Using Activity Theory to Analyze and Describe Elementary Students Understanding of Engineering Design

Abstract

Significant challenges are inherent in learning complex systems within the context of elementary classrooms. Students and teachers both focus on secondary concepts with little regard to how larger systems are represented. Engineering design can foster complex systems thinking embedded in real world referents as a pedagogy that incorporates the development of artifacts to contextualize the learning activity. In this study, students were asked to design a vehicle to meet specific challenges. Using activity theory, as both a theoretical and analytical tool, systemic tensions and the role they played in student understanding is examined. The intention of this study is to identify and examine specific instances that serve as exemplars of these complex systems and how they impacted students learning about design, structures and forces. The dualities and tensions that emerged allowed for an understanding of how systemic tensions could lead to outcomes that were not anticipated and could interfere with student learning.

Keywords: Activity Theory, Engineering Design, Elementary
Introduction and Background

Strong arguments have been made about the importance, difficulties, and implications for learning and integrating complex systems approaches in K-12 classrooms (Jacobson & Wilensky, 2006). Complex systems approaches allow researchers to examine “aspects of the real world for which events and actions have multiple causes and consequences, and where order and structure coexist at many different scales of time, space and organization. (Jacobson & Wilensky, 2006, p. 12).” Previous research has documented the difficulties students experience when learning concepts relevant to understanding larger complex systems (e.g. Stieff & Wilensky, 2003; Samarapungavan & Wiers, 1997) While difficult, a systems thinking approach is necessary in order to fully understand and generate viable responses to complex societal and global issues (e.g. climate change, alternative energy) that involve science, technology, engineering and mathematics (STEM). The higher order thinking skills enmeshed in such systems thinking approaches are a key feature of 21st Century learning frameworks (AAAS, 2009; Partnership for 21st Century Skills, 2009). Because of the importance placed upon a systems learning approach (e.g. Hmelo-Silver & Azevedo, 2006; Wilensky, 1999; Jacobson & Wilensky, 2006), research has been done that examines what makes these approaches challenging in addition to research on pedagogical approaches about how students approach systems (Perkins & Grotzer, 2005; Resnick, 1994). While research exists about complex systems learning (e.g. Resnick, 1996; Wilensky, 1999; Metcalf et al, 2011), little work has been done to examine how students participate and engage within systems in solving specific problems.

According to Hmelo-Silver and Azevedo (2006), complex systems consist of hierarchal, multiple levels of organization and interaction. Previous work by Hmelo-Silver and Pfeffer (2004) demonstrated this by examining how experts and novices think about complex systems. In their study, Hmelo-Silver and Pfeffer (2004) examined the representations of an aquatic system in middle grade classrooms by both novices and experts. What they determined was that the novices focused upon simple structures and were able to provide little functional descriptions while the experts were able to focus on the larger systems, giving more complex and complete explanations about aquarium systems. This study demonstrates what often occurs in classroom settings: students and teachers focusing on secondary concepts and scientific phenomenon with little regard to how larger scientific systems/concepts are represented or function. (Hmelo-Silver, Martathe & Liu, 2004;
This mindset emerges from the idea that complex systems will often conflict with students prior knowledge. Students prefer ideas that are simple and predictable (Resnick & Wilensky, 1998). Complex systems thinking challenges this approach to learning. To foster a systems thinking approach that is integrated or embedded into classroom practices, it is essential to introduce such an approach early on in elementary school science as students begin to explore the complexity of scientific phenomenon. Elementary students often do not plan or set goals to direct their learning; additionally, they can have difficulty in anchoring new knowledge to an emerging understanding (Vye et al, 1998). One area where a systems approach can be incorporated to develop this approach to thinking is through engineering design where students engage in activity that integrates complex design systems in real world referents.

In 2009, a National Research Council report on engineering education described the epistemic relationship between science and technology demonstrated through integrating technology/engineering design principles in classrooms that support the learning of science and mathematics. A study by Lewis (2006) examined the similarities and parallels between scientific inquiry, complex systems and engineering design. The potential benefits of such an integration include: (1) improved student learning and achievement in both science and mathematics, (2) an increased awareness by students of what makes up engineering and the work of engineers, (3) an understanding of and the ability to engage in an engineering design project, (4) an interest, by students, in pursuing engineering as a career, and (5) an increased technological literacy (NAE & NRC, 2009). When design has been examined at the school level, studies have shown that elementary students are interested both in building and taking apart structures, which are complex systems, in order to understand how they work (Cunningham & Hester, 2007). This challenges traditional approaches to learning which focus on simple structures rather than complex systems (Hmelo-Silver & Pfeffer, 2004).

According to the American Association for the Advancement of Science (AAAS) Project 2061 (1993) young children are typically veteran technology users by the time they enter school. Building on these interests, technology/engineering design activities can not only promote but foster the development of students’ problem solving and three-dimensional thinking skills, all while developing a sense of engineering and technological literacy. Previous studies (e.g. Sullivan, 2008) have demonstrated that activities, such as robotics, can be linked to improving scientific literacy through science inquiry. Elementary school students are
often more receptive to this type of design-based science instruction as previously shown in by Baynes and colleagues (1994).

The Framework for K-12 Science Education (NRC, 2012) has attempted to address this construct by including engineering practices and core ideas that engineers use as they design and build complex systems. The framework argues that by incorporating design students should “learn how science is utilized…and come to appreciate the distinctions and relationships between engineering, technology and science (NRC, 2012, p. 216)” and understand the complexities that exist within these systems. The consensus of this report was that design is the central practice of engineering; thus, the iterative cycle that constitutes the design process provides an opportunity for students to engage in applying scientific knowledge as well as engineering practices (NRC, 2012). These experiences also allow students to explore how scientific insights influence engineering design. Teachers who have integrated engineering design in their K-12 classrooms have found that their students motivation to engage in and learn about science has improved and the classroom instructional practices have been impacted (Douglas, Iverson, & Kalyandurg, 2004). Other studies, (e.g. Resnick et al, 2000; Cunningham et al, 2005; Kahn & Bers, 2005) established that design projects promoted an attitude of constant scientific inquiry. One way that this was demonstrated was shown by Penner and colleagues (1997) who demonstrated how design projects integrated into science instruction could increase students’ understanding and awareness of structure and functions as it relates to living things and physical objects.

Additionally, engineering design projects can be situated within the context of authentic problems that allow students to address personal and societal needs (Atman, Kilgore, & McKenna, 2008). In particular, technology/engineering design offers students the opportunity to experience the iterative nature of science as well as the meaning of testing alternative ideas in problem solving (Bers & Potsmore, 2005; Cunningham et al, 2005; Kahn & Bers, 2005; Resnick et al, 2000). Technology/engineering design also affords students the opportunity to begin to understand systems, a common theme in science education (e.g. Sullivan, 2008; Jacobson & Wilensky, 2006; Perkings & Grotzer, 2005; Hmelo-Silver & Azevedo, 2006). In order to understand these processes, the students need to understand “causal interactions and functional relations between parts of the system and other systems” (Hmelo, et al, 2000, p. 248).
Several studies have examined the impact of engineering design activities embedded within science teaching and learning (e.g. Atman et al, 2007; Bers & Potsmore, 2005; Kilgore et al, 2007; Sullivan, 2008). Others have explored the potential impact of utilizing LEGO™ materials in the classroom, to engage and motivate students in science (Cejka, Rogers, & Portsmore, 2006; Rogers & Portsmore, 2004; Sullivan, 2008). In most cases, the use of LEGO™ materials is not a new experience for students, since many have played with LEGO™ building blocks, or some variation of the blocks, at some point in their lives. In this study, LEGO™ engineering materials were utilized as a familiar instructional tool to examine how students appropriate the principles of technology/engineering design in an elementary science classroom while learning science process skills and content around structures and forces. This study’s approach of incorporating design problems into elementary science reflects the theoretical perspective of activity theory.

Design curriculum represents the current trend away from traditionalist models of learning, which tend to be didactic in their approach. The traditional approach meant that knowledge was conceptualized and communicated directly from teacher to student. Instead, the engineering design principles are couched in a social constructivist approach where students are engaged as active participants in their own learning experiences, working with structures within larger systems.

