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Review Paper

Integrating Engineering, Science, Reading, and Robotics across Grades 3-8 in a STEM Education Era

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ABSTRACT

Science, Technology, Engineering, and Mathematics (STEM) entered the general lexicon in the United States within the last ten years. Both Presidents Obama and Trump emphasized STEM education as a priority for the United States because the number of college graduates with STEM degrees is perceived as an important factor contributing to the global competitiveness of the United States. STEM refers to four disciplines but the acronym is generally interpreted to mean science or math rather than technology or engineering because only science and mathematics are included oftentimes in the school curriculum. In this paper, we describe our attempts to teach integrated STEM units to grades 3-8 students based on five different articles. The first two articles describe how we engaged grades 3-5 elementary students, in two different engineering design challenges (soda can crusher design and trash grabber design) by using our engineering design model. The third article summarizes how we taught epistemological aspects of engineering using picture books within an engineering design challenge. The fourth article illustrates how students in groups of two or three created biomimetic robots with coding. The fifth article details how students built an animatronic zoo showcasing a particular biome and animals living in it by using computational thinking.

INTRODUCTION

Science, Technology, Engineering, and Mathematics (STEM) entered the general lexicon in the United States within the last ten years. Federal and state governments heavily invested in STEM education driven largely by poor science and math performance of American students in international assessments such as Program for International Student Assessment (PISA) and Trends in International Mathematics and Science Study (TIMSS) (Johnson, 2012). Some cite that the policy related to reporting annual yearly progress under the No Child Left Behind Act of 2001 adversely affected the opportunities to learn science in elementary and middle grades and this particular Bush era legislation is blamed for the poor performance of American students in international science and math assessments (Johnson, 2012). Both Presidents Obama and Trump emphasized STEM education as a priority for the United States because the number of college graduates with STEM degrees is perceived as an important factor contributing to the global competitiveness of the United States (Johnson, 2012).

From the federal government's perspective, increasing the number of STEM graduates is a primary goal of STEM education; however, improving the quality of STEM education and achieving overall STEM literacy for the general public should specifically be targeted.

Bybee (2013) defined STEM literacy as an individual's

> •knowledge, attitudes, and skills to identify questions and problems in life situations, explain the natural and designed world, and draw evidence-based conclusions about STEM-related issues;
> •understanding of the characteristic features of STEM disciplines as forms of human knowledge, inquiry and design;
> •awareness of how STEM disciplines shape our material, intellectual, and cultural environments; and
> •willingness to engage in STEM-related issues and with the idea of science, technology, engineering, and mathematics as a constructive, concerned, and reflective citizen (p. 65).

STEM refers to four disciplines but the acronym is generally interpreted to mean science or math rather than technology or engineering because only science and mathematics are oftentimes included in the school curriculum (Vasquez, Sneider, & Comer, 2013). Even professionals in STEM-related fields do not have a clear understanding of the acronym (Keefe, 2010). Akerson et al. (2018) shared similar sentiments about the meaning of STEM and Bybee (2013) also suggested that the meaning of STEM is ambiguous and it varies across educational contexts. Hence, STEM is often seen as a political acronym with educational implications.

Despite the STEM acronym's political connotations, it quickly became an educational heuristic suggesting ways of organizing and delivering instruction involving the combination of at least two of the four disciplines. Vasquez, Sneider, and Comer (2013) provided an operational definition of STEM education as follows.

STEM education is an interdisciplinary approach to learning that removes the traditional barriers separating the four disciplines of science, technology, engineering, and mathematics and integrates them into real-world, rigorous, and relevant learning experiences for students (p. 4).

Vasquez, Sneider, and Comer (2013) also provided the following principles to guide the development and delivery of integrated STEM units.

