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Think-aloud Protocol Analysis as a Measure of Students' Science Learning through Design Assessment

Todd Kelley, trkelley@purdue.edu

Brenda Capobianco, bcapo@purdue.edu

Purdue University

A paper presentation at the National Association for Research in Science Teaching Annual Meeting, March 25-28, 2012, Indianapolis, IN

Abstract

Research has indicated that authentic engineering design tasks hold the attention and interest of students and can lead to deeper levels of science engagement (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Roth, 1996; 1997; 1998). However, there is a need for student assessments that can measure how students recall and possibly apply scientific concepts in the context engineering design-based tasks. Furthermore, there is a need for assessments that can identify students' transfer of learning from classroom to real-world science and engineering. One promising assessment methodology is the use of the concurrent think-aloud (CTA) protocol analysis (Atman & Bursic, 1998; Ericsson & Simon, 1993) to assess students' transfer of learning from classroom engineering design-based experiences. Although this assessment process is limited to small purposeful sample sizes, the technique allows researchers to observe in real time triads of students engaged in an authentic design task and identify which science concepts naturally emerge in the design team's dialogue. Using a coding process (Halfin, 1973), researchers in this study have successfully piloted a coding scheme for different cognitive strategies exhibited by elementary school students and furthermore, have systematically identified gaps and areas of overemphasis of the design process. Results were organized using frequency and percentages for time on code. Preliminary analysis of data collected from pilot studies indicated limited use of science terms within design thinking dialogue; however the science terms that did emerge were used accurately and appropriately. Implications of the study reveal that CTAs provide significant insight into students' design and inquiry thinking and if triangulated with other student measures, CTAs can enhance case study research.

Introduction

The current trend in K-12 science education is to infuse engineering practices as effective approaches for enhancing science education. More recently, engineering standards have become an integral part of the newly proposed *Conceptual Frameworks for New Science Education Standards* (NRC, 2012). This is compounded by newly adopted state-level standards that require students to engage in the engineering design process and/or explore the nature of technology and engineering practices. Underpinning these initiatives is the call for students to ask questions, define problems, develop and use models, plan and carry out design tasks, and use evidence based and newly acquired scientific knowledge to reason and argue for the best solutions to a problem (NRC, 2012). Assessment of these practices is both inevitable and undefined. Missing from the literature are systematic, purposeful attempts at assessing students' engagement in the engineering design process and more importantly, students' use of scientific knowledge in the process.

Interestingly, these reform efforts in science education parallel approaches taken by engineering education. Atman and Bursic (1994) argued that to improve the effectiveness of undergraduate engineering programs additional design- and project-based approaches to teach engineering design were warranted. Moreover, Atman and Bursic made the case that in order to determine the effectiveness of these curricular approaches, researchers must employ assessment methods such as the think-aloud protocol method. Atman and Bursic used think-aloud verbal protocol analysis to assess students' design processes, specifically to study how undergraduate engineering students solved open-ended engineering design problems. In this study, we explore the use of the think-aloud protocol as a methodology to explore how students engage in the engineering design process and make references to science concepts that emerge in students' dialogue. .

Purpose of the study

The primary purpose of this study was to examine the implementation of the think aloud protocol as a methodology for determining students' abilities to engage in the engineering design process. Researchers employed this method in an effort to identify and classify key reasoning skills students used while engaging in an authentic engineering design-based task. Furthermore, researchers attempted to identify key science concepts students used during the process as a way of shedding light on whether or not students can transfer scientific knowledge from a whole class design-based experience to a small group transfer application.

Research questions

The questions guiding this study include the following:

1. How do grades 5-6 school students conceptualize and learn design?
2. Which aspects of the engineering design process do students tend to emphasize?
3. Which aspects of the engineering design process do students tend to overlook?
4. Do students use or apply scientific concepts while engaged in the engineering design process?

Theoretical framework

The research frame for employing a think-aloud protocol in conjunction with a transfer problem is based on the *transfer of learning* theory (Bransford, Brown, & Cocking, 1999). Transfer of learning is a theory that provides students the opportunity to transfer existing and newly acquired knowledge to new situations. The transfer of learning theory suggests that when transfer is identified, it is an indicator of understanding. Royer (1986) expresses the theory this way: "Used as an index of understanding is equivalent to the idea that the ability to *transfer* learned information is evidence that understanding is present" p. 95. Royer also indicates that *near transfer* occurs when problems are solved that are similar to those problems encountered previously. A near transfer approach was used in this research study.

