point at the end that it's long hours but they love it and I think that's the key is love learning, and for my class the more kinds of things I can do like that encourage them to love learning, the better off they are.

> Valerie (MO): The one thing that I thought was really interesting that's actually something we try to do when we are doing group work is that there wasn't one person in charge; everyone was working together and typically what happens in my classroom is I have some girls who like to be the little control people, and so they always want to immediately 'you're doing this and you're doing this and you're doing this' and then others are like 'wait a minute why are you telling me what to do', and so it seemed like it worked so well for them because like the person that was doing the talking wasn't even the boss of the company, it was somebody else who they said was good at groups. So, one of the things we try to work on and that I want them to see is that it's going to go better if they're all working together instead of 'you're telling me what to do and you're telling him what to do', and so obviously they work that way and come up with a lot of great ideas, so the kids should watch that video.

Ruth (MA) and Jill (MA) include some specific norms that were articulated in the Deep Dive. Both state how they will incorporate those norms in their classrooms.

> Ruth (MA): That was actually kind of exciting because it was similar to the systems engineering project I did with the 6th grade in that we didn't necessarily, they didn't have to work in pairs; sometimes two groups would get together and make something together, so it was interesting although there's one thing that I underlined here: build on the ideas of others. One thing I haven't got across to the children is it's not just you see somebody next to you building something and you build the same thing; you can share ideas. I keep telling them it's the one time where if you look on somebody else's paper you're not punished, that's OK. Math tests, no you can't do that – engineering, absolutely.

> Jill (MA): Well yeah, the idea where nobody was in charge and how you had to keep an open mind to innovate, different ideas, and that's definitely something that I will incorporate in the classroom. I mean we pretty much do that anyway that, I let them all know that right now, we're thinking up ideas, we're trying to think of good ways to do things and there's no right and wrong until we test it and see it doesn't work, so that's definitely something.

Soon after, though, Nancy (MO), Ashley (MO), Elizabeth (MA) and Ellen (MA) focus on communicative roles, describe how these roles look in their classrooms in detail, and relate what they do to communicative roles they observed in the Deep Dive. Nancy (MO) talks about having brief autocratic moments with her students, just like emergent leaders did in the Deep Dive. Ashley (MO) talks about giving students in groups different colored markers to use so she can see at a glance that all students are participating – a communicative norm in the Deep Dive. Elizabeth (MA) describes a faith-based protocol for reaching consensus that incorporates several communicative roles she saw in the Deep Dive. Ellen (MA) describes how she pairs students to capitalize on individual strengths like Deep Dive designers do.

> Nancy (MO): They brainstormed, it was strictly brainstorm, I let them go, everybody has their own, in fact I'm not even sure what all of them are doing yet, that's their own deal, that's not me, and that was one of the things they talked about is you have short autocratic moments and that's what I have, I have short autocratic moments.

After describing the way she lets her students brainstorm without her guidance, Nancy (MO) gives a specific example of one of her short autocratic moments within the context of her snowman construction unit. Nancy (MO) continues:

> When we were in on the computer lab looking at all these little YouTube videos I would interject and say OK, tell me what did you see here, what are some of the common factors that you saw in X number of videos that we watched that you are now going to apply to yours because this is all new to them. So, God this is amazing. What I did right here is exactly… What they did is what I'm doing with the snowman construction.

> Ashley (MO): …We talk about if you're working as a group what are some things that you need to do; you all have to be responsible for things and you all have to contribute, so a lot of times what I'll do is if it's something where they're initially doing it on a piece of paper I give them each a different color marker and they have to sign their name on the back in that marker and then I know any idea that's on there in purple is, say Abby's idea, anything in blue is Joe's idea, and if I go around and I see Bobby has the black marker and there's nothing on there and he keeps saying well everything that I want to write down they already said, I'm like you're going to have to think of something else.

After describing her colored marker strategy for ensuring everyone in a small group participates, Ashley (MO) describes the many ways that her students respond and the group dynamics that result. She continues:

> So, sometimes it's outside of the box, sometimes it is that one different quirky thing that it took the obvious one, and sometimes those kids want to get something on there quick before that easy one gets taken and somebody has that idea that oh we could just put it in this kind of container or do this or do that, but they kind of like that, and also kind of make sure that like I don't want to see your whole poster with just red all over it because, Mary decided that she was going to write everything down and she was kind of taking charge of the project so it kind of splits up the equity in it a little bit which they kind of need help with in 3rd grade.

Elizabeth (MA) notices several specific communicative norms in the Deep Dive that relate to a specific faith-based process used in her school to solve social challenges. It is clear from her description of the faith-based process that she understands that the importance of brainstorming, listening respectfully, deferring judgment, supporting another's idea, and reaching consensus extends beyond the engineering community of practice and is generally useful in social situation.

> Elizabeth (MA): I feel like this is a familiar style; this is kind of the way we kind of do a lot of things even if it's solving a social challenge we often just sit down and meeting for business and present the challenge, and meeting for business is a [faith-based] term. I tend to use it more for social challenges that come up, so maybe at recess, this is one from the Fall, it's a very common one in the Fall is that there is conflict over some game that's happening and it can be either some group of people is feeling left out of the game or it can be that the game is too rough, like the soccer or football tend to lead to a lot of conflicts; either it's too rough, some may think something's not fair, the team's not fair, a whole list of complaints, and so we will sit them down and say we're hearing your complaints, we're hearing that it's not working, here's what we see as observers and what do we do about it? What do we do about it, and then open it up for different brainstorming, and part of the parameters we set are that you can't judge anybody's idea, anybody's idea it needs to be out there and heard and accepted. You can, so initially all ideas need to be heard and then at some point we can respond to the ideas but you can't say no that's a bad idea; you can't shoot an idea down. You can say if we did that then this might happen, and present a different perspective, and we try to guide the kids to consensus. There's another [faith-based] term, "sense of the meeting" which means, it doesn't mean that everybody agrees 100% but it means that it's the general understanding and a general agreement.

Ellen (MA) takes up the remark in the Deep Dive about controlled chaos and relates it to her strategy for pairing students to work with LEGOs. She emphasizes choosing pairs based on the relative strengths of the students so that they can learn from each other and so that students who are better builders can exhibit their strengths to classmates who perform better in other modes of learning.

> Ellen (MA): …but as long as it is controlled, and I know they said in there [the video] chaos, and if it's productive chaos then that is the way that you do learn. I love his idea about, that the boss isn't, you take who's good at what whatever it is and then they're the ones that will be in charge or they're the ones that will kind of push whatever you're trying to do, and in some ways I kind of did that with the LEGO piece, when I said about trying to find one that was, like that had some idea of LEGOs and tried to put them with someone that didn't because, I mean that's, what else it does is it gives self esteem to a child…because many times those LEGO builders are those that didn't shine academically because they were better with their hands so, in some ways it was great for them, for their self esteem to say…I am good at something…

In contrast, my first comment about communicative roles reveals none of the nuanced student interpersonal dynamics characteristic of the teachers' responses. I still pursue in detail how I perceive the cognitive communicative actions of the engineering process shown in the Deep Dive would transform to the elementary classroom.

> Ann McMahon: So, the students would have to look at all different ways that student desks are interacted with at school, and they would gather some information about what each of those people (students, teachers, principal, custodian, the person who buys them), what's important to them, so I would have them ask what is important to you about student desks and start there and learn as much about them as they can. So, the other thing I would do is to divide my class into teams to do this. So, in the video they had already decided that there were going to be different aspects of the shopping cart that they focused on. In their initial discussions, you know, safety emerged, theft, so what are those questions for student desks? So, it'd be interesting to find out what the class came up with or are there three, four, or five things about a student desk that they would want to focus on. So, that would mean really narrowing down the problem or the need.

When I refer to the whole class or small groups of students, I assume by my omission of any reference to group dynamics that the social and emotional aspects of learning will take care of themselves.

Emergent Similarities and Differences in Participant Discourse: Teachers' Social Roles in the Classroom

Teachers also talked proportionately more about their social roles in the classroom, roles they play that support students' enactment of the communicative actions and roles. Teachers' social roles differ from but are enacted with teachers' communicative roles in the classroom. Social roles for teachers involve managing the classroom so that students' social behaviors result in an environment conducive to learning. Communicative roles for teachers involve providing a set of experiences in which all students are invited to learn specific cognitive concepts and processes. Social roles focus on social and emotional behaviors of students while communicative roles focus on cognitive learning. These social and communicative roles for teachers were coded in the categories shown in Table 6,

The excerpts above that contain utterances about what the teacher does in her classroom contain one or more of these social role categories in addition to communicative role categories. Elizabeth's (MA) description above of a "meeting for business" that results in the "sense of a meeting" – a decision acceptable to all – is a systematic pedagogical example of enacting her social roles of encouraging collaboration and mediating conflict in the service of her communicative roles of facilitating student learning and ensuring participation by all students.

The social, emotional, and cognitive aspects of learning happen together (National Scientific Council on the Developing Child, 2011). Teachers facilitate all three aspects of this learning through their social and communicative roles as teachers. The teachers' discourse and mental models reveal integrated attention to the social, emotional, and cognitive pedagogical content knowledge needed to enact science and engineering in the classroom. Elizabeth's (MA) faith-based "meeting for business" protocol, Ashley's (MO) colored marker strategy, and Ellen's (MA) attention to pairing students based on complementary strengths reflect their awareness that they must manage students' social and emotional aspects of learning along with the cognitive aspects of learning.

A glance at the main mental model categories of Social Roles for Teachers and Communicative Roles for Teachers in Figure 3 reveals that all teacher participants spoke proportionately more about their social and communicative roles in the classroom than I did. My utterances prioritized the cognitive communicative actions of the engineering process. In contrast, several of the communicative roles from the Deep Dive captured teachers' attention more than the steps of the design process. Figure 4 shows the percentage of utterances for six of the eight subcategories within the communicative roles category compared by group. Teacher participants mentioned these roles more than designers in the Deep Dive and me. Furthermore, teachers spoke in detail about how they would teach these roles to their students. Sandra (MO) describes her scaffolded, painstaking, quarter-long process for teaching students to have one conversation at a time and build on the ideas of others while participating in small group and whole group activities. She begins by teaching students to listen actively and respectfully to each other in pairs and to reflect on their experience. As students become competent, Sandra (MO) gradually increases the listening groups from pairs to small groups until the whole class can listen actively and respectfully to each other when divided into two larger groups.

> Sandra (MO): The first thing that we start with is pairs, just two people, and then you learn and you create groundwork with those two people, rules so to speak; how do you talk to your partner, what would you say to your partner, how do you take turns, what does that look like, and they always keep saying the word respect and I was like well, what does respect look like? You've got to be able to see it, besides feel it what does it look like? So, we talk about what active listening is and we practice that quite a bit; we practice that almost for an entire quarter, a good eight or nine weeks, just turn to your partner, just tell your partner what are you doing. Stop and talk to your partner, so, trying to deflate the individualism just a little bit so that they can start working as a team.

In the first part of Sandra's (MO) process, she facilitates students' experience of having one conversation at a time, listening respectfully, and showing respect in multiple modalities: what it looks like and what it feels like. The active listening practice helps to develop students' self-regulation and working memory skills.

> Then the next thing, the second step would be adding a few more people and that would only be like two, maybe three, no I would not make it more than five, and that would be basically turn to your group. So, you would have your basic pairs and then you would have them group with another pair. So, turn to your groups and with those groups learning what a group dynamic is, and of course setting ground rules there adding to the ones you already have: how did you take turns, what does that look like, and what does the active listening look like now and what does the respect look like now?

Sandra (MO) shows understanding of how group dynamics change in her classroom when students go from working in pairs to working in small groups. She is careful to scaffold students' experiences of respect and turn taking by having them explicitly address how ground rules for communicating change when more people are added.

> Then from there of course adding a group and another group, so basically you've got half the class and half the class and you've got each half of the class talking to each other, and right now personally we're not there yet; we're still working in groups…we're working in bigger groups, so basically half the class and the other half, so you're working with about 10-12 people. Then of course I would probably start the discussion once again: what does this look like, how can you

> check yourself within that group, are you participating instead of just sitting there and listening, because I love what he [a designer in the Deep Dive] said, he said, you know, for you to have somebody listen to you is nice but you really don't want people to listen to you, you want people to argue with you, you want people to kind of go against what you're saying and that's how you get ideas and that's what I want them [her students] to say.

As the size of the groups increases, Sandra (MO) pays attention to issues of participation and non-participation, as well as how to disagree respectfully. She realizes that students can hide in or dominate larger group discussions, so she teaches her students about regulating ("checking") themselves in a larger group. Sandra's (MO) detailed attention to developing her students' social and emotional skills independent of cognitive content is reminiscent of Elizabeth's (MA) "meeting for business" protocol. Sandra (MO) chooses to emphasize these social and emotional skills in her public school classroom, while the development of those skills in students is embedded in the culture of Elizabeth's (MA) faith-based school.

