2019

Fostering computational thinking in technology and engineering education: an unplugged hands-on engineering design approach

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feature article

Figure 5. An example of student prototypes.

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an unplugged hands-on engineering design approach

This article, through the C-Boat lesson model, shows how an engineering design task can promote computational thinking in an engineering design context.

by Euisuk Sung

Introduction

Computational thinking has been popularized in the last decade, particularly with the emphasis on coding education in K-12 schools. The core idea of computational thinking has a close relationship with technology and engineering education (TEE). Jeannette Wing (2008) introduced the term *computational thinking* as, "taking an approach to solving problems, designing systems, and understanding human behavior that draws on concepts fundamental to computing" (p. 3717). Wing holds the view that computational thinking is a universal attitude and skill set that facilitates a human thought process similar to the approaches taken by a computer scientist. The concept of computational thinking is not a completely new idea. Similar concepts, such as computer literacy and information computer technology (ICT) education, have already been discussed and practiced in K-12 education (Papert, 1980).

It is obvious that the increasing interest in computational thinking brings great opportunities to technology and engineering educators. Hacker (2017) argued about the relationship between computer science and technological literacy and concluded that technology and engineering teachers can contribute to enhancing students' computational thinking skills and knowledge without major modifications of the TEE content. In fact, TEE has emphasized the use of computing skills to solve problems, and integrative STEM education encourages the adoption of math and science to solve engineering problems. Therefore, this article will examine the relationship between computational thinking and TEE and address a way to teach computational thinking using an engineering-design instruction model.

Computational Thinking in TEE

Technology and engineering education (TEE) has a long connection with the concept of computational thinking. K-12 TEE inherently associates with various fields of industry, including computer science. ITEA/ITEEA (2000/2002/2007) defined the term technology as, "the act of making or crafting, but more generally it refers to the diverse collection of processes and knowledge that people use to extend human abilities and to satisfy human needs and wants" (p. 2). Using the broader meaning of technology, computing is an application of technological activities, and computational thinking is a process and skill set that people have developed and accumulated to solve real-life problems.

Many researchers argued that computational thinking is a mental process, and therefore not necessarily obtained through learning computer programming or computer science (Lu & Fletcher, 2009; Lye & Koh, 2014; Wing, 2008). Voogt, et al. (2015) suggested that teaching computational thinking could be implemented through several forms in K-12 education, such as: an entirely separate subject, within cross-curricular practices, or as an afterschool program.

Computational Thinking in STEM Education

Standards for Technological Literacy (*STL*) did not directly mention the term computational thinking (ITEA/ITEEA, 2000/2002/2007). Instead *STL* used the term mathematical thinking as a concept similar to computational thinking. For example, *STL* Standard 2-W endorsed systems thinking, explained how technology education can use computational thinking to improve technological systems, and noted: "Students should have opportunities to use simulation or mathematical modeling, both of which are critical to the success of developing an optimum design" (p. 41). In addition, Standard 3-J described the relationship between computational thinking and mathematical thinking: "The mathematical and scientific ideas applied in the development of these digital devices promoted further developments that resulted in new tools, such as computer modeling" (p. 52). Although these standards did not mention directly the term computational thinking, they showed that the nature of TEE encourages students to develop and use computational thinking approaches.

Key Elements of Computational Thinking

1. Abstraction and automation.
2. Systematic process of information.
3. Symbol systems and representations.
4. Algorithmic notations of flow control.
5. Structured problem decomposition.
6. Iterative, recursive, and parallel thinking.
7. Conditional logic.
8. Efficiency and performance constraints.
9. Debugging and systematic error detection.

(Grover & Pea, 2013)

Table 1. Key Elements of Computational Thinking.

Next Generation Science Standards (*NGSS*) also noted computational thinking as an integral building block of science learning (NGSS Lead States, 2013). The *NGSS* framework stated that students should use the computational thinking approach to identify relationships of physical variables and to predict the behavior of the possible consequences. In addition, *NGSS* placed computational thinking as a core method of learning science, assigning the Scientific and Engineering Practices section as one of the core science teaching strategies. For example, *NGSS* MS-PS4-1 states, "Mathematical and computational thinking at the 6–8 level builds on K–5 and progresses to identifying patterns in large data sets and using mathematical concepts to support explanations and arguments" (p. 47).

