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Elementary Students’ Computational Thinking Practice in a Bridge Design and Building Challenge (Fundamental)

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Introduction

The increased focus on computational thinking (CT) has grown in recent years for various reasons, such as a general concern about (a) a lack of global competitiveness among American students and general literacy in science, technology, engineering, and math (STEM) fields (Hsu & Cardella, 2013), (b) maintaining the economic competitiveness of the U.S. (Yadav, Hong, & Stephenson, 2016), and (c) preparing students adequately for a society that is increasingly technological (NRC, 2011). CT can help individuals analyze and understand multiple dimensions of a complex problem and identify and apply appropriate tools or techniques to address a complex problem (Wing, 2010). Furthermore, children can benefit from improved technological literacy, content knowledge, and problem-solving skills (Hsu & Cardella, 2013) while practicing CT.

Literature Review

Despite the attention on CT, there is no consensus about what CT exactly is for younger learners (Weintrop et al., 2016). CT, as a single concept, can be ambiguous; it is also an umbrella term that encompasses numerous interdependent aspects of a problem-solving process (Brennan & Resnick, 2012; Wing, 2010). Wing (2006) described computational thinking (CT) as a skill set everyone should want to learn and use. Grover and Pea (2013) echoed Wing's perspective and described CT as a competency that encompasses various thinking skills for problem solving. CT practice refers to the approaches that students use to solve problems, as well as an exhibition of a competency, along with other critical thinking needed for problem solving. CT can also be conceptualized as a complex metacognitive and engineering design process (Yang, Baek, Ching, Swanson, Chittoori, & Wang, 2018).

The various aspects of CT that are included under this practice provide some clarity on what CT encompasses for K-12 students. Components of CT have been articulated in various terms, ranging from abstraction, decomposition, communication, conditional logic, and algorithm (Grover & Pea, 2013); abstraction and generalizations (Wing, 2010); data collection as well as analysis (Lee et al., 2011); modelling/simulation, problem-solving, and system thinking practices (Weintrop et al., 2016). Detailed information on various CT components are presented in Table 1.

Table 1: *CT Components (Yang, Swanson, Chittoori, & Baek, 2018)*

CT Component	Description
Vocabulary and terminology	Such as variables, data, modeling, testing and debugging, iterative (Brennan & Resnick, 2012; Lye & Koh, 2014)
Abstraction	Reducing complexity to make sense of things. The abstraction process allows building complex designs and large systems (An & Lee, 2014; Lee et al. 2011; Wing, 2006)

CT Component	Description
Algorithm	Applying specific set of tools or sequence of steps (processes) to solve problems (Barr, Harrison, & Conery, 2011; Yadav, Zhou, Mayfield, Hambrusch, & Korb, 2011)
Communication	Written and oral descriptions supported by graphs, visualizations, and computational analysis (Astrachan & Briggs, 2012)
Conditional logic	Using strategy such as an "if-then-else" construct to clarify problems and solutions (Wing, 2006)
Data collection	Gathering data to define or solve a problem (Grover & Pea, 2013; CSTA, 2009)
Data structures, analysis and representation	Exploring data to find patterns, causes, trends, or results to facilitate the knowledge construction and problem solving (Grover & Pea, 2013; CSTA, 2009)
Decomposition	Simplifying problems or specifying steps to solve problems (Catlin & Woollard, 2014)
Heuristics	Applying experience-based strategy that facilitates problem solving, such as "trial and error" (Yadav et al., 2011)
Pattern recognition	Recognizing repeated patterns such as iteration or recursion (Grover & Pea 2013; 2018)
Simulation and Modeling	Manipulating data or concepts through controlled programs or exercises or creating such programs for data manipulations (CSTA, 2009)

Although CT has traditionally been implemented in only one or two subject areas at a time, more recent research studies/practices have taken an integrated STEM approach involving more than one subject or content areas (Yang et al., 2018). Regardless of differences in CT integration approaches or real-world implementation challenges, research from the National Research Council (NRC) stated that CT can be effectively integrated into K-12 STEM education and inquiry (Yang et al., 2018).

