Examining Elementary School Students' Transfer of Learning Through Engineering Design Using Think-Aloud Protocol Analysis

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Abstract

The introduction of engineering practices within the *Next Generation Science Standards* provides technology educators with opportunities to help STEM educators infuse engineering design within a core curriculum. The introduction of teaching engineering design in early elementary grades also provides opportunities to conduct research investigating how young students use engineering design as a way to solve problems. There is a need for research to assess how students experience engineering design as a pedagogical approach to learning science. This article will feature research on elementary students' cognitive strategies used during engineering-design science activities. We adopted the concurrent think-aloud (CTA) protocol analysis method to capture how students conceptualize design and enhance science learning. During the 2012–2013 school year, we video recorded 66 CTA sessions, and this study examines six of those sessions. NVivo (Version 10) was used to code each video using common cognitive strategies categorized by Halfin (1973). Research findings indicate that participants increased the amount of time spent on mathematical thinking by 34% when given a math-specific design task. Pre- and post-tests showed that participants gained significant science content knowledge. However, we also confirmed that participants struggled with applying accurate mathematical and scientific knowledge to solving the given design problem.

Keywords: concurrent think-aloud protocol; design cognition; transfer of learning

Design is a core component of technology education (Lewis, 2005). Engineers, designers, and others in technology design and create solutions to given problems. Therefore, technology educators have been implementing the engineering-design approach as an effective way to teach technology. Although technology education is putting greater emphasis on engineering design (Hill, 2006; Lewis, 2005; Wicklein, 2006), recently, K–12 science education in the United States has proposed the teaching of engineering practices alongside the teaching of science practices. For example, the *Framework for K-12 Science Education* (National Research Council [NRC], 2012) includes engineering-design learning standards. The framework provides a strong platform for teaching engineering and technology contexts to enhance students' science learning. The document states:

> Engineering and technology provide a context in which students can test their own developing scientific knowledge and apply it to practical problems; doing so enhances their understanding of science—and, for many, their interest in science—as they recognize the interplay among science, engineering, and technology. We are convinced that engagement in the practices of engineering design is as much a part of learning science as engagement in the practices of science [(National Academy of Engineering and National Research Council, 2009)]. (p. 12)

Many states, including Massachusetts and Minnesota, have created academic standards requiring students to engage in the engineering-design process and to explore the nature of technology and engineering practices within science standards (Robelen, 2013). Conceptually, the driving force behind these educational reforms is the emphasis on students developing the abilities to define problems by asking questions, create and apply models, generate plans, engage in design challenges, and apply evidence-based scientific knowledge to create and select the best possible solution to a problem (NRC, 2012).

With the introduction of the *Next Generation Science Standards* to the elementary science classroom, technology educators can use their long history of design study in the secondary grade level to investigate the use of engineering design with elementary students. This will provide technology educators with a better understanding of how young students solve problems using the engineering-design approach. In addition, technology educators have shown that engineering design not only enhances STEM teaching and learning but also helps students develop cognitive capabilities by practicing engineering design as a problem-solving strategy (Lammi & Becker, 2013).

One measure used to investigate students' cognitive approaches is the think-aloud protocol. Atman and Bursic (1998) employed the think-aloud protocol method as an evaluation tool to assess students' design and problem-solving capacity. They used it to understand how undergraduate engineering students solved open-ended, ill-defined engineering-design problems. Similar to Atman and Bursic's studies, this study used a concurrent think-aloud (CTA) protocol in an elementary setting to inform technology education and STEM education about how elementary students solve design problems.

As a part of Science Learning through Engineering Design (SLED), a Math Science Targeted Partnership (MSP) funded by the National Science Foundation (NSF), we conducted two studies in which we collected data from CTA sessions to measure students' problem-solving ability. In the first study, data were collected on Cohort 1 in the 2011–2012 school year. In the second study, which is the subject of this article, data were collected on Cohort 2 in the 2012–2013 school year.

In the original study of Cohort 1, we collected data from 33 CTA sessions to measure the students' problem-solving ability in the 2011–2012 school year. Key features of engineering-design thinking often require many cognitive strategies; however, in the findings from Cohort 1, students showed limited use or no use of these strategies. The Cohort 1 findings revealed that the students spent very little time in computing (4%), managing (1%), testing (3%), and predicting results (4%). Students spent almost half of their time generating ideas (47%). CTA sessions from Cohort 1 indicate that student teams (triads) did not emphasize the use of computing (CO) and testing (TE) during the protocol sessions. Additionally, the cognitive strategy interpreting data (ID) was missing from all the protocol sessions. Even though mathematical reasoning skills such as computing, testing, and interpreting data are the key elements of engineering design, the results indicate that students were not using these skills. The results of the Cohort 1 study are compared with those of Cohort 2 in the Results section.