1. Focus on integration-Combining two or more disciplines.
2. Establish relevance-Why should students care about this?
3. Emphasize twenty-first century skills-Accessing information when needed and how students use that information creatively to solve problems and communicate ideas and concepts collectively. Teamwork and collaboration, along with critical thinking, problem solving, creativity, and communication collectively known as "twenty first century skills".
4. Challenge your students-Students must be intrigued not bored.
5. Mix it up-Allowing a variety of outcomes in STEM units (p. 18-19).

In this article, we describe our attempts to teach integrated STEM units to grades 3-8 students based on five different articles and guided by Vasquez, Sneider, and Comer (2013)'s framework. These articles are either published or about to be published in the National Science Teachers Association (NSTA) journals such as Science & Children and Science Scope. The first two articles describe how we engaged grades 3-5 elementary students in two different engineering design challenges (soda can crusher design and trash grabber design) by using our engineering design model (see Figure 1). The third article summarizes how we taught epistemological aspects of engineering using picture books within an engineering design challenge. The fourth article illustrates how students in groups of two or three created biomimetic robots. Biomimicry occurs when engineers mimic nature to increase efficiency and solve complex human problems. This article focuses on how students build robots mimicking joints and muscles in the skeletal system. The fifth article details how students built an animatronic zoo showcasing a particular biome and animals living in it.

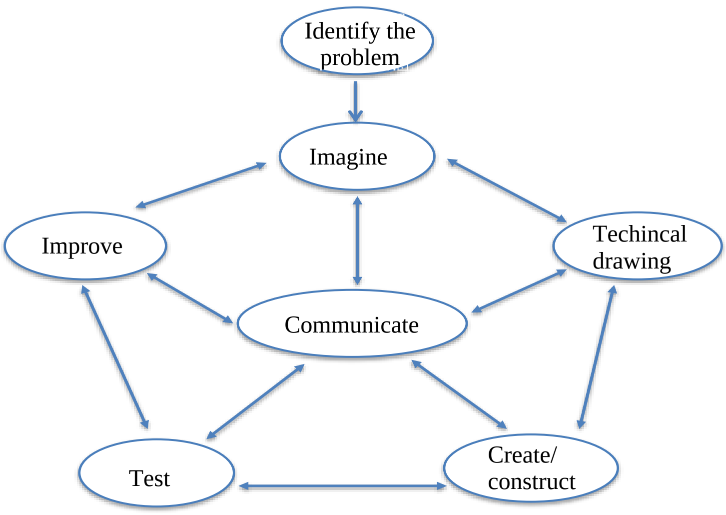

Figure 1. Engineering Design Model

Teaching Engineering Design Process and Its Epistemological Aspects to Grades 3-5 Students

Article 1: The Soda Can Crusher Challenge: Exposing Elementary Students to the Engineering Design Process

Deniz, H., Kaya, E., & Yesilyurt, E. (2018). The soda can crusher challenge: Exposing elementary students to the engineering design process. Science & Children, 56(2), 74-78.

We engaged elementary students (grades 3-5) in designing soda can crushers for five weeks (three hours per week) in a Saturday STEM program. We thought that addressing a real world problem such as finding an effective way to store soda cans for recycling would sustain our students' interest during the engineering design process. Students conducted a small needs analysis by asking people in their neighborhood whether they would purchase a soda can crusher, what qualities they are looking for in a soda can crusher, and how much money they would spend on a soda can crusher. They also searched the Internet for commercially available soda can crushers in the market. Students were provided criteria and constraints such as ease of use, reliability, portability, storage space, and aesthetics before they start designing their soda can crushers. First, students brainstormed about possible soda can crusher design ideas. Students were encouraged to make quick sketches of their design idea to be able to better communicate their thinking. Then, they agreed upon one design idea as a group and they did a technical drawing of that particular design idea. After completing the technical drawing, each group started building their own soda can crusher. Students in each group iteratively improved and revised their designs after testing. When each group finalized their designs, they evaluated each other's soda can crushers based on the criteria and constraints provided at the beginning of the engineering design challenge.