Building upon the previous work of Roth (1996;1998; 2007), Crismond (2002) and others (e.g. McRobbie et al, 2001; Stein et al 2002), this study seeks to describe and understand elementary students’ learning and understanding of the complex systems involved in engineering design through the lens of activity theory (Vygotsky, 1978; Le’ontev, 1978). Students were presented with engineering design challenges, that allowed them to explore structural implications and the impact of forces within a larger activity system. The focus challenge in this study was as follows: Design and build a LEGO™ vehicle that is sturdy and able to withstand the forces associated with a crash into the wall. Evaluate the design of the device. This paper represents a study in the early development of a LEGO™ Curriculum (see Wendall et al, 2010) used to teach design principles, structures and forces to students at Grayson Elementary School (pseudonym) in the Northeast United States. In designing our study, we were guided by the following research questions: 1) What do elementary students know about engineers and engineering? 2) How do students use engineering design
principles to solve authentic complex system problems?; and 3) How do designed-based learning experiences play out in elementary science classrooms?

**Conceptual / Theoretical Framework**

The notion that engineering design problems can foster systems learning is supported by the theoretical perspectives of activity theory. The activity theory framework is “designed to be used to understand human activity situated in a collective context” (Yamagata-Lynch, 2007, p. 453), in this case the classroom. Activity theory allows for attention to broad patterns of activity, understanding user’s perspective and varied data collection; it can be used to analyze the successes, failures, and contradictions in complex situations without reductionist simplifications (Engeström, et al, 1999; Roth & Lee, 2007). The activity system is understood through examining the internal contradictions (Engeström, et al, 1999; Leont’ev, 1978). Based upon this starting point, we utilized activity theory as conceptual / theoretical framework of this study. Using activity theory as the conceptual/theoretical framework allows for a holistic approach to analyzing activity (Roth & Lee, 2007). We posit that engineering design is one kind of activity that reflects this construct through requiring both the use of science practices and science content knowledge in the creation of a final engineered project.

Activity theory (Vygotsky, 1978; Le’ontev, 1978) is a multi-disciplinary theory that uses a naturalistic emphasis in order to provide a framework that allows for the description of an activity and a perspective on how that activity can be linked to individuals and social interactions (Leont’ev, 1974; Nardi, 1996). When used as a descriptive tool, activity theory provides a set of basic theoretical concepts that allow researchers to understand the relationship between the mind and activity from which methods of analysis to understand activity can be derived (Bannon & Bødker, 1991; Nardi, 1996). Activity, in this instance is not simply “doing” as a separate stand-alone action, but rather “doing” with the intent of transforming an object within a larger activity system (Kuutti, 1996). An activity system includes the participants or subjects and the objects that they act upon. The relationship between the subject and the object is mediated by various factors that include tools, community rules, and division of labor. The objects transformed through these interactions can be materials, conceptual understandings, or other types of problems (Nardi, 1996).
As a conceptual framework, activity theory provides an ecological perspective of human activity, allowing for an analysis of human actions and interactions with artifacts created within a cultural, historical and environmental context. In activity theory, activity cannot be analyzed outside the context in which it occurs; it explains social and cultural practices in real-world contexts (Vygotsky, 1978). Activity theory emphasizes that all activity is mediated by tools which can be external (e.g. LEGO™) or internal (e.g. ideas). These tools will be socio-cultural specific in that they are influenced by and dependent upon both social experience and cultural knowledge. These tools are created and transformed over the course of an activity system and carry with them cultural-historical remains from the developmental process of inquiry.

The activity system is understood through the internal contradictions that emerge (Engeström et al, 1999; Leont’ev, 1978) with a focus on the elements of the system that promote or resist change. For example, in this study the subjects are the students and the objects they transform are the LEGO™ vehicles. The LEGO™ become the tools for this transformation, the engineering design principles are the rules and the labor is divided among group members to build the vehicle. The activity system consists of interaction among all of these factors that will come to bear on the activity at any given time (Cole & Engeström, 1994; Engeström et al, 1999). The system as a whole will represent the minimum unit of analysis which means that the subject, object, tool, division of labor, community and rules cannot be thought of independently from which the system that they are a part (van Eijck & Roth, 2008).

In activity theory, the community of the system is composed of individuals within the group who share the same tools and objects and are often defined by the way in which they divide their labor within the group. The components within an activity system do not exist in isolation, nor are they static, but are dynamic and continually interacting within the activity system. When examining any scientific phenomenon using an activity theory lens, it is important to examine the dynamics between all of these components within the system. Additionally, it is critical to recognize that activity systems are nested such that what is recognized as a tool in a current action may have previously been an object or outcome in a previous action. Activity theory focuses upon how participants within a group transform objects and how the components of the system help to mediate that transformation. It is this perspective that informed the analysis of this study.
When activity theory is applied to design activity, an individual’s knowledge about related science concepts can be appropriated to the tangible design products as well as to the others participation in the design process. From an activity theory point-of-view, we can further propose that design is based upon a situative, distributive framework (Driver et al, 1994; Greeno, 1998) that can characterize student learning as both a social enculturation into the practices of and construction around the ideas of design. We suggest that students can effectively learn about engineering design principles while they are engaged in solving authentic problems through writing with, talking with and physically using the cultural tools and symbolic resources connected with engineering design. Engineering design is an authentic activity that requires participants to use both practice and content knowledge associated with science and engineering. Design, in this instantiation, can be defined as the activity of creating plans for a product that solves an open-ended, ill-defined challenge (Dym, 1994; Simon, 1996). Building on this definition, engineering design is the organized development and testing, using scientific knowledge and models, of an artifact that has been created to perform a specific function without violating known, defined constraints (Davis & Gibbin, 2002; Dym & Little, 2004).

Because activity systems are characterized by contradictions or tensions that emerge from within the activity, when using activity theory as an analytical tool it becomes necessary to clarify and identify these systemic tensions and the role that they play in order to create a framework for a more focused analysis. In this particular instance, the focus is upon students’ learning and understanding of engineering and engineering design principles. Activity theory situates this by conceptualizing learning as practice and practice as learning (Engström, 1999) in such a way that context becomes the activity system that integrates the subject, object, tools, communities and rules into the larger learning experience. In other words, distinctions such as these found between practice and understanding or the individual and the context become inconsequential (Barab et al, 2002; Barab & Duffy, 2000). Practice becomes a part of these activity systems which integrate content, participants, objects, tools and communities with their rules and division of labor (Engström, 1993). By analyzing the sum of these components and the inherent tensions which exist, one can begin to understand how they influence the transformations the participants have on the objects. The intention of this study is to identify and examine specific instances that serve as exemplars of the broader issues at play within this classroom implementation of a LEGOSTM curriculum that impacted students’ learning about structures, forces
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and design principles. These exemplars will serve to provide teachers with the necessary tools and understanding of the classroom impact of a design curriculum within a science classroom. This paper addresses the tensions that emerged from the implementation of the design principles with diverse consequences from participants, their activity within their groups and our understanding of their participation in those contexts.

**Research Design, Methodology and Analysis**

This study uses both quantitative and qualitative data to provide a holistic view of students’ knowledge and understanding of engineers, engineering, and the design process. Data was collected from three primary sources: the Draw-An-Engineer Test, survey instrument; and ethnographic data. The data collected (1) documented the students’ conceptions about engineers and engineering; (2) captured their reasoning through the engineering design process; and (3) supported and refuted emerging hypothesis about students’ understandings and the tensions that emerged from the students’ work (Barab, et al, 2002). In analyzing the data, we utilized a naturalistic inquiry with grounded interpretations (Guba & Lincoln, 1983). Data analysis adhered to the domains of interpretive research that were iterative and inductive, including emergent analytic coding (Haney et al, 2004). The sections that follow address the context, design, methods and analysis used throughout this study.

