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Assessment on Student Learning Design: Concurrent Think-aloud Protocols

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Abstract

The current trend in K-12 STEM education is to implement engineering design-based instruction as a pedagogical approach to teaching STEM concepts. Specific evidence of this trend the movement of over fifteen states beginning to implement engineering and technology focused standards at the K-8 level, including strands such as *The Design Process* (Indiana Department of Education, 2011), *The Nature of Science and Engineering* (Minnesota Department of Education, 2009), and *The Nature of Technology/Engineering* (Massachusetts Department of Education, 2006). Another example is the proposed *Conceptual Frameworks for New Science Education Standards* (NAS, 2012) that includes engineering standards as an integral part of the framework. This trend is similar to reform in engineering education within the last two decades. Atman and Bursic (1998) indicated at during that time of engineering education curriculum reform there was an increased focus on design, thus, a need existed to locate assessment practices that allowed researchers to move beyond assessing design products to assessing the process taken by designers. Atman and Bursic chose the think-aloud protocol as a research methodology to assess the design process taken by undergraduate engineering majors.

Today with a barrage of K-12 STEM education curriculum efforts (Project Lead the Way, Infinity Project, Engineering is Elementary, Engineering by Design, Children Designing and Engineering), it is important to once again locate assessment practices that shed light on the process taken by students as they learn STEM concepts through a design based approach to learning. Researchers on the NSF targeted MSP Science Learning through Engineering Design (SLED) have employed a transfer problem and think-aloud protocol analysis (Atman & Bursic, 1998; Erecsson & 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 a researcher to observe in real time students (teams of three) engaged in authentic design thinking and identify which science concepts naturally emerge in the design team's dialogue. The researcher is able to assess the accuracy of the science concepts employed and identify any misconceptions that remain. Using a special coding process (Halfin, 1973), SLED researchers have successfully piloted a coding scheme for different cognitive strategies exhibited by elementary school students. The SLED researchers also have systematically identified gaps and areas of overemphasis of the design process. The coding results were organized using frequency and percentages for time on code. Preliminary analysis of data collected from pilot studies within the SLED project indicated limited use of science terms within design thinking dialogue; however the science terms that did emerge were used accurately and appropriately. Preliminary findings of early data collection for the SLED project will be

presented along with discussion regarding limitations of this methodology as an approach to assessing student learn.

Introduction

A recent trend exist in K-12 education use engineering design-based instruction as the vehicle to deliver STEM education (Brophy, Klein, Potsmore, & Rogers, 2008; Douglas, Iverson, Kalyandurg, 2004). More specifically, some approaches have endorsed the use of design as the approach to teach science and support learning science inquiry (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner, 2006). This approach appears to be timely with engineering design embedded in the recently proposed *Conceptual Frameworks for New Science Education Standards* (NRC, 2012) Furthermore, newly adopted Indiana Science Standards (Indiana DOE, 2011) require students to apply science knowledge to engineering design in order to develop an understanding of the nature and practice of technology and engineering. These educational initiatives seek to engage students in engineering design experiences that allow students to construct questions, define design problems, create models, brainstorm ideas, and use newly acquired science knowledge to inform design solutions (NRC, 2012). However, there is a need for locating appropriate assessments that will help researchers and educators accurately assess these newly proposed pedagogical approaches to teaching. Assessments are necessary to uncover how students conceptualize design and apply the design process to solve engineering problems. One assessment that can bring insight to these constructs is the concurrent think aloud (CTA) protocol method. While it is clear that K-12 science education is at a critical juncture, embracing engineering design as a possible vehicle for delivering science instruction, locating proper pedagogical approaches and assessment practices remains undefined. In recent years, engineering education also was required to locate assessments to help understand how students come to understand design. College level engineering programs across the country began to require infusing design into the engineering curriculum due to ABET accreditation (Dym, Agogino, Eris, Frey, & Leifer, 2005). Understanding how students were learning design and how it improved their understanding of engineering was of great interest of engineering educators. Researchers Atman and Bursic (1998) embraced the idea of improving engineering instruction to include design and project based approaches to teaching engineering as outlined by ABET. Furthermore, Atman and Bursic suggested that to assess the effectiveness of these pedagogical approaches to teaching engineering, researchers should use assessment techniques to assess how students conceptualize the design process. Atman and Bursic endorsed concurrent think-aloud verbal protocol analysis as a form of assessing the process employed by students' as they design solutions to open-ended engineering problems.