Students participating in this study are engaged in authentic engineering design activities. Students are grouped into design teams by the teacher and openly share individual design ideas with their design team and later report out to the entire class (community of

learners). As a whole class, students are encouraged to ask challenging questions about their design ideas and those of other design teams, thus, allowing each individual to build their own understanding of science and engineering design.
Unique to this study is the application of the think aloud approach whereby students are exposed to a new task (transfer problem) in a smaller group setting away from the entire class. Researchers carefully examine if and how students use, apply, and transfer what they learned in their entire class setting in this smaller context. This learning may include key engineering and science practices as well as scientific concepts.

Science Learning through Engineering Design Partnership

The context of this study is a recently funded Math Science Targeted Partnership entitled *Science Learning through Engineering Design* (SLED) (see: http://www.sledhub.org). The partnership entails a collaborative effort across four colleges within a large, research-intensive university and four school corporations in the central Midwest. The primary aim of the SLED Partnership is improve grades 3-6 student achievement in science learning through the engineering design process. Over the course of five years, approximately 100 preservice and 200 inservice teachers and over 5,000 grades 3-6 students will participate in the partnership. For the purpose of this study, researchers analyzed data for the first year of implementation of the SLED initiative that focused primarily on grades 5-6 students.

Context of the Study

This research study was drawn from emerging urban school district positioned in the north central Midwest. In the 20010–20011 school year, there were 7,075 students enrolled in the school district, with 59.5% of the student population identified as White/ Caucasian (INDOE 2012). The school district had 20.5% Hispanic, 12.3% Black/Non-Hispanic, .7% Asian, 6.6% multiracial, and 0.4% American Indian, with just over 60% on free- and/or reduced-lunch. During the 2010-11 school year, there were 1,008 students enrolled in the grade 5-6 middle school (SLED school site #1), with 59.9% of the student population identified as White/ Caucasian (INDOE 2012). The middle school had 18.1% Hispanic, 13.4% Black/Non-Hispanic, and 7.7% multiracial, .4 % American Indian, just over 60% on free- and/or reduced-lunch.

Participants

This study used *criterion sampling,* a participant sampling process that selects cases to satisfy a specific criterion. The criterion sampling method is used in many research studies investigating educational programs (Gall, Gall, & Borg, 2007). Participants for the think-aloud protocols were purposefully selected by the SLED teachers. Teacher recommendations were based upon: a) students' ability to express themselves verbally, b) student record for successfully functioning as a contributing member of a design team, c) the student's willingness to volunteer for the study, d) returned the required university internal review board (IRB) parent consent form. Triads of student design teams were created for each SLED classroom participating in the research. Welch (1999) suggests that paring or grouping student participants allows for the design process to emerge naturally as most design efforts occur in groups of two or more people working together. All groups were heterogeneous, similarly to how most groups were formed in their classrooms. Table 1 outlines the distribution of students by classroom and within each triad selected from its respective class at school site #1. For example, Classroom #1 has a total of 53 students and one male student and two female students were selected as a triad.

Table 1.

Classroom demographics: class size and gender information for triads

Classroom	1	2	3	4	5	6	7
Total classroom size	53	52	46	53	53	59	45
Demographics of triads	1 M 2 F	2M 1F	2M 1F	1M 2F	2M 1F	1M 2F	2 M 1F

Data Collection

Overview of Concurrent Think-Aloud Protocols

Concurrent think-aloud protocol (CTA) is a research methodology that requires one or more participants to speak aloud his/her thoughts as he/she performs a task or activity. CTAs began as a popular methodology in cognitive psychology (Cooke, 2010). Some early examples of CTAs include the work of Otto Selz in the 1930s who investigated creative thought processes of individuals, and later in the 1940s de Groot used the think-aloud method to study cognitive strategies employed by expert chess players (van Someren, Barnard & Sandberg, 1994). Ericsson and Simon (1993) assert that concurrent think-aloud and talk-aloud verbal reports are the closest reflection of cognitive processes of individuals not modified from their natural state, making it an excellent research methodology to understand human cognition. Ross (1984) employed verbal protocols to discover that participants are capable of retrieving previously encountered problems and solutions to those problems when presented with similar but different new problems. van Someren, et al. (1994) theorized that think-aloud methodologies are easier approaches for a participant to engage in naturally when compared to more structures elicitation techniques because the participant is able to use their own language within their own natural dialogue.