Purpose of the Study

The purpose of this study was to investigate how triads of students collaboratively developed solutions and applied scientific and mathematical concepts to inform their solution to engineering-design challenges. The questions guiding this study included the following:

1. How do Grade 5 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. To what extend do students apply scientific concepts and mathematical reasoning when engaging in an engineering-design transfer problem?

Theoretical Perspective

The theoretical perspective for studying participants' cognitive strategies through design is based upon the construct of *transfer of learning* (Bransford, Brown, & Cocking, 1999). Transfer of learning suggests that students can transfer their prior knowledge, skills, and experiences to new situations. When students are presented with new opportunities that are similar to pre-existing experiences, learning transfer can occur. Learning transfer is an indicator of understanding. Royer (1986) further describes the concept of transfer of learning: "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). In this study, we carefully crafted transfer problems that were similar in structure and scope to those presented to the students during a prior learning experience in order to assess a near transfer of learning (Thorndike, & Woodworth, 1901; Bransford, et al., 1999). We observed and coded student dialogue to determine if students transferred what they had learned during the SLED activities to the transfer problems. Specifically, we were looking for students to transfer key engineering and science practices, scientific concepts, and the use of mathematical reasoning.

Literature Review

A CTA protocol is a procedure that allows a researcher to study the verbal report of one individual or group of individuals speaking their thoughts while engaging in an assigned task or problem. Recently, the CTA method has been applied to a wide variety of contexts, such as studying human operations of process controlling systems (Sanderson, Verhage, & Fuld, 1989), cognitive studies on writing (Ransdell, 1995) and reading (Pressley & Afflerbach, 1995). CTA protocols are endorsed as a promising tool to capture cognitive and metacognitive thinking in engineering education research (Atman & Bursic, 1998). Multiple CTA studies have investigated engineering-design approaches within engineering education (Atman, Chimka, Bursic, & Nachtmann, 1999; Atman, Cardella, Turns, & Adams, 2005; Gainsburg, 2015) and team-based engineering design and problem solving (Mentzer, 2014; Stempfle & Badke-Schaub, 2002).

However, investigating the cognition of designers during design is challenging. Ericsson and Simon (1993) suggest that CTA methods may provide the most authentic approach to achieve a record of cognitive activity during design because the designer is allowed to perform in his or her natural state of mind not altered by outside influences beyond verbalizing thoughts. Unlike structured elicitation approaches to cognitive investigations, CTA investigation seeks to place the participant in his or her most natural state of design thinking during the protocol sessions (van Someren, Barnard, & Sandberg, 1994).

Some questions have arisen regarding CTA as a proper method to capture all aspects of design cognition. Lloyd, Lawson, and Scott (1995) reported that CTA methods may accurately capture short-term thought processes but fail to capture long-term states of memory. However, allowing designers to express ideas graphically allows for both short-term and long-term cognition (Ullman, Wood, & Craig, 1990). In addition, the CTA method requires participants to use their own language and to approach the assigned task as they would naturally solve it. Furthermore, some researchers questioned the validity of CTA data from young children. However, van Someren, Barnard, and Sandberg (1994) found that

> In our experience, the quality of verbalizations is not strongly associated with other properties that can easily be observed or measured. One possible exception is age. Young children usually find it difficult to think aloud. It is not clear if this is due to their verbalization skills, to the content of their thought processes or to the general difficulty of concentrating on a problem-

solving task. (p. 35–36)

In a usability study, Donker and Markopoulos (2002) stated: “We expected methods like think-aloud that require high verbalization skills to be less effective for younger children or children with fever verbalization skills. Our expectations were not confirmed” (p. 314). We acknowledge these possible limitations of CTA protocols and, therefore, provided participants with the opportunity to create design sketches during the protocol sessions and to allow participants to work collaboratively and in their most natural state.

Research Design

Context of the Study

This study is part of an NSF-funded MSP entitled SLED (for more information, see https://stemedhub.org/groups/sled). The collaborative partnership is made up of four colleges within a large, research-intensive university and four school corporations located in the north-central Midwest. The primary goal of the SLED project is to improve achievement in Grades 3–6 students’ science learning through an engineering-design pedagogical approach. Over the course of 5 years, approximately 100 preservice teachers, 200 in-service teachers, and 5,000 students in Grades 3–6 will participate in the partnership.

This research study was drawn from two SLED partnership schools. School Site 1 was located in an emerging urban school district, and School Site 2 was located in a rural fringe school district (see Table 1 for demographics).