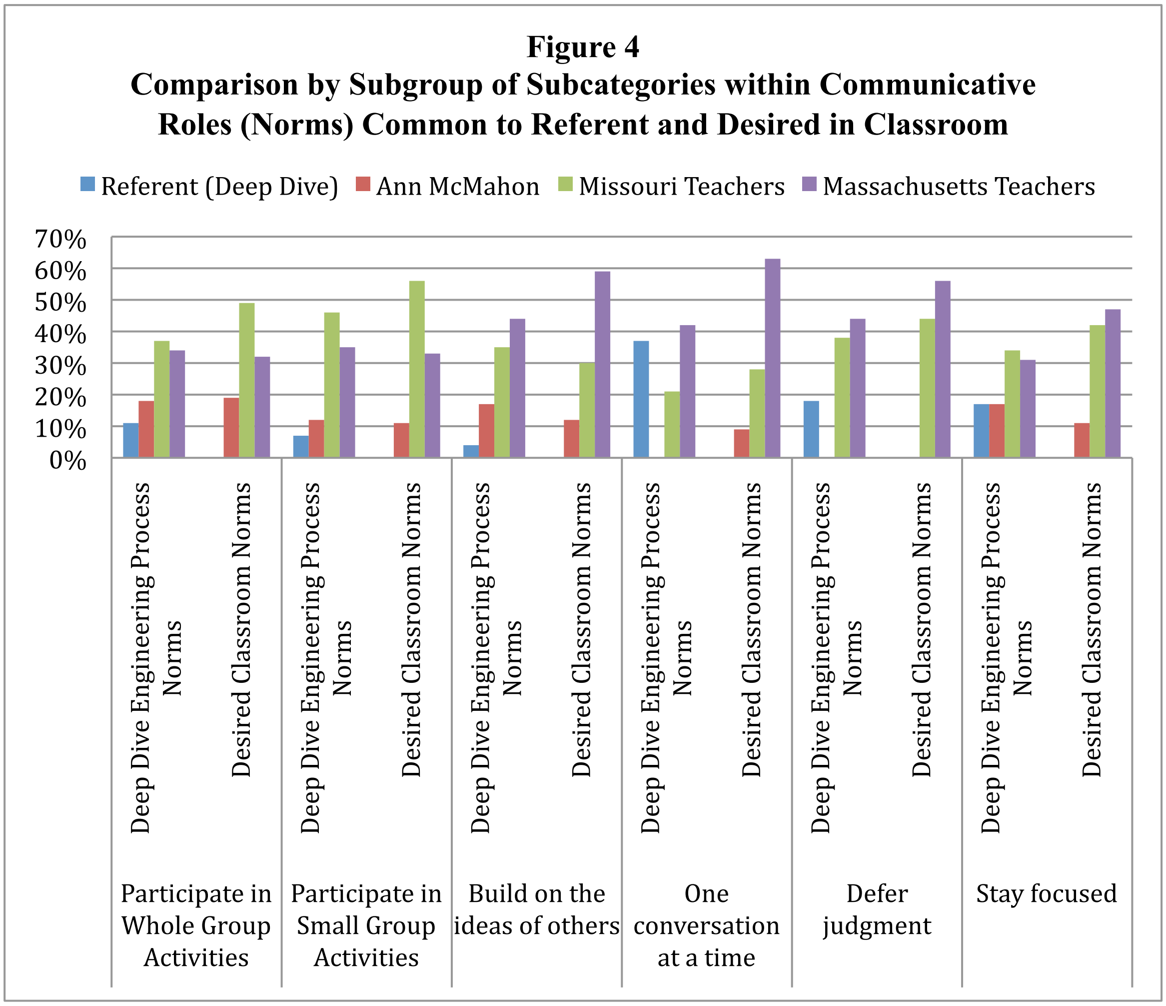

Figure 4. Comparison by Subgroup of Subcategories within Communicative Roles (Norms) Common to Referent and Desired in Classroom

Figure 4 shows that Missouri teachers spoke more than Massachusetts teachers about participating in small group and whole group activities. Massachusetts teachers spoke more than Missouri teachers about building on the ideas of others and having one conversation at a time. Both sets of teachers spoke nearly equally about deferring judgment and staying focused. Both groups of teachers spoke more about all six classroom norms than I did. In fact, I did not mention two roles – one conversation at a time and defer judgment – in the Deep Dive at all. Neither did I decide to transfer the defer judgment to the classroom. In contrast, teacher comments about deferring judgment emphasized how difficult that and the other norms are for elementary children to demonstrate. Ashley (MO) relates how she helps students learn to defer judgment then offer criticism using "a wish and a star," a strategy she transferred from language arts to science.

> Ashley (MO): Normally they have a little sheet of some things that they can use to help kind of respond, like 'I like how you said this' or 'I agree with you but'…After they share they get to call on somebody for a wish and a star. So, a star is something you liked about their thing and a wish is something that you wish that they would have done…so it doesn't sound like criticism…[or] you just shot my idea down. But I think those things… help to just get that classroom community going.

Valerie (MO) relates how she helps her students practice deferring judgment and offering feedback respectfully. She indicates that those practices are difficult for her students and that she spends instructional time rehearsing them.

> Valerie (MO): Yes, so we do a lot of group work in here and ideally I want my groups to work like they do on here [the Deep Dive], you know, no one's really in charge, everybody's kind of working together, no one's – one of the things I put on here was no one was supposed to be allowed to shoot somebody else's idea down which is a really hard thing because when someone [her student] comes up with an idea they're very passionate about it and they want that to be the way to go, and when somebody else [says] my idea's better, then they want [to say] your idea's not good, and sometimes they can be mean about it, but we do a lot of practicing on how can I tell someone I don't agree with their idea but in a way that's respectful to them.

Ruth (MA), the LEGO specialist who works with students year after year as they progress from kindergarten though 6th grade, discusses how her consistent insistence from kindergarten onward that students practice deferring judgment pays off in the upper grades.

> Ruth (MA): They [the designers in the Deep Dive] were working together, they were designing a single thing. They were throwing out all these ideas. I like this, I underlined this [in the notes she took while viewing the video]: encourage wild ideas, because sometimes kids will come up with an idea and other people will shoot them down and that's something that I nip in the bud, and I have to say by 4th grade they throw out the cockamamie ideas that you could ever imagine, and everybody sits there and listens politely…

Elizabeth's (MA) faith-based school incorporates these six classroom norms into all aspects of its school community. In the comment from Elizabeth (MA) about "sense of the meeting" quoted above, she describes her community's steps to resolve conflicts and reach consensus in small and large groups through focused, systematic conversation that incorporates deferring judgment and building on the ideas of others. She notes that consensus does not mean that everyone agrees with the solution. It means that no one is "going to stand in the way of the decision," that each person can "make peace with the decision," and that each person "need[s] to be able to live with it, basically." Jody (MA) had a student whose mother worked on a children's television show about engineering called *The Design Team*. She asked this mother to provide footage of student designers working together well and not well. Jody (MA) used this video footage of students like her own to frame a class discussion about all of these classroom norms.

> Jody (MA): I said [to the student's mother] I know you do *The Design Team* and…I know you probably have all kinds of issues with these students cooperating. Do you have any footage of the students not working well or working well together that I could maybe use and share with my students because they're just not, this is actually becoming a big hurdle, they're not getting enough of the science because they're so busy fighting or one person's sitting back and doing nothing…

Jody (MA) recognizes how social, emotional and cognitive learning happen together, and how difficult it is for her to facilitate, despite the social competency programs her school offers (and she describes below). She takes advantage of the opportunity to reach out to a parent for help facilitating social, emotional and cognitive learning in the context of engineering design.

> …and so she lent me some footage of some clips from these students on the design team working and we watched it as a class and did an open circle kind of thing where we, which is a social competency program where we discussed cooperative learning, what did they do well, what didn't they do well, how can we use that, and so then it became sort of like our anchor experience, and so whenever I saw students having trouble with that I was like hey remember those kids in that video and that clip and how did they do it and what was wrong. So, it started, I saw some slow movement and slow progress in that direction…

It is clear from both groups of teachers' mental models and discourse that in their view, the communicative roles of students for enacting the communicative actions of engineering design must be intentionally taught, and that the teaching of those roles is complex, cross-curricular, time-consuming, and needs reinforcement throughout the elementary years. Both groups of teachers characterize these communicative roles as the matrix within which the communicative actions – the steps of the engineering process – take place. Jody's (MA) comment sums up the communicative issues teachers face in the classroom, her frustration with them, and how they impede student learning:

> Jody (MA): …this is actually becoming a big hurdle, they're not getting enough of the science because they're so busy fighting or one person's sitting back and doing nothing…

Compare the teacher discourse above to the way communicative and social roles are represented in the Deep Dive referent video and in my responses – the engineers' perspective. The Deep Dive Reporter lists the communicative roles (norms) that designers use in their communicative actions: one conversation at a time, stay focused, encourage wild ideas, defer judgment, build on the ideas of others. These norms are shown posted prominently in the designers' workspace. The designer leading a brainstorming session reminds the designers to defer judgment or he'll ring a bell to indicate that someone has criticized an idea. This is also his social role within the group, as is his direction to the group about voting for buildable ideas.

> Deep Dive Reporter: Day two and the start of IDEO's unique brand of brainstorming. They call it a deep dive, a sort of total immersion in the problem at hand. IDEO's mantra for innovation is written everywhere: one conversation at a time, stay focused, encourage wild ideas, defer judgment, build on the ideas of others. [Video footage shows banners with these norms posted prominently on walls around the IDEO workspace.]
>
> Deep Dive Designer: That's the hardest thing for people to do is restrain themselves from criticizing an idea, so if anybody starts to nail an idea they get the bell [designer rings a bell].

In this representation of the design process, the leader need only remind team members of the norms ahead of time and in the moment with his bell, and he expects them to comply. This means that team members are expected to know how to contribute to the discussion and check themselves within the group, which are social and emotional behavioral goals that Sandra (MO) stated above for her students. The cognitive behavior the leader expects from his team members is stated in the excerpt below. In this community of practice, it is clear that social, emotional, and cognitive performance happen together.

> Deep Dive Designer: Vote with your post-it not with an idea that's cool but with an idea that's cool and buildable. If it's too far out there and it can't be built in a day then I don't think we should vote on it.

The social roles that support the communicative actions in the Deep Dive emerge from within the group, as the following excerpts show. "A group of self-appointed adults" refocus the group's Deep Dive and stop the process of brainstorming and ideating because the designers are still engaged in the ideating process and the "adults" are aware that the group needs to build prototypes and arrive at a final design within a time limit.

The designers' use of the word "adult" is a reference to the demonstrably playful and fun atmosphere that encourages childlike creativity in the IDEO workplace. The social role of "self-appointed adult" emerges to move the whole group forward from an action step in which the group is happily absorbed, through the rest of the communicative actions of design. The culminating design is a combination of four previous prototypes. The communicative actions and communicative and social roles are aggregated by the designer into "an amazing team" dedicated to "pulling this [design task] off."

> Deep Dive Reporter: It is noon, worried that the team is drifting, what can only be called a group of self appointed adults under Dave Kelley holds an informal side session. Like it or not the team is told it will split into groups to build mockups covering four areas of concern that have been identified: shopping, safety, checkout, and finding what you're looking for.
>
> Deep Dive Designer: Yeah, that's because we have no choice but to stop that cycle [of brainstorming and ideating]. I mean if you don't work under time constraints you could never get anything done because it's a messy process that can go on forever.
>
> Deep Dive Designer: So, we took the best elements out of each prototype, designed this entire cart in a day, and then this cart was fabricated in a day with an amazing team of people in our machine shop pulling this off and working in shifts throughout the night.

The communicative actions and communicative and social roles in which the Deep Dive designers engage are intertwined in the video example, as they are in a classroom. However, it is their process for innovation – best defined in the communicative actions for engineering – that is the subject of the narrator's report. The designers communicate multimodally their joyful engagement throughout a process that is hard work. It is this joyful engagement with the design process and the participation structures that captivated the reporter and the teachers.

> Deep Dive Reporter: It wasn't this effortless, oh my god, so that's how it works thing that I saw there. It was actually hard work.
>
> Deep Dive Designer: It's a lot of hard work. We all love it so it doesn't look like hard work, but it's a lot of hours.
>
> Deep Dive Reporter: A lot of hours, also an open mind, a boss who demands fresh ideas be quirky and clash with his, belief that chaos can be constructive, and teamwork, a great deal of teamwork, and these are the recipe for how innovation takes place…

Sandra (MO) summarizes the teachers' perspective on the participation structures the teachers saw in the Deep Dive and reveals her hopes for her classroom norms.