**Study Context**

Grayson Elementary\(^1\) is an extended services elementary school in the Northeastern Public Schools system. Grayson is among the most culturally and ethnically diverse in Northeastern Public Schools. At the time of this study, Grayson had 211 students with thirty-six different languages spoken among the student population. Seventy-eight percent (78%) of Grayson’s students were learning English as a second language (ESL). During the time of this study, 49% of students identified as Latino(a), 23% as African American, 17% as Caucasian, and 11% as Asian. Eighty-five percent (85%) of the Grayson students met the federal poverty guidelines to participate in the free or reduced price lunch program.

Two mixed grade level classes participated in this study. Class A consisted of students in grades one through three (N=15, 5 small groups), while Class B (N=19, 6 small groups) consisted of students in grades

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\(^1\)Psedonyms were used for the school, district and student names throughout this paper.
four and five. The classes met with the school’s science specialist once a week for fifty minutes while this study was implemented over the course of six weeks. LEGO Mindstorms kits (RCX Blocks) were used for the implementation. The curriculum used in this study was an early iteration of the Transforming Elementary Science Education through LEGO Engineering Design (TESLED) (Wendell et al, 2010). The activities that were implemented during this study ultimately became a part of the simple machines module within the curriculum.

**Data Sources**

As previously noted, the data for this study was collected from three primary sources including a survey, drawings, and ethnographic data sources. Ethnographic data sources included direct observations of classes, field notes, digital video and digital audio recorded during the activity. The data were analyzed to identify development of design with respect to the ways in which students: 1) took up the practices (e.g. tool use, problem solving, student inquiry) and utilized the resources (e.g. tools, concepts implemented); 3) progressed through the designing and building of the stable vehicle; 4) engaged in the design activity; and 5) supported and/or refuted emerging researcher’s hypotheses about how practices, resources, task constraints, task manifestations, and student learning evolved over time during the course of implementation of the LEGO design project (Barab et al, 2002). Nine of the eleven groups of students who worked on the design challenge were ultimately successful in developing appropriate models for solving the design challenge. The researchers in this study functioned as participant observers in the classroom, sometimes taking on the role of the teacher/facilitator when working with or observing a small group of students.

*Draw-An-Engineer Test and Survey* - Prior to engaging in the design activity, we collected data on students’ understanding of engineers and engineering. The Draw-An-Engineer Test (DAET) was intended as an idea eliciting task. The DAET (See Appendix A) was adapted from the Draw-A-Scientist (DAST) developed by Chambers (1983). Both of these tests have their basis in Goodenough’s (1926) psychological tool entitled *Draw A Man* test. According to Chambers (1983), children’s drawings of scientists can be examined to identify specific attributes of a child’s mental image of a scientist. When drawings are collectively examined, stereotypical attributes or images emerge (Finson, 2003; 2009), revealing notions about a student’s embedded ideas (Finson, 2003; 2009; Osborne & Freyburg, 1987). Students were given a sheet with the
following instructions: “In the space below, draw an engineer doing engineering work.” In addition to the written instructions, students were also given the same directions orally to ensure that all students understood the task before them. The sheet consisted of a box for students to draw their image of an engineer. Students were encouraged to add notes about what their engineer was doing in their drawing. In order to ensure that students had ample time to complete their drawing, students were given approximately thirty minutes to complete the task.

In coding the drawings, we developed and used a checklist that came from emergent analytic coding (Haney, 2004). This checklist provided a set of features that emerged in analyzing the drawings of the students. Members of the research team independently reviewed student drawings, recording the various features of the drawings. Checklists were compared and condensed into a list of core codes. Raters worked to code features in the drawings that were either present or absent. Additionally, the raters looked for features that were present in the drawings but were absent from the code sheet. Coding results were then compared and formal descriptions were developed. For example, a drawing that included a person positioned over the engine or under the car was coded in the following way: Car = Artifact and Action =Fix/Repair. Codes were then grouped into categories such as mechanic, technician, train engineer. The process of independently constructing categories and reaching a consensus provided for a degree of triangulation that reduced the possibility of bias and subjectivity and thereby increasing the validity of our analysis (Lincoln & Guba, 1985). To ensure consistancy in the coding process, an inter-rater reliability of 0.9 was established. Cohen’s kappa was calculated to show that $k=0.84$ which indicates that the frequency with which raters agree is much stronger than chance alone. This kappa value indicates a strong agreement which correlates with the inter-rater reliability percentage.

In addition to the Draw-An-Engineer test, a survey (See Appendix A) was constructed to gain insight about students’ interest and attitudes towards engineering concepts. The survey data was analyzed using SPSS and correlated to the corresponding data for the drawings. This allowed us to look across the data to understand student thinking about plant structure and function both at a large and fine grain level. Descriptive statistics and frequencies were calculated across the surveys.
Activity Theory as a Tool of Analysis

Activity theory was used as both the theoretical lens and tool of analysis in order to examine the systematic tensions emerging within the classroom activity sets. The relationship of the participant to the object as it was mediated by the components of the activity system was examined. These components included: (a) the tools (the LEGO™), which were both human and technology based; (b) the classroom microcultures which demonstrated the emergent norms of the classroom activity; (c) the division of labor as indicated by the group dynamics and the student-teacher interactions and how these impacted the transformation; and (d) the rules which governed the activity, which, in this case, were the engineering design principles.

The classroom dynamics were analyzed by looking at a sequence of events or ‘nested activities’ using the visualization developed by Engstrom (1999) shown in Figure 1 below:

[INSERT FIGURE 1 HERE]

This diagram demonstrates that activity systems are complex formations in which equilibrium or balance is the exception; tensions, disturbances and local interventions are the rule that drive the transformation or appropriation (Barab et al, 2002). When this schematic is applied to the LEGO™ activity system the model is transformed to illustrate the activity system shown in Figure 2:

[INSERT FIGURE 2 HERE]

We examined actions, and in some cases sequences of actions, that allowed the framing of the activity with respect to the mediating tools (LEGOs™) and components of the activity system.

For this study, the goal was to use the overarching tensions as the framework of analysis for the classroom implementation of LEGO™ activity to teach principles of engineering design. In identifying these tensions, we examined field notes and conversations transcribed from video/audio recordings. Data artifacts were coded using grounded theory with a constant comparative method (Strauss & Corbin, 1998). Data analysis of these artifacts was an iterative and inductive process. In analyzing the data, we developed and used a list of codes for the tensions that emerged from open coding. Through the examination of the emergent

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2 Transcription was coded using Jeffersonian notation as described in G. Jefferson, “Transcription Notation,” in J. Atkinson and J. Heritage (Eds.), *Structure of Social Interaction*, New York: Cambridge University Press, 1984. See Appendix B for a key.
dialogue between the students and teachers through a constant comparative method (Glaser & Strauss, 1967), systemic tensions were identified as characteristic of the groups. Tensions were defined as dualities between two opposing forces which drive creativity and change within the activity system (Barab et al, 2002). Members of the research team independently reviewed transcripts and field notes and coded for emerging tensions. The team then came together to compare and condense code lists, creating a set of defined tensions. Raters then went back and coded further, using the defined set of tensions, looking for features that were present in the artifacts, but absent from the tensions code list. Coding results were compared a second time and a final formal description was developed for the tensions that had a high level of agreement. Discrepancies were discussed until consensus was reached. Once the common tensions were identified, a third round of coding occurred and an inter-rater reliability of $r=0.95$ was established. Data was triangulated across the data sources in order to increase trustworthiness and validate the findings of this study (Lincoln & Guba, 1985).

In the following section, we present our findings as two lines of data analysis and discussion. First, data derived from the Draw-A-Engineer Test (DAET) and interest survey will be analyzed. Second, we will use illustrative examples of student engagement as instances of learning about design principles. Examples provided were representative of the types of interactions that occurred with respect to each systematic tension among all of the groups. The results section will elaborate on these in detail.

**Results**

**Draw-A-Engineer Test and Interest Survey Analysis**

Prior to the beginning of the design activity, students were asked to complete two tasks. First, a survey was administered, modified from a previously validated survey (Moore & Foy, 1997), that gauged students’ attitude and self-efficacy with respect to science, engineers and engineering (Appendix A). Self-efficacy can be defined as a confidence or belief that one can achieve or complete a task. This builds upon the work of Bandura and colleagues (2001) who correlated students’ self-efficacy as predictors of children’s aspirations and career trajectories. According to Bandura (2001):

Perceived occupational self-efficacy gives direction to the kinds of career pursuits children seriously consider for their life’s work and those they disfavor. Children’s perceived efficacy
rather than their actual academic achievement is a key determinant of their perceived occupational self-efficacy and preferred choice of work-life (p. 187).