To develop the abstraction CT component with middle and high school students, Lee et al. (2011) outlined how students were tasked with designing a robot that could sense and react to stimuli in simulated environmental conditions. Students needed to consider how to convert the interactions to abstract true-false (or numerical) values usable by the software control program. Brennan and Resnick (2012) used Scratch to elicit various CT components, such as conditional logic, where students would program objects to perform a desired action only if a particular condition was met. Yang and her colleagues (2018) designed a STEM+CT curriculum that showcased how CT components were embedded into inquiry activities and engineering design challenges where students collected data about Mars, extrapolated (i.e., abstraction) the environmental conditions, and communicated their findings with peers.

Lee et al. (2011) noted that there are multiple possible domains (e.g., web design, mobile app development, robotics) that can be used to help develop CT practice in students. Moreover, what CT exactly looks like in practice can be dependent to some degree on the specific domain or field in which it is applied (Weintrop et al., 2016; Wing, 2010; Yang et al, 2018). Nevertheless, despite the variability in terms of potential methods of CT realization, there are numerous benefits when including CT practices in a discipline, and these benefits are not limited to scientists, mathematicians, engineers, programmers, computer scientists, or related professions/fields (NRC, 2011; Wing, 2010). The NRC (2011) highlighted the use of CT as part of the core practices for the scientific and engineering practices in its framework for K-12 science education. However, little research has been conducted on how students practice CT in their engineering practice.

Purpose of study

This study examined upper level elementary students' CT practice while they were engaged in an engineering design challenge. The research question was how do students practice CT while they are engaged in a bridge design and building challenge?

Method

Context of Study: The Bridge Design and Building Challenge

The Bridge Design and Building Challenge was an eight-week scientific inquiry and engineering design program. Scientific knowledge and engineering concepts (e.g., earthquakes, bridges) were introduced in the first four weeks. The engineering design challenge (e.g., developing possible solutions and building prototypes) began in the fifth week, when students designed and built an earthquake-resistant bridge with K'NEX sets and prepared for a final competition. Each of the K'Nex pieces had an associated price tag, which the students used to keep track of the cost on a sheet (referred to as the cost sheet) while building their bridges for the final design challenge. In the eighth week, students competed for the best bridge design. To win the challenge, the team had to design a bridge that met the design specifications, passed the pre-determined earthquake testing criteria, and cost the least. The design specifications consist of the dimensions of the final bridges. The testing criteria were that the bridges had to remain intact and sustain certain weight placed at different locations (e.g.. at the middle of the deck and at one end of the deck) while being tested on a shake table. The following picture (Figure 1) shows a shake table built by the research team that was used for testing the bridges.

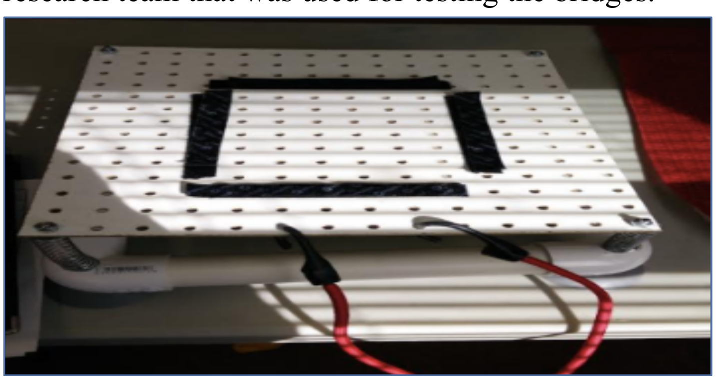


Figure 1: Shake table for testing

The Bridge Design and Building Challenge program focused on CT literacy (e.g., CT concepts) and students' ability (e.g., CT practices) to solve problems using CT (Grover & Pea, 2018), which are listed in Table 1. The program was guided by project-based learning (PBL) with a driving question, sub-questions, hands-on scientific inquiry (Buck Institute of Education, 2017), and engineering design. Table 2 illustrates the PBL guided bridge design and challenge program.

Thirty-six students from grades fourth through sixth participated in the Bridge challenge in small groups of three or four that were facilitated by one teacher in an afterschool program with two ninety-minute sessions per week, for eight weeks.

