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

Abstract

Educating K-12 students in the processes of design engineering is a movement that is gaining in popularity in public schools. Several states have adopted standards for engineering design. Beginning in the mid 1990s, curriculum designers began producing curriculum units for all grade levels at an ever-increasing rate, despite the fact that no common agreement exists on what should be included in the engineering design process used in K-12 education. Furthermore, very 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 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.

Lave and Wenger’s work with communities of practice and van Dijk’s multidisciplinary theory of contexts as mental models provide the theoretical bases for comparing the mental models of two groups of teachers to the mental models of design engineers (including this engineer/researcher/educator). The first group of teachers teaches from textbook and/or kit-based science programs. The second group teaches at least one unit in an engineering-based curriculum. The design engineers include this engineer/researcher/educator as well as professional designers featured in a video. These elementary school teachers and this engineer/researcher/educator observed a video of 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 their students. The participants’ mental models are generated from their discourse using van Dijk’s components of context models; they are displayed side-by-side in color-coded columns.

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 the results of this study are presented.
Mental Models in the Design Disciplines and K-12 Education

In 1943, Craik\(^2\) 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. Merrill\(^3\) defines a mental model as a schema or mental representation combined with a process for manipulating the information in the schema (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.\(^3,4,5,6,7,8,9,10,11,12,13\)

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 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.\(^13,14,15,16,17,18\) 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\(^19\) conducted a large-scale study of the design process in eleven different companies and created a general description of the process. Furthermore, the design process was demonstrated by IDEO, a design and innovation consulting firm, for the ABC news show Nightline in a story that aired on July 13, 1999. The design process shown in the IDEO story, called The Deep Dive\(^20\), represents best practices in design and is used to elicit participants’ mental models.

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\(^21\) (pedagogical content knowledge\(^22\), metastrategic knowledge\(^23\), and pedagogical design capacity\(^24\)). 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\(^25\) 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” (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

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\(^1\) In this document, the words “engineering” and “design”, as well as “engineer” and “designer,” will be used interchangeably.
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. 

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 references the design process in Massachusetts Science and Technology/Engineering Curriculum Framework. This design process consists of the following eight steps: identify need or problem, research need or problem, develop possible solutions, select best possible solution, construct a prototype, test and evaluate solution, communicate solution, and redesign. There are three reasons for using the design process in 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. 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.

Theoretical Background and Research Design

The theoretical basis for this study is the work of Wenger on communities of practice as well as that of discourse analyst van Dijk 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. 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” (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)” (p. 220).

This is a qualitative study that 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”, van Dijk 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 Merrill’s 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 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 data collected from participants. The participants and interview protocol are described below.

Purpose of Study and Research Questions

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 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.

This study elicits and compares the mental models of the design process held by two groups of six elementary school teachers and Ann P. McMahon who is an engineer/educator/researcher. Our mental models are elicited and analyzed vis-à-vis a videotaped example of best practices in design engineering. The research questions addressed are:
1) What are participants’ mental models of the design process?
2) How does each teacher’s mental model compare to the design process represented by professionals at IDEO in the Deep Dive video and by this engineer/researcher/educator author?
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?
Participants

I am a participant in this study and had an interviewer 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. 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,4,11,12,13,14,15,16,17,18,19 which is why I chose this video as a referent to show to the teacher participants. Furthermore, 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. 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 this study. One group of six teachers came from schools in the St. Louis, Missouri, area. The Missouri 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 Boston, Massachusetts, area. These teachers have taught at least one engineering-based unit developed by the Tufts University Center for Engineering Education and Outreach (CEEO). The Massachusetts 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, Missouri 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 Missouri included two teachers from faith-based schools, two from schools in low achieving districts, and two from schools 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, Massachusetts area and likely to become available in Missouri in the coming school years. 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. In the references to and excerpts from participants that follow, the abbreviation for the state in which each teacher practices (MO or MA) appears next to her name.

Instrumentation and Data Collection Procedures

After I received IRB approval for this study, I was interviewed using the same protocol used with other participants. Then 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 a mental model elicitation procedure that consists of
teachers 1) describing their teaching practice, 2) watching the Deep Dive video, 3) responding to prompts about what they saw and how they would transform it to their classrooms, and 4) explaining their responses in a semi-structured interview. Participants’ answers to these prompts, combined with their explanations of their answers in a semi-structured interview yielded each teacher’s mental model as defined by Merrill3 – a schema or mental representation combined with a process for manipulating the information in the schema. 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 the data.

I had an interviewer elicit my own mental model of the process prior to my interviewing teacher participants, following the same procedure, in order to incorporate it into this study 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. working in small groups 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 ongoing feedback to students in formative assessments);
• Shared and social knowledge and beliefs associated with the Deep Dive 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” in the Deep Dive culture, engineering is creative in the school engineering culture, and the specific science topics taught at each grade in the school science culture);
• 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 for the Deep Dive designers, and to facilitate students’ mastery of science/engineering concepts for the teachers);
Communicative and other actions for engineering and for science, defined as the steps of the engineering process and the scientific method, respectively.

The eight steps of the design process represented in the Massachusetts Science and Technology/Engineering Curriculum are included as communicative actions for designing (which represents content knowledge). How each participant notices, names and deems these steps relevant (or not) to include in her plan, combined with the other information elicited represented each participants’ 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 research questions.