What are the Core Concepts of Computational Thinking?

A variety of research on computational thinking has been conducted in K-12 education. Research on computational thinking can be broadly grouped into two fundamental questions: (1) What is the core component of computational thinking? and (2) How can young students develop computational thinking abilities? Glover and Pea (2013) reviewed the recent computational thinking research studies and summarized nine key elements of computational thinking (Table 1).

Although most of the elements in Table 1 were written in computer science terms, Grover and Pea (2013) noted that the imple-

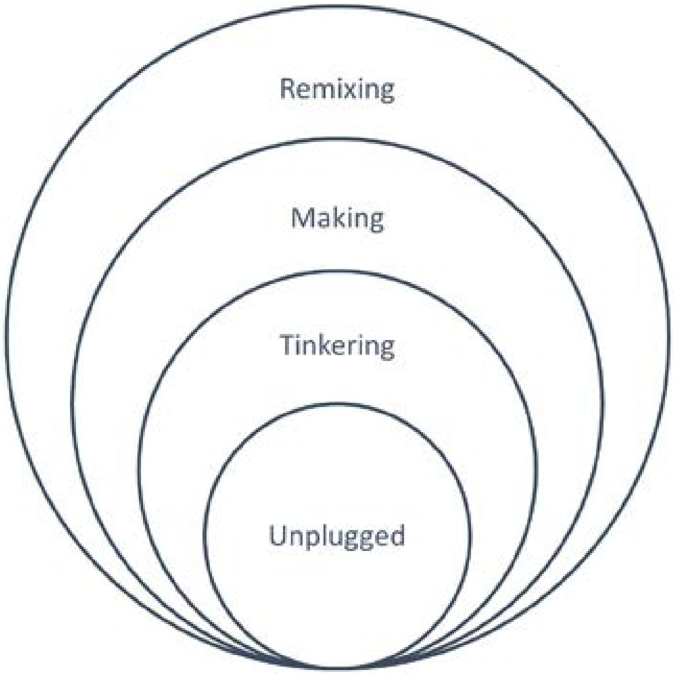


Figure 1. Four practical experiences of computational thinking. (Kotsopoulos et al, 2017, p. 6).

mentation of computational thinking practices can be achieved through multiple approaches and does not necessarily require the use of computers. For example, *abstraction* and *automation* are essences of computational thinking, and an *algorithm* is a key procedure to build an abstraction. In computer science, *abstraction* represents the process of generalizing that simplifies complex phenomena or problem-solving procedures (Lee, et al., 2011). A computer system is made up of thousands of subsystems, and building one subsystem is called an abstraction. The abstraction benefits people and enables them to use the complex computer system without knowing how the internal system works. Wing (2008) positioned abstraction as a core component of computational thinking and asserted that students should learn the concept of abstraction. Wing believed that learning the concept of abstraction helps students develop higher-order thinking abilities to think like a computer scientist.

Fostering Computational Thinking Through an Unplugged Design Activity

Kotsopoulos, et al. (2017) conducted research on the computational thinking framework used in K-12 education and presented four pedagogical experiences to teach computational thinking (Figure 1). Kotsopoulos pointed out that learning a programming language can be a barrier when students learn computational thinking. Therefore, when students first learn concepts of computational thinking, teachers might need to start providing them with a variety of problem-solving experiences using algorithms, rather than learning a computer language first. In fact, many educators often focus on teaching technical skills to operate electronic devices such as *Vex Robots*, *Arduino*, *Raspberry Pi*, or *LEGO Mindstorms* without teaching fundamental elements of computer science. Although college level students majoring in computer science need to use programming languages to learn advanced computational thinking, young students need to start learning the basic thought processes and core elements of computational thinking like a computer scientist.

Building Computational Thinking Through an Unplugged Approach

This article will present a practical approach to teach computational thinking strategies to TEE students using an unplugged learning experience. The unplugged approach has been addressed to teach core concepts of computer science through engaging games, puzzles, or solving real-life problems, using simple computer algorithms (CS Unplugged, n.d.). The lesson, titled *C-Boat*, was designed to incorporate a hands-on engineering design activity with computational thinking practices. In the *C-Boat* lesson, students will use the computational thinking approach to accurately predict the outcome of their solution in the problem-solving process. Key to the engineering design process is the ability to predict results prior to testing prototypes (ITEA/ITEEA, 2000/2002/2007). The *C-Boat* lesson consists of two design parts: (1) Design a boat model with a trial-and-error approach; (2) Redesign the boat model through a computational thinking practice. Below is the design brief for the *C-Boat* lesson.