Table 2: *PBL Guided Bridge Design and Building Challenge Program*

PBL Component	Description
Program Description	In groups of three to four, fourth to sixth grade students research earthquakes and bridges. Students design an earthquake resistant bridge. Students build and test their bridges under simulated earthquake conditions.
Subject Knowledge Required	Engineering, Geoscience, Math, Technology
Driving Question	How can we build a strong bridge for the Mountain River to resist earthquake forces?
Sample Sub-questions	What is a bridge and why do we need it? How is a bridge designed?
Sample Hands-on Activities	Researching information on different types of bridge; designing, building and testing a bridge
Design Challenge	A bridge designed and built by each team to meet the specified design criteria

Research Design

A case study was used to examine students' CT practice while they were engaged in the process of designing and building a bridge. Yin (2009) defines a case study as, "An empirical inquiry about a contemporary phenomenon (e.g., a "case"), set within its real-world context-especially when the boundaries between phenomenon and context are not clearly evident" (p.18). A case study provides an in-depth description and analysis of a case and allows the researcher to study multiple individuals in an activity or activities (Creswell, 2013). This case study took place in a setting with small groups engaged with hands-on activities in the community centers' afterschool program.

Data Collection and Analysis

Students working in small groups were video recorded and the recordings were analyzed. One researcher watched the video recordings and recorded both students' actions and conversations regarding CT practice. The off-task behaviors and conversations which were not related to bridge design or building were excluded. A second researcher recategorized the student actions and conversations recorded by the first researcher that involved CT practice into various engineering design process stages according to a problem-solving chart which is depicted in Figure 1. At the same time, the second researcher also watched the same video recordings as a recheck for accuracy of the data analysis.

Students' artifacts such as drawings and sketches of their bridge design were also collected. In an effort to describe the CT practices students exhibited during the bridge design and building process, the researchers used a problem-solving process chart (Yang et al., 2018) (see Figure 2) to guide and organize the data analysis and results. The problem-solving process chart had CT components mapped into different processes of the K-12 engineering design. The chart was created to facilitate students' CT practice in their scientific inquiry, as well as in the engineering design challenge.