> Sandra (MO): I'm hoping that we'll have more companies like that. That would be wonderful. So, there's a lot of cooperation happening in there, there's a lot of camaraderie, everybody seemed to support each other, no idea was ever put down, everybody felt as an equal no matter what their background was, and I know as a teacher we hope that happens in our classrooms, but we're human and we know that sometimes it doesn't, and for a 10 year old it takes a while for them to really learn that [to enact those norms]…

As an engineer who has worked as a designer in industry for many years, I am also captivated by the design process. For me, and for my professional colleagues described in the research literature summarized in Chapter 2, the object of design focuses our attention and energy outside ourselves. We know that the object we must design is too complex to design alone, and we know we must collaborate with others who have different knowledge and skill sets to accomplish the task. For professional designers like me and the designers in the Deep Dive, the steps of the design process are the matrix within which the communicative and social roles are navigated. This is reflected in the *cursory* attention I give the communicative roles of students and the communicative and social roles of teachers. Unlike the teachers, I spoke in most detail about the communicative actions of design, and only in broad terms about the communicative roles of students and how a teacher might enact her communicative and social roles.

> Ann McMahon: So, there needs to be some whole class discussion and then that should identify some questions or narrow a problem, and I might divide the class into design teams, and for a class of 25 I might have five teams addressing how to redesign the student desk, so each team would come up with a different prototype.

> Ann McMahon: And what problems they might be having, then that could focus the team on where they want to go with their redesign. So, after they talk to people then they have to generate, they have to share what they learned, so there's a share or communicate what they learned, and so that would be another maybe a whole class discussion; it would certainly be a team discussion. OK, so that would be a team discussion, a whole class discussion, and then that would also be a really good assessment point for me. So, I could ask each person on the team what they found out, who they talked to, who did you talk to, what questions did you ask, what did you learn…

> Ann McMahon: So, they've had a whole class discussion and then they generate ideas for the redesign, and again this is another assessment point, so if they're working as a team how are they going to capture all the different ideas that they came up with? So, we might have them draw on Post-Its and then post those on a chart like the people in the IDEO video did. They could also draw in their notebooks which is a little less interactive with their other team members, so draw in Post-Its, draw in the notebooks, but generate different ideas for the redesign, and then they need to come up with a team idea, a team idea that they'll develop further.

In the three excerpts above, I state cognitive tasks (define the problem, research the problem by talking to people, brainstorm solutions, choose a solution, create a prototype, and communicate their findings), I conflate that cognitive process with the social and emotional norms and processes (interview experts, work in large and small groups, one conversation at a time, defer judgment, reach consensus) that facilitate the accomplishment of the cognitive steps.

> Ann McMahon: If I were to teach a design course there really aren't any right answers; there are big process ideas that need to get communicated and those are spending a lot of time defining the problem, because how you define the problem really drives the kind of solutions you'll come up with, and so I would spend a lot of time in teaching critical thinking and critical questioning and the evaluation of

> information and how to go about choosing experts to talk to and what to do with the information you get from that, and then how to use the scientific method once you've started developing ideas of building prototypes. That's when you use the scientific method when you're evaluating how good your prototype is. Is it going to perform the way you would like it to? So, I would spend time teaching that process, teaching how to communicate, teaching how to communicate the design, teaching how to go out into the field and gather data and information and feedback about your design, and then how to turn that into a redesign. So, this is completely different than what I do when I teach the big ideas of science.

I presuppose that students can enact the collaborative communicative roles, as evidenced by these utterances I use: "they've had a whole class discussion," "they're working as a team," and "they have to share what they've learned." My nod to the pedagogy of communicative roles is "I would spend time teaching…how to communicate." By "how to communicate", I mean the cognitive engineering process of a design review in which team members present their design to others for formal critique (as described in Chapter 2). In transforming the design experience to the elementary classroom, I default to norms of communication I have experienced in an engineering community of practice. As both groups of teachers indicate, these norms do not exist in their classrooms; they must work with their students to create an environment with such norms.

Emergent Similarities and Differences in Participant Discourse: Social Knowledge and Beliefs

There are social knowledge and beliefs that engineers use that, when teachers interpret them from the classroom perspective, are not transformed effectively for student learning in engineering. Figure 5 shows a comparison among both teacher groups and the engineers of how many times we mentioned the shared and social knowledge and beliefs of design engineers as shown in the Deep Dive (see Table 7 for the coding categories).

Figure 5 shows the percentage of utterances for seven subcategories within the shared knowledge and beliefs category compared by group, with me and the designers in the Deep Dive combined to form a group.

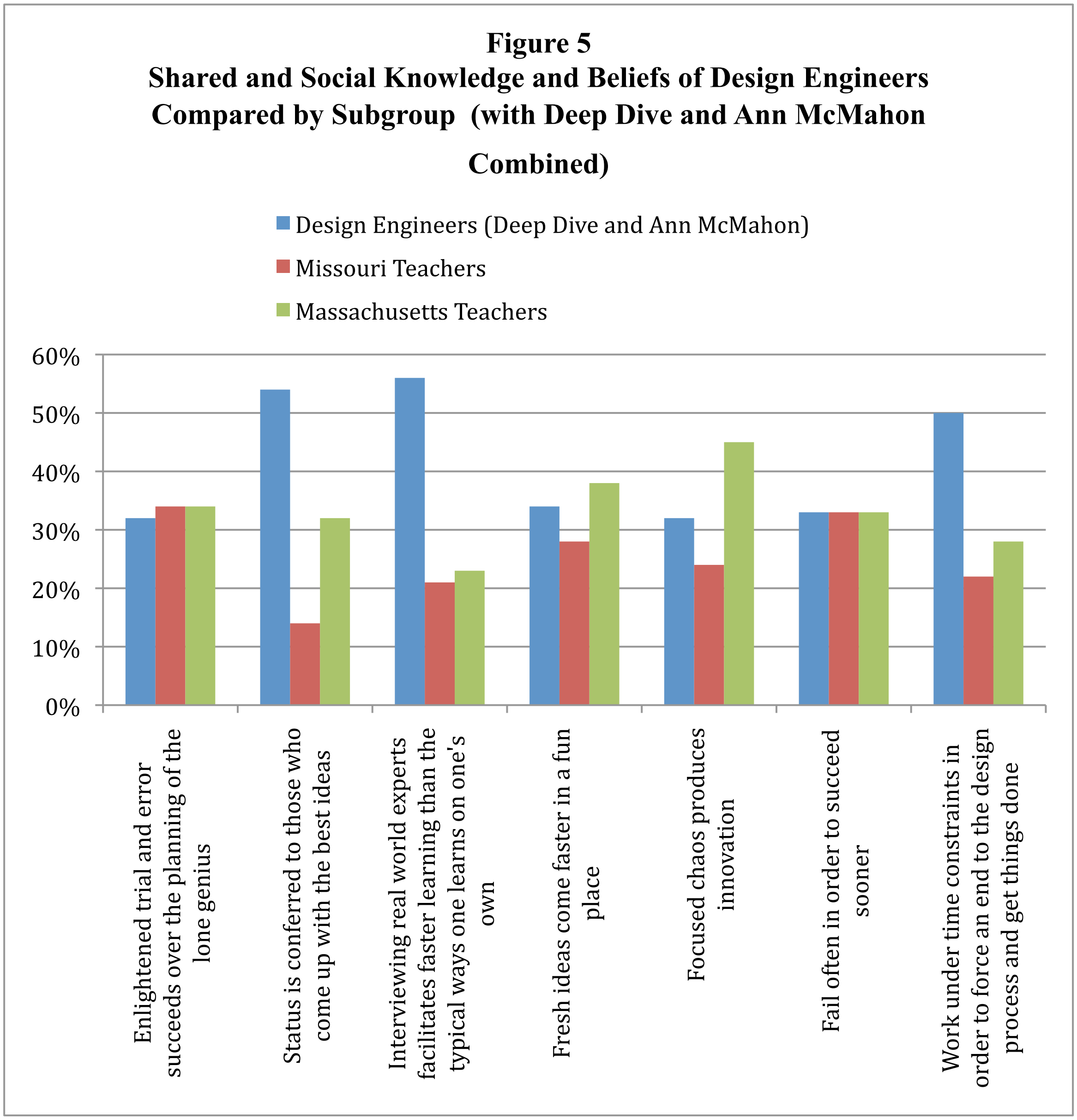

Figure 5. Shared and Social Knowledge and Beliefs of Design Engineers Compared by Group (with Deep Dive and Ann McMahon Combined)

This figure shows that both groups of teachers as well as engineers spoke equally often about enlightened trial and error, fresh ideas, and failing often to succeed sooner. The Massachusetts teachers spoke more often than the Missouri teachers about focused chaos, because some experienced this with their students while teaching the design process in the LEGO units. Teachers spoke less often than engineers about status conferred to those with the best ideas because, as Jody (MA) stated, she does not get to choose her students and they come with different strengths and abilities. She works to develop the strengths and abilities of all her students equally. Teachers also spoke less often about working under time constraints to force an end to the process. Both groups of teachers addressed time limitations for each unit as a whole rather than for each step within the design unit.

Engineers mentioned working with outside experts to address a design solution more often than either group of teachers did. The Deep Dive designers and I spoke in detail about how to decide what experts to consult and the questions to ask them. This illustrates the shared beliefs in engineering communities of practice that engineers value information accessible through outside experts and that consulting with experts outside the design group is an important and indispensable part of the information gathering process. I indicated that as a teacher, I would spend time teaching students how to decide who makes a credible source of information, how to formulate useful questions, and how to incorporate interview information into a design.

> Deep Dive Designer: In corporate America many bosses measure whether their people are, you know who the good people are or the people who are performing, or the ones that they see at their desk all the time. They couldn't be further from the truth; the people who are really getting the information are out here talking to the Buzzes [a store worker who maintains shopping carts] of the world, going to meet other experts – much more useful than sitting at your desk.

> Deep Dive Designer: The trick is to find these real experts so that you can learn much more quickly than you could by just kind of doing it the normal way and trying to learn about it yourself.
>
> Deep Dive Designer: People [the designers] went off into the four corners of the earth and they're coming back with the golden keys to innovation. Each team is going to demonstrate and communicate and share everything that they've learned today.

The three excerpts above emphasize the importance designers place on speaking to people who work directly with the designed object – the shopping cart. It is "more useful than sitting at your desk," quicker than "trying to learn about it yourself," and interviewing experts contains "the golden keys to innovation." These are strong value statements in this community of practice. In the excerpts below, I frame my entire transformation of the Deep Dive to the classroom around a design problem (student desk) that guarantees the presence of experts that students can interview within the school setting. I also acknowledge that I would need to teach students how to decide who to ask, what to ask, and how to apply what they learned in their design process. This shows that I, in my identity as an engineer, also highly value the input of experts who work with the designed object, and that this value translates into my identity as a teacher.

> Ann McMahon: And I would probably choose something that can be found in the school so that we would have access to it and we would have access to people who buy them, so that would be maybe the district's or the school's facilities people and the people who repair them, so, you know, we might talk to custodians. So, let's say we're working with a student desk. So, the principal, the custodian, the teacher, and then I might have the person who chooses what kind of student desks to buy. I don't know who that is in the district but I would find that out and then invite that person to come and allow the students to interview them. So, the students would have to look at all different ways that student desks are interacted with at school, and they would gather some information about what each of those people (students, teachers, principal, custodian, the person who buys them), what's important to them, so I would have them ask what is important to you about student desks and start there and learn as much about them as they can.

> Ann McMahon: So, after they talk to people then they have to generate, they have to share what they learned… and then that would also be a really good assessment point for me. So, I could ask each person on the team what they found out, who they talked to, who did you talk to, what questions did you ask, what did you learn…I want them to be keeping design notebooks as they were doing these interviews so I could check their design notebooks.
>
> Ann McMahon: So, now we have five teams, each with a different design, so then I would have all teams present to each other, or I might have each design team take their design to the people they interviewed for feedback.
>
> Ann McMahon: I could look at the sources they chose to consult outside of the school or on the Internet, so have them do some critical thinking about who to ask and why and rather than just bringing information in from anybody, you know, why do we ask the people we ask, and how do we determine who will be credible people to give us information?
>
> Ann McMahon: So, I would spend time teaching that process, teaching how to communicate, teaching how to communicate the design, teaching how to go out into the field and gather data and information and feedback about your design, and then how to turn that into a redesign. So, this is completely different than what I do when I teach the big ideas of science.

Conversely, teachers in both groups acknowledged the need to access experts for students to consult, and gave *cursory* attention to interviewing experts as part of the research process.

> Sandra (MO): Well, science is of course observation. You've got analyzing the data; they [the Deep Dive designers] actually went out and they took pictures and they were looking at wow, this is what we saw as far as safety, this is what we saw, so they were analyzing what they had seen and what they had observed. Some of them may have drawn some sketches, I think that they did and they were analyzing their sketches.
>
> Valerie (MO): So something I could probably do was to tell them [her students] that we would like to make crystals because we're talking about the rock cycle and how those things form, and if they were following the process of the video they would have to research what are the best ways to make crystals, what are the best materials that I'm going to need? So that would involve maybe looking in books, looking things up on the internet, maybe asking other people have you ever made crystals and what did you use, and then maybe trying to get them to take the ideas or the things that they read and adapt it and change it…

Sandra (MO) and Valerie (MO) made nonspecific comments about observing in the field and asking experts. Lillian (MO) wondered below about experts she and her students might know in their community for whatever design unit she might construct, while Lenora (MA), and Ellen (MA) identified what Deep Dive designers did without transforming it to their classrooms.