During soda can crusher design, students also read books aligned with phases of the engineering design process.

Book Titles	Relevant NOE Ideas	Summary of the Book	Sample Questions Posed to Students	CCSS- ELA Reading Literature
Designing Dandelions  Hunt, E. M., & Pantoya, M. L. (2013). *Designing dandelions: An engineering everything adventure.* Lubbock, TX: Texas Tech University Press.	Introduction to EDP Creativity and Imagination	*Designing Dandelions* tells the story of aliens repairing their spaceship through applying the engineering design process.	How did aliens use engineering design process to repair their spaceship? Were aliens creative while they were repairing their spaceship? If so, how?	**CCSS.ELA-LITERACY.RL.3.7** Explain how specific aspects of a text's *illustrations* contribute to what is conveyed by the words in a story (e.g., create mood, emphasize aspects of a character or setting)

Figure 2. The alignment of reading with engineering design process.

The soda can crusher design challenge has also natural connections to scientific concept of force. Each soda can crusher is either operated by a push or pull force. Students start to appreciate the inverse relationship between the force needed to crush the soda can and the length of the lever applying the push or pull force. Students started to use mathematics and computational thinking in describing the relationship between the force needed to crush the soda can and the length of the lever applying the force. This particular engineering design activity also naturally lent itself to math integration. For example, students drew scaled bar graphs to represent their needs analysis data with several categories. One bar graph represented the number of people who said "Yes", "No" or "Maybe" to the question "Do you need a soda can crusher?" This activity also gave students ample opportunity with practicing measurement skills while building their soda can crushers.

Article 2: Integrating 3D Design and Printing with Mechanical Trash Grabber Design Challenge within the Context of the Next Generation Science Standards

Kaya, E., Deniz, H., & Yesilyurt, E. (in press). Integrating 3D design and printing with mechanical trash grabber design challenge within the context of the Next Generation Science Standards. Science Scope.

We used the same engineerig design model (Figure 1) to engage elementary students (grades 3-5) in designing mechanical trash grabbers for five weeks (three hours per week) in a Saturday STEM program. The mechanical trash grabber design challenge was similar to the soda can crusher design challenge described above. Science, math and reading integrations that were made in the soda can crusher design challenge were also made in mechanical trash grabber design challenge. In addition to these integrations, we also integrated 3D design and printing to the mechanical trash grabber design activity. We asked our students to 3D design and print at least one moving piece of their mechanical trash grabbers. We introduced our students to 3D design with a cloud-based application called TinkerCAD. After students finished their 3D designs in TinkerCAD they printed them using the MakerBot Replicator+ 3D printer.

Article 3: Teaching Nature of Engineering with Picture Books

Deniz, H., Yesilyurt, E, & Kaya, E. (in press). Teaching nature of engineering with picture books. Science & Children

Nature of engineering. Students should experience the engineering design process in their science classes but the activity itself should not be enough. Students should reflect on the epistemological aspects of the engineering design process (nature of engineering) as well. Understanding the nature of science is considered as an essential component of scientific literacy (AAAS, 1993; NRC, 2000) since it provides insights into how scientific knowledge develops in real world. Similarly, the nature of engineering should be considered an important component of larger STEM literacy because it helps people to appreciate creative, subjective, tentative, social, and socio-cultural aspects of the engineering design process while engineers develop solutions to human problems. Epistemic beliefs about engineering (nature of engineering views) can influence the knowledge acquisition, interpretation of problems, and selection of problem solving strategies during the engineering problem solving (McNeill, Douglass, Koro-

Ljungberg, Therriault, & Krause, 2016). From this perspective, the nature of engineering should be an integral part of any engineering design activity.

Explicit-reflective Nature of Engineering Instruction. Explicit-reflective instruction purposefully makes the nature of engineering ideas visible to the learner by drawing learners' attention to the relevant nature of engineering aspects through discussion and reflection. This is similar to explicit-reflective instruction suggested for teaching the nature of science (Lederman, 2007). While the explicit part of explicit-reflective instruction refers to making nature of engineering aspects visible to the learner, the reflective part refers to encourage learners to revise their nature of engineering ideas in light of new ideas they encounter.