Allowing students to communicate their design thoughts in a natural way is critical when working with younger aged children; it removes the risk of the researcher imposing upon the participant natural cognitive strategies while designing (Ericsson & Simon, 1993). van Someren, et al. provide discussion on the difficulty of understanding the thought processes of designers. They cite examples of research on professional designers such as architects require methods beyond interviewing an architect how he or she goes about designing. Designers, even experts with multiple years of experience struggle to self-reflect on the thought process employed while designing. Furthermore, van Someren, et al. also indicate that looking at drawings of the architects also provide only limited understanding of the process taken in designing because the researcher is looking at a design ‘product’ instead of the process itself. The order of approach to design is also important in understanding how the designers will lead to a design solution. Atman and Bursic (1994) endorse the power of using think-aloud protocols:

> By measuring both the ‘product’ and the ‘process’, we can then explore whether a relationship exists between the type of process a student uses and the quality of the final design. Knowing this relationship, we can then distinguish between good and poor

> processes and indicate specific problems that must be addressed as we teach design. (p. 130)

Dorst and Cross (2001) identified that designers navigate back and forth from *problem space* to *solution space* as the designer works through the design process. The problem space is the phase of the design process where the designer focuses on understanding the problem itself. It is the “what am I asked to do?” question that students often ponder when presented with an assignment. In the think-aloud protocol session, the participants are working within the problem space when they are reading and re-reading the transfer problem, seeking to identify constraints and criteria, asking questions about the problem, any dialogue where the participants seek to clarify the assigned task (Cross & Dorst, 1999). Understanding the thought process of a designer requires a concurrent study of the designer while the individual or teams of designers are engaged in the design process.

Donovan, Bradford, and Pellegrino (1999) state that research on experts has revealed that when given the opportunity to speak aloud their thoughts, they were able to express their conceptual understandings and reflect on prior experiences as they developed deeper understanding.

> In research with experts who were asked to verbalize their thinking as they worked, it was revealed that they monitored their own understanding carefully, making note of when additional information was required for understanding, whether new information was consistent with what they already knew and what analogies could be drawn that would advance their understanding. (p. 13-14)

The think-aloud protocol method may provide greater insight into how students are learning engineering design and science inquiry as they tap into to their meta-cognition and make meaning of their experiences individually and as a community of learners within their design team. However, working with elementary children poses some difficult challenges when seeking to understand how they engage in design. Do elementary students have the capacity to express the nature of the thought process taken when creating a design? Are elementary students cognitively developed enough to tap into their meta-cogitation in order to self-reflect on prior design experience? These are possible limitations of research methodologies that require students to metacognitively retrieve and reflect on prior learning experiences. Researchers in this study employed concurrent think-aloud protocols to allow the young designers to cooperatively engage in a design task in a similar way that the original design task was presented to them. This research methodology allows the participant to naturally reflect upon their existing knowledge of science and engineering design and model their approach to design.

Think-Aloud Instructions

Ericsson and Simon (1993) identify there are three different levels of verbalizations used in the think-aloud method. Level one requires the participant to simply vocalize their thoughts about a particular subject or problem presented. Level two requires participants to verbally explain their thoughts as they work through a problem or task. Level three requires participants to also explain their thoughts but additionally to link the current problem or topic presented to previous thoughts or experiences that relate to the current problem. This study employed a level three approach to identify transfer of knowledge occurring in student dialogue when students are presented with a similar design challenge to the classroom-based design activity.