Table 1
Demographics of School Sites 1 and 2

Category	School Site1	School Site 2
Enrollment	552	124
Ethnicity		
White/Caucasian	56%	76.6%
Hispanic	27.7%	12.1%
Black/non-Hispanic	10.1%	4.8%
Asian	0.4%	0.0%
Multiracial	5.1%	5.6%
American Indian	0.5%	0.8%
Free or reduced-price lunch	71.9%	43.6%

Student Design Activities

In the second year of the project, the design team developed two math-embedded SLED activities to provide students' mathematical reasoning practice. These activities were also designed to address science standards. The activities were (a) the CO_2 Device activity in which student designed a device utilizing a balloon filled with carbon dioxide and (b) the Recycling Paper activity. Table 2 gives an overview of the design activities (see Appendices A and B for the design activity prompts). The series of science lessons implemented to support the engineering-design tasks was between five to seven 45-minute lessons delivered by SLED teachers. These science inquiry lessons contained the science content knowledge required to successfully complete the engineering-design tasks. These lessons targeted students' misconceptions regarding conservation of mass, which have been documented by Driver (1983) and Driver, Squires, Rushworth, and Wood-Robinson (1994).

Table 2
Overview of the Two New SLED *Design Activities for the Grade 5 Conservation of Mass Focused Design Tasks*

Title	CO_2 Device	Recycling Paper
Description	The CO_2 device activity required students to design a device utilizing a balloon filled with carbon dioxide generated from mixing vinegar and baking soda.	The recycling paper activity involved students calculating the volume and mass of an irregular material (pile of shredded paper) or mixture of paper and water (sludge) while designing a process to make recycled paper.

Participants

During the 2012–2013 school year (Cohort 2), we collected data from a total of 66 CTA sessions. Analysis of data from the 66 sessions provided general design patterns of the cognitive approach that students took in the engineering-design challenges. Data from six sessions were further analyzed to understand how students used cognitive strategies to solve math-embedded design problems.

We used *criterion sampling* to select cases that satisfied a specific criterion (Gall, Gall, & Borg, 2007). Participants for the think-aloud protocols were purposefully selected by the SLED teachers. Teacher recommendations were based upon (a) the students' ability to express themselves verbally, (b) their ability to successfully function as contributing members of a design team, (c) their assent to participate in the study, and (d) parental consent for the students to participate. Triads of student design teams were formed for each SLED classroom participating in the research. Welch (1999) suggests that pairing or grouping student participants allows for the design process to emerge naturally because most design efforts occur in groups of two or more people working together. Table 3 lists the total classroom size and genders of the three students selected as part of the triad for the six case studies. For example, Classroom 1 had a total of 54 students, and one male student and two female students were selected to form a triad.

Table 3
Think-Aloud Participants: Classroom Size and Student Gender Demographics of Triads

	School Site 1			School Site 2		
School	Classroom 1	Classroom 2	Classroom 3	Classroom 4	Classroom 5	Classroom 6
Classroom size	54	55	48	59	30	29
Student gender	1 M, 2 F	2M, 1F	2M, 1F	1M, 2F	2M, 1F	2M, 1F

Data Collection

Concurrent think-aloud protocol. The study employed the CTA protocol to capture students' cognitive thinking processes and thoughts. After each participant classroom completed the SLED design activity, we selected a triad of students to participate in the CTA protocol. According to the Ericson and Simon's (1993, p. 18) suggestion for CTA data collection, we provided students with two guidelines: (a) explain their thoughts directing their attention to the problem-solving procedure and (b) utilize their prior knowledge from the classroom-based design activity to the transfer problem presented in the protocol session.

Transfer problem. The transfer problem was a key instrument used to provide each triad with the opportunity to study design problems similar to the SLED design activities. As Cross (1994) suggested, transfer problems consist of three parts: (1) a goal, (2) constraints to address, and (3) design criteria to gauge the final design solution against. In this study, we focused on creating authentic engineering-design problems that required the use of science concepts embedded within the task. The problem scenarios were created based on situations that students might encounter in their daily lives or on designing products that were familiar to them. One transfer problem, Scotty's Scooters in Appendix C, was created for both the Recycling Paper and the CO_2 Device tasks because they addressed the same science concept, conservation of mass.

SLED knowledge assessments. To investigate the gap between knowing and applying scientific knowledge, we adopted a set of pre- and post-knowledge tests. Using an approach similar to Singer, Marx, Krajcik, and Chambers (2000) and Fortus, Dershimer, Krajcik, Marx, and Mamlok-Naaman (2004), we constructed a multiple-choice test that contained items of low, medium, and high cognitive demand to assess students' preexisting knowledge and to measure gains in knowledge. As Fortus et al. (2004) described, in order to get accurate indication of student's growth in knowledge from the SLED activities, researchers must first determine what students already know about the science. Pretest assessments were administered at the start of the academic year, and posttests were administered within 10 days of completing the SLED activity. Because one of the participants was absent when the pretest assessment was administered, pre- and post-test scores were only available for 17 participants.