This paper will explore the use of the concurrent think-aloud protocol as a student learning assessment when the engineering design process is used as an approach to teach science.

Purpose of the Study

The purpose of this study was to explore the application of the concurrent think-aloud protocol analysis as a measure of students' capabilities to use engineering design to solve problems and learn science. Researchers used concurrent think aloud protocols as an assessment to identify and classify key reasoning skills employed by fifth and sixth grade students when they were engaged in an engineering design-based activity. Additionally, researchers also sought to locate key science terms and concepts participants used during the protocol as a method to

provide insight on students' ability to transfer scientific concepts learned from a class implemented STEM lesson to a transfer problem.

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 framework for employing a concurrent think-aloud protocol employs a transfer problem and is couched in the learning theory *transfer of learning* (Bransford, Brown, & Cocking, 1999). This theory is based on the premise that when given a chance, students will transfer their understanding of recently learned knowledge to new situations. Royer (1986) adds additional explanation of the theory: "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 indicated that there is a *near transfer* theory and a *far transfer* theory. Near transfer is when problems encountered are similar to the problems previously experienced. The researcher used the near transfer approach for this study when creating transfer problems to be used during the protocol sessions.

The students participating in this study were engaged in authentic engineering design activities during their participation in science lessons and design tasks using an engineering design approach. The students were grouped into teams by their teachers and shared individual design ideas with their teammates and later report out to the whole class (community of learners). All students were encouraged to challenge their own and other classmates design ideas, thus, allowing each student to build his or her individual understanding of science and engineering design.

Using the think aloud approach as a form of design assessment is unique to this study and requires participants to be exposed to a new task (transfer problem) in a triad sample of students pulled out from the entire class. Researchers carefully investigated if and how participant use, apply, and transfer what they learned from the science lessons to the transfer problem during the protocol session. During the protocol sessions, participants may identify key science terms and concepts as well as engineering and science practices.

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

Criterion sampling was the method used to select participants for this study. Many educational researchers have used this sampling technique to investigate the effectiveness of educational programs (Gall, Gall, & Borg, 2007). The SLED teachers were provided with criterion for the sample that included: a) the student's willingness to volunteer for the study, b) student record for successfully functioning as a contributing member of a design team, c) the student's ability to express thoughts verbally, d) returned the required university internal review board (IRB) parent consent form.

Student participants were grouped in triads to form a multi-gender design team similarly to how they were grouped during SLED lessons. Welch (1999) recommends creating multi-member design teams in order to allow the design process to materialize naturally, a rationale that design in practice often occur in groups of people working together. Table 2 outlines the distribution of students by grade level, gender breakdown within each triad, and class size.

Coding Frame

This study used a coding scheme based on the work of Halfin (1973) who created a list of universal cognitive strategies used during the various stages of the design process. Using a Delphi technique, Halfin's validated lists of cognitive strategies indentified from the writings of ten high level designs including Frank Lloyd Wright, Thomas Edison, The Wright Brothers, and

refined definitions of each strategy based upon the recommendations of the Delphi panel. Two letter codes have been created to allow the researcher to code segments of the video transcripts based upon the cognitive strategies employed. See Appendix A for a list of the Halfin codes and definitions.

Data Collection

Overview of Concurrent Think-Aloud Protocols

Concurrent think-aloud protocol (CTA) is a research technique that requires one or more participants to talk aloud his/her thoughts as the individual or team participates in a task or solves a problem. Early development of the CTA methodology occurred in the field of cognitive psychology (Cooke, 2010). Otto Selz in the 1930s investigations of indivduals creative thought processes of individuals is one early example of the application of CTAs. de Groot was also an early developer of CTAs investigating cognitive strategies used by expert chess players (van Someren, Barnard & Sandberg, 1994). Ericsson and Simon (1993) suggest that the natural state in which a CTA are conducted make the technique a strong reflection of human though processes. The ability of participants to engage in the problem solving process authentically, the way they would naturally approach the problem is believed to be a more effective approach than more structures elicitation techniques (van Someren, et al., 1994). Researchers have used CTAs to identify if participants can tap into previously experienced problems and solutions to those problems in order to solve the problem assigned by the researcher (Ross, 1984). Studies on design have discovered that even expert designers find it difficult to self-reflect after designing a solution to a problem (van Someren, et al). van Someren also found that studying designers' drawings and design sketches provides a limited window of understanding because the researcher is looking at one 'design product' and the process taken to develop the design. Atman and Bursic (1998) 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)