> Lillian (MO): Well, they'd [her students] go to the internet, the library…I always bring in, no matter what we're studying, I bring in tons of resources…and then they would probably make lists. Well who could we ask…who would be an expert in this, who could we call, who could we talk to, and of course they have their parents they could interview and then other people that we could get to come in. I could have people come in and they could ask questions…
>
> Lenora's (MA) Notes: Talk with those who build carts – find out issues from experts
>
> Ellen (MA): I mean I think they [the Deep Dive designers] did that; they went out and they went to the supermarkets and they took pictures and they kind of did a data collection of their own, you know, because they were getting data from other people, so I mean I think that there would have to be some sort of research part of it [the unit she would design for her students].

Ruth's (MA) and Jody's (MA) comments below reflect their recognition that interviewing outside experts is important but their ability to give their students field experiences like the ones they saw in the Deep Dive is constrained by their school settings.

> Ruth (MA): …but we [her students] talked about it, we put all our ideas on the board, we do some research, now they [the Deep Dive designers] went to, that would be nice to actually go out and actually talk to people about how does this shopping cart or whatever work, but we [her students] just did research online, so…
>
> Jody (MA): So, that was something that was going through my mind but the process was definitely the engineering design process which is you research your idea which they [the Deep Dive designers] did, and I just thought oh, if I could do that with my kids that would be so fun, but we have to pay for buses, we have to get permission, we have to…so I just keep thinking this [the process she saw in the Deep Dive] is so contrary to the school paradigm… Then I thought they'd [her

> students] need to have interviewing skills if we really did get to go out in the real world and really do that…

These teachers' comments reflect their limited resources to allow students do the kind of direct interviewing that designers in the Deep Dive do. Furthermore, designers' use of information from outside experts serves a nuanced purpose that teacher comments do not capture, perhaps *because* of teachers' limited resources: contextualizing the problem or need and defining the solution space in which the brainstorming process will occur. When engineers talk to role-alike experts or cross-disciplinary experts or end users of the designed object during the research phase, they narrow and contextualize what the designed object must do. My comment about asking a list of outside experts what is important to them about a student desk is evidence for this shared belief. Dave Kelley, one of the self-appointed adults in the Deep Dive, is emphatic about interviewing key people for their perspectives, and a designer expresses a deal-breaking design specification that emerged from their interviews:

> Dave Kelley: You have to designate some people to make damn sure that the store owner's point of view is represented.
>
> Deep Dive Designer: It's more nesting [when one shopping cart fits inside another so that they take up less space than when they are positioned one behind another], it [the redesigned shopping cart] sort of has to nest; if it doesn't nest we don't have a solution.

The responses of both groups of teachers indicate that they view the research action in engineering like the research action they teach in science: gather existing information about the objects or phenomena that students are studying. That approach makes sense in the context of teaching school science. In school science, students are investigating objects and phenomena that already exist and for which information already exists. It is possible to gather information that has been generated by others as well as through first-hand observation. In their context-setting comments, all of the teachers indicated that they use instructional materials with which students investigate objects and phenomena in this way. For example, it is possible for a student to gather and summarize information about the life cycle of a butterfly, observe the life cycle of a specific butterfly, and produce an account that agrees with the scientifically accepted explanation of the butterfly's life cycle. The research action in the context of elementary school science supports this kind of learning.

In engineering, that approach to research does not work because both professional and student engineers bring into existence something that did not previously exist. Therefore, the research action for engineering is focused on gathering information about how the designed object has been used, will be used, by whom, and what it needs to do. Some experts will have information about how an existing designed object, like the shopping cart, is used and what are the existing design's affordances and constraints. Experts who have a need for a designed object that does not yet exist will have information about what the object needs to do. Experts who manufacture and maintain designed objects will have information about affordances and constraints of production methods and materials. Such information serves to *inform* the next design, not determine it. There are many possible solutions for a given design challenge. The "correctness" of a design solution is determined by criteria set by the posers of the design challenge and/or the feedback of the users. Correctness equates to usefulness in engineering. Designs that were once embraced by users become obsolete as new designs with more appealing form and functions take their places. The evolution of the portable and personal music-playing device is a case in point. That device has evolved from boom boxes carried on shoulders to mp4 players clipped to shirtsleeves. At the time they were heavily used, every one of the music-playing devices in that evolutionary line was useful. Now, not all of them are manufactured anymore – kept in production or retired to museums based on user demand.

Summary of Answers to Research Questions 2 and 3

The mental models of all teacher participants included the subcategory codes in the Communicative Actions for Engineering that described the steps in an engineering design process. The Massachusetts teachers spoke about the steps with awareness that the engineering steps constituted a cyclic process, and, in some cases, referred to a global design process. Five of the six Massachusetts teachers referred to a poster, provided by Tufts, that depicts the engineering design process. The Missouri teachers were able to name and describe the steps based on what they observed designers doing in Deep Dive referent video. These Communicative Actions for Engineering constitute the cognitive part of the design process. While both groups of teachers recognized these cognitive steps, they spoke more about the social and emotional parts of the engineering process defined by the Communicative Roles of Students, Teachers, and Designers in the Deep Dive. In teachers' transformation of the design process to the classroom, they set the steps of the design process into a larger context of establishing classroom norms like those depicted in the Deep Dive. The only difference in how each group of teachers privileged the social and emotional aspects of the design process is that the Massachusetts teachers could provide examples specific to enacting the steps of the design process in their classrooms. The Missouri teachers mentioned the identical concerns, contextualized to their science teaching.

Within the cognitive part of the design process steps, both groups of teachers missed an important interpretation and transformation of the research step: interviewing outside experts in order to better frame the challenge designers would solve. Within the social and emotional matrix, Massachusetts teachers emphasized the social roles of one conversation at a time and building on the ideas of others, while Missouri teachers emphasized large and small group work, as shown in Figure 4. It is reasonable to connect the Massachusetts teachers' classroom engineering experiences with their emphasis on these communicative roles over more generic group work roles. Teacher discourse in both groups indicates that they want to teach students to defer judgment and value all ideas. (Teachers also spoke about the practice of evaluating idea quality to confer status on a given project as contradictory to valuing all ideas and considering students equally.) Design engineers consider these two processes differently: the brainstorming step is divergent thinking while the evaluation step is convergent thinking. Both are necessary to accomplish the design task, and designers will gain status by turns according to their personal strengths and the nature of the design problem. The designers assume that the team members will reach consensus on the best idea.

There were far more similarities both within and between groups than there were differences. The differences were minor, based on teacher experience with engineering curriculum, and have been described above. The key finding is this: ***both groups of teachers embedded the cognitive steps of the design process into the matrix of the social and emotional roles of students. Conversely, the Deep Dive Designers and I embedded the social and emotional aspects of the design process into the matrix of the cognitive***

steps of the design process. This finding sends a message to curriculum developers and professional development providers. I will expand upon that message in the next chapter.

CHAPTER 5: Key Findings and Conclusions

The Intersection of Professional Engineering and School Engineering

Professional engineering and school engineering intersect in the communicative actions for engineering. See Figure 6.

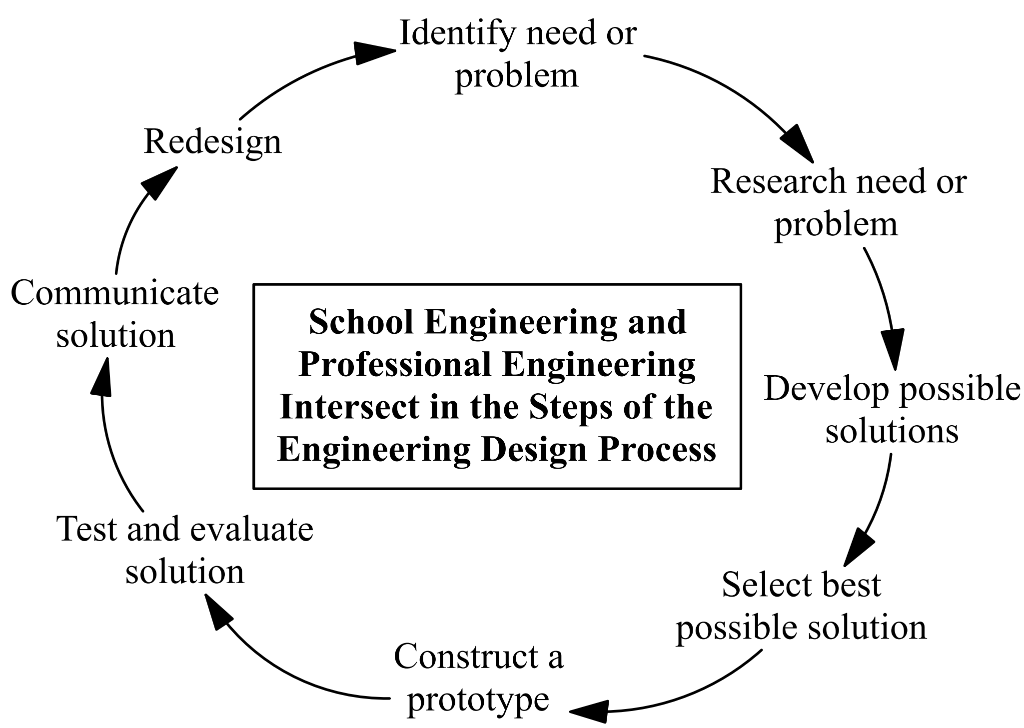

Figure 6. The Design Process: the Intersection of Professional Engineering and School Engineering

Professional engineers are invested in complex design challenges requiring the skills of many engineers so that they willingly navigate communicative roles in order to reach a design solution. Recall the perspectives of the many types of engineers in Figure 2 on page 34. The engineer representing each group in the cartoon must collaborate with all the others who have competing priorities in the process of designing an airplane. They need one another in order to succeed. Engineers also realize that useful information exists outside the design team, in experts of other disciplines and colleagues with similar roles who have had experiences relevant to the design task at hand. Furthermore, engineers who enjoy the design process are motivated to engage in it *in spite of* communicative and social roles that might be difficult for them. Thus, in my analysis, the engineering design process is the matrix within which communicative roles and shared social knowledge and beliefs work in engineering communities of practice.

This is not the case in elementary education communities of practice. Many engineering curriculum developers have students work with materials such as LEGOs and K'Nex that are intended to engage elementary students. Indeed, the Massachusetts teachers in this study reported that students enjoy working with LEGOs, and teachers from both states reported that students find such inquiry-based science engaging. Engineering curriculum developers, in order to mimic collaborative conditions in professional engineering, also specify that students work in pairs or groups to solve the design challenges. They are unlikely to formulate design challenges that require students to seek expertise outside the classroom setting because there is no consistency of resources available to all schools that might adopt the curriculum. However, this study ***dispels*** the assumption embedded in many curricula that students will embrace engineering communicative roles when working with these materials and design challenges, and that teachers will figure out how to manage the social and emotional classroom dynamics so that the cognitive part of the engineering learning takes place. The low level of complexity of most design challenges precludes the *need* for many diverse skill sets to solve them. Furthermore, students who have experience building with materials such as LEGOs or K'Nex are likely to have built many things on their own without a partner or group. Even those for whom these building materials are new can experience success building without help because the materials themselves are designed to be child-friendly. The conditions that motivate professional engineers to enact communicative roles and shared knowledge and beliefs for collaboration do not transform directly to elementary school engineering. Teachers must actively manage and facilitate the communicative roles of students through their own social and communicative roles. They must also work within the constraints of their school and community settings when considering whether and how to facilitate students' interactions with outside experts. As both groups of teachers revealed in their discourse, this focus on communicative roles of students becomes the matrix within which the engineering design process happens in education communities of practice.

Combining the Strengths of Teachers and Designers: Key Findings

Research in child development combines the antecedent cognitive, emotional and social competencies that signify school readiness into constructs called executive functions (National Scientific Council on the Developing Child, 2011). Executive functioning is defined along three dimensions: working memory, inhibitory control, and cognitive or mental flexibility.

> Working memory is the capacity to hold and manipulate information in our heads over short periods of time…Inhibitory control is the skill we use to master and filter our thoughts and impulses so we can resist temptations, distractions, and habits and to pause and think before we act… Cognitive or mental flexibility is the capacity to nimbly switch gears and adjust to changed demands, priorities, or perspectives. (p. 2)

Executive function skills are the precursors for the kind of social, emotional, and cognitive skills students need to be successful in school and in life. The neurobiological circuits for executive function skills are formed in the years of life before formal schooling begins. While executive functions develop throughout the K-12 years, a student's neurological substrate is set before s/he enters kindergarten (Damasio, 1999; Fonagy & Target, 2005; LeDoux, 1989; National Scientific Council on the Developing Child, 2007, 2011; Perry, 1999, 2007, 2008; Perry & Bender, 2004; Perry & Hambrick, 2008). To change neurological circuits underlying executive functions and therefore, cognitive, social and emotional competencies requires practice. Missouri and Massachusetts teachers spoke in detail about how much practice this takes. Today's cognitive oriented school culture, as well as the professional designers and I, privilege the cognitive competencies involved in teaching and learning the engineering process. The teachers' comments excerpted above reveal that the pervasive social and emotional challenges in the classroom have the potential to impede students' abilities to attend to the cognitive processes.