In the first-round design phase, students will design a boat model that needs to hold 20 golf balls. The design task provides

C-Boat Problem Statement

A boat manufacturer is seeking to create a new line of instant emergency boats that are portable for hikers. The company would like to hire you to design a boat for this purpose. To test your design ability, a senior designer will provide you with a sheet of aluminum foil (40 X 30cm) and ask you to build a boat model that could hold at least 20 golf balls afloat on water. The boat with the 20 golf balls should not become submerged or sunk. In addition, you have to identify the maximum capacity of your boat model. You will have 10 minutes to design your model that will demonstrate your design ability.

Your Task

Before you start designing the boat model, identify the following items suggested in the problem statement:

1. Who is the client?
2. What is the problem?
3. What is the criteria?
4. What are the constraints?

Figure 2. *C-Boat* Design Brief.

students with ten minutes for designing and the material needed—a sheet of aluminum foil, size 40 X 30 cm. The first round of the design activity does not provide any scientific knowledge or computational thinking practice. The teacher simply provides the design brief to students, so students use intuitive skills to solve the problem. When finished building a model, students should test how many golf balls the model will hold and record the results.

Intervention: Computational Thinking and Making

After the completion of the first-round design, the *C-Boat* design instruction provides students with computational thinking practice. The science concept embedded in this design problem is buoyancy. The concept of buoyancy can be explained through Archimedes' principle. Archimedes found an upward force when the body of an object is immersed in a fluid and explained that the buoyance force of the fluid is equal to the amount of water displaced by the object. So, when we put an object into the water, the height of the water level increases because the water is displaced by the volume of the object. In addition, when an object is denser than water, it will sink in water. Conversely, an object will float if its density is less than water, as shown in Figure 3.

In normal conditions, the density of water is 1 ml/g (military/gram), and the formula for the density of water can be represented through the density formula triangle in Figure 4.

When computer scientists solve problems, they often create or use algorithms that consist of various optimal logics of problem solving. In this design task, students could build an algorithm that illustrates several steps of procedural logics to accurately predict the maximum capacity of their boat design. Technology and Engineering teachers encourage students to build an algorithm using guiding questions such as those presented in Table 2 (page 12). For example, the guiding questions (1, 2, and 3) allow students to simplify the design requirements and set the variables presented in the design brief. Guiding questions 4 and 5 help students create formulas for problem solving and lead them to illustrate the formula in a visual chart.

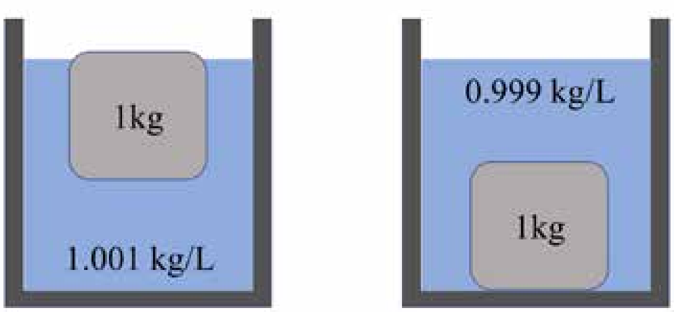


Figure 3. Water displacement by the weight of an object.

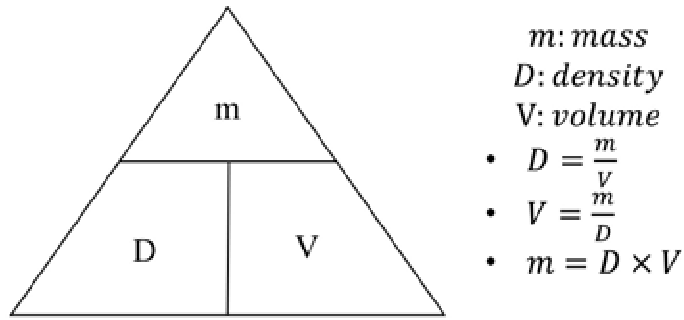


Figure 4. Density formula triangle.