Following this line of inquiry, students were asked to draw (modified from Chambers, 1983) “an engineer doing engineering work.” Both of these instruments were used to gain insight into what prior conceptions and interests students had about engineers, and engineering. Our initial assertion was that students association with and understanding of engineers/engineering were vague at best. This was reflected both the survey and drawing results. This was problematic in the impact such an understanding could potentially have on goal setting and self-efficacy with respect to design and science learning. If students did not have positive models for learning, then they might be less inclined to pursue careers in science and engineering because they have not been exposed to situations where they are able to build their self efficacy in those disciplines (Bandura et al, 2001).

The codes that emerged from the analysis of the drawings could be grouped into two distinct categories: 1) What is the engineer doing? (action); and 2) What is the engineer using to do his/her work? (artifacts/objects). The codes were grouped based upon the recurring patterns that emerged from the analysis of the drawings. Three categories of characteristics that students assigned to their engineers became apparent. These codes were:

1. Conception 1: An engineer is a mechanic who can fix car engines or drives cars, trucks, or airplanes.
2. Conception 2: A engineer is a person who fixes or build things such as roads and buildings.
3. Conception 3: An engineer is a technician who fixes electronic equipment such as computers and televisions.

A fourth code was added after the analysis. This code was Conception 4: An engineer is someone who designs.

It is important to note that when looking at these conceptions, three of the four notions involve depictions of an engineer as a person who builds, fixes or works with engines, other vehicles, building or electronic equipment. Across the drawings one common theme emerged – the presence of an object or vehicle being “fixed” by the

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3 It should be noted that the DAET was given prior to beginning the design challenges. Students did not know that they would be asked to design a vehicle so as not to influence their drawing choices.
engineer. The fourth conception was added by the research team, but was not readily observable in the drawings by the students.

Conception 1: An engineer is a mechanic who can fix car engines or drives cars and trucks. For a large number of the students, an engineer is a person they associate with repairing, working on or driving a variety of vehicles including cars, trucks, trains and airplanes. Many of the drawings showed an engineer performing some type of manual labor such as working working under the hood of a car or driving some type of vehicle (87%). These students associated engineering activities with “fixing things” (63%) and connected engineers with being male (56%). It should also be noted that in thirty-seven percent of the drawings the sex of the person in the drawing could not be determined. Cars appeared in eighty-two percent of the drawings (See Figure 3).

Conception 2: A engineer is a person who fixes or build things such as roads and buildings: This conception can be differentiated from conception one by the emphasis on the action of the engineer and the artifacts that they use. In this case, students were drawing an example of a skilled laborer such as a construction worker (5%) or a plumber (5%). Students made consistent and strong connections between the “engineer” tradesman and the types of tools that they used to engage in their practice.

Conception 3: A engineer is a technician who fixes electronic equipment such as computers: Student drawings that fell into this category demonstrated a person who was working directly with some type of electronic equipment (e.g. television) or a computer (15%). These drawings implied that there was a needed skill in order to complete the task. It was also interesting to note the types of artifacts or tools that were present in these drawings including computers, software, and cords.

In analyzing the survey, ninety-percent of the students that responded either agreed or strongly agreed that they were generally interested in science and engineering topics. Similar positive responses were given when asked about the students’ desire to visit an engineer at work, read books about engineering, or watch television programs on the topic. However, despite these positive responses to the questions on the survey, when the same students completed the DAET the students’ drawings revealed alternative conceptions about the type of people in engineering and the nature of their work. In general, students were unable to provide
detailed information about the types of individuals who became engineers or what these engineers actually did. Students typically drew cars, mechanics, airplanes and in some instances included computers.

This analysis demonstrated that while students stated that they had an interest in engineers and engineering, their conceptual understanding of the types of individuals who are engineers and the nature of their jobs differed from traditional conceptions. These findings are similar to previous studies (e.g. Copaobianoco, Diefes-Dux, Mena, & Weller, 2011; Oware, Capobianco & Diefes-Dux, 2007; Cunningham, Lachapelle & Lindgren-Streicher, 2005; Cunningham & Hester, 2007) concerning students’ conceptions of engineers and engineering. These findings might have contributed to students initial difficulty in understanding the design principles being implemented to solve complex engineering challenges.

[INSERT FIGURE 3 HERE]

Activity Analysis of the Challenge – Building a sturdy and fast vehicle

Four dimensions of difference or systemic tensions emerged from the data collected during the LEGO™ activity study. Tensions were previously defined as dualities between two opposing forces which become driving forces for transformation and creativity in the activity system (Barab et al, 2002). The first dimension of difference, or systemic tension, that emerged resulted from students’ persistence of aesthetic features for their vehicle. This tension was apparent on the first day of the project when students expressed that they were going to “make their car look cool” during their pre-design planning. During data collection and the analysis process we identified numerous instances where this tension between design aesthetics and design functionality occurred. The second tension that surfaced related to the role of the individual versus the other activity groups. This tension occurred as students migrated between activity systems within the classroom environment. Like the first tension, this tension emerged from the start of the group formation. The third tension developed involved the group versus the physical classroom environment. In this instance, students would migrate between their group activity system to other constructs within the classroom. Finally, the last tension emerged from the interactions within the groups and the students’ roles within the group. Combining these tensions resulted in a framework to examine the potential for using LEGO™ robotics to teach the principles of engineering design. The following analysis looks at these tensions and the instances where they surfaced as exemplars of some of the broader issues that unfolded during the implementation of this project.
and impacted students learning and understanding of design principles. These tensions were common across all of the groups in the classroom. The exemplars presented represent the types of conversations that typified a set of practices within an activity group in each systemic tension.

**Systemic Tension 1 – Aesthetics Versus Function** - The first tension to emerge from this study was aesthetics versus functionality of the vehicle. In examining this tension, we provide example actions that represent what occurred across the larger classroom group. These actions help to illustrate how students focused on the aesthetics of their vehicle instead of being concerned with designing a car that was structurally functional and could withstand forces placed upon it. This tension was common across all of the groups within the classroom. Aesthetics became an important component in each groups final design and implementation.

The examples described below typify the types of exchanges that related to aesthetic features versus functionality. In this first example, Kevin and Joey focus on a specific part of the vehicle that they wanted to design around because they thought the LEGO™ part looked “cool” instead of finding parts which would help their design. While they had planned prior to beginning the building process, once they focused on the specific part the plans appeared to be forgotten. The following dialogue illustrates this point:

**Group A / Action A**

**Kevin:** So what are we going to do to make the car faster and stronger?

**Joey:** Put three wheels on the car (2 seconds) that would look good!

**Kevin:** Ummmm (.)Can you make the car bounce with these (picking up purple LEGO™ pieces that look like tubes), you know, like hydraulics?

**Mr. Smith:** Does that make the car faster?

**Kevin:** It makes it look good (picking up the pieces again)

**Joey:** It’ll be cool!

**Mr. Smith:** But does looking good mean that it is fast and will not break apart if it crashes?

**Joey:** But it’ll be cool! It’ll look the best – that’s what we want – <the best.>

**Mr. Smith:** If you want the best, you will need to have the car be able to withstand the force when it crashes, can it do that? Will it be stable?
Kevin: I don’t know (.) But it will look good (2 seconds) Maybe it will be strong too.

This dialogue portrays how easily the students were distracted from the initial design challenge of creating a fast, stable vehicle; they became more concerned with aesthetics and making a vehicle that “looked good.” Kevin was initially focused on the challenge of building a sturdy vehicle, but Joey immediately sought to enhance the aesthetics of the vehicle. He drew Kevin away from thinking about the vehicle design as a matter of function. Instead, by being focused on the aesthetics, the students forgot about the structural design of the vehicle. They were drawn away from the design principles or “rules,” creating a tension between rules and the object being transformed, the LEGO vehicle. Another example of the aesthetic tension is demonstrated in the dialogue between Diego and Ana. Like Kevin and Joey, Diego and Ana are focused on a design structure that enhanced the aesthetics of the vehicle as opposed to the functionality:

Group B / Action A:

Ana: I really like the wings we can add here (3 seconds) It makes the car look pretty!