Unique phases of the design process were identified by Dorst and Cross (2001). These phases of the design process have been identified as *problem space* and *solution space*. Dorst and Cross identified that designers iterate back and forth between *problem space* and *solution space* as they works through the design process. The problem space is the portion of the design process when the designer seeks to clarify and identify the problem. This phase can best be described as the time in the process where the designer asks key questions about what specifically is the design problem. Both Lawson (1979) and Kruger and Cross (2006) indicate that designers often are locked into one of these spaces within design and become *solution driven* or *problem driven*. Lawson indicates that the solution driven approach is more representative of a design based problem solving approach, whereas problem driven can constrain a design and limit the ability to develop a solution. During a concurrent think-aloud protocol session, the designers will begin by

reading and often re-reading the transfer problem. Likewise, the participants may also list constraints and criteria and ask probing questions about the problem. The designers are seeking clarification of the problem (Cross & Dorst, 1999).

Donovan, Bradford, and Pellegrino (1999) worked with expert designers and found that they were able to express their design thinking and general conceptual understanding as well as reflect on prior experiences that help inform design decisions.

> 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 researchers for this study believe that concurrent think-aloud protocols may be an ideal method to assess how students conceptualize design as well as understand when and to what level students dialogue science inquiry and science concepts as they relate to a design problem. The researchers believe that allowing students to work in triads provide opportunities for students to make meaning of existing science knowledge and design experiences in a community of learners made up of the triad design team. The researchers acknowledge that challenges exist when working with elementary level students. Possible challenges may include a) elementary students may struggle to express design ideas verbally; b) students at this young age may not be developmentally capable to use their metacogntion to self reflect on prior knowledge and experiences.

The researchers employed concurrent think-aloud protocols to allow 5th and 6th grade students to engage in a design task (transfer problem) as members of a design team (triad of students) in a similar way to the original design task (SLED design task). This research methodology allows the participants to naturally reflect upon their existing knowledge of science and engineering design and model their approach to design.

Think-Aloud Instructions

There are multiple techniques to create protocol sessions ranging from simply asking participants to talk aloud their thoughts to requesting participants to further describe the approach they are using to complete a task, or design a solution (Dunker, 1926; Ericsson & Simon,1993 ; Patrick, 1935; Smith, 1971). Ericsson and Simon (1993) suggest three approaches to think-aloud protocols instructions. The first technique simply encourages participants to speak aloud thoughts about a topic, problem, or task. The second technique for conducting verbal protocols requires the participants to verbalize thoughts and provide additional explanations as the participant works though the task or problem. The third technique requires participants to verbalize thoughts and link the current task or problem studied to previous thinking, learning, or personal experiences. This study employed the third technique in order to identify transfer of knowledge within student dialogues when asked to solve a similar design challenge (transfer problem) to the SLED classroom-based design task. The purpose of this approach was to allow participants to use their newly acquired science knowledge obtained by the SLED lesson. Moreover, participants were asked how they would assess the final design solution and what test could be conducted to help assess the design. Researchers were hoping to gain insight into how

students might design fair test investigations, one possible science inquiry skill that might emerge in the dialogue.

Constructing Transfer Problems

Robertson (1990) identified that transfer problems are: "problems that are structurally, but not conceptually unfamiliar to the solver-have long been used as a measure of understanding" (p. 253). The researchers carefully constructed transfer problems to provide opportunity for participants to transfer their recently acquired science knowledge. Furthermore, a transfer problem that addresses engineering design requires authentic elements of the nature of design. Cross (1994) suggests that design problems have three basic elements: 1) a goal; 2) constraints to work within; 2) and criteria to determine an achieved successful solution. The researchers used Cross's three features and also created transfer problems that were ill-defined, open ended, situated, and dynamic as suggested by Jonassen (2000). Furthermore, researchers consider the context of the transfer problem and carefully located problems and write scenarios that students might encounter in their daily lives. See Appendix B and C for examples.