The system model in Figure 7 shows relationships among the cognitive categories of shared and social knowledge and beliefs and communicative actions, and the social and emotional categories of communicative roles enacted by Deep Dive designers, students, and teachers. The model includes executive functions in order to encompass participant teachers' concerns about the social and emotional aspects of teaching engineering to elementary school students. This visual representation maps my path of reasoning to the main finding of this research: ***Teachers' mental models show that they perceive that students' social and emotional communicative roles in the classroom***

drive their cognitive understandings of the engineering process, while my engineer's mental model shows that I perceive that students' cognitive understandings of the engineering process drive their social and emotional roles in the classroom.

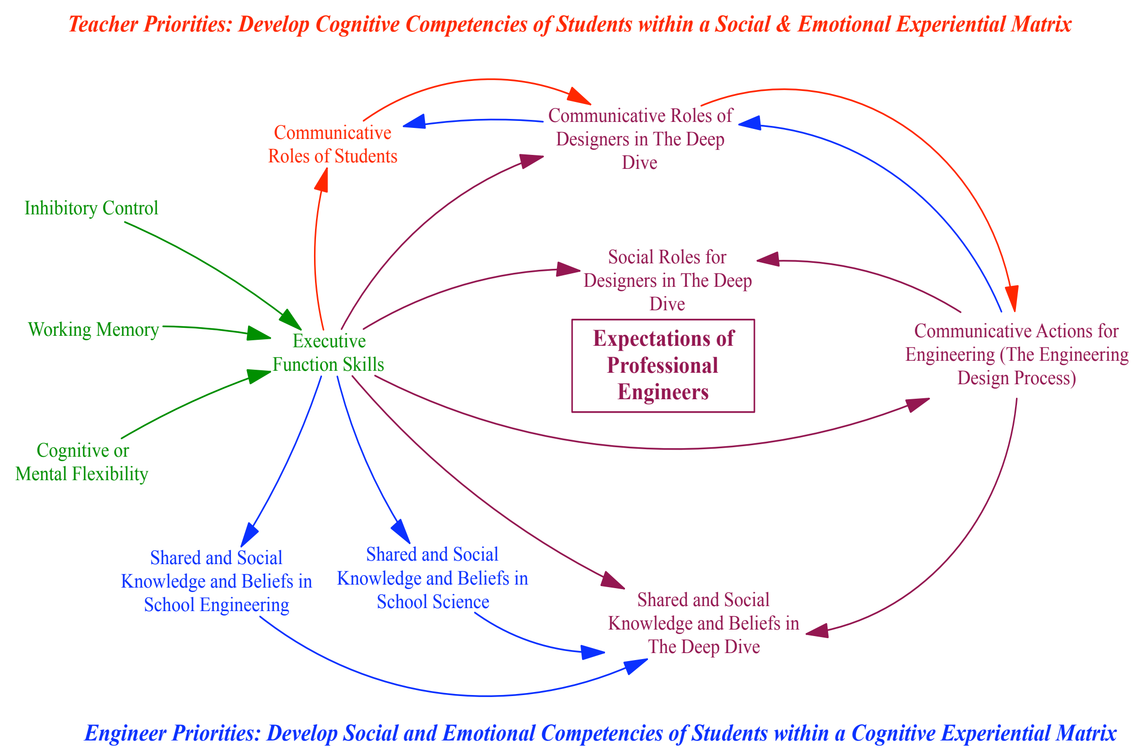

Figure 7. Representation of the Influences Among Communicative and Social Actions, Roles, Knowledge and Beliefs and Executive Function Skills

The arrows indicate relationships between the constructs they connect. The colors indicate student competency priorities shared by both engineers and teachers (green and purple), student competencies prioritized higher by teachers (red), and by engineers (blue). Read from left to right, the arrows connecting inhibitory control, working memory, and cognitive or mental flexibility to executive function skills indicate that they are the components of and influence executive function skills. Their green color indicates that executive function skills are important for all students, whether or not they pursue engineering. The red arrow connecting executive function skills and communicative roles for students indicates that student executive function skills influence their social and emotional communicative roles. The red color indicates that this connection was prioritized by teachers. The blue arrows connecting executive function skills and shared social knowledge and beliefs for school science and for school engineering indicate that student executive function skills also influence their cognitive shared and social knowledge and beliefs for both school science and engineering. The blue color indicates that these connections were prioritized by engineers. The purple arrows connecting executive function skills to communicative roles, social roles, communicative actions, and shared and social knowledge and beliefs for designers in the Deep Dive indicate that executive function skills influence social, emotional and cognitive roles, as well as knowledge and beliefs of professional engineers. The purple color indicates that both teachers and engineers recognize all of these as common goals for students in school engineering. The purple arrows leading from communicative actions for engineering to social roles and shared knowledge and beliefs in the Deep Dive indicate that both teachers and engineers recognize that the engineering process steps influence the social roles and shared knowledge of professional engineers. The red arrows connecting executive function skills to communicative roles of students to communicative roles of designers in the Deep Dive to communicative actions for engineering indicate teachers' perceptions that students' cognitive communicative actions are influenced and achieved primarily through the social and emotional communicative roles as exemplified by designers in the Deep Dive. The blue arrows connecting communicative actions for engineering to communicative roles of designers in the Deep Dive to communicative roles of students indicate engineers' perceptions that students' social and emotional communicative roles are influenced and achieved primarily through communicative actions and roles as exemplified by designers in the Deep Dive. ***In other words, teachers' mental models show that they perceive that students' social and emotional communicative roles in the classroom drive their cognitive understandings of the engineering process, while my engineer's mental model shows that I perceive that students' cognitive understandings of the engineering process drive their social and emotional roles in the classroom***.

Interpretation of Key Findings

Shulman (2005) provides an interpretive frame for the results stated above in his study of "signature pedagogies" of the professions of law, medicine, engineering and the clergy (Shulman, 2005). He studied these professions because the programs that prepare future practitioners have defining, or signature, features that are consistent across teaching institutions – i.e. clinical rounds in medicine, the argument of both sides of a case in law, and establishing the boundary conditions of a problem in engineering. He found that in the educational preparation for these professions, teachers teach and students learn in ways that are "habitual, routine, visible, accountable, interdependent, collaborative, emotional, unpredictable, and affect-laden" (p. 12). Shulman further parses these characteristics of signature pedagogies into "pedagogies of *uncertainty*, pedagogies of *engagement*, and pedagogies of *formation"* (p. 13). The pedagogy of uncertainty addresses the condition that students and practitioners in these fields rarely have all the information they want or need in order to choose a course of action, yet they must act. The pedagogy of engagement refers to the condition that students and practitioners in these fields must participate visibly, accountably, interdependently, and collaboratively in order to practice the profession. In other words, one cannot lurk as a student or practitioner in these professions. Shulman's words about the pedagogy of formation speak directly and compellingly to the key findings summarized above:

> I mean "formation" now in the theological seminary sense, or the religious education sense. They are pedagogies that can build identity and character, dispositions and values. They teach *habits of mind* because of the power associated with the routinization of analysis. But I think in a very deep sense they also teach *habits of the heart*, as well, because of the marriage of reason, interdependence and emotion. (Shulman, 2005, p. 13)

The teacher participants noticed and privileged "habits of the heart" in transforming the signature pedagogy of engineering to their classrooms, while I privileged "habits of mind." My training and professional experience as a practitioner of the engineering profession has shaped my identity, disposition, character and values to make certain "habits of the heart" implicit in my practice in the engineering community. As I transformed what I saw in the Deep Dive to classroom practice, these "habits of the heart" noticed by teachers and exemplified in the communicative roles of Deep Dive designers remained implicit for me. I did not perceive the need to teach them explicitly. My findings indicate that an authentic transformation of the signature pedagogy of engineering to the classroom must include pedagogies of uncertainty, engagement, and formation. Furthermore, the pedagogy of formation must address habits of mind ***and*** heart.

In my training and professional practice as a science and engineering educator, I have focused on developing students' "habits of mind" as exemplified in the communicative actions for science and engineering. The engineering literature reviewed in Chapter 2 and the design process shown in the Deep Dive illustrate the challenge of uncertainty in design pedagogy and in professional practice. The education literature includes many different lines of research on student engagement in general and for science, specifically. Many studies exist of project-based and design-based learning that focus on participant structures in the form of student roles, activity structures for project-based learning, and rituals and practices for design-based learning as a means of engaging students to learn science (Herrenkohl, 1998; Kolodner, Camp, et al., 2003; Kolodner, Gray, & Fasse, 2003; Pohlman, 2004). Perhaps a synthesis of those lines of research might yield a pedagogy of formation for K-12 science and engineering. I know of no studies that address the interrelation of the communicative roles and actions and shared knowledge and beliefs of engineering through the lens of a pedagogy of formation as Shulman defines it. My key findings highlight the need for the construct of pedagogical formation to be included in the pedagogical bridge built between engineering and K-12 education communities of practice. As a legitimate liminal participant in both communities of practice addressed in this research, I see the need for future research that unpacks this marriage of reason, interdependence, and emotion in the communicative roles and actions and shared knowledge and beliefs involved in teaching engineering in the elementary classroom. The recommendations that follow are based on the key findings presented above, with acknowledgement of the limitations of this study and the need for future research.

Research Question 4

What implications do these mental models have for designing curriculum and professional development in elementary engineering education? The limitations of this study preclude generalizing these findings to all elementary teachers and all engineers.

Nonetheless, if we regard the production of school engineering curriculum and professional development for teachers as true design activities (Edelson, 2002), then the findings here provide valuable information to inform the next iterations of school engineering curriculum and teacher professional development. Based on my findings, I recommend the following:

Recommendations for Curriculum Development:

1) Formulate design challenges for which it is necessary or highly advantageous to gain expert or user input.

The objectives of this recommendation are to move beyond simple performance criteria for the designed object and to introduce students to a different goal of research: to empathize with a user in order to further define the problem or need and the specifications for viable solutions. This also allows teachers to reinforce the social and emotional skills associated with empathy and perspective-taking. This supports the inhibitory control and cognitive flexibility dimensions of executive function skills.

2) Formulate design challenges that require a) multiple students and/or groups to collaborate to produce a single complex object featuring multiple subassemblies that do not operate independently or b) multiple independently operating designs that combine to form a complex interdependent system.

The objective of this recommendation is to create an authentic need for students to work collaboratively and to think about the system in which their design will operate. This kind of teamwork is more than assigning roles, objects or tasks to teams and team members; it is intended to create cognitive, social and emotional interdependence among and within work groups, without which the whole class design will not be successful.

The airplane in Figure 2 on page 34 is a real-life example of a single complex object featuring multiple subsystems. Multiple teams must design pieces of the airplane that do not operate independently. The teams must work together to make sure all their subsystems come together to make an airplane that flies. A school example of this might be a robot that moves about, climbs over obstacles, and tosses a ball into a basket. FIRST Lego League offers design challenges like this.

As an example of the second system, Ruth (MA) showed me an amusement park that her 6th grade students designed and built. An amusement park is an example of multiple designs that can operate independently and are joined to form a more complex, interdependent system. Ruth (MA) waxed effusive about the creative ways her students collaborated:

> This is the amusement park, right, so they'd be talking to each other how much space do you need, you know, what else do you need, where should we put it? So, there was a group that did that, and then there was another… Most of the groups made rides but then they would talk to other people around them to see if they could have like walls in common or share resources…One group made the teacups that not only spun in a circle but each little teacup also spun around…One group went around and did signs. I don't know if you can see it from here, but it's a teacup sign. They took tinfoil and they put it on little bushings like this and they stuck it into to a beam, so it said teacups in tinfoil. So, we had a group that did signs, we had a group that arranged everything, you know, where it was going to be positioned. We had a lot of people that were just building amusement rides…The things they can do, the heights they can reach, it's just they were amazing…I mean it was just, it was a wonderful experience.

3) Scaffold teacher ability to enact engineering curriculum by including a multimedia facilitator's guide or section for each engineering unit that makes explicit the engineer's mental models for enacting the engineering design process.