This article describes how we integrated reading picture books into engineering design process and how we used these books to generate explicit and reflective discussions around the nature of engineering ideas (see Figure 2). This reflective approach intentionally drew students' attention to the relevant nature of engineering ideas while students are engaged in the engineering design process.

Integrating Robotics with STEM Education

Educational robotics gained significant popularity in pre-college engineering education with the release of Next Generation Science Standards (NGSS Lead States, 2013) and CSForAll initiative (CSForAll, 2016). Educational robotics enables teachers to address computer science concepts and practices as well. Teaching computer science integrated with STEM provides students a more authentic representation of contemporary science and it enables students to acquire marketable skills for future employment (Swanson et al., 2017). Additionally, conducting scientific research is increasingly becoming dependent upon computing (Beheshti et al., 2017). Students' access to computer science concepts and practices can be improved by integrating computer science concepts and practices with STEM disciplines (Swanson et al., 2017). This can also help address the growing need to expose students to computer science concepts and practices so that they can utilize computational tools as future scientists and engineers. The Next Generation Science Standards acknowledged the importance of computation in science education by including "Computational Thinking" as one of eight science and engineering practices. A number of researchers also recommended the integration of computational thinking into K-12 education (Weintrop et al., 2016; Wilensky et al., 2014; Wing, 2006). Educational robotics often provides an array of learning experiences that are complementary to integrated STEM education.

Article 4: Celebrity Statues: Learning Computational Thinking with Designing Biomimetic Robots

Newley, A., Kaya, E., Deniz, H., & Yesilyurt, E. (2018). Celebrity statues: Learning computational thinking by designing biomimetic robots. Science Scope, 42(1), 74-81.

In this article, we provided details about how to build robots mimicking joints and muscles in the skeletal system. We offered a 10-week (20 hours) extra-curricular educational robotics club for students in grades 6-8. We chose to use Birdbrain Technologies Hummingbird robotics kit. Students were required to construct celebrity statues by using cardboard and glue. We helped students code their celebrity statues by using Snap! Programming language. Snap! is a visual and powerful programming tool that can work with hummingbird robotics sets. Biomimicry can be defined as using movement and behavior of nature to design solutions to human problems. Particularly, considering biomimicry allowed students to explore the human skeletal system with joints and muscles and understand the concept of movement. Moreover, we engaged students in a meaningful way by integrating science, engineering and computer science.

They learned the scientific vocabulary and created a moving model of the human body with the support of an educational robotics kits. In this engineering design challenge, students worked in teams to design biomimetic robots that mimiced the behavior of humans by using iterative design.

Article 5: Animatronic Lions, and Tigers, and Bears Oh! My!: How computational thinking and 3D printing can help students create an animatronic zoo

Newley, A., Kaya, E., Yesilyurt, E., & Deniz, H. (2019). Animatronic lions, and tigers, and bears Oh! My!: How computational thinking and 3D printing can help students create an animatronic zoo. Science & Children, 56(8), 64-71.

This activity followed Bybee's (2004) 5E learning cycle and engaged students in a socially relevant issue by designing an animatronic zoo. The animatronic zoo is expected to provide educational affordances of a real zoo without resorting to keeping animals in captivity away from their natural habitats. In the first meeting, the students were engaged by a mock video call asking students to respond to a client's request about building an animatronic zoo so that people could still learn about the animals without animals leaving their natural habitats. In the next session, students researched about different biomes and animals living in them. Then each group selected a different biome and created an animatronic zoo showing the characteristic of that particular biome and animals living in it. By using the engineering design process, students designed a zoo from everyday materials and placed 3D models of five animals that could be found in that particular biome. Birdbrain Technologies Hummingbird robotics kit was used in this activity as well. We helped students code their animals by using Snap! Programming language integrated with Hummingbird robotics kit. For example, in the forest biome, bears roar with a sensor if people got too close; model rabbits hopped around a pond; a raccoon climbed up and down a tree, and the forest glowed green with LED lights. This activity provided us the opportunity to teach about life science concepts integrated with engineering design process and robotics.