Science Learning Through Engineering Design: One case example

Think-aloud protocol sessions were conducted in each classroom for each implemented SLED activity. Currently, a total of 23 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 from one SLED school site reviewing the protocols data from one SLED classroom across four different SLED lessons and across two grade levels, 5th and 6th grade. A summary of the details of the SLED lessons per grade level and embedded science content is presented in Table 1. Data presented in this paper is from a novice teacher's classes. The teacher in this case example, Denise Erickson (pseudonym), has a total five years of teaching experience. Although Denise Erickson is a novice teacher she quickly embraced the engineering design approach to teaching science and implemented three SLED design activities within the first two months of the school year. To date, she has implemented more SLED activities than any other SLED teacher during the 2011-2012 school year with a total of six design activities. She is also the in-service teacher representative on the STEM faculty design team that works to develop SLED lessons for the SLED project.

Table 1. SLED lessons by grade and science content

Grade Level	SLED Lesson Title	Science Content
	Prosthetic Leg	Prosthesis, volume, mass
5th	Water Filtration	Volume
	Compost Bin	Decomposers, role in ecosystem

	Sensing Vibrations	Energy transfer, potential and kinetic energy
6th	Bottle Racer	Energy transformation, forms of energy, potential and kinetic energy
	Roller Coaster	Energy transformation, potential and kinetic energy

CTA Data Collection

All CTA protocol sessions started by one participant reading aloud the transfer problem statement. Students' dialogues were recorded for further analysis using a digital video camera capturing non-verbal communication as well as audio data. Each taped CTA session was pre-reviewed by researchers and later segments of the recordings were coded by cognitive strategies of the participants as the team worked to develop a solution to the design problem. The cognitive strategies were organized by frequency and time spent on each of the coded cognitive strategies. Additional data included students' design sketches and notes. Moreover, each document were digitally scanned and included in a file for the protocol session to be used as additional evidence for analysis.

Table 2. General and Triad demographics for Miss Erickson's class

Class Size	SLED Activity	Triad by Gender
5th grade, 22 students	Candy Bag	1M, 2 F
	Compost Bin	1 M, 2 F
6th Grade, 21 students	Bottle Racer	2 M, 1 F
	Sensing Vibration	1 M, 2 F

Table 3.

Cognitive Strategies (Halfin Code) by total time (minutes) on code Miss Erickson's classes

SLED lesson Title	Candy Bag	Compost Bin	Sensing Vibrations	Bottle Racer

Halfin Codes (time in minutes)	AN:	02:38	AN:	02:41	AN	02:40	AN	01:12
	CO:	00:16	CO:	03:13	DE	13:32	DE	08:18
	DE:	07:25	DE:	10:31	DF	01:03	DF	00:39
	DF:	00:18	DF:	02:26	MO	00:04	MO	00:29
	MO:	01:08	MO:	01:40	PR	01:26	PR	00:27
	PR:	00:56	PR:	00:37	QH	01:27	QH	00:49
	QH:	01:24	QH:	02:40	TE:	00:00	TE	00:09
	TE:	01:14						
	Total:	15:19	Total:	23:47	Total:	20:12	Total:	12:03