There are a variety of approaches to providing instructions for the protocol session range from simply requesting participants to speak aloud their thoughts to requiring participants to explain the approach they are using (Dunker, 1926; Ericsson & Simon ,1993 ; Patrick, 1935; Smith, 1971). Researchers in this study purposely requested participants attempt to explain how they would design a solution to a transfer problem. Researchers instructed participants to use their science knowledge obtained from their experiences with the SLED activity and explain how they were addressing constraints and criteria within the design problem. Furthermore, participants were asked how they might test design solutions generated. This complementary instruction was important for the research findings to determine if students transfer their understanding of science content to create prototype testing procedures such as a fair test to assess the effectiveness of final design solutions. Studying these dialogues of student designed fair-test investigations of design solutions was critical in understanding how students navigate between science inquiry and engineering design.

Transfer Problems

Robertson (1990) defines transfer problems as “problems that are structurally, but not conceptually unfamiliar to the solver-have long been used as a measure of understanding” (p. 253). When creating the transfer problem, careful consideration in crafting a problem statement that provides an opportunity for participants to transfer their science knowledge obtained from the activity is critical. Furthermore, the transfer problem must be authentic to design. Cross (1994) argues that all design problems have a) a goal; b) constraints to work within; c) and criteria to determine an achieved successful solution. The transfer problems were created to share characteristics of an ill-defined, complex, situated, and dynamic design problem as defined by Jonassen (2000). Researchers in this study also developed authentic design transfer problems using these features described by Cross. Careful consideration was also taken in selecting a context to which students could relate as well as excite and inspire students. Transfer problems created for the study included scenarios describing situations that students might experience in their daily lives as the context for the transfer problem. For example, one transfer problem described two siblings who get a Frisbee stuck in a tree and want to develop an effective way get it down. The transfer problem encouraged the students to use their knowledge from the classroom activity to devise a solution to help the children retrieve the stuck Frisbee. The scenario was created as an authentic life experience where students could self identify and in a context to which they could relate.

SLED School Site #1

Think-aloud protocol sessions were conducted in each classroom for each implemented SLED activity. Currently, a total of 21 CTAs have been collected for the SLED project, with an estimated goal of over 30 protocols collected during the 2011-2012 school year. This paper will present the CTA data collected at school site #1 from seven classrooms observing seven design teams. The SLED activity *Prosthetic Leg* was implemented across all 5th grade classrooms at school site #1. This mass implementation provides and excellent opportunity to compare CTA data across multiple classrooms at the same school, during the same time of the school year.

Each CTA session began with one member of the triad design team reading aloud the transfer problem statement. A video camera recorded students’ dialogues as well as non-verbal communication that occurred during the transfer problem session. Each videotaped CTA session was review by researchers and coded according to the various cognitive strategies employed by students as they worked to create a design solution. The cognitive strategies were organized by frequency of use and time on code. Additionally, participants were given sketch paper, allowing each participant to graphically communicate their design ideas. Design sketches were digitally scanned, labeled and including in CTA data files to provide additional evidence for analysis of protocol sessions.

SLED Activity: Prosthetic Leg activity

The prosthetic leg design activity required students to work in teams to build a model of a prototype for a prosthetic leg to function like a human leg joint and strike the ball. Lessons for the prosthetic leg included information about the human musculoskeletal system as well as recent developments in prosthetic technology. The students were given some basic model building materials and common fasteners to create the model to kick a plastic golf ball. Similar model building tasks have been developed to teach about human musculoskeletal systems and the functions of a human elbow (Penner, Giles, Lehrer, Schauble, 1996).

Transfer Problem: Paper Football kicker

The transfer problem for the prosthetic leg activity was created to allow students to apply their knowledge about prosthetics as well as their science knowledge about the human musculoskeletal system. Think-aloud protocol participants were required to design a device that will mimic a human finger flicking motion to “kick” a paper triangle football to propel it through a model football goal post at various distances, see Appendix C. Student participants were also required to consider how the device would be tested to determine the effectiveness of the design. Again, the transfer problem was created in a context that students could relate and identify while also providing opportunity to apply science knowledge related to prosthetics.

Retrospective Reports

Ericsson and Simon (1993) suggest using retrospective reports that require the participant to report out about the protocol session directly after the think-aloud protocol occurs. Researchers investigating the effects on the SLED project discovered that additional information about the participants’ thoughts on the transfer problems was necessary. Retrospective reports were necessary for this research study in order to provide additional prompts to participants in order to allow reflection on recently obtained science knowledge, thus, allowing the participants to express their understanding of these concepts as they relate to the transfer problem.