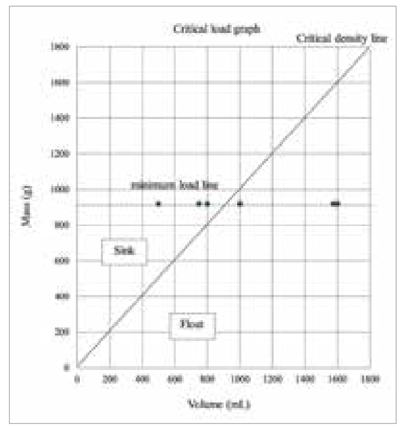
Building a clear algorithm helps students not only simplify a complex set of logics in an *abstraction*, but also helps them focus on the next level of problem solving. In computer science, simplifying a big problem into smaller pieces is often called *problem decomposition* or *divide and conquer*. Additionally, a well-defined algorithm is equivalent to a flowchart of problem solving. Usually, programming starts with building a flowchart that illustrates specified logic from the initial stage to the final stage.

Using the guiding question strategy, the *C-Boat* instruction could provide students with a strategy to more accurately predict the maximum capacity of the boat model and develop their computational thinking as well. This practice provides an accurate mathematical prediction of the maximum capacity and also guides the thinking processes that can create a mathematical algorithm to solve the given problem. In this design task, the boat must have a capacity of at least 920 cm^3 of volume (assume the mass of one golf ball is 46 g).

Conclusion: Incorporating Unplugged Design Activity with Computational Thinking

The computational thinking movement is emerging along with a rapidly developing intellectual revolution. Bundy (2007) wrote an article, "Computational Thinking is Pervasive," and claimed that our computer-dependent society not only calls for students to have the ability to use computer technologies in an effective way, but also requires them to change the way they think in order to cope with new types of problems. This article, through the *C-Boat* lesson model, shows how an engineering design task can promote computational thinking in an engineering design context. A number of ways have been addressed to develop computational thinking. The unplugged approach shows that TEE can promote computational thinking abilities by modifying existing engineering design lessons. In addition, this unplugged approach can serve as an important stepping stone to the "plugged in" approaches such as *Vex Robots*, *Arduino*, *Raspberry Pi*, or *LEGO Mindstorms*.

Table 2. An Example of Computational Thinking Practices.

Guiding Questions	Use of Computational Thinking
1) What is the weight of a golf ball?	Weight of a golf ball using a scale. e.g., $m_{golf\ ball} = 46g$
2) What is the total weight of 20 golf balls?	Build a formula to get the total weight. $m_{golf\ ball} \times 20 = 46g \times 20 = 920g$
3) What is the formula to get the volume of a boat that holds 920g?	Using the density triangle, complete the volume formula that meets the critical load. • $V_{critical\ load} = \frac{920g}{D_{water}}$, $D_{water} = \frac{1g}{1ml}$ • $V_{critical\ load} = 920cm^3$, $1ml = 1cm^3$
4) What is the minimum length, depth, and height for the critical load?	Compute the volume of your design model. • $920cm^3 < L_{cm} \times D_{cm} \times H_{cm}$
5) How would the critical load be illustrated in a graph using the formula? The graph should include two lines that represent critical density numbers and minimum loads.	Illustrate a graph that represents the critical density of water and minimum loads. 
6) What is the theoretical number of golf balls that your boat model loads?	• $m_{max\ load} = D_{water} \times V_{raft\ model}$ • e.g.) L = 15cm, D = 15cm, H = 5cm, $V_{LXDXH} = 1125cm^3$ • $m_{max\ load} = 1125g$ • $Predicted\ number\ of\ golf\ balls = \frac{1125g}{46g} = 24.46$

Furthermore, the lesson can be used to teach the relationship between technology and other fields of study such as mathematics and science. Many engineering students believe using mathematics or science simply provides a correct answer. In the *C-Boat* design instruction, the following formulas enable a mathematical solution that can be seen as a true solution.

$$46g \times 20 = 920g,\ V = \frac{960g}{D_{water}},\ D_{water} = 1g/cm^3$$

$$V_{boat\ model} > 90cm^3$$

However, the mathematical formulas only provide the minimum requirements for solving the engineering problem. These calculations do not guarantee the success of problem solving. In fact, the boat model could fail if it has any structural shortage, like a hole in the bottom or a leak in a corner of the folded aluminum foil. If the boat model loses balance while loading golf balls, it may sink. Similarly, the *C-Boat* design activity also shows many of the challenging aspects of engineering design, such as failure, uncertainty, constrants, and optimization (Koen, 2003; Petrosky, 2006). This lesson shows how students apply mathematics and scientific knowledge and explains the relationship between scientific/mathematical knowledge and engineering design.