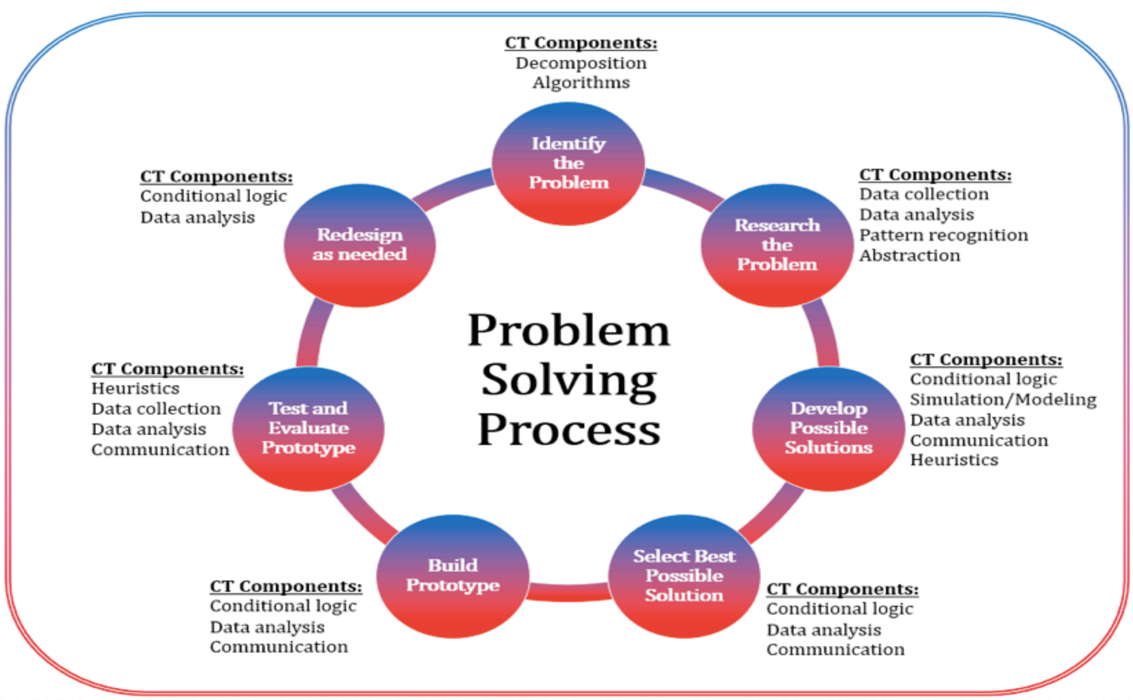


Figure 2: The problem-solving process chart

Results

Results showed that students exhibited various CT practices, such as data collection, data analysis, abstraction, communication, simulation and modeling, and decomposition during the engineering design challenge. Table 3 lists the results of students' CT practices in different engineering design processes, with examples taken from the video recordings. These results help to identify how students demonstrate CT when solving engineering problems.

Table 3: *CT Practice in Engineering Design and Challenge*

Design Process	CT Practice	Example
Identify the problem Identify the problem	Decomposition	The students were discussing exactly what the bridge needed to be like before they started to draw a sketch of their design.
	Algorithms	The students decided that they would first review earthquakes and bridges, then sketch their bridges, and finally build their bridges.
Research the problem	Data collection	Students took notes on their findings throughout their simulations with four types of bridges (beam bridge, arch bridge, cable bridge and suspension bridge) at the bridge simulation stations.
	Data analysis	Student A decided to observe the bridges his peers had created to get a better idea of the design objectives. Once Student A returned with some ideas, the students discussed whether they should simply copy the other designs or start their own.
	Pattern recognition	As students tied themselves up to make suspension bridges, as they were trying they realized that the rope needed to be tighter and tauter for suspension to occur.
	Abstraction	Students explained why the model bridge (built with different materials such as sponges) could hold so much weight and hypothesized that the distribution of force was spread out. Students understood how the distance across created a need for different bridges.
Develop possible solutions	Conditional logic	Students practiced by using different amounts of paper to build a bridge and understood that more paper (materials) would make the bridge stronger. They worked to add paper and rearrange the supports to make the optimal bridge design.
	Simulation & modeling	Students used paper to create models of potential bridges and used books to act as supports. Students were able to use the modeling materials to understand why supports were needed.
	Communication	Students communicated with their teammates regarding possible solutions, such as how to make a stronger bridge to resist earthquake forces by adding more layers of materials to a deck.
	Heuristics	A student worked through the process of building an arch bridge out loud, asking the others how he should approach this challenge. The student ultimately decided that he should dive in

Design Process	CT Practice	Example
		with the materials and use trial and error to see what would happen.
Select best possible solutions	Conditional logic	Students discussed how pedestrians would get up their bridge. They decided that “if” there was an elevator, then people would be able to reach the walkway. Students also discussed the possibility of ramps and stairs.
	Communication/ data analysis	Students analyzed their drawing (a sketch of a potential bridge design) and talked about whether the design was realistic and would meet the objectives of the final design challenge.
Build prototype	Conditional logic	Students created different parts of a bridge at different time—but had to put the pieces together to meet the design criteria. When putting pieces together, they had to figure out where and how to do that.
	Communication	Students used their design sketches to illustrate what they had completed on building their bridge and what they still had to do.
	Data analysis	Student A followed Student B’s lead and began to review the cost sheet of their bridge and replaced larger pieces with smaller pieces to save money (and pieces).
Test and evaluate prototype	Heuristics	One student used heuristics while measuring the height of his bridge to see if it met the required height. Once they observed it was too short, they added pieces and measured again. He continued using trial and error to figure out what 1 ½ feet equals in inches.
	Data collection/ data analysis	Students measured the deck of their bridge to determine whether or not it met the requirements of the design challenge criteria, which would help the team move forward in the building process.
	Communication	Upon completion of the deck, one student became concerned that the deck could not hold weight, since it was sagging in the middle. Students brainstormed how to improve the deck.
Redesign as needed	Conditional logic	Students used the data that they had observed from the earthquake test and to decide if their bridge met the design challenge criteria and if further modifications were needed.
	Data analysis	Students reviewed the cost sheet and recognized that they were using too many pieces and it was going to cost more for them to build their bridge. They wanted to reduce the cost and use fewer or less expensive pieces.