Diego: I don’t want a pretty car = I want one that is cool! But we can use the wings, they are cool! IT MAKES IT LOOK LIKE OUR CAR CAN FLY!!!!!

Mr. Smith: That’s a nice looking car you have there, but does it go fast? Does it stay together if it crashes?

Diego: Of course it does = see it has wings, IT CAN FLY!

Mr. Smith: How do the wings help?

Ana: I don’t know = they’re pretty?

Diego: Ana, I don’t want a pretty car = I TOLD you I want a COOL car!

Mr. Smith: But does it go faster because of the wings Diego?

Diego: I don’t know, but it looks cool!

Mr. Smith: We need to think about how the car will be strong and stable and run fast too – don’t forget that while you are designing and building!
This exchange highlighted the tension which emerged when students skipped from the planning stage and moved straight to the building phase of the vehicle, or the object. In their excitement to utilize the LEGOSTM (the tools), students from groups across both classes followed this pattern. Lack of pre-planning and discussion about design with respect to object outcomes often became problematic during the implementation of these types design-based projects (Atman et al., 2008). As a result, a cross activity tension between the students and the rules for designing a vehicle was observed. This tension emerged when the students focused on the aesthetics of the vehicle as opposed to its functionality. The focus on aesthetics did not necessarily correspond to the design principles needed to design a stable vehicle (e.g. Hmelo-Silver, 2004; Stieff & Wilensky, 2003; Samarapungavant & Wiers, 1997). This was a dynamic in continual conflict with most of the student groups. As a result, a second tension between the rules of design and the community/class norms of the initial challenge become apparent.

Students became too immersed in the system versus being a deliberate designer, thinking about the outcomes of their design work. In both of these instances Mr. Smith (the teacher), as the mediator, attempted to re-direct both pairs of students back to the original object outcome, building a fast and stable vehicle. Instead of following Mr. Smith’s lead, both groups immediately went back to the idea of creating a “cool car.” Within these micro-scenerios, it did not necessarily mean that the structural issues of the cars were ignored; students would return to their design after completing an unsuccesful trial. It demonstrated, however, that the students did not always look past the surface features of their vehicles in their initial design implementations. This notion became important because it shaped how students understood and developed their own design practice as well as how they made meaning of specific engineering design situations with which they were presented (Atman et al., 2008). What resulted were multiple iterations in order to improve their final vehicle (Roth, 1998).

**Systemic Tension 2 – Individual Versus Group** - The second tension that emerged was the interest the individuals within the small groups had in other activity systems or groups existing within the classroom space. This type of interaction was common across all of the small groups within the classroom. Students moved between the groups for various reasons, with both positive and negative outcomes. Positive outcomes occurred when the students interacted with other activity sets (groups) in the classroom and were able to bring
information, ideas, and sometimes LEGO™ parts back to their own activity set. While this often helped
students to continue on within their own nested activity group, more often than not it resulted in the group
members losing focus on their own tasks. This cross activity system interaction is demonstrated in the
conversation shown below:

**Group C / Action B:**

**Devin:** How are we goin’ to stop the car from breakin’?

**Cory:** I don’t know (2 seconds) are you sure it will break?

**Devin:** yeah (4 seconds) I think we should °

(( Cory wanders away toward another group ))

**Cory:** Whatcha doin’? ((asking the group (Group A) situated next to his own))

**Joey:** We’re fixing our car – it broke when it hit the wall.

**Kevin:** Yeah, we need to make the wheels stronger so they don’t fly off, even if
our car looks cool () it’s the coolest () but it broke - so I guess we need to
start over ê ((continuing to work on his car))

**Cory:** ê Hey Devin, ((calling over to his own partner)) look and see what Joey is
doin!! Their wheels went flying off when it hit the wall- it was cool! Did
ya see that? Maybe we should make our wheels different - what do ya
think?

**Devin:** ((from across the way)) Look and see what they’re doing – maybe we should do that
too…..

Another example of this tension is demonstrated with Luis and Asad’s group shown in the dialogue below:

**Group D / Action B:**

**Asad:** I can’t believe our car broke again!! That’s THREE times now…..

**Luis:** I know - How come their’s didn’t break? ((points to Diego and
Ana))
Asad: I don’t know (. ) It has super powers? We need to make this better - Hey Luis, can you go get some more LEGO bricks from over by Mr. Smith’s desk?

Luis: ((Ignoring Asad, Luis wanders over to see what Diego and Ana are doing)) Whatcha doin’? ((asking Diego and Ana))

Diego: Putting the rest of our car together - IT IS THE BEST – NUMERO UNO!!! ((to Ana)) Let’s cross the LEGOs like this - that should make it stronger and then it won’t break as easy (when it hits the wall )

Ana: Ok, I’ll get some more LEGO pieces - we need a lot more. Luis, can you PLEASE move?!!!

Luis: D- why you crossing the LEGO bricks like that?

Diego: It makes the car better, it is harder to break if it hits the wall.

Luis: ↑ HEY ASAD! ((calls across the room)) Look at this – Diego and Ana have a good idea, maybe we should try this…

The result of these crossovers between activity sets are additional tensions imposed upon the overarching tensions which already existed. There was a new tension that was found between the subjects (the students) of the groups as Cory and Luis moved from their own activity sets to the sets occupied by Kevin and Joey (Cory) and Diego and Ana (Luis).

In the first instance, Cory engaged with Kevin and Joey to further develop his own group’s design. Kevin and Joey had already created a product outcome which, upon testing, had failed by breaking apart upon impact with an immovable object (Petroski, 1992). This failure resulted in Kevin and Joey’s attempt to re-design the vehicle, identify the reasons for failure, and to build a new end product (Kelley, 2001; Atman et al, 2008). Cory and Devin sought to incorporate the lessons Kevin and Joey had learned into their own initial design to create a stable structure that could withstand the forces placed upon their vehicle when it encountered an immovable object (e.g. a wall). Cory had observed their process, however, he and Devin still did not give much thought as to how these new ideas might impact their own construction and design. He did realize,
however, that the design changes were helping Joey and Kevin’s new design. The tensions that emerged between the activity sets resulted in the subjects of both activity systems communicating ideas about design that potentially resulted in an improved final product (Kelley, 2001; Atman et al, 2008).

As in the first example, Luis moved away from his partner, Asad, to engage the design ideas of Diego and Ana. Like Kevin and Joey, Diego and Ana participated in a re-design process to strengthen their design and build a new end product (Kelley, 2001; Atman et al, 2008). Luis brought the ideas of Diego and Ana’s design back to his group in order to incorporate what Luis perceived to be an improvement in the vehicle design structure. What both groups in the examples demonstrated in these system interactions was that there could be multiple solutions to their single challenge (Atman et al, 2008) and that the design process itself was a social activity, where everyone shared ideas to develop a better final product (Petroski, 1992).

**Systemic Tension 3 – Group Versus Classroom** - The third tension of focus that emerged was very similar to the second tension. In this case, however, the tensions were between the subject of the student activity set and the subject of the larger classroom activity set. This particular tension, however, was not common across all of the groups. Rather, it was focused upon two of the five groups in Class A and one of the six groups in Class B. Despite fewer students who were engaged with this tension, it is important to address when looking at the larger classroom implementation. As the students proceeded through their building process, there was much interest in other materials and constructs set up in the classroom as shown in the figure and dialogue below:

**Action C:**

**Mr. Cole [researcher]:**  
((Observation - Sam from Group A noticed the tornado in the bottle set up in the classroom near their group. He is intrigued by the apparatus as he is losing interest in their current progress on their lego car. He leaves his group to go and investigate.))