Data Analysis

Think-aloud protocol analysis. The study adopted Halfin's (1973) codes to analyze the think-aloud data. These codes were created during Halfin's Delphi study that researched commonly used cognitive strategies by successful professional scientists, engineers, and inventors. Seventeen cognitive strategies were generated, and detailed descriptions were developed from the research and validated by 28 panel members. One advantage to using Halfin's codes for this analysis is that it provides problem-solving processes as well as comprehensive cognitive strategies usually used in design activities. Halfin's coding scheme allowed us to investigate students' abilities to apply their design and problem-solving capabilities to transfer problems (Hill, 1997; Kelley, 2008; Kelley, Capobianco, & Kaluf, 2015; Wicklein, 1996).

Interrater reliability of think-aloud analysis. Several steps were followed to ensure interrater reliability when analyzing the video data. First, two researchers carefully reviewed the coding scheme and definitions created by Halfin (1973, pp. 135–204) and mapped students' dialogues to these codes. Seven codes were determined to be outside the parameters of the protocol sessions, so these codes were removed from the coding list for the purpose of this research.[1] As a result, we utilized 10 of the 17 codes developed by Halfin (1973). The 10 codes used in this study are described in Appendix D. Second, sample video clips were viewed by the two researchers together, and their interpretations of the selected segments were discussed in order to reach coding consensus. Finally, the two researchers independently coded the video segments, and their analyses were compared. The kappa coefficient for interrater reliability was calculated. Hruschka et al. (2004) suggested that at least 20% of the data set

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[1] Due to the time limitations for the protocol sessions, participants were not able to construct models or conduct experiments.

results should be compared between two independent researchers. In this study, we analyzed one third of the CTA sessions to ensure interrater reliability. Each video from the six CTA sessions was segmented into three parts, and one segment from each session was analyzed for interrater reliability. To achieve acceptable levels of intercoder reliability, we followed Hruschka et al.'s iterative coding method (p. 311), and a Kappa coefficient of 0.91 was calculated using NVivo (Version 10) with 99.45% agreement.

SLED knowledge assessments analysis. In order to measure that participants successfully gained scientific and mathematical knowledge through the SLED engineering-design lessons, we compared pre- and post-test scores using a paired sample *t*-test using SAS (Version 9.4), a statistical analysis software.

Results

Concurrent Think-Aloud Protocols

Data from 66 concurrent think-aloud protocols were collected during the 2012–2013 school year (Cohort 2). The mean percentages for the coded sessions are displayed in Figure 1.

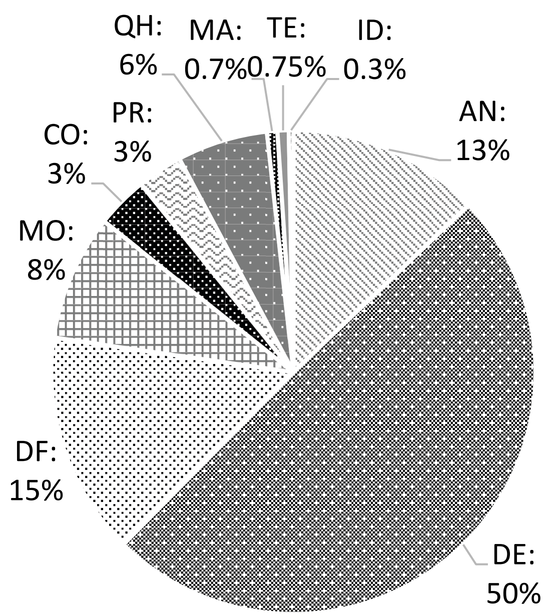

Figure 1. Result of total group mean percentages per code in Cohort 2.

Based upon the coded data for Cohort 2, we found that:

a) Participants continued to effectively define the problem and identify constraints and criteria when compared to the results from Cohort 1.
b) Students spent, on average, 50.4% of their time designing (DE), 14.4% of the time analyzing (AN), and 32.4% of the time defining the problem (DF). These percentages were comparable to the Cohort 1 findings.
c) Eleven sessions involved student dialogues that included numerical data, estimating, and mathematical predictions compared to zero sessions from Cohort 1. One reason is that design activities such as the CO_2 Device and Recycling Paper activities contain numerical data, estimations, volume, or surface area within the design brief. We also noticed that the overall length of several protocol sessions that included computing dialogue. In some cases, this was due to students focusing on computing numbers instead of designing solutions.

We further investigated how students engaged in math-embedded design tasks to determine if learning transfer occurred accurately and if students demonstrated proficiency in the key science standards. Six CTA sessions were selected from the CO_2 Device and Recycling Paper activities to further investigate the dialogue of triads within the time they spent computing. For School Site 1, CTA sessions from the CO_2 Device activity were chosen for all three classrooms (Classrooms 1, 2, and 3). For School Site 2, a CTA session form the Recycling Paper activity was chosen for one classroom (Classroom 4), and CTA sessions from the CO_2 Device activity were chosen for the other two classrooms (Classrooms 5 and 6). Figure 2 shows the coded analysis of each CTA protocol session as a percentage of time; the segment representing computational thinking is labeled CO (dark shading with dots). The six sessions selected showed that students spent 11% to 46% of their time on computational thinking (Figures 2).