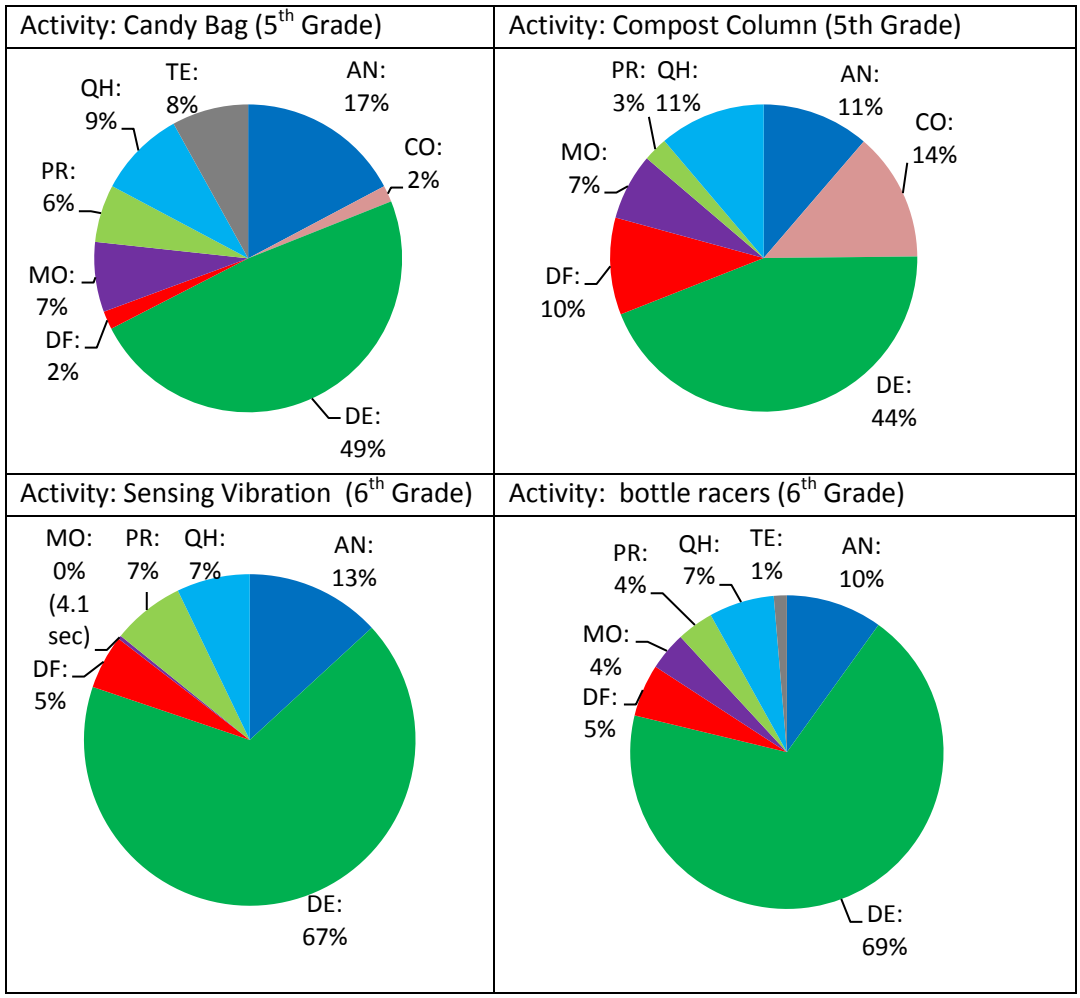

*Figure 1.*Coded results of cognitive strategies for % time on task for the design activities for Erickson's students.

Upon review of the cognitive strategies employed by Miss Erikson's students, a distinct and similar pattern emerges. Note that the students spent a majority of their time in the *design space*

with a range of 44% to 69% coded designing (DE) color coded in dark green. These students also spent limited time in the problem space which included *defining the problem* (DF) color coded red and analysis (AN) color coded dark blue. The percentage range for defining the problem was 2% for the candy bag activity and 10% for compost bin transfer problem. The range of percentage for analysis was from 10% to 17%.

The first CTA session was the candy bag protocol. The candy bag activity was designed to introduce students to the design process and was not a specific science learning lesson. The candy bag task required students to develop better packaging for a local candy store. The transfer problem for the candy bag task required students to create a bag for peanuts to sell at a local baseball park. The task was similar to the candy bag tasks, but provided a different context. The design team participants for this protocol navigated through the design process in a unique way. After reading the transfer problem aloud, participants first listed materials required to create a prototype bag. The participants fixated on listing materials as the first step in the design process, a similar finding with the participants for the CTA compost column session. Next, participants drew a line under the list of materials and created a list of constraints and criteria the participants identified in the design problem and constraints and criteria the design team would impose on the solution. Again, another line was drawn on their sketch paper and finally the students began listing possible ways to use the materials to solve the design task. Later, discussing this method of listing with Miss Erickson, she expressed that she had no idea where the students developed a listing method but indicated that she stresses to the students to first consider creating a listing materials to use when solving a design challenge. Design sketches were then created and additional discussions about the possible designs emerged and a final design choice was selected and documented in a team design sketch. It appears that the participants in this case navigated through the design process in a segmented and linear way. The candy bag activity was the first design task implemented in Erikson's class, so participants had limited experience using the design process. Students in this protocol demonstrated their knowledge of science process skills that could possibly lead to science inquiry by dialoging ideas for prototype testing ideas, coded TE and color coded gray for a total of 8 % of their time on code. The design team also revisited the problem statement at the end of the protocol session to clarify and ensure that the problem was defined appropriately; however, this dialogue was limited and only represented 2 % of the time on code, DF color coded red.