**Sam:**  
This is cool, how does it work again? ( (to no one in particular))

**Mr. Cole [researcher]:**  
((Observation – Anthony from Group F hears Sam’s comment and comes over to join Sam in order to show him how it works.))
Anthony: This is how it works – (shaking the bottle around) - It looks like toilet water! (referring to how the spinning action of the water))

In this example, the tensions between two separate activity systems were observed. The first inter-system tension existed between the subject of the student activity set and the subject of the classroom activity set. By being immersed in the classroom setting with the various science manipulatives out and available, the students, in this case, Sam and Anthony, were easily distracted into an alternative activity set (Tornado Bottles). While this classroom distraction still resulted in science learning at some level (in this case tornadoes), it was not the anticipated content learning of structures and forces that was associated with the intended design activity. Instead, the tornado bottle became their tool, but this tool was unable to directly help them with their stated goal of designing and building a fast, stable LEGO™ car.

This classroom distraction contributes to the second tension in this set between the Rules of the Group, which were dealing with the Design Principles, and the Tools of the Classroom Set, which were the classroom science activities (e.g. tornado bottles). In this particular instance, the tools of the classroom were set out for other classes during the design activity. While this was helpful for the teacher in his preparation for other classes, it provided a distraction for the students in this class. According to Mastropieri and Scruggs (2000), when classroom structures are not conducive to student learning, then students will lose focus on the intended tasks. In this example, while students were supposed to be actively building their cars, Sam was drawn away due to the structure of the classroom. This could be avoided in future implementations by restructuring the placement of materials within the classroom environment.

The third tension that resulted between the intended outcome of the original activity set, the creation of a fast and sturdy car, and the outcome of the classroom activity set which was, simply put, science learning. While the students worked on their own designs and methods in this process, the classroom environment, within which they existed, drew students attention away from their task. Hands-on activities have been shown to benefit all students (Grumbine & Allen, 2006; Scruggs & Mastropieri, 1994), however, specific classroom adaptations are needed in order to create an environment that helps all students focus on specific task (Mastropieri, & Scruggs, 2000). Classroom structure then becomes an important factor in the harnessing and
development of these tensions. When they are not, students will be drawn away from their task (the activity system) and lose the full impact of the learning experience (Mastropieri & Scruggs, 2000).

**Systemic Tension 4 – Individual Versus Individual** - The final systemic tension that emerged from this data set came from the interactions of group dynamics, also referred to as the division of labor or roles within the individual activity systems (Engström, 1987). Tension was created between the students of the activity set in their power struggle to appoint a “group leader” or “expert” to take charge of the group. While leaders naturally seemed to emerge, they were often forceful or seemingly independent in their leadership approach. This led to ‘bossy’ students emerging as was demonstrated in the interaction below:

**Group E / Action D:**

Jose:  
Aw man, you put the wrong thing on the front again… watch and learn

Antwan:  
((Stops what he is doing and defers to Jose who has taken charge of the direction of the group.))

**Researcher Note:** It should be noted that while Jose was seemingly bossy, he did listen to his group members, although indirectly. For example, when Antwan offers a suggestion, Jose initially ignores Antwan, but returns several minutes later to include Antwan’s original ideas.

A second example was observed in the Group F activity set:

**Group F / Action D:**

Anthony:  
I’m doing the engine - Navarro is doing the wheels

Marcus:  
No I want to do those!

Anthony:  
No, you did the bottom of the car, Navarro is doing the wheels

Navarro:  
Yes I want to do the wheels, but that’s not all!!!

**Researcher Note:** An important aspect here was that while these arguments were occurring, all of the students took turns with the car in this group, sharing parts and working towards the final end product of the car.

A third example is seen with Group A activity set (See Figure 7):

**Group A / Action D:**
Kevin: I think that it is important to make sure that we cross our bricks. If we do that, then when the car hits the wall hard – a REALLY strong force then it won’t break.

Joey: I think that is a good idea, but remember we still want to make it look good – what can we do for that?

Max: I agree with Joey about looking good, but we want it to stay together, what else can we do??

Kevin: Maybe make it thicker somehow? (( tries to show by putting some bricks together in the way that he is trying to describe ))

Researcher Note: This was one of the first times that this group began to work together.

They were sharing ideas, thinking about the forces impacting the car when it would hit a wall and how their design would impact that result. Students were trying to show what they meant by building a small version of the design aspect.

In the end, students had variable understandings about the success (or lack of success) designing and constructing the vehicles. This might be attributed to the way in which the labor was divided within the group during the design and building process. Since not all students worked on all parts of the vehicle, the complete picture of the process was sometimes lost with the students when they moved from the design phase to the construction phase and finally to the testing phase of the process. This lack of connection between the various stages indicated a need to help students to develop more effective ways to communicate their ideas and participate in a discourse with members of their group during the design process in order for all members to contribute to the final product in meaningful ways (Atman et al, 2008).

In the examples noted above, it became clear that Group A was beginning to understand this type of collaboration and discourse. The construction of the vehicle (the object or artifact) became the focus for the students’ discursive activity that allowed for the negotiation of shared meaning in the development of their vehicle. In the case of Group E and Group F their was an emergence of a leader who took charge of the design process, but neither group exhibited the type of discursive activity found with Group A, focusing on the impact of forces on their vehicle design. How students were able to “appropriate and use the language of
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engineering design” (Atman et al, 2008, p. 309) to participate in the discourse of their community/group impacted their participation in the process and their potential understanding of the design process (Atman et al, 2008; Cross, 2006).

Discussion

An analysis of our data demonstrated the tensions that emerged within the activity systems that students engaged. By using an activity theory framework to analyze the data components, how these students intentionally participated in the design process was examined. The tensions demonstrated how students not only interacted with their own groups (or activity systems), but also how they worked between groups (or activity systems). The factors involved (e.g. tools, community, rules and division of labor) influenced the design outcomes by the students as well as created additional tensions with the activity systems as demonstrated throughout the study. The simultaneous interaction of these factors created affordances that both enabled enhancement and sometimes limited the design process within a group (Barab et al, 2002).

This study focused on how the changes that occurred within these small groups, or activity systems, created (or inhibited) how students engaged with the design process in order to solve a complex systems problem. In this instantiation, creating a LEGO™ vehicle was mediated by the components of the activity system framework, mainly: the tools students were afforded (the LEGO™es); the microculture of the classroom (emergent norms); the division of labor (group dynamics and between group dynamics); and the rules that were established (design principles, formal rules, informal group rules and technical rules). All of these factors helped to support, or inhibit, students’ engagement with the design principles through their design and creation of the LEGO vehicle rather than the rote memorization of the principles. By participating in the process of design, students, over time, began to focus on the larger systems at play, the final product, rather than the simple components of the structures such as aesthetic features of the vehicle (Hmelo-Silver & Pfeffer, 2004).

Using design to solve complex system problems

What became apparent from the observation of small groups within the classroom was that the design process did not emerge from solitary ideas and skills, but were situated within interactions of the community, the materials and tools that were available to the students, and the previous design iterations represented from the work of the group (Roth, 1996). By participating in the design process, students were able to engage in the
creation of real world referents that were connected to larger complex problems (Jacob & Wilensky, 2006; Stieff & Wilensky, 2003; Hmelo-Silver & Azevedo, 2006). One issue that emerged during the process was that student drawings did not always resemble the vehicles being constructed and tested in the design process. Instead, designs that emerged into final products reflected the types of interactions and conversations that were occurring within and between groups of students.

What these factors (community, rules and division of labor) did not always support was the students’ development and appropriation of the language of design. Students often had difficulty verbalizing their design intentions to their group(s). “Conversations” would often consist of students demonstrating their ideas with the tools that were available to them. By having these tools (e.g. LEGO bricks, gears and motors) readily available, the students were often able to demonstrate the ideas they could not always verbalize. These interactions allowed them to not only see their ideas in actions, but to also begin to see the possible limitations of their designs. More authentic appropriation of design discourse could have been accomplished through increased engagement of the classroom teacher (the expert) with the students in utilizing this new vocabulary in these situations than what occurred (Roth, 1996; Stein et al, 2002; Hmelo-Silver & Pfeffer, 2004). Additionally, while there was some cross-activity system interactions through these conversations as was demonstrated in Systemic Tension Two – Individual versus Group, these interactions were often spontaneous and did not necessarily occur between all groups. De-briefing sessions at the end of the classes by the classroom teacher would help to bring all of the student ideas out into the larger conversations and design processes, allowing all students, and not just those who migrated between groups, learn from each other.

