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Engineering First: How Engineering Design Thinking Affects Science Learning

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The integration of science, technology, engineering, and mathematics (STEM) disciplines has been emphasized over the past decade in many reform documents[1, 2]. These fields hold promise for filling jobs of the future, and schools across the country have developed STEM programs or adopted STEM initiatives to meet the growing needs and interests of students, as well as the changing needs of the workforce. Curriculum integration intends to model the idea that authentic "real-world" problems are rarely isolated to one subject, but rather are solved in interdisciplinary and cross-curricular ways. Research on teacher's use of STEM-related curriculum and instructional practice is emerging, however, we know less about how STEM is integrated at the elementary level. This is primarily because there has historically been a lack of engineering curriculum geared toward young learners[3]. In addition, most elementary teachers are prepared as generalists and have not had engineering training as part of their teacher preparation. As a result, they may struggle to identify curricular connections, and may find integration of the content challenging.

This study investigated teachers' decision-making and practices for implementing and integrating science and engineering curriculum. Although elementary science curriculum (i.e. FOSS, STC, Insights) and elementary engineering curriculum (i.e. Engineering is Elementary, Project Lead the Way) exist, they are typically not integrated. The STEM disciplines are still taught as independent silos. Elementary teachers typically have different curriculum materials for each subject, and elementary engineering curricula is in its infancy. In other words, a 'STEM Curriculum' does not yet exist, so teachers are expected to teach separate engineering and science curriculum. This leaves minimal opportunities for integration of science and engineering, much less for math and technology integration. "One of the biggest educational challenges for K-12 STEM education is that few general guidelines or models exist for teachers to follow regarding how to teach using STEM integration approaches in their classroom[4]" (p. 32).

This project explored how five elementary classroom teachers integrated science and engineering in their classrooms while piloting engineering curriculum. Our specific research questions were:

1. How do teachers integrate science units with engineering design units?
    a. What aspects of the curriculum or content do they struggle with?
    b. What do teachers feel most influenced their implementation in terms of their instructional goals or learning outcomes?
2. How does the instructional sequence (engineering first or science first) impact the teacher's integration of the content?

Curriculum Materials

The teachers in this study piloted new science curriculum resources (Project Based Inquiry Science [PBIS]:*Water Quality: Living Together*) during the previous school year and wanted to extend the science unit by pairing an engineering unit (Engineering is Elementary [EiE]: *Water, Water, Everywhere: Designing Water Filters*) for the current school year.

The EiE unit, *Water, Water, Everywhere: Designing Water Filters,* includes four main lessons. The first lesson introduces a storybook that contextualizes the problem students will solve. The EiE unit describes it in this way[5]:

Salila lives near the Ganges River in India. She loves animals, so when she finds a little turtle emerging from a very polluted stretch of the river, she's upset. Salila's mother is an environmental engineer, so she helps Salila learn about water pollution, microbes, and the different ways that water can be purified. With this information, Salila designs a water filter to purify river water, so she can make a pollution-free habitat for her turtle.

In the second lesson of the unit, students investigate what environmental engineers do by using a map/mural to investigate possible sources of pollution a small American community. In the third lesson, students test different materials that could be useful as a water filter, and then apply what they learned to build their own water filters in lesson four.

The PBIS unit includes three main modules (called 'Learning Sets'). In the first learning set, students investigate the question, "*How do flowing water and land interact in a community?*" They observe pre-prepared jars of sample water with various sediments and are asked whether they would drink the water. They investigate and build watersheds to see how water and land interact. A main goal of this learning set is to think about what factors affect water quality. In learning set two, students investigate, "*How do you determine the quality of water in a community?*" They investigate how duckweed affects water quality in ponds, and what effect pH, temperature, dissolved oxygen, turbidity, and fecal coliform have on water quality. In learning set three, students investigate, "*How can changes in water quality affect the living things in an ecosystem*?" They collect and observe macro-invertebrates and consider food webs and food chains. At the conclusion of the unit, students make a presentation based on all they have learned to a fictional city council about whether the fictional chemical company, FabCo, should be allowed to build on the river bank of their fictional town, Wamego.

How does water quality affect the ecology of a community?	
Project-Based Inquiry Science	**Engineering is Elementary**
Water Quality: Living Together	*Water, Water, Everywhere: Designing Water Filters*
How do flowing water and land interact in a community?	Storybook: Saving Salila's Turtle
How do you determine the quality of water in a community?	Who are Environmental Engineers?
How can changes in water quality affect the living things in an ecosystem?	Exploring Water Filter Materials
Final Recommendations to City Council of Wamego	Engineering Challenge: Designing a Water Filter
Field trip to water treatment plant	

Table 1. Overview of curriculum units

The teachers and students also took a field trip to a local water treatment plant where students learned how water is treated and filtered locally on a large scale. The field trip occurred early in the semester and was closely tied to the concepts in the science curriculum, while also serving as a large-scale model for the water filtration challenge in the engineering curriculum. Some classes attended the field trip while in the science unit and other classes attended the field trip during the engineering unit.

Methods

This study was conducted in a central [state blinded for peer review] school district that serves approximately 7000 students K-12. Five teachers from three elementary schools volunteered for this study. Four of the five teachers attended training on the new engineering curriculum during the summer, and all five teachers met weekly to discuss how their lessons were going and what they could do to support each other. Each teacher piloted the engineering unit during the fall of 2015. The overarching question tying the two units together was, "*How does water quality affect the ecology of a community?*" Two teachers taught the science curriculum first followed by the engineering curriculum, two teachers taught the engineering curriculum first followed by the science curriculum. One teacher staggered the two curricula during the same time period by alternating science and engineering lessons (see table 1). The teachers chose which sequence of units they wished to teach, they were not assigned to a particular sequence of instruction. Each of the classes also took a field trip to the local water treatment plant.