The facilitator's guide is designed to enhance and support the teacher's engineering content knowledge (CK), pedagogical content knowledge (PCK), metastrategic knowledge (MSK), and pedagogical design capacity (PDC). The CK, PCK, MSK and PDC for school engineering are distinctly different from those of school science for one overarching reason: in school science, students are investigating objects and phenomena that exist; in school engineering, students are creating objects and phenomena that do not yet exist. In the process of creating designed objects, students (and teachers) have the opportunity to use the science knowledge and skills they have learned. It is unreasonable to assume school engineering to be similar to school science and to expect teachers to possess CK, PCK, MSK or PDC for a school engineering process that is distinctly different from school science.

Recommendations for Teacher Professional Development

1) Incorporate social and emotional facilitation skills for the elementary engineering context into engineering professional development for teachers.

Many schools participate in one of several nationally recognized school climate/character education programs and/or implement other prosocial curricula (Center for Character & Citizenship; National School Climate Center). Align engineering curriculum with these programs and integrate their implementation strategies into the school engineering context. Help teachers in faith-based school settings integrate their community's communicative norms into engineering units. This supports the inhibitory control and cognitive flexibility dimensions of executive function skills.

2) Make explicit the cognitive and metacognitive features within each communicative action for engineering and each communicative role of professional engineers. Demonstrate in context how they influence one another and how they

unfold in the course of a unit. Demonstrate how they can be formally and informally observed and assessed.

The school engineering process is messy, nonlinear, iterative, and different from the school science process. The engineering process is characterized by the management of uncertainty and ambiguity as well as convergence and divergence in thought and action. Steps in the design process may need to be repeated and/or performed out of order depending on circumstances within the process. Correctness of a design is achieved through performance criteria and feedback from users. Help teachers understand how to fit these conditions into structured school settings.

3) Incorporate the characteristics of a creative, innovative, and joyful design environment into professional development in ways that transform directly to the classroom.

Teachers in this study noticed and valued the following characteristics in the environment depicted in the Deep Dive:

- Enlightened trial and error succeeds over the planning of the lone genius
- Status is conferred to those who come up with the best ideas
- Interviewing real world experts facilitates faster learning than the typical ways one learns on one's own
- Fresh ideas come faster in a fun place
- Focused chaos produces innovation
- Fail often in order to succeed sooner
- Work under time constraints in order to force an end to the design process and get things done

Several teachers shared strategies they use to create one or more of these conditions in their classrooms. Collect and share teacher-proven strategies that can comprise a pedagogy of formation. Conduct rich case studies of students and teachers enacting engineering in ways that exemplify the findings and frameworks articulated in this dissertation so that the strategies and conditions for effective implementation can be described.

Researcher Reflections and Implications for Future Research

I have enjoyed multi-year careers as a practicing aerospace engineer, as a practicing elementary school science teacher and K-12 district science coordinator, and as a professional developer of K-12 teachers. My experiences in the engineering and education communities of practice allow me to position myself for this research at the borders of both as a legitimate liminal participant (Penuel & O'Connor, 2010). I have deep, implicit and explicit knowledge of both communities of practice that I have synthesized through conducting this research. In searching for a representation of the engineering design process to show to teacher participants, my experiences as an engineer enabled me to recognize the Deep Dive as a representation that rang true both with my own experience and with the literature on what engineers do and how they do it. I recognized that the authenticity in the Deep Dive video extended beyond just the cognitive engineering design process steps, and portrayed what makes engineering practice fun and engaging – the social and emotional aspects of the practice. I did not realize when I chose the Deep Dive that the social and emotional aspects of engineering design practice would dominate my findings as they have. I am surprised and delighted by that. It has made explicit what has heretofore been implicit about my enthusiasm for and commitment to inspiring the next generation of scientists and engineers – that engineering work is deeply engaging and satisfying not only cognitively, but socially and emotionally as well. In fact, my findings show that the social and emotional aspects of engineering education should be addressed simultaneously if students are to learn the cognitive content. In other words, if students cannot engage socially and emotionally with the design task, it is unlikely that they will attain cognitive mastery and produce a design that meets criteria for success. I have brought this implicit engineer's mindset to my work in education all along; I consider teaching and professional development design activities with all the opportunities for cognitive, social and emotional engagement that my professional engineering design challenges held.

Van Dijk's (2008) theoretical frame was comprehensive enough to go beyond the cognitive repertoire of ways of doing things that the community of practice literature emphasizes, and the schema-based procedures that the mental model literature describes. Van Dijk's coding paradigm allowed variables to emerge as coding subcategories that encompass cognitive, procedural, social and emotional enactments within the context of both communities of practice contained in the discourse. This produced more nuanced coding subcategories that allowed for a much finer grained analysis. It was a surprise to me that I had to enlarge my expected unit of analysis to the subcategory level rather than the lexical and syntactic level within subcategories. However, my pursuit of the broader story in the data produced findings that can inform future research into effective elementary engineering curriculum and professional development at that level and at finer-grained units of analysis. These findings can and should invite research questions that address the interrelation among cognitive, social and emotional learning in engineering.

I intend to consider using van Dijk's method in future research studies. However, the language he uses to describe his main categories of mental/context models is unwieldy and needs customization to the domain within which the research takes place. I recommend renaming and defining the main categories to make their meaning more transparent to the reader. For example, in van Dijk's main category of Communicative Actions, I chose to add the words "for Engineering" and "for Science" to create two separate main categories and keep his original category name (see Table 3). However, in future studies, I would change van Dijk's main category of Shared and Social Knowledge and Beliefs to something less wordy and cumbersome and more specific to my study. For this study, I simply added the words "in School Engineering" and "in School Science" to create two separate categories. Because I chose to preserve all of van Dijk's main category names by adding language that references engineering, science, school, teachers, students, and the Deep Dive (see Table 3), I intentionally labeled my subcategories with language that engineers and educators understand and that enable them to infer the meaning of van Dijk's main category from them. His main categories are malleable enough to be expanded effectively at the subcategory level with one exception. I recommend expanding his main category called "setting" into multiple main categories that include cultural, physical, and institutional settings.

Conclusion

The Deep Dive represents the signature pedagogy of engineering and provided participants in this study an opportunity to transform what they saw in the Deep Dive to their own elementary pedagogical practice. Participants' mental models, generated from van Dijk's framework, revealed key differences in what is privileged by practitioners of design engineering and by practitioners of education. These practitioners in the engineering and education communities of practice agree on the engineering process – the steps that need to happen in order to produce a designed object. This study reveals the need for explicit and intentional instruction of students in how to have the contextualized human interactions necessary to enact those steps. The interpersonal and interdependent norms in the engineering community of practice necessitate that their transformation to the elementary education community of practice include integrated cognitive, social and emotional instruction – habits of mind ***combined*** with habits of the heart.

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APPENDICES

Appendix A:Teacher Survey – Textbook and Kit Users

Teacher Survey – Textbook and Kit Users

I. Contact Information

Name: ____

District: ____

School: ____

E-mail Address: ____

II. Background Education/Classroom Information:

1. Degrees

Please indicate the degrees you have earned and indicate in which field (e.g., English Literature, Mathematics, etc.)

☐ Bachelors

(Field____)

☐ Masters

(Field ____________________________________)

☐ Doctorate

(Field____)

If you have teacher licensure, what grade levels are you licensed for?

____

What type of program best describes your teacher preparation program or teacher certification program?

☐ Undergraduate ☐ Emergency Route

☐ Graduate ☐ Other

____

☐ Alternate Route

What best describes your science experiences in academia?

☐ Science Major ☐ Took science classes beyond requirements

☐ Science Minor ☐ Took required science classes only

☐ Took no science classes ☐ Other ____________________________

2. Teaching Experience

Grade level currently teaching: ____

Grade levels previously taught: ____

Years Teaching (total):

____

Years teaching current grade level: ____

3. Other Professional Experience

Have you had other work experiences besides teaching? ☐ Yes ☐ No

If you answered yes above, please describe your non-teaching work experiences.

____

____

____

Have you had work or recreational experiences with design and/or engineering?

☐ Yes ☐ No

If you answered yes above, please describe your experiences with design and/or engineering. ____

____

____

4. Subjects in Classroom

Please indicate all subjects you are currently teaching in your classroom.

- ☐ Science
- ☐ Mathematics
- ☐ English/Language Arts
- ☐ Social Studies
- ☐ Art
- ☐ Music
- ☐ Engineering
- ☐ Technology
- ☐ Foreign Language
- ☐ Other ________________

How much time per week do you generally spend teaching engineering (if any)?

____

If you do teach engineering, tell us a little about how you do so.

____

____

5. Science Lessons

How much time per week do you generally spend teaching science?

____

Do you teach more than one class science? If so, how many?

____

Are you a science specialist? _______________________________________

Rate your comfort level when teaching science lessons:

1	2	3	4	5
Very Comfortable	*Moderately Comfortable*	*Neither Comfortable nor Uncomfortable*	*Moderately Uncomfortable*	*Very Uncomforta ble*

Comments:

6. Computer Access

Do you have access to a computer in your classroom? ☐ Yes ☐ No

If not, do you have access to a computer in your school? ☐ Yes ☐ No

Rate your comfort level with using educational computer software:

1	2	3	4	5

Very Comfortable	*Moderately Comfortable*	*Neither Comfortable nor Uncomfortable*	*Moderately Uncomfortable*	*Very Uncomforta ble*

Comments:

Thank You!

Appendix B: Teacher Survey – LEGO Curriculum Users

Teacher Survey – LEGO Curriculum Users

I. Contact Information

Name: ____

District: ____

School: ____

E-mail Address: ____

II. Background Education/Classroom Information:

1. Degrees

Please indicate the degrees you have earned and indicate in which field (e.g., English Literature, Mathematics, etc.)

☐ Bachelors

(Field____)

☐ Masters

(Field ____________________________________)

☐ Doctorate

(Field____)

If you have teacher licensure, what grade levels are you licensed for?

____

What type of program best describes your teacher preparation program or teacher certification program?

☐ Undergraduate ☐ Emergency Route

☐ Graduate ☐ Other ______________________

☐ Alternate Route

What best describes your science experiences in academia?

☐ Science Major ☐ Took science classes beyond requirements

☐ Science Minor ☐ Took required science classes only

☐ Took no science classes ☐ Other ____________________________

2. Teaching Experience

Grade level currently teaching: ____

Grade levels previously taught: ____

Years Teaching (total):

____

Years teaching current grade level: ____

3. Other Professional Experience

Have you had other work experiences besides teaching? ☐ Yes ☐ No

If you answered yes above, please describe your non-teaching work experiences.

____

____

____

Have you had work or recreational experiences with design and/or engineering?

☐ Yes ☐ No

If you answered yes above, please describe your experiences with design and/or engineering. ____

____

____

4. Subjects in Classroom

Please indicate all subjects you are currently teaching in your classroom.

☐ Science ☐ Music

☐ Mathematics ☐ Engineering

☐ English/Language Arts ☐ Technology

☐ Social Studies ☐ Foreign Language

☐ Art ☐ Other

____

How much time per week do you generally spend teaching engineering (if any)?

____

If you do teach engineering, tell us a little about how you do so.

____

____

5. Science Lessons

How much time per week do you generally spend teaching science?

____

Do you teach more than one class science? If so, how many?

____

Are you a science specialist? ______________________________________

Rate your comfort level when teaching science lessons:

1	2	3	4	5
Very Comfortable	*Moderately Comfortable*	*Neither Comfortable nor Uncomfortable*	*Moderately Uncomfortable*	*Very Uncomfortable*

Comments:

6. Computer Access

Do you have access to a computer in your classroom? ☐ Yes ☐ No

If not, do you have access to a computer in your school? ☐ Yes ☐ No

Rate your comfort level with using educational computer software:

1	2	3	4	5
Very Comfortable	*Moderately Comfortable*	*Neither Comfortable nor Uncomfortable*	*Moderately Uncomfortable*	*Very Uncomfortable*

Comments:

<u>III. LEGO™ Experience</u>

How long have you been exposed to building with LEGO?

____

In what contexts have you used LEGO? (Please check all that apply.)

☐ Childhood toy ☐ Creating models

☐ Used in school as child ☐ Robotics

☐ Playing with a child in a home ☐ Other

____

☐ Used in own classroom with students ☐ None

If you used LEGO in your own classroom, what was the purpose? (Please check all that apply)

☐ Academic in nature ☐ Playtime

Please elaborate on any past academic uses of LEGO.

Please indicate your level of proficiency with each of the following:

Experience	Excellent	Good	Fair	No
a. Building with LEGO bricks	☐	☐	☐	☐
b. Building with LEGO wheels	☐	☐	☐	☐
c. Building with LEGO axles	☐	☐	☐	☐
d. Building with LEGO connectors	☐	☐	☐	☐
e. Building with LEGO beams	☐	☐	☐	☐
f. Building with LEGO gears	☐	☐	☐	☐
g. Using LEGO motors	☐	☐	☐	☐
h. Using different LEGO themes (Ex: Trains, Ferrari, Batman, etc.)	☐	☐	☐	☐
i. Using LEGO MINDSTORMS RCX	☐	☐	☐	☐

j. Using LEGO MINDSTORMS NXT ☐ ☐ ☐ ☐

k. Using other LEGO Education tools ☐ ☐ ☐ ☐

Specify tools: ____________________

____

Thank You!