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 1 below and defined above.

Table 1. Fifteen Main Coding Categories that Define Mental Models, Based on van Dijk’s Elements of Mental Models.

<table>
<thead>
<tr>
<th>Communicative Actions for Engineering</th>
<th>Shared and Social Knowledge and Beliefs in The Deep Dive</th>
<th>Intentions of Designers in The Deep Dive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communicative Actions for Science</td>
<td>Shared and Social Knowledge and Beliefs in School Engineering</td>
<td>Goals of Designers in The Deep Dive</td>
</tr>
<tr>
<td>Communicative Roles of Designers in The Deep Dive</td>
<td>Shared and Social Knowledge and Beliefs in School Science</td>
<td>Teacher Intentions</td>
</tr>
<tr>
<td>Communicative Roles of Students</td>
<td>Social Roles for Designers in The Deep Dive</td>
<td>Teacher Goals</td>
</tr>
<tr>
<td>Communicative Roles of Teachers</td>
<td>Social Roles for Teachers</td>
<td>School Setting</td>
</tr>
</tbody>
</table>

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 fifteen elements of mental models defined above. 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. Each utterance had the potential to be coded in multiple categories and subcategories because of the synergy among categories and subcategories. 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) and are included in Table 2 below. A code book with representative examples for each coding category was used for coding and organizing the data. There were 15 main coding categories and 95 subcategories.

Data Analysis Procedures

A table of total utterances per category and subcategory was constructed using spreadsheet software. 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.

Table 2 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 links are explained below. 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. Executive functioning is defined along three dimensions: working memory, inhibitory control, and cognitive or mental flexibility. I will expand upon the relevance of executive function skills to communicative roles and actions in the Key Findings section.

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 2. Communicative Actions and Roles for Engineering and for Science

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

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).
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. A second-level analysis revealed that the contextual subcategories considered most relevant to the Deep Dive designers and myself 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.

Data Analysis

First, I describe the features of the mental models of the professional designers (including myself) 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 construct conclusions and recommendations.

Research Question 1: Constructing Mental Models

There were twelve teacher participants. Figure 1 below 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 2). 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 1: Mental Model Representations for Referent and All Participants (van Dijk's Context/Mental Model Categories)

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.
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.

Research Questions 2 And 3

The answers to questions 2 and 3 are taken from an analysis of participants’ mental models and supported by excerpts from participant discourse.

2) How does each teacher’s mental model compare to the design process represented by professionals at IDEO in the Deep Dive video and by this engineer/researcher/educator author?
3) What are the within group and between group similarities and differences in mental models?

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. 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. 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.

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 from Tufts CEEO 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.
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) does 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…

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 LEGO] 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. 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 2). 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 2). The teacher participants transformed the roles for designers in 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 P. McMahon: OK, I noticed that the designers took something that I’ve used lots and lots of times and they completely remade it.

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... 

Elizabeth (MA): Problem solving. There’s a problem and they went through their design process and came up with a solution.

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.

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 who work in Silicon Valley industries 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. 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.

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 [the designers in the video] because 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 and state how they will incorporate those norms in their classrooms. 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. 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.

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 a remark in the Deep Dive about controlled chaos and relates it to her strategy for pairing students to work with LEGO. 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.

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 P. 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.

When teachers talked about what they do in the classroom, many utterances contained 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.36 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 1 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 2 below 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. Sandra 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. 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. 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. 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’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 2 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 to vote only for buildable ideas. 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 (if needed), 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. “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.”

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’ idealized 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 the aerospace industry for many years, I am also captivated by the design process. For me, and for my professional colleagues described
in the research literature, 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. 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), and 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 P. 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.

Ann P. 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.

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. 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 intentional 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 3 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 3 for the coding categories). Figure 3 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 3: Shared and Social Knowledge and Beliefs of Design Engineers Compared by Subgroup (with Deep Dive and Ann McMahon Combined)](image-url)
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. I would emphasize the importance designers place on speaking to people who work directly with the designed object – in this case, the shopping cart. As Deep Dive designers stated, 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 fact, I frame my entire transformation of the Deep Dive example to the elementary school 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.

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) 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 to gather information from experts without transforming it to their classroom practice. 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, the information they gather allows them to 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.

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.

Key Findings

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 has implications for curriculum developers and professional development providers.

Professional engineering and school engineering intersect in the communicative actions for engineering, as shown in Figure 4.

![Diagram of the Design Process: the Intersection of Professional Engineering and School Engineering](Image)

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.
Engineers on a design team must collaborate with all the others who have competing priorities in the process of designing an object. 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.

Research in child development combines the antecedent cognitive, emotional and social competencies that signify school readiness into constructs called executive functions. 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. 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 and summarized 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. 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 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. 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 boundaries 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 (p. 13).

The teacher participants in this study 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 here 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.46,47,48 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 activities24, 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. It is also intended to foster a student habit of heart and mind that values the unique and diverse perspectives and abilities each student brings to a design challenge.

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. 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. Elicit, share and build on teacher-generated strategies that emphasize the characteristics above.

**Researcher Reflections**

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. 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 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.

Conclusions

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 a definition of 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.

Limitations

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.

Bibliography