CONCLUSION

All STEM activities that we summarized in this article are well aligned with the principles to guide the development and delivery of integrated STEM units suggested by Vasquez, Sneider, and Comer (2013): (1) activities meaningfully integrated two or more STEM disciplines; (2) they were relevant and engaging to students; (3) they all required team work, problem solving, creativity, and communication skills; (4) STEM activities were challenging but students were able to complete them with appropriate scaffolding; and (5) STEM activities had a variety of outcomes. One caveat with these STEM activities is that rather than an actual classroom, these activities were all taught in an after school program setting. Nevertheless, the activities would likely be just as effective in actual classroom instruction that focus on STEM integration.

The Next Generation Science Standards explicitly included engineering design process and acknowledged the importance of computation in science education by including " using mathematics and computational thinking" as one of eight science and engineering practices. The NGSS encourage integration of STEM disciplines and computational thinking. However, teachers need professional development to successfully develop and teach integrated STEM units in their own classrooms. Without appropriate professional development, federal and state level STEM education campaigns cannot make an overaching impact at the classroom level. The influence of STEM education campaigns are more likely to remain within the confines of after school STEM programs if teachers continue to teach STEM disciplines in silos.

Despite previous reform efforts (AAAS, 1993; NRC, 1996) to improve science and engineering education, it is no secret that science and engineering are often neglected to maximize literacy instruction across grades K-5 (e.g., Conderman & Woods, 2008; Dillon, 2006; McMurrer, 2008; Pratt; 2007). Within the context of school accountability, instructional time allocated to science is decreased in favor of reading programs especially for at-risk students (Gamse et al., 2008). Furthermore, many teachers have the misconceived notion that science and engineering instruction should be delayed until students become proficient in reading (Duke & Pearson, 2002). Concerns over school accountability coupled with elementary teachers' lack of science and engineering background and confidence to teach these subjects reduce time for science and engineering instruction in favor of reading. However, even after perennial reform initiatives driven by school accountability, reading comprehension has remained problematic especially for at-risk, low socioeconomic status (SES) student populations (Gamse et al, 2008; Kemple et al., 2008).

As many states in the United States move towards adopting computer science education standards, this decision adds another layer of complexity to classroom instruction because computer science standards should be meaningfully integrated with other subjects to ensure that there is enough time spent on computer science as well as other subjects. While computer sciece education standards provide an overarching framework but it does not specify curriculum. The standards are the policies that must be translated to curriculum and instruction. These standards are not actionable unless they are translated into curriculum and teachers feel comfortable in teaching the curriculum aligned with the standards. Most teachers need computer science curriculum and associated professional development to successfully integrate computer science education standards into their own teaching. We suggest that computer science should be meaningfully integrated with science, engineering and reading to extend elementary school students' exposure to computer science before middle school.

Introducing STEM+ Computer Science (CS) at the pre-college level is necessary to improve students' problem solving skills. It is also important to spark students' interest in STEM before they develop stereotypes towards STEM+CS careers that negatively impact the attitudes of underrepresented groups and female students towards these fields. Innovation is born from solving problems including ones we don't know exist. More and more of the future is defined by innovation through STEM+CS and all students should be exposed to STEM+CS and then decide whether or not they want to continue. By exposing students to STEM+CS in early grades, there is greater opportunities to improve their STEM literacy and help them make more informed decisions in their career selections in the future. Without an enriching integrated STEM learning experience in K-12 education, students loses the occasion to realize the potential of STEM+CS in their development and possible career path.

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