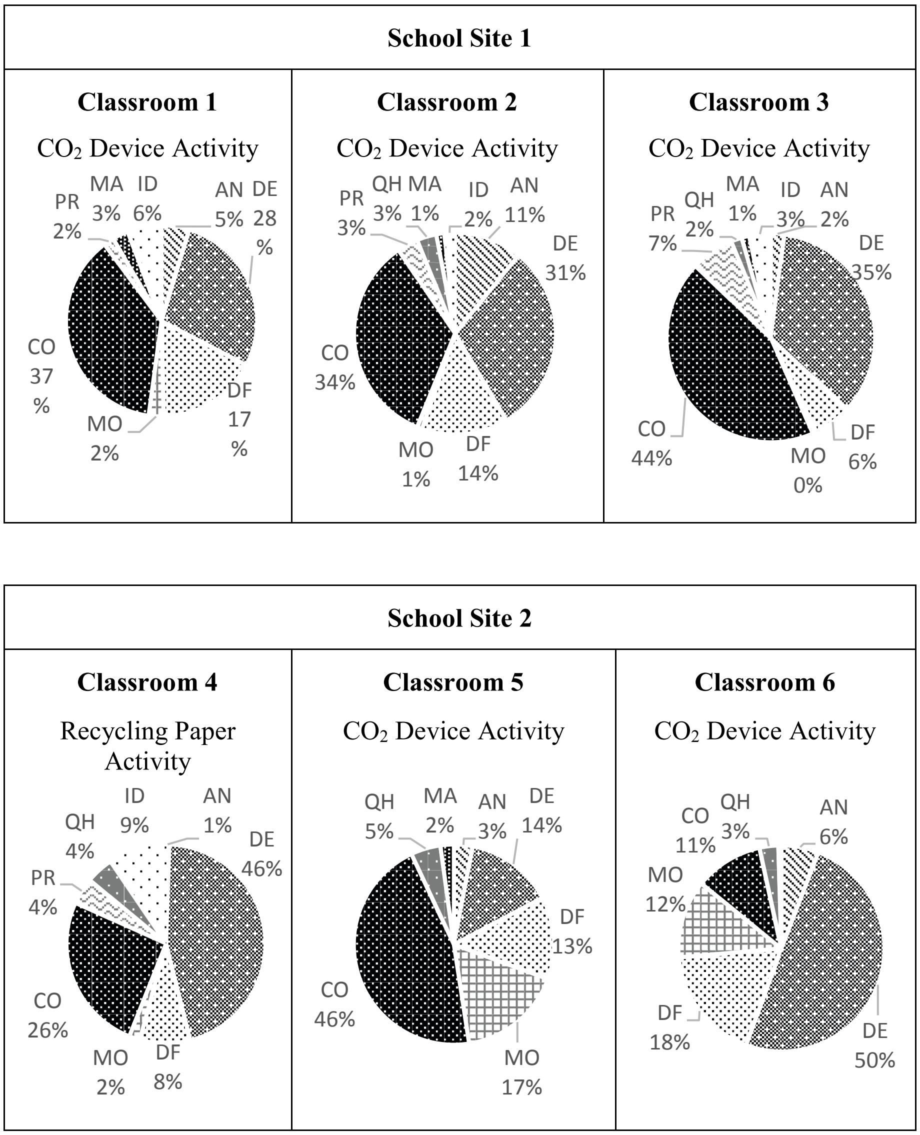

Figure 2. Percent of time spent on each cognitive strategy from School Sites 1 and 2.

Science and engineering-design knowledge test. Seventeen participants took pre- and post-test exams to measure knowledge gained by participating in the engineering-design activity. A paired-sample *t*-test was performed to determine if these gains were statistically significant. The mean scores for the pretest and posttest and the results of the paired *t*-test are shown in Table 4. The paired *t*-test indicates that the sample means from pre- to post-test are significantly different at the $p < 0.0002$ level.

Table 4
Paired t-test Result from Knowledge Test Scores

	Pretest		Posttest		95% CL for mean difference			
n	*M*	*SD*	*M*	*SD*		DF	*t*	*p*
17	9	1.90	11.94	1.72	1.85, 3.78	16	4.88	< 0.0002

Applying science and math concepts to engineering-design task. The primary science concept being taught during the Recycling Paper and CO_2 Device design tasks was conservation of mass. In order to assess students' ability to apply the science concept to engineering-design tasks, we included a prompt in the transfer problem asking "What is the mass of the re-designed scooter?" We analyzed the computing (CO) segments of the CTA sessions for the triad's discussion regarding conservation of mass. Two of the six triads (Classrooms 1 and 2) correctly answered that the mass is the same, three triads (Classrooms 3, 4, and 5) tried to determine a new mass, and one triad (Classroom 6) did not address the question regarding conservation of mass. In order to illustrate this, we include the dialogue and sketches for two of the triads here: one triad who answered the question correctly, and one who did not. The dialogue from the triad from Classroom 1, who correctly answered the question regarding conservation of mass, appears below, and their sketch for their solution is shown in Figure 3.