Data Analysis

Halfin (1973) used a Delphi method to identify the cognitive strategies universal in the works of ten highly successful professional engineers and inventors. Halfin studied the writings of such well-known designers as Frank Lloyd Wright, Orville and Wilber Wright, Buckminster Fuller, and Thomas Edison to name a few. Halfin’s research findings generated a list of 17 cognitive strategies commonly used by designers. The Halfin’s cognitive strategies list created the defined coding categories for data analysis of this study as suggested by Merriam (1998). Using this methodology allow the researchers to investigate students’ ability to transfer their design and problem solving capabilities to a transfer problem (an open-ended, ill-defined problem). See Appendix A for a list of commonly used Halfin codes and definitions.

Table 2.

Cognitive Strategies (Halfin Code) by total time (minutes) on code

Classroom 1 AN: 01:11.3 CO: 00:46.4 DE: 15:40.3 DF: 03:00.5 MO: 01:42.8 PR: 01:29.1 QH: 01:47.6 Total: 25:38.0	**Classroom 2** AN: 03:26.8 DE: 13:20.2 DF: 02:22.2 MO: 01:10.4 PR: 02:12.1 QH: 01:22.5 Total: 23:54.2	**Classroom 3** AN: 01:08.1 CO: 00:02.4 DE: 15:15.4 DF: 03:57.9 MO: 00:39.2 PR: 00:42.8 QH: 00:59.8 Total: 22:45.6	**Classroom 4** AN: 06:51.9 CO: 00:04.7 DE: 15:11.6 DF: 04:58.6 MO: 00:43.5 PR: 01:24.6 QH: 00:52.2 Total: 30:07.2
Classroom 5 AN: 01:07.0 CO: 00:31.8 DE: 07:50.4 DF: 03:02.5 MO: 01:33.0 PR: 01:02.7 QH: 01:45.9 TE: 00:16.7 Total: 17:10.0	**Classroom 6** AN 02:38.7 DE: 07:29.0 DF: 02:43.8 MO: 02:05.4 PR: 00:31.6 QH: 01:06.4 TE: 00:52.1 Total: 17:27.0	**Classroom 7** AN: 04:20.7 CO: 00:04.7 DE: 03:24.7 DF: 05:42.5 MO: 00:04.7 PR: 00:38.9 QH: 00:45.6 TE: 00:50.1 Total: 15:51.9	