Students' CT Practice in Their Artifacts

Similarly, the researchers examined the collected students' artifacts (i.e., drawings and sketches of their design) for CT practice. The following picture (Figure 3) shows two students' final design products: Bridges built with K'NEX kits. Table 4 presents the students' work regarding their CT practice during the engineering design process while designing and building a bridge. The students' work illustrates the processes they used to answer the driving question and sub-questions, and to compete in the Bridge Design and Building Challenge.

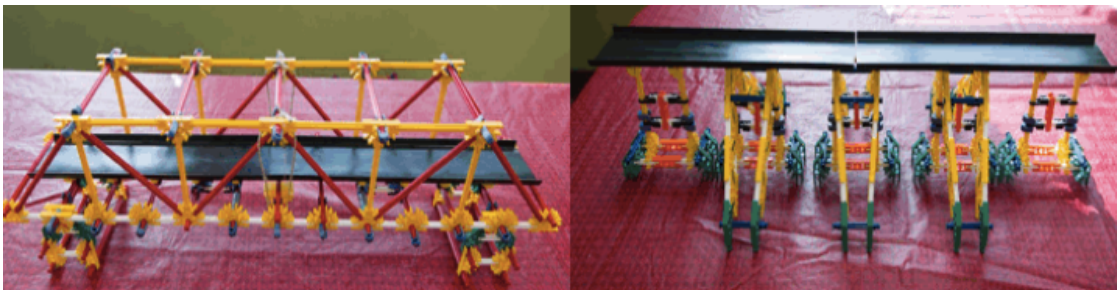
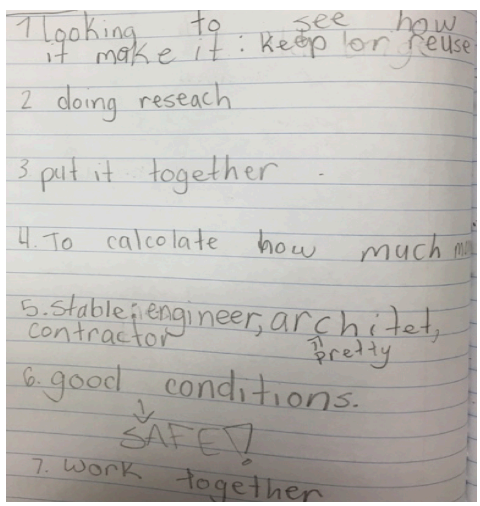
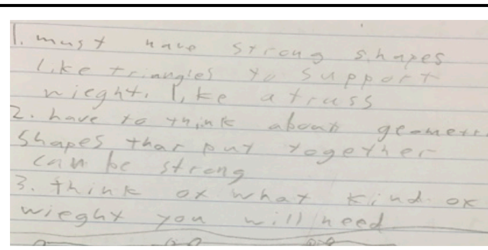
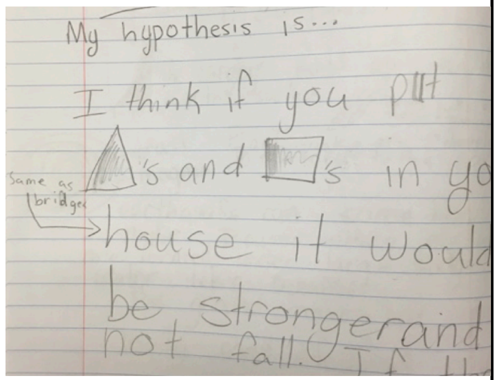
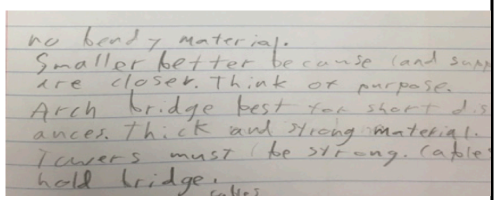
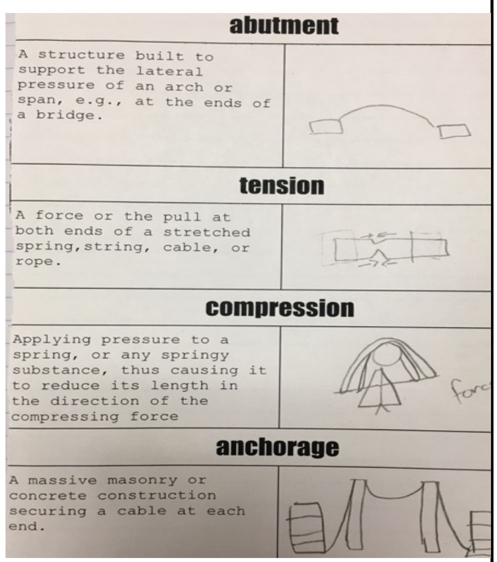
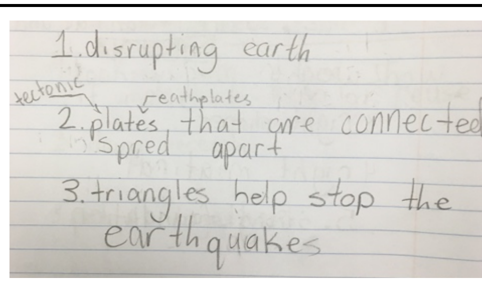