Student A: What is the mass?
Student B: The scooter mass is …
Student C: Wait… the mass does not change.
Student A: Yes, mass does not change. It is gonna [*sic*] be the same the scooter mass.
Student B: [what about] not the tires?
Student A: No, the tires are the part of the scooter. It won't change

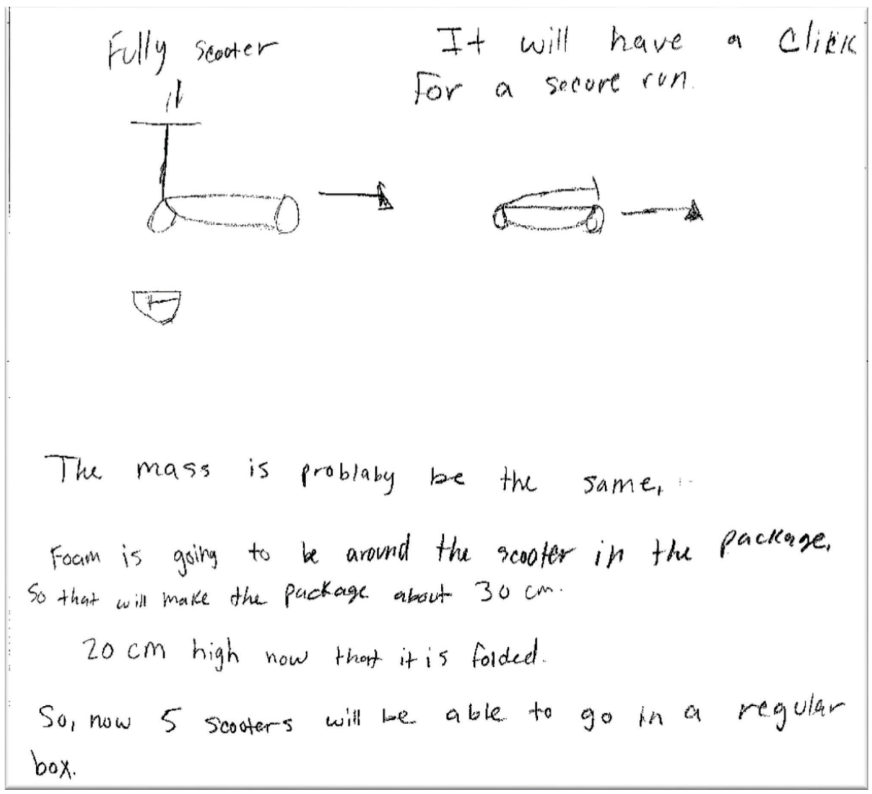

Figure 3. Sketch from the Classroom 1 triad.

Although the triads in Classrooms 1 and 2 answered the question correctly, three triads forgot that the mass does not change even when the scooter is collapsed or disassembled. The triad in Classroom 5 drew the sketch shown in Figure 4, which illustrates their calculations, and their dialogue from that session appears below.

Student X: We need to figure out what the mass could be. … Old one was 70 cm, 80 cm, and 15 cm. So, we do, 55 times 40 and 15… [Calculating numbers, they multiplied height by width and depth]. The scooter … Yes I got 30,000 pound?
Student Y: Pound? It is mass.
Student X: It would be gram?
Student Y: No, kilogram? 30,000 kg.
Student X: That's heavy. [sigh]

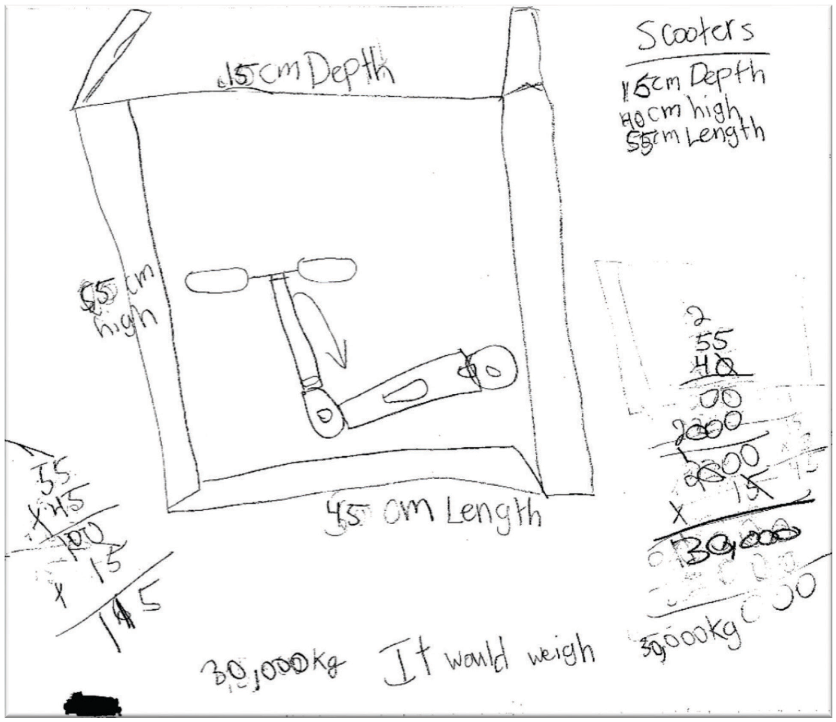

Figure 4. Sketch from the Classroom 5 triad.