Appendix C: Eliciting Teachers' Mental Models Protocol

Eliciting Teachers' Mental Models Protocol

For these protocols each participant will be asked to complete a questionnaire (see attached). Each participant will be asked to watch a 20-minute video and answer some questions verbally and in writing. Participants may take notes during and/or after watching the video. After viewing the video is complete, participants will be asked to write and elaborate on responses to a set of written prompts. The interview should take approximately 60-120 minutes. For their participation each subject will be given a $25 gift certificate redeemable at a restaurant of their choice.

Procedure:

- Open the Livescribe notebook to a blank, two-page spread.
- Turn on tape recorder and the Livescribe Smartpen. Tap the Livescribe Smartpen on the Record box at the bottom of the first page of the two-page spread. Press the record button on the tape recorder.
- Record on the tape the participant's first name and last initial and the date of the interview. Have participant write his/her first name, last initial and date in the Livescribe notebook at the top of the first page of the two-page spread.
- Go over permission form, answer any questions about it and obtain signed informed consent.
- Explain how the Livescribe Echo pen works.
- Read opening narrative (below) and allow the participant to respond to the embedded questions.

- Give the participant the card of questions and allow him/her to read the questions on the card.
- Start the video.
- When the video stops, ask the participant to respond to the questions on the card.
- Ask if the participant would like to replay the video.
- Use additional probes (below) as time and interest allows.
- All interviews will end with the question: *Is there anything you would like to add?*
- Make sure to thank the subject and give him/her the gift certificate.

If they have agreed to be recorded, interviewer says:

Are you over 18 years of age?

Do you know that you are being recorded?

We are trying to learn more about how people who teach science with different instructional materials perceive what design engineers do. We would like to know about your particular school and how you teach science there.

Please describe your science teaching practice.

Please tell me about the affordances and constraints of teaching science in your school.

In a moment, I'll play a video of designers at work. As you watch the video, I would like you to keep in mind the questions on this card. [Show participant the card and allow him/her to read it.] You will have time to answer these questions after the video ends, but feel free to take notes on the special paper in front of you as you watch the video. This pen and the special notebook will connect the notes you write during the video with what you're hearing as you write. After the video ends, I'll ask you to write in the notebook your answers to the questions on the card. You may watch the entire video again or replay parts of it if you wish. You may tap with the pen what you've written in the notebook and the pen will play back the sound that was playing on the video as you wrote. After you have answered the written questions, I will ask you a few follow-up questions about your process and/or what you have written so that I understand it. Do you have any questions for me?

Questions on the Card

- What did you notice happening in the video?
- How would you teach your students to enact what you noticed people doing in the video?
- What instructional materials would you need?
- How would you assess whether your students were learning the relevant content and the process skills you identified (formative assessment)?

- How would you evaluate their final results (summative assessment)?
- How does your plan relate to what you already do in your science teaching practice?

Additional Probes

Possible questions after participants respond to prompts:

- ✓ At what point in the video did you notice this (referring to something specific in a participant's response)?
- ✓ What did you see in the video that prompted you to add this to your plan (referring to something specific in a participant's response)?
- ✓ How would you use the instructional materials you identified?
- ✓ What might the scoring guide for this assessment look like?
- ✓ How much time might you spend with your students on this specific part of your plan?
- ✓ How many class periods might you allow for your students to complete this entire experience?
- ✓ Can you say more about this (referring to something specific in a participant's response)?

Appendix D: Code Book with Representative Examples of Coded Utterances

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Communicative Actions for Engineering			
Global Reference to Engineering Process	…we're kind of experts on the process of how you design stuff…	…a guide that outlines the steps and says what each one has in it…	Elizabeth: …they went through their design process …
Identify need or problem	…to bring the supermarket shopping cart into the 21st century.	…so if I was going to redesign a student desk for example...	Nancy: …redesigning a shopping cart that meets a better need of the consumer…
Research need or problem	…making those lists about the kind of questions we're going to ask.	So, examine how they are used, and if I have them do what the people in the video did then they would talk to other students, so there would be interviews, they would talk to others who work with the items.	Ellen: …they kind of did a data collection of their own, you know, because they were getting data from other people, so I mean I think that there would have to be some sort of research part of it.
Develop possible solutions	…if it doesn't nest we don't have a solution.	…after they came back with all of their information they generated some ideas…	Jill: So, they came up with possible solutions then they didn't necessarily right away pick the best solution; they went and looked at four different ways to do it…
Select best possible solution	Vote with your post-it…	…then they took the best ideas from each…	Jill: …from that they picked their best… solution.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Construct a prototype	So, we took the best elements out of each prototype…	…they made four prototypes…	Jill: …then they build the prototype…
Test and evaluate solution	…take it over to a local supermarket and see what they say.	Then they took it back to the supermarket where they presented it to the users… and then they got feedback in their design…	Jill: …they built the prototype and then they tested it…
Communicate solution	Here's how you would scan an item: you reach over and pick up anything like this salad dressing and I would scan it and if I want to accept that item I would just press + and then drop it in my basket.	Then they took it back to the supermarket where they presented it to the users…	Renee:…then they would have to present what their idea was.
Redesign	I think if you take a piece of each one of these ideas and kind of back it off a little bit and then put it in the design.	…they're further developing the design for production…	Valerie: …then deciding what they want to change, and then I would hope that they'd be started on the second crystal that they were going to do making their changes.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	Examples from Referent Deep Dive Video	Examples from Ann McMahon	Examples from Teacher Participants
Communicative Actions for Science			
Global Reference to Scientific Method	Not Applicable	…and then how to use the scientific method…	Valerie: …following the steps of the scientific method…
Question		…what questions, what happened, what did we observe, to why questions; why did this happen, what are the underlying big ideas?...	Renee: …there are focus questions for that part of the investigation...
Hypothesis		…we might look into explanations as to about why the phenomenon we observed happened.	Ashley: …what do you think is going to happen in some of those kinds of situations?
Procedure		…I set up experiences with objects and phenomena that allow them to make observations of those objects and phenomena and we look at the observations, we look for patterns in them…Then we'll look at the data that comes out of those observations and we'll look for patterns…	Valerie: …do they follow the directions of whatever it is that they've picked, are they doing those things in order, are they working together…
Data Collection		…make observations of those objects…	Lillian: …they kept records of how long it took…
Data Analysis		…we'll look for patterns…	Sandra: …analyzing the data…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	Examples from Referent Deep Dive Video	Examples from Ann McMahon	Examples from Teacher Participants
Conclusion	Not Applicable	…explanations as to about why the phenomenon we observed happened.	Renee: …and a content inquiry chart where the, and I kind of really guide this so I get the important facts on that chart…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Communicative roles of designers in The Deep Dive			
Participate in whole group activities	Each team is going to demonstrate and communicate and share everything that they've learned today.	So, there needs to be some whole class discussion…	Jody: …we generate ideas as a class…
Participate in small group activities	Like it or not the team is told it will split into groups to build mockups …	…we divide up into 5 teams and go from there…	Jody: …then they were put into groups
Interact with experts outside the design group	The trick is to find these real experts and so that you can learn much more quickly …	…they would talk to others who work with the items.	Lillian: …they talked to experts…
Build on the ideas of others	… then you build on those wild ideas…	…encourage wild ideas-build on the ideas of others	Ruth: And build on the ideas of others…
One conversation at a time	…one conversation at a time…	Not present in transcript	Sandra: …there's one voice at a time, or one conversation at a time…
Defer judgment	…restrain themselves from criticizing an idea…	Not present in transcript	Renee: …respecting each other's opinions…
Stay focused	…stay focused…	…must refocus deep dive	Sandra: …stay focused on the topic…
Encourage wild ideas	…encourage wild ideas…	…wild ideas are built on to generate innovation	Renee: …wild ideas are as good as conservative ideas…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Communicative roles of students			
Participate in whole class activities	Not Applicable	…Whole class discussion…	Sandra:…I would actually pull them back as a class to talk as a class.
Participate in small group activities		…I could have all 5 design teams combine their design into a class design…	Sandra: I would have them work in their groups…
Participate in pair activities		Not present in transcript	Nancy: OK, now they're only working in groups of two…
Contribute ideas to group product		…asking students to talk about their contribution to the process…	Ashley: …like I like how you said this or I agree with you but just to kind of get the, we call them conversation starters…
Listen respectfully to others		…so there's a share or communicate what they learned… I could ask each person on the team what they found out, who they talked to, who did you talk to, what questions did you ask, what did you learn…	Lenora: I do have to encourage hearing each other…
Resolve conflicts within the group		Not present in transcript	Valerie:…most of the time I want them to work it out on their own….