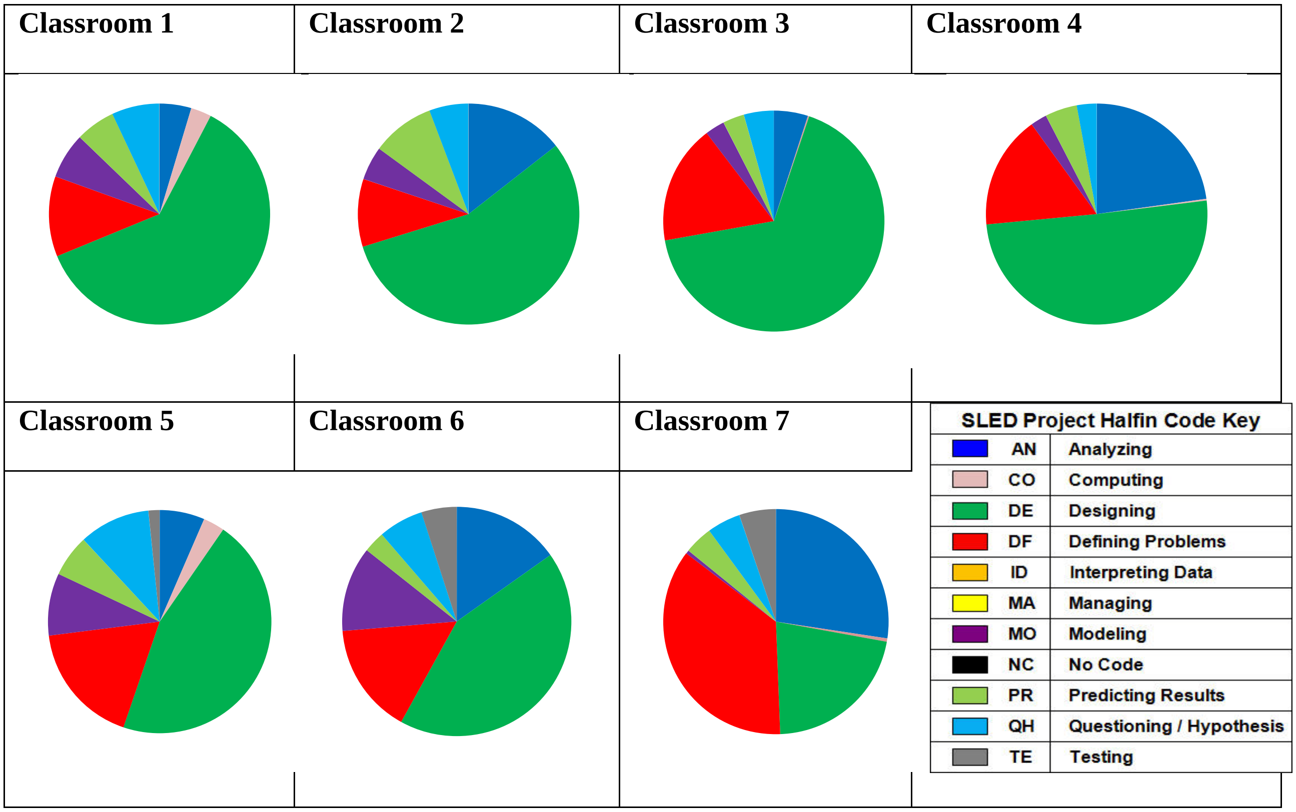

*Figure 1.*Coded results of cognitive strategies for % time on task for the prosthetic leg activity.

Figure 1 shows a general pattern of cognitive strategies for the seven triads of 5th grade student design teams across seven classrooms, one triad per classroom. The Halfin code key at the bottom right of the figure provides identification of 11 of the Halfin codes used by participants. Reviewing the pie charts, readers will note important cognitive strategies that indicate problem spaces and solution spaces of the design process (Dorst & Cross, 2001; Kruger & Cross, 2001). Color code red indicates *Defining the Problem* (DF) and *Analysis* (AN) is coded dark blue, these two Halin codes represent participants working in the problem space of the transfer problem, thus, working to understand the problem and identify constraints and criteria. Color code dark green indicates Designing (DE) and indicates the solution space where students are brain storming and refining design solutions. Classrooms 1- 6 yielded ranges from 43- 67 % for DE (designing) and 10% - 18% for DF (defining the problem) and 4 -23% AN (analysis). The exception to this was the design team for the classroom # 7. Classroom # 7 participants spent much more time in the problem space, resulting in 36% of their time defining the problem, 27 % of their time analyzing and only 22 % of their time designing. For a closer look at the results between Classroom # 7 and the other participating classrooms, mean scores were generated for classes 1-6, with DE = 49%, DF = 12.8 % and AN = 20.8 %. In summary, Classroom # 7 spent over 2.5 times more in the *problem space* compared to the other participating classroom group mean scores and less than half the time in the *solution space* when compared with the group mean score percentages. An interesting distinction between the classroom #7 teacher and the other SLED teachers is that she has extensive experience (over five years) teaching science through a design based approach. During the transfer problem session for classroom #7 students, the SLED researchers noticed that the design team immediately moved into the problem space by first defining the problem. Each design team member created a one sentence statement that defined the task within the transfer problem. The design team worked cooperatively to refine this statement until all members of the team were satisfied with the problem statement. Next, classroom #7 design team created a list of materials that they would need to address the problem. The design team also sought to identify the client and user within the transfer problem. Throughout the think-aloud session, the design team members were revisiting these statements as well as ensuring that they were meeting the identified constraints and criteria. Although classroom #1-6 design teams also addressed these phases of the problem space at some point within their dialogue, classroom #7 design team began in the problem space to ensure that all design ideas would specifically address the problem. Classroom # 7 also used the least amount of time of all the sessions for a total of 15:51 minutes, working efficiently to complete the task. The SLED researchers used the retrospective session after the transfer problem session with classroom #7 students to gain more insight on the strategy used by the design team. The design team responded that they were taught to ask the following questions: “What is the problem?; What are the materials?; Who is the client?”. Atman and Bursic (1998) suggest that it is critical to identify how students engage in problem scoping within the design process. Classroom # 7 design team effectively engaged problem scoping and was a prime example of a triad of students moving into expertise level of designing.