The dialogue from the students Classroom 5 showed three types of mathematical and science errors. First, the students failed to recall the concept that the mass does not change even though the physical appearance of the object has changed. Second, to determine the mass of the redesigned scooter, they drew a box around the scooter and multiplied the dimensions of the box. This indicates that they did not understand the difference between the concept of mass and the concept of volume. Third, the value calculated for the mass was incorrect (it contained mathematical errors).

Discussion

The results from the math-embedded tasks demonstrated that students spent additional time engaged in computational thinking during the protocol sessions. However, it also revealed that some students still struggled to accurately transfer science concepts especially conservation of mass. One triad from School Site 1 and two triads at School Site 2 (Classrooms 4, 5, and 6) attempted to calculate a new mass for the disassembled scooter, which showed that they did not recognize that mass is conserved. Two of the three triads at School Site 1

(Classrooms 1 and 2) did correctly identify that mass was conserved when the scooter was disassembled. These results differ from the knowledge test results which indicated gains for all students from pre- to post-test. The results indicate that students were successful at identifying the concept of conservation of mass on a multiple-choice test but most of the students were unable to transfer it to a new situation. The results should be used by stakeholders within STEM education who seek to improve learning through engineering to help students use numerical data to inform their design decisions. Furthermore, using CTA protocols as a form of assessment for design thinking and problem solving revealed gaps in understanding that were not evident from the pre-and post-test knowledge assessments. We believe that using CTA protocols effectively assesses students' abilities to apply or transfer this knowledge to different situations.

Limitations

We acknowledge that there are some limitations to this research. First, we acknowledge that the criterion sampling approach may not provide sampling that best represents the average ability of the student body from each classroom due to potential bias of the teacher when selecting participants for this study. Second, the concurrent think-aloud methodology is a qualitative approach to study individual cases; therefore, these findings cannot be generalized to the entire population. We acknowledge that additional attention should be given to using alternative data methods such as open-response questions within knowledge tests in addition to the think-aloud protocol in order to strengthen the assessment of students' knowledge of science content.

Conclusions and Implications

The purpose of this study was use a CTA protocol methodology in order to classify participants' cognitive approaches to problem solving while engaged in an engineering-design task. Verbal data collected from each CTA session were categorized and organized using Halfin's (1973) codes to help us identify strategies of problem-solving and design-thinking skills. Additionally, we sought to locate within the protocol places where the transfer of learning of science concepts were present and to assess the accuracy of this transfer. The findings from this study revealed that participants were able to apply numerous cognitive strategies while creating design solutions and working in triads. This research confirmed results from previous studies finding that students were able to navigate through the design process moving from the problem space to solution space (Kruger & Cross, 2006) and not getting "stuck" in either space (Kelley, Capobianco, & Kaluf, 2015). Results from the six case studies revealed that students increased the time spent on computational thinking when given math-embedded design tasks.

Although SLED teachers used techniques such as Predict, Observe, Explain (POE) investigations suggested by educational researchers to help overcome misconceptions regarding the law of conservation of mass (Dial, Riddley, Williams, & Sampson, 2009), misconceptions remained for some students. It is not enough for students to know basic science, math, and engineering practices; it is important for students to know how to apply their knowledge and skills to solve real-world problems. We believe that the findings from this study provide strong rationale to use CTA protocol methods to assess student's abilities to apply their knowledge, skills, and practice to transfer problems set in scenarios with real-world contexts.

Elementary science teachers using engineering design as an approach to improve science learning should provide additional opportunities for students to improve their ability to transfer science and mathematical reasoning beyond the initial design tasks. Some suggest that mathematical reasoning needs to move beyond traditional classroom practices (Lesh & Yoon, 2004), requiring students to consider different approaches to thinking when problems are posed or requiring them to transfer their learning to real-world problems (Chamberlin & Moon, 2005). Elementary teachers could also use *Model Eliciting Activities* (Diefes-Dux, Moore, Zawojewski, Imbrie, & Follman (2004) to help students' practice applying mathematical thinking and spatial reasoning to solve problems in a similar way to the transfer problem used in this research study. Additional research needs to be conducted to better understand the results from this study. The findings from this study help to shed new light on (a) the complexities of knowledge transfer, (b) the limits of students' mathematical reasoning, and (c) how the engineering-design approach to teaching science provides new challenges and new opportunities to promote STEM education.