Experts and Novices in Complex Systems Thinking: Within the first systemic tension, aesthetics versus functionality, the role of the classroom teacher (the expert) could have been more developed within the activity system. In this instance, the teacher could have worked with the groups to engage the students in thinking about how their designs could be modified to create the viable end product, the vehicle, while still maintaining the aesthetics that were important to them in their design (McRobbie, Stein & Ginns, 2001; Vye et al, 1998). For example, we saw evidence that design and construction of the vehicle provided a means and opportunity for students to really engage in principles of design. This was demonstrated in Group A (Kevin and Joey) and Group B (Ana and Diego) in Action A, as Mr. Smith (teacher) attempted to engage both groups in discussion.
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about how their aesthetic choices impacted their functional design and final product. The students seemed to acknowledge that tension, but did not appear to address the impact of aesthetics on the function. Instead, both groups focused upon the vehicle’s aesthetic appeal. Students did not acknowledge that the aesthetics might interfere with the overall goal of the design activity. This highlighted the need for Mr. Smith to scaffold the design activity in order to re-focus the students on the structural design components. As the expert who was focused on the larger systems within the activity, Mr. Smith needed to scaffold the student thinking to move beyond simple structures into more complex systems that made up the final designed vehicle (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver & Azevedo, 2006). Without this scaffolding, the student groups would not necessarily be able to push their understanding beyond the level of the artifact to begin to focus on the forces impacting their vehicles (Fortus et al, 2004).

This relates to the previous work of Vye and colleagues (1998) who found that elementary students often have difficulty in anchoring new knowledge to an emerging understanding. The scaffolding by Mr. Smith would allow this thinking to emerge. What was seen, as students worked through the iterations, was that they began to think more carefully about the re-design process when the scaffolding occurred. This was particularly salient with Group A in Action D. Within this action, the students in the group (Kevin, Joey and Max) were beginning to account for the types of forces that impacted their vehicle (Roth, 1998). They had moved beyond the aesthetics conversation and were beginning to have meaningful interactions regarding functional design. This type of interaction needed to become the norm, rather than the exception between the activity groups.

It became the role and responsibility of the classroom teacher to help the emergence of this systematic tension by supporting students in developing their own constraints, whereby using the expertise of the teacher to push the vehicle creation in a manner that was consistent with and supportive of the design principles (Barab, Squire, & Dueber, 2000; McRobbie, Stein, & Ginnis, 2001; Hmelo-Silver & Pfeffer, 2004). In this way, the teacher became a secondary tool, the expert, in support of the student activity from outside the activity group. Without teacher intervention, students did not necessarily develop the understanding or the language to discuss interactions beyond the actual artifact being constructed (McRobbie, Stein, & Ginnis, 2001; Hmelo-Silver & Pfeffer, 2004). The community practice (norms, classroom microculture) embedded
within this activity system enabled this discourse between the students and the teacher to not only occur, but be sustained over a period of time (Erduran, Simon & Osborne, 2004).

While this tension of aesthetics versus function continued to exist throughout the activity and among the groups, it was important to acknowledge but not necessarily eliminate it. Instead, this tension needed to be balanced and harnessed in such a way that the aesthetics could facilitate students motivation and engagement with the design principles, creating the intended final product (the fast, stable vehicles), while still maintaining some aesthetic appeal. The aesthetic feature of the vehicles made the problems “real” for the students because they emerged as a goal for success that they had themselves determined (McRobbie, Stein & Ginns, 2001; Hmelo-Silver & Pfeffer, 2004). These results are similar to those of Schauble and colleagues (1991) who found that students often focus upon form over function when designing or building structures.

With respect to the systematic tension found between individuals and groups, Action B, the components that most directly impacted the activity system were the subjects, community, division of labor and the rules (design principles). Student movement between the group activity systems resulted in both positive and negative outcomes. For example, when Cory left his group (Group C) to join with Group A in Action B, it was because he had lost focus on his own group’s activity. While this was a negative outcome for the initial group (Group C), at the outset, it was positive in the sense that he (Cory) engaged with Group A (Kevin and Joey) about the logistics of their vehicle design. By asking questions and participating in the discourse of Group A, Cory engages ideas that ultimately contribute to a better design for his own group. In this instance, the learning environment allowed Cory to participate in the larger learning community where design practices and building resources were shared. Cory and his group were able to draw upon the expertise of their more knowledgeable other, in this case, their peers Kevin and Joey. This emergent student-directed learning and discourse between groups led to more effective communication within the community and across the activity systems as the construction of the cars continued (Barab et al, 2002;Taxen, 2003). This type of open-ended problem solving is what Zhang and colleagues (2006;2009) referred to as opportunistic collaboration.

As both groups worked through iterations of their designs, they began to see that solutions to problems in design could potentially be found in other activity groups. Students were able to look at design successes
and failures of other groups to help them in their re-design by incorporating lessons learned from others into their own vehicles. This re-design “co-opting” sometimes resulted in successful final products (Atman et al, 2008; Kelley, 2001; Roth, 1996; Stein et al, 2001). However, the successful re-design might not have been accomplished without the cross system dynamics exhibited in the classroom. In essence, this became a object driven learning experience (creating the vehicle) mediated by the subjects (students), community and rules (Engström, 1987; Le’ontev, 1974).

The tensions that emerged within the group activity systems, Action D, centered primarily on the division of labor and roles within each group. Students appeared to struggle with group dynamics and the leadership roles that emerged within each group. As the groups worked through the design process, it became important for the students within each of those groups to be able to negotiate and contribute ideas about the structural design of their vehicle. Conversations, and demonstrations, within the groups needed to reflect a negotiation of these ideas that would require other group members to become flexible, particularly when comparing alternative design perspectives. Leaders that emerged were typically the individuals who were able to convince the group to use their own specific design idea. Often the leader’s ideas were not based upon sound design principles, but rather about the confidence of the individual and the forcefullness of the approach as was seen in Group F’s (Action D) interactions. Students in the groups seemed to lack effective mechanisms for communicating ideas and participating in the ongoing discourse. This lack of a communication mechanisms resulted in only select members of a group contributing to the design and construction of the vehicle in meaningful ways (Atman et al, 2008). Conversely, Group A’s (Action D) interactions showed the Kevin, Joey and Max describing reasons for why they were making changes in their car design so that when the vehicle hit the wall, the force would not cause the vehicle to break apart. This lead to a richer discourse around the design that allowed for neogiation and framing of solutions to problems they faced in their designs (Roth, 1996). The emerging artifact (the vehicle) provided the students (Group A) with a focus for their discursive activities that allowed for the negotiation of shared meaning that contributed to the convergence of meaning about design, structures and forces within the collective group (Roth, 1998). As previously described with the first systematic tension, the role and responsibility of the classroom teacher could help the emergence of this system through supporting students by mediating their discourse and helping to direct students in such a
manner that all voices are heard in the design process. This would not only allow all student ideas to be heard, but would also direct the students towards their final objective (Atman et al, 2008).

Design is a social activity where collaboration and teamwork around a number of ideas is key to creating a successful end product (Petroski, 1992; Atman et al, 2008). Embedded reflection-in-action (Schön, 1987) would help to provide meaning to this activity. While students had design notebooks where they recorded their ideas, there no space for intermediary steps in the notebook that would have allowed for this reflection-in-action (Schön, 1987). Additionally, this activity emphasized the situated nature of cognition and meaning (Barab et al, 2002, Barab & Plucker, 2002) suggesting a “reformulation of learning in which practice is not conceived of as independent of learning and in which meaning is not conceived of as separate from practices and contexts in which they are developed (Barab et al, 2002, p.104).” By creating specific challenges, students were placed in the role of an engineer to design the most effective vehicle to meet the challenge. This allowed students to begin to place into practice the design principles an engineer would use in a manner that allowed for the learning to become part of the context of the activity. The drawback within this learning process emerged from the survey (Moore & Foy, 1997) and Draw-A-Engineer Test (Finson, 2003) that students participated in prior to beginning the design project. The vague understanding of the role of engineers and engineering seemed to persist throughout the learning process. One way in which this could be addressed is through exposing the students to career information within the activity in order to increase student understanding of the role of engineers within their communities and how they implement design principles. Through engagement with engineering practitioners during the learning experience, students would have a role model that would help to enhance their own perceptions and information about the activity they are participating in as well as exposure to careers and goal setting in science, engineering and the design process. This could potentially enhance their own attitudes and self-efficacy with respect to completing engineering design tasks.