Limitations to the Study

There are three distinct limitations to the study: 1) amount of data collected; 2) level of analysis completed thus far; and 3) fidelity of the protocol. More data needs to be collected in order to make firmer assertions. Additional analysis needs to be conducted to support claims with evidence. The existing protocol needs to be revised such that emphasis is placed more on students’ engineering thinking rather than science conceptual understanding. Additional attention should be given to using alternative data methods (open response questions) as a supplement to the think aloud protocol to strengthen the assessment of student’s knowledge of science content. For example, one participant from a triad could be asked an open response question that forces the student to use existing scientific knowledge to answer the question. This data could be triangulated with data from the protocols, providing additional emphasis on science content knowledge (and not be confused with inquiry or design).

Conclusions and Implications

The purpose of this study was to employ a concurrent think-aloud protocol as a methodology for identifying students’ cognitive abilities while engaged in an authentic engineering design-based task. Cognitive strategies of participants were categorized and organize to identify patterns design thinking and problem solving reasoning. Additionally, researchers attempted to identify key science concepts students used during protocol sessions to identify if students possess the ability to transfer scientific knowledge from SLED design-based class experiences to a similar design problem. Research findings from this study indicate that participants applied multiple cognitive strategies as they developed design solutions in triad design teams. Each design team in this case example navigated through the design process moving from the problem space to solution space without becoming “stuck” in one design space.

This finding would indicate that students have learned how to successfully navigate through the design process by defining the problem, identifying constraints and criteria, moving to brainstorming multiple solutions. However, findings also indicate that science concepts did not naturally emerge in student's dialogues during protocol sessions. More research is necessary to determine what science concepts were retained and became a part of their language. Although some science processes such as prototype testing (Halfin code TE, coded gray) emerged in the dialog of some triads (classroom #5, #6 , and #7) an indication of knowledge of inquiry practices, most triads did not use specific science terms or concepts in their design thinking dialogue. This finding indicates that more student knowledge assessments are necessary to follow up the CTA sessions such as open response assessments that force students to apply science conceptual understanding.

The findings of this case example indicate that CTAs provide insight into the thought processes that students employ when using engineering design; although additional data would need to be collected on SLED teachers in order to link the CTA findings to classroom practices. Some triads (Classroom #1, #7) indicated during the retrospective interviews that they were using the same approach employed by their teachers in their science classes. Further investigation comparing teacher data would be necessary to confirm these student statements. Some participants even imposed constraints such as cost of materials; a constraint created by their teacher or selected only materials that they used in the SLED activity even though these constraints were not specifically identified in the transfer problem. These are strong indicators that students were attempting to transfer their classroom experiences to the transfer problem session.

The implications of these finds indicate that more work needs to be done to ensure that students can identify the science content embedded within an engineering design activity. Furthermore, using a CTA as an assessment approach to measuring science learning has its limits and cannot be administered an entire classroom population. However, these findings indicate that it provides an assessment of high level cognitive achievement that emerges through students' cooperative design dialogues. Although opportunities to address all phases of the design process are not possible during a twenty to thirty minute think-aloud design session, observing how participants framed the problem critical and is a key stage to understand the process of designers (Dym, Agogino, Eris, Frey, & Leifer, 2005).