The last CTA session (compost column) conducted with Erickson's students yielded results that indicated that students are transferring knowledge from the SLED lessons to the transfer problem and CTA session. The SLED compost column lesson requires students to create a compost column prototype in order to design an appropriate procedure for producing rich compost, see Appendix B for more details. The transfer problem required students to apply their knowledge to create a method for creating compost for a farm that wanted to use an organic method to fertilize crops, see Appendix C. One important element within the transfer task was scaling up a proper 'recipe' for compost to supply needed fertilizer for the farm. The participants were asked to consider generating enough compost for an area approximately the size of their school. The students began the design process similarly to many of the other protocol sessions by reading the problem statement, listing materials needed, and starting to generating design ideas. This design team created a unique approach by creating a map of the farm and for a number of minutes the participants began designing a farm instead of a compost recipe by creating a sketch of farm plot layout. When the design team returned to the design problem, they created a key

using symbols of all important ingredients needed to create compost. Next, they tackled the scaling issue. They began to dialogue how much farmland would be necessary to create a compost bin that could be spread on an area of the approximate size of the school. The design team began estimating the area of the school building. They settled on an area and volume for the compost pile to be 300 feet x 100 ft x 2 ft = 60,000 cubic feet by estimating and using a heuristic of a football field to help them judge large distances. They debated units of measure when they asked the question: "How much (water) should the farmer add if this is for the area of our school building…50 Liters?… What is the area of our compost column?" (column created in class)?" Next the design team dialogued that maybe 1/10 of the area of the pile would work as an estimate. Finally, the students began to question this amount, here in the dialogue a promising comment emerged, "Let's think about the compost column we created in class"(transfer of learning)… "Miss Erickson…think about the compost column that we created in class, she added 200 ml of water every week, then think about a 2 L bottle of Coke…that is 2 liters, right?, you know" then a debate began about using Metrics or English units of measure. In the end, the students abandoned providing an exact amount of water to their 'recipe' and suggest that the farmer add water when needed. The participants defended this decision on the rationale that they could not predict when it would rain. This dialogue from the protocol session was coded *computing* (CO) and is color coded in pink. These results from this protocol indicate that participants have begun transferring some engineering thinking and science knowledge from class experiences to the transfer problem. The participants realized that they needed to locate appropriate heuristics in order to provide appropriate estimates for a scaled up compost recipe (Koen, 2003). Mental models of measurements such as the 200 ml of water from the classroom activity, the size of a football field, and the size of a Coke bottle were examples of basic heuristics students were using from their preexisting knowledge to inform their design decision making. Unfortunately, the students abandoned this discussion when they determined that they were unsure of an appropriate estimate for water needed for the compost recipe. However, this should serve as an example of how students can construct mathematical models to inform design solutions. Although this was an exciting discovery of students' engineering thinking, they had limited dialogue of science inquiry. One student used the term decomposition once during the session, and although the design team realized the ingredients needed to be added to the pile in layers, no rationale was given as to why layering the ingredients was important. Moreover, the students did not provide a rationale for the ingredients they used, never discussing carbon, nitrogen, decomposers, and other science concepts explored in the SLED compost column lesson.

CTA sessions for the 6th grade class were the bottle racer and sensing vibration activities. The results of both CTA sessions provide similar patterns of cognitive strategies with five of the seven cognitive strategies within 3 or less percent when compared. The cognitive strategies, defining the problem (DF) and questioning (QH) were the exact same percentages, 5 % and 7% respectively. Both CTA sessions began with students quickly moving into the design spaces and generating design solutions. The bottle racers group struggled to stay on task and the sensing vibration task was very difficult for students to develop a design a solution; however, both design teams persevered working to develop a final solution.

The review of all CTA data collected from triads drawn from Erikson's class emphasized design, spending the majority of their time in the solution space and limited time in the problem space.

Limitations to the Study

There are some basic limitations of this study: a) limited data collected; b) limited analysis of preliminary data; c) general fidelity of the protocol. Each of these limitations will require additional research and data collection to provide needed evidence creating opportunity to make stronger claims. Transfer problems should be revised to focus on engineering design thinking as demonstrated by the compost column session. Additional data collection methods in combination with CTA data can provide stronger assessments for students' science conceptual understanding. For example, purposeful sampling from within the triads could require one participant to apply his/her science knowledge to solve an open response question. The open response item could be created to require the application of science concepts, currently the transfer problems only provides opportunities for the application of science knowledge. This data could be triangulated with CTA data, providing additional emphasis on science content knowledge not just inquiry or engineering design knowledge.