Acknowledgement

The lesson used in this article was developed as part of an NSF-funded project titled TRAILS (DRL – 1513248), but any opinions and findings expressed in this material are the author's and do not necessarily reflect the views of NSF. The author wishes to acknowledge Dr. Kelley, Dr. Bartholomew, and Dr. Strimel at Purdue University for helping develop and refine the lesson idea.

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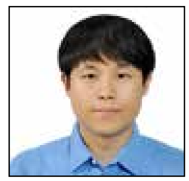

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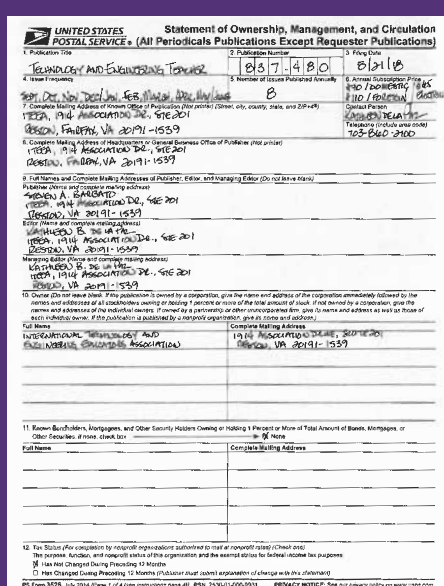

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3. Filing Date: 8/21/18
4. Issue Frequency: Sept, Oct, Nov, Dec/Jan, Feb, March, Apr, May/June
5. Number of Issues Published Annually: 8
6. Annual Subscription Price: $90 / Domestic; $110 / Foreign
7. Complete Mailing Address of Known Office of Publication (Not printer) (Street, city, county, state, and ZIP+4®): ITEEA, 1914 Association Dr., STE 201, Reston, Fairfax, VA 20191-1539
Contact Person: Kathleen De La Paz
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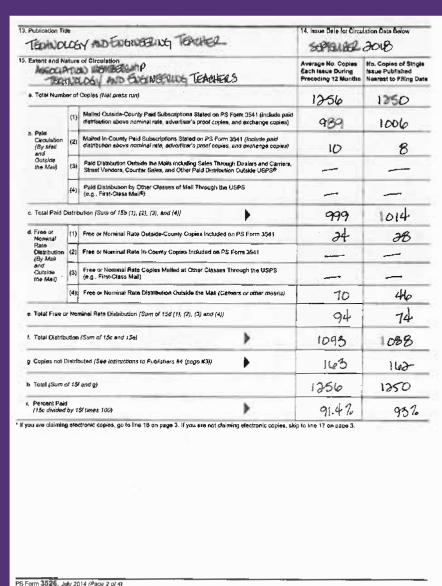

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14. Issue Date for Circulation Data Below: September 2018

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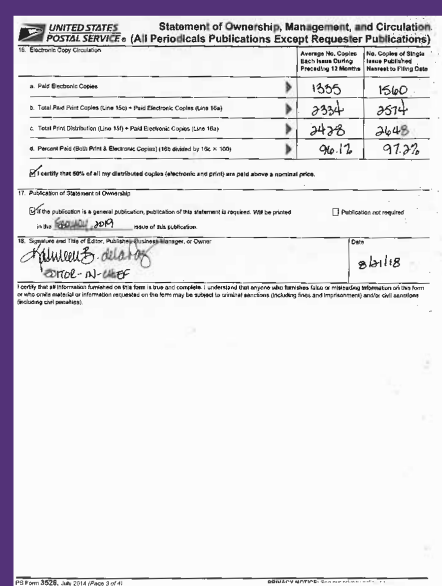

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