Secondary technology educators must be prepared for students to enter their classrooms with preexisting knowledge of and experience with the engineering-design process due to the *Next Generation Science Standards*. Additional technology educators should seize the opportunity to put students in new and novel situations that require them to use their math and science knowledge while engaging in engineering design. We hope that technology educators will use these research findings to adapt and refine their own engineering-design curriculum. Technology educators can leverage the new opportunities of engineering design within science education to reinforce the application of science and mathematical thinking in technology education classrooms; this is one way to continue to position technology education within STEM education.

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APPENDIX A

Design Task 1: Recycling Paper

SLED Science Learning through Engineering Design

Recycling Paper for Your School

The greater Lafayette area is facing the problem of increased paper waste. The city of Lafayette is interested in recycling the paper waste. They need your help to design a strainer system for the recycling plant that will produce very thin recycled paper.

Criteria

- Paper produced should be as thin as possible
- Paper should have equal or consistent thickness throughout the paper
- There should not be any holes on the paper
- Paper should be at least 3”x 5”
- Use 2.5 liters of water

Constraints

- You can only use the materials, tools, and paper available to you in the class
- Paper blending has to be done only by your teacher

Deliverables

- A dry recycled paper that has dimensions of 3 inches by 5 inches.

*The design task was developed by Şenay Purzer, Venkatesh Merwade, Brad Harriger, David Eichinger, and Erin Doherty.

APPENDIX B
Design Task 2: CO_2 Device

An employee of the Indiana Sand Dunes Chemical Company noticed that a byproduct (a substance made during a reaction, but not used) of the chemical process he was developing was a gas. In fact, the employee noted that a lot of this gas was formed after combining two reactants, vinegar and baking soda. The gas, carbon dioxide, was enough to inflate a balloon. The Indiana Sand Dunes Chemical Company is convinced that the production of the gas can be used to make a useful product and they are asking you to help them design a product that people would want to buy and use. Your team is limited to one balloon filled with gas.

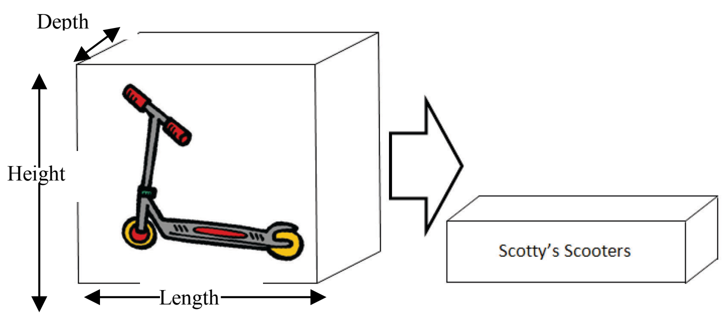
You may use the following materials to generate the amount of gas necessary for your device:

- One 16 - 24oz empty plastic drink bottle (avoid wide-necks)
- 12” helium quality balloon
- 200mL distilled white vinegar
- 3 level teaspoons (or 1 level tablespoon) Baking Soda (15 – 20g)
- Bag clip

* The design task was developed by Kari Clase, Melissa Colonis, John Grutzner, Bryan Hubbard, Alyssa Panitch, and Nancy Tyrie.

APPENDIX C

Transfer Problem: Scotty's Scooters



The Problem

The owner, Scotty, has a brand new line of scooters that he has designed and must package for shipment. However, storage at *Scotty's Scooters* is limited. Scotty realizes that fully assembled packaged scooters take up too much space. A re-design of the scooters is necessary to allow them to collapse or break apart to fit in smaller boxes. Scotty has asked for your design team to help in re-designing his scooter so that it will collapse and fit in the smallest packaging as possible.

Scotty is looking for the following re-design features:

- The scooter design must collapse or break apart.
- All pieces MUST be in the shipping package.
- The package must take up as little storage space as possible.

Scooter Facts:

- The size of the fully assembled scooter has a length of 70 cm, a height of 80 cm, and a depth of 15 cm.
- The scooter's mass is 3.5 kg.
- The fully assembled scooter fits in a box 75 cm long x 90 cm high x 20 cm deep.

Scotty's questions about your re-design:

- What is the size of the box to hold the re-designed (collapsed) scooter?
- What is the mass of the re-designed scooter?

- How much space can you save with the re-designed scooter?

Your Task
Describe how you would re-design a scooter that will collapse or break apart to create smaller shipping packages.

- Please describe aloud how you would start the design task - where would you begin?
- How would you design to include all the features listed above?
- How would you answer Scotty's questions?

APPENDIX D

Cognitive Processes Identified by Halfin's (1973) Study of High-level Designers
(10 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.
Managing	MA	The process of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system.
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.