Conclusions and Implications

The purpose of this study was to apply a concurrent think-aloud protocol as a form of assessment of student learning of science through an engineering design approach. Concurrent think-aloud protocols are limited to small purposeful samples eliminating the ability to generalize to the entire population. However, the technique allowed researchers to observe triads of students engaged in authentic design thinking as a way to identify science concepts that naturally emerge in the design team's dialogue. Protocol data collections of students' cognitive strategies were organized by frequency and time on code in order to identify patterns of approaches to design. Organizing the data in this way allows the researchers to identify common patterns and gaps in design thinking or overemphasis of cognitive strategies. Preliminary results indicate that students do not often dialogue specific science concepts learned in the SLED lessons when designing during the CTA sessions; however, in the case of the compost column CTA session, the triad began to transfer knowledge from the SLED lesson in order to create an appropriate mathematical model for locating an ideal design solution. This example of engineering design thinking was a promising discovery and these research results can help inform the SLED partnership to develop SLED lessons and teacher professional development experiences that teach this important engineering thinking skill. SLED teachers can benefit from reviewing this CTA session to witness how students attempt to transfer their knowledge from the SLED lesson to a different design task. Understanding why students eventually abandon the process when details are required such as calculating numerical data is important to explore. Likewise developing pedagogical approaches to support this type of design thinking is necessary. The findings from the CTA compost column session exposed students' inability to complete the thought process of applying heretics and transferring their science knowledge from the SLED lessons to the transfer problem. The promising findings from the think-aloud protocol for the compost column include: a) participants attempted to transfer their experiences from the SLED lesson to the transfer problem; b) participants attempted to apply rules of thumb (heretics) of distances from their existing experiences to the transfer problem; c) the participants realized that numbers could help inform their final design solution and were necessary for a complete design solution. Each of these findings is important for the SLED project and may not have been discovered with other student learning research methodologies. Additional CTA sessions need

to be conducted to determine if science concepts will emerge within student dialogues. CTA findings must be triangulated with other data sources, both teacher and student data. Other data collection methodologies such as open response exercises and semi-structured interviews would provide students an opportunity to identify specific science content within an engineering design context. These data sources can be triangulated with CTA data to provide deeper insight into students' understanding of science knowledge within engineering design instruction.

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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)

Cognitive Strategy		**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: Compost Column SLED design activity

Design and Build a Compost Column

Design Challenge: "How can we build an efficient compost column?"

The citizens of Haiti need your help. Haiti is a country located on the island Hispaniola and is one of the poorest countries in the Americas. Approximately 2/3 of Haitians depend on agriculture as both a source of income and food; however their soil quality is poor. Due to deforestation, drought, and soil erosion caused from hurricanes and flooding catastrophes Haitians are unable to cultivate their land and produce crops. Compost bins are an efficient means of replenishing the soil with nutrients by decomposing organic matter. Haiti would like to hire your design team to develop an efficient compost column to restore the soil and enhance agricultural productivity.

You will work as a member of a small design team to design and construct a compost column. Your team will study what ingredients should be included, how long decomposition takes, and the best conditions for quick decomposition. You will need to observe the color, temperature, smell, and texture of the compost components, measure the mass of your compost, and sketch organisms present each week and record all of these observations in your design notebook. The organic material in your compost column should be organized in such a way to maximize rate of decomposition.

Constraints:

- **You may include up to 5 ingredients**
- **The total mass of your ingredients must be between 20g and 40g**
- **You must add water, between 200ml and 400ml, every few days**

Appendix C: Compost Column Transfer Problem

Wanted: Compost
For
The Pieper Family Farm

The Problem

The Pieper family farm is taking a more "Green" approach to farming. They recently installed windmills and solar panels to heat the cow barns during the winter. They are currently looking for an alternative way to fertilize their crops.

The Pieper family heard that you recently learned how to make compost constructing your own compost columns. The family would like your design team to create a way to make compost for their farm. It is your job to create a compost system or procedure so the Pieper's can successfully create their own compost.

Working as a design team, you will need to:

1) design a compost system or procedure for making the compost.
2) create a list of what would be good ingredients for the compost.
3) propose a way to contain the compost.

Remember also that this is taking place on a farm, so equipment, such as tractors or plows, will be available and the size of the compost pile will be large.

Constraints:

- The compost should use as many "waste" products on the farm as possible
- The compost generated should be able to cover an area the size of your school
- Safety concerns regarding the location of the compost pile or bin should be considered

Your Task

Describe how you would design a compost system or procedure for Pieper Family Farm that uses what you know about composting 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 compost system to include all the features listed above? What types of tests would you conduct to ensure that your device works?