Coding Main Category (Bold Color) and Subcategory (Pale Color)	Examples from Referent Deep Dive Video	Examples from Ann McMahon	Examples from Teacher Participants
Take turns	Not Applicable	…give each other feedback…We might be able to be each others own critical friends…	Valerie:…but they kind of take turns talking…
Reach consensus		So, they'll come up with a team idea…	Elizabeth:…There's another [faith-based] term, "sense of the meeting" which means, it doesn't mean that everybody agrees 100% but it means that it's the general understanding and a general agreement.
Learn from the ideas and preferences of others		…after they've come up with their own ideas…they also might choose to contact companies that make student desks as well…	Ruth:…Really I mean it actually works better if they share ideas, and some of them are very generous…
Defer judgment		Not present in transcript	Sandra: …no idea was ever put down…
Invest in another's idea instead of one's own when appropriate		…Even if what they suggested doesn't get incorporated in the design there's still a discussion about what that contributed to the discussion of, and the decisions about the design…	Elizabeth:…it's more like most people think this and unless you feel extremely strongly and you're not going to stand in the way of the decision; if you can make peace with the decision we're going to move forward.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Communicative roles of teachers			
Establish the instructional objectives of the unit	Not Applicable	…the way I set up my courses is with an inquiry method, usually guided inquiry, which means that I have objectives in mind for my teacher-learners to achieve…	Lenora: I've taken maybe three or four lessons and put them into one activity and tried to do more with just one rather than trying to do each lesson…
Direct instructional activities in the classroom		…experiencing the events that my co-instructors and I plan for them…	Renee:…the next week is when they would start working in their smaller groups. I think it would take a couple of days, probably 2 days for them to come up with their ideas…
Provide students with instructional materials		…I'd have to get some student desks, so get student desk or backpack or several different backpacks…	Sandra: Whatever materials the kids have listed, if they list wood, you know, metal pieces, PVC pipes, whatever, hopefully we can get a lot donated and if not I may have to, you know, look on the internet and look where I can to get mini grants to go purchase those things…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Facilitate student learning as needs emerge (reteaching, troubleshooting)	Not Applicable	…what I would have them do is see if they could rig up the existing desk and chair that exists in the classroom if they can add materials to bring that up the way their design tells them to so they have a prototype, and I would have to figure out how to get whatever they needed to rig things up…	Jody:…There should be time for exploration but there should also be structures in place that students are really, you know, are getting something out of it…
Facilitate student learning through sense-making events		…What I look for in the reflections that teachers turn in every week is their ability to reflect on what they know and how they know it and to integrate the experiences they have with us and the discussions that come out of those experiences into what they already know and to articulate how what they know changes, or how what they know is reinforced…	Elizabeth:…different partnerships were responsible for different sections of the process, like some people talked about the engineering process, some people talked about different experiments that were done, some people talked about the design challenge, and then it was all videotaped.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Communicate criteria by which students will be assessed	Not Applicable	…I'd also need a roadmap for my students…how would I assess whether my students were learning the relevant content and the process skills I identified, so that's formative assessment	Lillian: The rubric would list the things that I had told them I was looking for and then they would, you know, be able to determine that too.
Ensure participation by all students		…they also need to be able to say how did I contribute and answer that question…	Ruth: …I was going from group to group to group reminding them you can't do it all and have your partner sit there and watch you.
Provide formal and informal feedback to students		…the scoring guide for the kind of assessments that I noted here really has a lot of judgment built in; it's more of a critical thinking scoring guide…	Jody:…as you're floating around checking in with each group and working in, you know, maybe doing whole group check-ins…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Shared and social knowledge and beliefs in The Deep Dive			
Enlightened trial and error succeeds over the planning of the lone genius	That's right, enlightened trial and error succeeds over the planning of lone genius.	…enlightened trial and error…	Renee:…just try it…being playful is important… go ahead and try it and then you see why it does work or it doesn't work…
Status is conferred to those who come up with the best ideas	Status is who comes up with the best ideas…	…status is best ideas	Lenora:…so you might try Alan's idea because well he always does things right, you know, someone might just defer to Alan for that reason…
Interviewing real world experts facilitates faster learning than the typical ways one learns on one's own	The trick is to find these real experts and so that you can learn much more quickly than you could by just kind of doing it the normal way and trying to learn about it yourself.	…they went out to shopping cart users and those users were people at the store who bought them for their store, so they were store owners, and people who I guess repair them because they had a maintenance guy. They talked to a bunch of people about that…	Lillian:…who could we ask, who, you know, who would be an expert in this, who could we call, who could we talk to, and of course they have their parents they could interview and then other people that we could get to come in…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Fresh ideas come faster in a fun place	…fresh ideas come faster in a fun place.	…fresh ideas come faster in fun areas…	Jody:…they're used to them they've played with them and now they can work with them, and then also just the more they explore them and play with them and open it in a way the more willing they are to use different parts or try different things…
Focused chaos produces innovation	Organized chaos, it's not organized; what it is is it's focused chaos.	…focused chaos…	Renee:…I like their idea of this organized chaos that's focused…
Fail often in order to succeed sooner	…fail often in order to succeed sooner…	…fail often to succeed sooner…	Nancy:…don't be afraid to fail…
Work under time constraints in order to force an end to the design process and get things done	…if you don't work under time constraints you could never get anything done…	…So, a whole quarter three times a week, so that's 9 weeks times 3 sessions a week, so that's about 27 class periods.	Nancy:…You can give them two weeks, two months two years and in the end human nature, most human nature says you get the most work done when you're under the gun in the last couple days.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Shared and social knowledge and beliefs in school engineering			
Engineering topics must fit grade level science requirements	Not Applicable	… if you're going to design something big like a physical desk I would put that with a force and motion unit, I would put that with a properties of matter unit…	Jody:…in 4th grade we swapped out simple machines and the animal unit with the Lego kits, but we supplement the Lego kits with part of the NSRC kits…
Engineering is creative		If I were to teach a design course there really aren't any right answers; there are big process ideas that need to get communicated…	Jill:…all four of their support columns had different bases and they were all so creative.
Engineering engages students		…what I might try to do is take this process and switch it to something that they know, so what is it that 3rd and 4th grade students interact with sort of regularly, like adults interact with shopping carts?...	Ruth:…every once in a while we have someone who's outstandingly good at it so they become like an assistant teacher, and oddly enough it's usually the kids that struggle academically that seem to excel with the Lego's…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Engineering includes scientific experimentation	Not Applicable	…that's when you use the scientific method when you're evaluating how good your prototype is…	Elizabeth:…we have the different components that needed to be explored and we gathered the information through the different experiments…
Assessment based on products meeting design criteria		The scoring guide for the whole design would be its functionality and it would actually be determined by feedback of the users…	Lenora:…we had three conditions that they had to meet and then I added a couple of conditions as we went along.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Shared and social knowledge and beliefs in school science			
Specific science topics per grade	Not Applicable	…They're interested in taking what we present in the class back to their teaching practice and incorporating it into their teaching practice at least as long as they're with us for the semester…	Valerie: We have a scope and sequence that's laid out for us on the [name of school district] website that kind of tells us the curriculum…
Prescribed science activities implemented in classroom		…they are required to write a journal entry every week and turn it in, and a journal entry really just has then reflect on what they did during the time they were with us during class time.	Renee: Well, they are divided into investigations, there are 3 or 4 investigations and divided into parts as well…
Science vocabulary assessed against standards	Not Applicable	Not present in transcript	Sandra:…As far as the final summative we've got vocabulary that we have to cover, so they will be tested on vocabulary…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Science process skills assessed against standards		…what we look for is a clear articulation of learning goals, learning the big ideas that they're going to teach their students, and then a road map through experiences that they're going to provide to their students that leads to those big ideas, and then we look at the kind of evidence they collected about what they did, how their students responded to it, and then ultimately the assessment pieces that talk about how their students learned what they presented…	Ellen:…I'm marking them on the report card even though we just do a developmental scoring like exceeding, progressing…but if I'm writing a beginning or a basic I need to show a parent why that is…
Science notebooks assessed against standards		…look at their notebooks, so to assess look at design notebooks.	Lenora: …Then we keep a science notebook with certain steps and requirements and so that's the other assessment piece…
Science engages students		Well, we have teachers who come to us who are motivated, they're self selected and they're paying to take the courses, so that implies some motivation on their part…	Ellen: They love science…they really enjoy it.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Social roles for designers in The Deep Dive			
Team members are chosen for their skills and expertise	…Project leader because he's good with groups, not because of seniority…	…Project leader is good with group…	Jody:…So, they weren't even engineers but what he said they were good at was the process…
All team members contribute to all parts of the design process	…it's the team that's able to really judge what the best idea is.	…draw on post-its-post on chart…	Nancy: I said nobody wants to be in a group project with a slacker, and I said nobody in here is going to be a slacker…
Roles on team are determined by strengths and abilities	…The rest of the team is eclectic and that's typical here…	…mech engineer…	Jill: …we all have different strengths, different weaknesses, …we all have different strengths
Team members function as equals	Everyone appears to be equal and they love to mock corporate America.	…We might be able to be each others own critical friends…	Sandra: …accept the fact that everybody has an idea and every idea is great, it's OK…
Leaders emerge and disappear as needed	10:00 AM as the team works it becomes clear there are no titles here, no permanent assignments.	Not present in transcript	Nancy: …there's always going to be a leader emerge…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	Examples from Referent Deep Dive Video	Examples from Ann McMahon	Examples from Teacher Participants
Social roles for teachers			
Teacher makes judgments about the ability of students to enact social and communicative roles	Not Applicable	…They're self selected; they're for the most part motivated learners…	Lillian:…I don't have a group that is good at working together yet; I'm teaching them how to do that, so I would very carefully pick who goes into what group.
Teacher controls instructional activities in the classroom		…the way I set up my courses is with an inquiry method, usually guided inquiry…	Elizabeth: And, so we did stick with the 10 lesson plans…
Teacher mediates conflicts among students		Not present in transcript	Nancy:…If they simply cannot come to an agreement I just rock-paper-scissor it… and that's when my autocratic moments come in.
Teacher encourages collaboration among students	Not Applicable	And ask student to describe a final design and her contribution to it…	Elizabeth: Our hope was it would be very collaborative and that both partners would be sharing the work, by and large I would say that was true…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Teacher takes peer-to-peer dynamics into account when grouping students for activities		Not present in transcript	Ashley:…So, I try and just split up, you know, the ones that are like the go getters and the workers versus the ones that kind of sit back but do have some creative ideas when you call on them to share or when they know that they have to contribute something maybe just a little bit more reluctant or hesitant, and just kind of split it up so it seems like it's kind of mixed abilities and that they're all kind of even…
Dynamic student-to-student interactions influence classroom instruction		Not present in transcript	Ruth:...I do different things depending on the children involved.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	Examples from Referent Deep Dive Video	Examples from Ann McMahon	Examples from Teacher Participants
Intentions of designers in The Deep Dive			
Redesign something old and familiar to audience	…take something old and familiar, like say the shopping cart and completely redesign it for us in just 5 days	…what I might try to do is take this process and switch it to something that they know, so what is it that 3rd and 4th grade students interact with sort of regularly, like adults interact with shopping carts?...	Renee Notes: redesign shopping cart for 20th century
Improve the form and function of the familiar object	…we tend to put up with things that may not work particularly well or may look especially unattractive simply because we're accustomed to them and because no one has ever suggested redesigning those things.	…does the new design work better than the old design?...	Nancy: OK, so what they talked about was form, function, and attraction; those were the three key essential elements…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Goals of designers in The Deep Dive			
Improve safety of shopping cart	Safety emerges early as an important issue.	…Define problem => safety emerges early…	Jill Notes: Safety (important).IDEO
Improve efficiency of check-out process in store	…four areas of concern that have been identified: shopping, safety, checkout, and finding what you're looking for.	…shopping, safety, checkout, finding what you're looking for…	Lenora Notes: shopping, safety, checking out, finding what you're looking for.
Improve ease of finding items in the store	…four areas of concern that have been identified: shopping, safety, checkout, and finding what you're looking for.	…safety, shopping experience, checkout, where to find stuff in the store…	Lenora Notes: shopping, safety, checking out, finding what you're looking for.
Reduce the potential of shopping cart theft from stores	And theft; it turns out a lot of carts are stolen.	…gets rid of baskets to avoid theft…	Ashley Notes: avg life of cart? theft?

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Teacher intentions			
Teach science according to school or district mandates	Not Applicable	…what to redesign based on the big science ideas that I need to teach, so if I was going to redesign a student desk for example, I might do that in the context of a force and motion and properties of matter unit so that you're actually looking at how strong something is, the physical properties something has.	Sandra: They really focus more on, they really want us to focus more on reading, writing, and math…
Teach science based on perception of the subject matter		I would also incorporate math into it because if you look at shapes, geometric shapes, you know, triangular sections or square sections or round sections you can look at how strong each of those shapes are…	Valerie:…I just give them the lab and they have to figure out how much they're going to need which is kind of a hard thing for them but, you know, it gets them thinking instead of me just saying all the time you're going to need two cups of this and you're going to need five rubber bands or whatever.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Teach science based on perceptions of students' needs	Not Applicable	…Engineers and designers have to represent their ideas in a number of different ways, and so I would make sure that many ways were represented and the kids have lots of practice to do that…	Lillian: …I found that with the class that I had last year they were way beyond what was provided in those kits…so I found myself constantly having to add things to it to make it more difficult and to kind of follow them…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Teacher goals			
Students master grade level science skills and concepts	Not Applicable	…Well, for the whole plan I can see that it would take easily a quarter, so it would be a whole unit…	Valerie: Yeah, so we have common assessments that we give every quarter so that kind of helps us know, you know, where we're going and then it kind of helps us all stay on track…
Students are prepared to perform proficiently on state tests		Not present in transcript	Lenora: Well, unfortunately for the past few years science has taken a back seat. We have had literacy and math issues on our MCAS [high-stakes state test], and so the focus has been on making sure that you are doing exactly what you need to do in the literacy side of things…
Challenge students	Not Applicable	…So for instance if you design a student desk that has an all-in-one desk and chair where you can't scoot the chair in you have to look at the reach of the different size children who will use it because you have to make sure you can design it so everybody can reach the desk…	Lillian:…they'll come up with questions and then I'll say well why don't you find out, and you know, so that kind of follows our way of thinking…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	Examples from Referent Deep Dive Video	Examples from Ann McMahon	Examples from Teacher Participants
Students think critically		…it's more of a critical thinking scoring guide…	Renee:…So, it allows them to think. They have a situation and this is what you have and so how can you solve this problem, or how can you change this to meet your needs?
Students solve problems		…So, there would be opportunities for assessing that kind of knowledge depending on what they chose to do, the problem that they chose to do…	Elizabeth: Problem solving. There's a problem and they went through their design process and came up with a solution.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
School Setting			
Defined science curriculum	Not Applicable	…The courses I teach are a couple of physics courses and an astronomy course. I teach a course on basic solar system astronomy, I teach a course on electricity and magnetism, a course on force and motion, and a course on light and sound…	Valerie:…so it tells us each quarter this is the topic area that you need to cover, these are the objectives that we want you to cover…
Bound to state standards (public school district)		…We're also trying to impart to our students a kindergarten through 8th grade storyline about the topic of the course…	Ashley: And the GLE's [state Grade Level Expectations] are what the state is assessing on…so we've been teaching the GLE's the last couple years because we have to so that they're ready for that…
Pacing guides		Not present in transcript	Lenora:…we do have a pacing chart…
Prioritized math and literacy blocks		I would also incorporate math into it…and so you can do a whole science piece around mean, median, and mode based on the measurements of different size children who will use that desk.	Sandra: I feel personally that they focus more on reading, writing, and math than they do science or social studies. They have actually requested that science and social studies be reduced to a half an hour…

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
High-stakes test	Not Applicable	Not present in transcript	Lenora:…We have had literacy and math issues on our MCAS [high-stakes state test]…
Science time cut short to accommodate other curricular needs		Not present in transcript	Jill:…if there's an enrichment activity going on that interferes with the day it's usually science that's cut out, but normally I teach science every day for an hour…
Flexible science times		…and then depending on how much time I had for the unit I might ask the class to come up with another iteration of the design, and that can be kind of time dependent…	Elizabeth: Because I have the flexibility to, you know, wrap everything into reading and writing and everything, or I have the flexibility to say we're not going to be reading all week and we're going to just do this…
Science/Engineering materials provided		… what I would have them do is see if they could rig up the existing desk and chair that exists in the classroom if they can add materials to bring that up the way their design tells them to…	Ellen:…Last year I taught sound and properties of materials and I used, they asked me to do only the Lego materials which is what I did.

Coding Main Category (Bold Color) and Subcategory (Pale Color)	**Examples from Referent Deep Dive Video**	**Examples from Ann McMahon**	**Examples from Teacher Participants**
Expressed overwhelm at amount to teach	Not Applicable	…teaching is a hard job, and so when teachers come to us at the end of a full teaching day a lot of times they're tired, and so it's a real challenge for them to engage in the way, you know, we'd like them to engage…	Lenora:…We are all so overwhelmed, we are so overwhelmed with you have to do this, you have to do that, and…