Design Based Learning In Classrooms

The data presented in this study also suggests that it is important to look at the complexities of the dynamics of using design activities that exist within classroom environments. These dualities or tensions that arise can lead to outcomes which have not been anticipated, as was demonstrated in the Group versus
Classroom tension and the Individual versus Group (Group A / Group B) tensions previously described. The Group versus Classroom tensions (systematic tension three) resulted in students participating in science learning within the classroom structure; however, learning was not related to the assigned design challenge. The structure and setup of the classroom learning environment became a key element in engaging students in the activity. Classroom environments that are not structured for student learning will result in students losing focus (Mastropieri & Scruggs, 2000). In this study, Sam and Anthony both removed themselves from their activity group in order to engage with other science materials that were set up in the room (Action C). While science learning occurred, it was not the intended focus of the activity in which the students were participating.

The experiences within this study can alter how future studies are situated and put into practice within the classroom context, by creating environments where collaboration and scaffolding is a natural part of the process, resulting in richer discussions and guidance that lead to successful final products (e.g. Roth, 1996; 1998; McRobbie, Stein, Ginn, 2001; Stein et al, 2002). By harnessing tensions such as those described in this study (e.g. aesthetics versus function, individuals versus the group), teachers and researchers will be able to analyze their impact upon classroom culture and learning goals in both positive and negative ways (McRobbie, Stein, Ginn, 2001; Stein et al, 2002). Finally, it will be important in future studies to collect additional data as students proceed through the curriculum such as student interviews, post-tests and videotape of student interactions. This will allow for a more effective triangulation of data in order to provide a richer description of whether this type of LEGO™ activity is meeting the goal of teaching and engaging students with engineering design principles.

Conclusions and Implications

Situative perspectives suggest that learning and practice are inseparable from the contexts from which they emerge (Lave & Wenger, 1991). In this particular instantiation of the LEGO™ curriculum, we tried to account for context by situating the learning within a rich activity system – the engineering design process (Barab et al, 2002). The result of authentic situation was that the learning outcomes by the student participants were applications of the content, the construction of successful vehicles, and not just a rote memorization of the steps of design. All students benefited from the hands-on activities that allowed students to immerse
themselves in hands-on learning in such a manner that they became participants and not objects receiving information (e.g. Zuckerman, 1998; Mastropieri & Scruggs, 2000; Sandoval & Reiser, 2004; Grumbine & Alden, 2006). Through this LEGO™ design activity, the teacher and students created an environment that helped to support students to begin to understand the principles of design through the design, construction, testing and re-design of their vehicles. Through interactions within and between the activity groups, students began to develop effective ways to communicate their ideas and participate in the group discourse. This was particularly evident with Group A in Action D. While students did not always have the vocabulary to describe their ideas, they did have the ability to manipulate materials, use non-verbal gestures and handle objects in a manner that allowed them to convey their design ideas (Stein et al, 2002). Additionally, students began to think about the forces that impacted the structural design of their vehicles. Through the emergence of the activity systems, the students were able to begin to own the outcomes of their learning and progress toward a better and (eventually) deeper understanding of design principles and the science that helped to shape them. According to Lave (1997), “[t]he more the teacher, the curriculum, the texts and the lessons ‘own’ the problems or decompose steps so as to push learners away from owning the problems, the harder it may be for them to develop the practice” (p.33). In this study of the LEGO™ design project, the teacher, Mr. Smith, was the expert who worked to facilitate rather than transmit the knowledge goals of the larger complex system – to understand principles of design, structures and forces (Hmelo-Silver & Pfeffer, 2004). By participating in the system in this manner, the students were directed towards actions and design that helped them to begin to learn the intended content rather than focus only on the simple structures that made up the larger complex system (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver & Azevedo, 2006). The ownership of this problem by the students, through their pursuit of a design of their own choosing, provided them the opportunity to fully engage with and learn about the design process at a deeper level that what they would experience in more traditional, step-by-step experiences (Lave, 1997; Hmelo-Silver & Pfeffer, 2004).

We used activity theory as both a theoretical lens and analytical tool for understanding the tensions that emerged from the activity. This provided a mechanism where interactions with the system and between the systems were not viewed in isolation, but in concert as a means of demonstrating the complexity of the
learning that occurs in a classroom (Roth & Lee, 2007). By analyzing the class environment in this way, it allowed for an understanding of how systemic tensions lead to outcomes that were inconsistent or interfering with the students learning of engineering design. Additionally, these shed light on how to restructure the implementation of the rest of the LEGO™ curriculum to make it more effective. By working with the students as part of the larger system, it allows for the teacher to help alleviate frustrations in order that the interplay among the tensions (e.g. learning technology vs. learning design principles) can be facilitated to create a successful learning environment (Barab et al, 2002).

This analysis used activity theory as a way to attempt to demonstrate how this LEGO™-based curriculum supported the emergence of actions that transformed objects through which students, who participated in these actions, were able to begin to develop an understanding of design principles and the science that informed the construction of their artifact, the vehicle. The systemic tensions that emerged provided a framework to analyze the impact of using this type of curriculum within elementary classrooms. It also presented insight into the types of issues that often arise when implementing project based curriculum in elementary classrooms. By understanding and addressing these issues at the forefront, teachers can prevent difficult classroom environments and instead focus on the intended learning outcomes.

References


Running Head: ACTIVITY THEORY TO UNDERSTAND DESIGN


ACTIVITY THEORY TO UNDERSTAND DESIGN

of Learning Sciences, 15:1, 53-61.


Appendix A

In the space below, draw an engineer doing engineering work.
### Survey

<table>
<thead>
<tr>
<th></th>
<th>Here is a list of activities. Please fill in the circle under <strong>like</strong>, <strong>not sure</strong>, or <strong>dislike</strong> to describe how you feel about each of these activities.</th>
<th>Like</th>
<th>Not Sure</th>
<th>Dislike</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Visiting a science museum.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>2</td>
<td>Listening to a famous scientist or an engineer talk.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>3</td>
<td>Solving computer problems.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>4</td>
<td>Solving math puzzles.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>5</td>
<td>Visiting an engineer at work.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>6</td>
<td>Joining an invention club.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>7</td>
<td>Reading about science and engineering.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>8</td>
<td>Participating in an invention fair.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>9</td>
<td>Working as an engineer.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>10</td>
<td>Learning about energy and electricity.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>11</td>
<td>Creating new technology.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>12</td>
<td>Using a computer.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>13</td>
<td>Taking classes in science and math.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>14</td>
<td>Inventing.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>15</td>
<td>Watching science or engineering related programs on TV.</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
</tbody>
</table>
Here is a list of activities. Please fill in the circle under **I cannot, I don’t think I can, Not Sure, I think I can, or Yes I can** about how well you feel you can do the activity.

<table>
<thead>
<tr>
<th>Activity</th>
<th>I CANNOT</th>
<th>I DON'T THINK I CAN</th>
<th>NOT SURE</th>
<th>I THINK I CAN</th>
<th>YES I CAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Earn an A in math.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>2. Earn an A in science.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>3. Use a computer.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>4. Find information I want to learn about online.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>5. Invent something to solve a problem.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>6. Figure out the materials I need to buy for my invention and their cost.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>7. Figuring how long it will take to take the subway from Allston to South Station.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>8. Design and describe a science experiment that I want to do.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>9. Create a design for something I want to create.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>10. Predict the weather from weather maps</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>11. Construct and interpret a graph of rainfall amounts by state.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
<tr>
<td>12. Develop a hypothesis about why kids watch a particular TV show.</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️ ☀️</td>
</tr>
</tbody>
</table>