Acknowledgements

This work was made possible by a grant by the National Science Foundation (DUE 0962840). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Appendix: A

Cognitive Processes identified by Halfin's 1973 Study of High-level Designers
(nine of the 17 total codes that emerged in the CTA sessions)

Proposed mental methods		**Definition**
Analyzing	AN	The process of identifying, isolating, taking apart, breaking down, or performing similar actions for the purpose of setting forth or clarifying the basic components of a phenomenon, problem, opportunity, object, system, or point of view.
Computing	CO	The process of selecting and applying mathematical symbols, operations, and processes to describe, estimate, calculate, quantity, relate, and/or evaluate in the real or abstract numerical sense.
Defining problem(s)	DF	The process of stating or defining a problem which will enhance investigation leading to an optimal solution. It is transforming one state of affairs to another desired state.
Designing	DE	The process of conceiving, creating inventing, contriving, sketching, or planning by which some practical ends may be effected, or proposing a goal to meet the societal needs, desires, problems, or opportunities to do things better. Design is a cyclic or iterative process of continuous refinement or improvement.
Interpreting data	ID	The process of clarifying, evaluating, explaining, and translating to provide (or communicate) the meaning of particular data.
Modeling	MO	The process of producing or reducing an act, or condition to a generalized construct which may be presented graphically in the form of a sketch, diagram, or equation; presented physically in the form of a scale model or prototype; or described in the form of a written generalization.
Predicting	PR	The process of prophesying or foretelling something in advance, anticipating the future on the basis of special knowledge.
Questions/hypotheses	QH	Questioning is the process of asking, interrogating, challenging, or seeking answers related to a phenomenon, problem, opportunity element, object, event, system, or point of view.
Testing	TE	The process of determining the workability of a model, component, system, product, or point of view in a real or simulated environment to obtain information for clarifying or modifying design specifications.

Appendix B

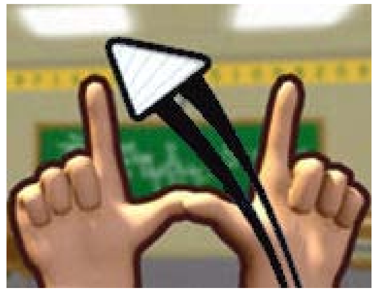
Design a Prosthetic Leg to Kick a Soccer Ball

Boiler BioTech, a company in Warsaw, Indiana, needs assistance in designing a leg for a young child. The prosthetic leg will need to be designed so that it will be able to kick a soccer ball. Everyone faces challenges every day. To help us, engineers have designed glasses for people who need help seeing, hearing aides for people who need help hearing, crutches and canes for people who need help with bearing weight, and artificial limbs for people who have lost a limb. Designing aids for all of these human needs requires understanding what function you are augmenting and lots of creativity. In this unit we are going to learn about the musculoskeletal system and then you will be given an opportunity to test your design skills by building a prosthetic leg and test it by using it to kick a ball.

During the lesson you will:
- Design a prosthetic leg to kick a ball
- Measure the volume of different types of balls
- Find the weight of the balls
- Kick different types of balls with your prototype to see which one goes the farthest

Design Constraints:
- The leg should hinge like a real joint (move back and forth)
- The leg is being designed to strike a ball (move the ball or propel it on it’s own). Typically, the rubber bands would be used to make the spring loaded leg snap to propel the ball.
- A list of items and potential monetary value is provided. Students may be asked to determine how much their design costs and they can “buy” additional items, if needed.
- Elapsed time can be recorded for further math exercises.
- The lesson is meant to design something that functions like a leg when it kicks a soccer ball.
- Students do not have to mimic anatomy.

Appendix: C



Paper Football Kicker

The Problem

Your younger brother Joey is the Recess Paper Football Champion of his grade, but he's bummed he can't play since he broke his right "kicking" finger playing basketball. Joey's friends say if he can come up with something that flicks the football for him, they'll let him keep playing, but Joey knows he can't kick paper footballs with his opposite hand for accuracy. Joey heard you talking about learning about prosthetic legs, so he thinks you can help him out by designing a device that will kick the paper football for him.
Recess Paper Football game is played using two goals posts – one 3 feet away, and one 5 feet away – so your device must be accurate to these varying lengths.
Your brother Joey is looking for the following design features for this paper football kicker. Your design should be able to:

- Hinge like a real-jointed finger that is flicking the paper football
- Be designed to strike a paper football and propel it far enough to go through the goalposts
- be accurate at various distances (3 ft. to 5 ft.) Take up the floor space no larger than a typical textbook.

Your Task

Describe how you would design a paper football flicker to flick paper footballs different distances in a fun and creative way. Please describe aloud how you would start the design task - where would you begin? How would you design the device to include all the features listed above? What types of tests would you conduct to ensure that your device works for both desired distances?