Figure 3. Sample student final products

Table 4: *CT Practice in Students' Artifacts*

Engineering Design Process	CT Practice	Student Work	Explanation
Identify the problem	Decomposition		The steps as presented in the image showed the student's idea of how to make the bridge safe and hold weight.
Research the problem	Data analysis		The student built upon knowledge learned previously to answer the question of bridge construction considerations.

Engineering Design Process	CT Practice	Student Work	Explanation
Develop possible solutions	Data analysis		The student built upon previously learned knowledge to propose a hypothesis, such as if a house was composed of squares and triangles, then it would never fall. This proposed them to use triangles for their bridge.
Develop possible solutions	Conditional logic		The student explained his logical reasoning for constructing a stronger bridge.
Select best possible solution	Communication		The student drew different types of bridges according to the descriptions provided.
Build prototype	Data analysis		The student used earthquake-related data to explain why an earthquake took place.

Discussion and Conclusion

Based on the analysis of the video recordings and students' artifacts, the participants practiced various CT components throughout their design and building of earthquake-resistant bridges. Within one process of the engineering design, students also practiced various CT components. For example, during the Research the Problem process, students practiced various CT components such as, data analysis, pattern recognition, and abstraction. During the Develop Possible Solutions process, students practiced conditional logic, simulation & modeling, and communications. The practices of CT components also seemed to be dependent upon the specific design activities throughout the whole Bridge Design and Building Challenge such as those in the Research the Problem and Develop Possible Solutions processes. The students' practice of CT varies according to the specific design tasks and objectives, and is consistent with previous findings and suggestions (Yang et. al., 2018). Yang and her colleagues (2018) investigated student CT practices in a project-based learning environment and found that students communicated their design and redesign of robot and bridge strategies via routines of data analysis and representation, or algorithm for solving problems at different times during the learning process.

These results of this study should be taken with caution. A common argument against case studies is that the generalization of results may be limited since the study focuses on only one age group. However, the purpose of a case study is not to produce statistical generalizations. Case study generalizations should be viewed from an analytic perspective, rather than statistical grounds (Yin, 2012). Since this case study aims to contribute to the limited amount of literature on CT practices in a K-12 engineering design challenge, the results may inform subsequent quantitative research that could produce more statistical generalizations.

Future studies are needed to provide detailed descriptions of each specific student's CT practices in every engineering design process in a chronological order so a comparison and tracking the growth of CT practice might be possible. Nevertheless, this study contributes to the teaching and integration of CT in K-12 science and engineering education. From the perspectives of research as well as practice, learning environments are important for fostering student CT practice as results show that specific CT practices seem to relate to specific design and redesign tasks (Yang, Swanson, et al., 2018). Therefore, the design of a suitable environment is critical for the integration and fostering CT in students.

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