Teacher (pseudonym)	Years of Teaching Experience	School (pseudonym)	Sequence of Units
Julia	9	Roosevelt Elementary	Engineering → Science
Lauren	9	Roosevelt Elementary	Science → Engineering
Lisa	6	Roosevelt Elementary	Alternating lessons
Callie	17	Truman Elementary	Engineering → Science
Jill	7	Lincoln Elementary	Science → Engineering

Table 2. Participant details

Three main types of data were collected during this project. First, semi-structured interviews were conducted with this sample of five teachers. The interviews centered on examples when engineering was incorporated, how science and engineering were integrated, how the teachers felt about the integration, what they tried that failed and/or succeeded, and what they planned to change in the future. These interviews occurred before the teaching of the first unit (whether it was science or engineering) and again after the completion of both units. Second, classroom lessons were videorecorded using an iPad provided by the research project. Teachers focused on videorecording their engineering lessons and science lessons.

Third, we leveraged existing Professional Learning Community [PLC] meetings to incorporate focus group interviews with participating teachers. During these meetings teachers discussed difficulties and successes, problems gathering materials for lessons, adaptations they made to their curriculum materials, the major field trip associated with this unit, and interesting conversations they were hearing among their fifth grade students. This data was used to investigate whether teaching science first or engineering first affects teacher implementation and/or integration of science and engineering units.

This rich set of data are still in the process of analysis. All of the lessons have been taught and videorecorded, and each teacher has completed the semi-structured pre and post interviews with a member of the research team. The interviews are transcribed verbatim and being coded using an open coding, inductive approach[6, 7] because of the exploratory nature of this research. The videos are being analyzed with V-Note qualitative analysis software (http://v-note.org). The bulk of this analysis is ongoing, and will be ready for conference presentation during the summer. During the

data collection and initial analysis phase, we noticed some themes in the videos and teacher interviews. We present those initial themes here with much more detailed and triangulated findings to be presented at the conference.

Findings

Engineering First

Initial findings suggest integration of science and engineering can contribute to more meaningful and complex discussions of science ideas, and there may be advantages to sequencing engineering before science. Julia anticipated that teaching engineering first would help her students learn the science more in-depth and to see themselves as engineers. She stated,

> I feel like the likely sequence of things is to teach them engineering and then let them make their recommendations like…here's all the content knowledge you need…to understand why we'd build a water filter. So let's try building water filters and then make the recommendation. And I feel like…like my hypothesis I guess is that they'll proceed through this unit with a higher sophistication like a greater level of sophistication about problem solving and to look at problems from different angles and…I want them to see themselves as engineers who are potentially going to help with this as opposed to just taking in information. (Julia, pre-interview).

The two teachers who taught engineering before science reported that the conversations they heard from their fifth grade students during the science unit were far above and beyond what they heard during the same science unit in the previous school year. Julia reported,

> Teaching the engineering unit… well, the engineering design process. before teaching the science content helped my students to be more systematic when working on our water quality science investigations. They referenced the results of their filter testing many times throughout the water quality unit, and they often discussed the benefits of different filter types and approached the water quality unit with a problem solving perspective. (Julia, post-interview).

The teachers felt that by "planting the seed" of engineering design before the science unit, students' ideas were situated with a context and a purpose for learning the science content. Callie reported, "I liked that we did [engineering] first…because now we can refer back to it. Remember when we did that… " (pre-interview). Because of the prior engineering design experience, students were positioned to apply what they learned in the science investigations and presented an argument to the city council on whether or not a chemical plant should be allowed to move into the fictional town of Wamego. Teachers also reported that by learning the engineering design unit first, their students could apply what they learned at the water treatment field trip in a meaningful way. Julia reported,

> The engineering unit served as a foundation for our trip to our local waste water treatment plant. My students were WAY more engaged in the field trip than classes from previous years, and I feel confident that is because they had great background knowledge gained specifically from the water filter engineering unit. (Julia, post-interview).

All of their collective experiences, within the engineering and science units, informed their ideas in deep ways.

Science First

On the other hand, teachers who taught engineering after their science unit had mixed feelings about what they would do when teaching these two units again in the future. They saw benefits to the sequence, for example, with how students were able to apply what they learned on a field trip to the waste water treatment facility to their engineering challenge designs. Lauren said:

> They would refer, to going to see the waste water treatment plant, you know, when they were trying to figure out what were the solutions for, um, Salila's water, they were saying, well you have to filter it. And you need to put filtration, and how could we make sure the Ganges was, um, being cleaned up along the way or how could we make, you know, how could we get to a point where people weren't dumping, or that waste was not running in. Like what are the things could be done? And they were, they were also, in that situation they were drawing upon the things that need to happen in far as rules, regulations, somebody needs to oversee this. Um, the government needs to be involved. So yes they were pulling a lot of that in (Lauren, post-interview).

But they also saw drawbacks to teaching engineering after science. One complaint was that the students were "burned out" (Lauren, post-interview) of writing claims, evidence, and reasoning by the time they got to engineering. The other fifth grade classes had moved on to a social studies unit, and the students "were like why are we doing more science?" (Lauren, post-interview). Lauren decided that she would switch the order when she taught them again. "I'd do it first next time around. Doing [engineering] at the end, I think it lost some of its, *oomph*, it just lost some of the impact that it could have probably had" (Lauren, post-interview).

Alternating Lessons

A teacher who chose to teach the engineering unit in the middle of the science unit, argued that by alternating the lessons students would be able to apply what they learned in the first section of the science unit to their understanding of why water filtration was important for the engineering unit. Lisa explains her decision for inserting the engineering unit within the science unit:

> So I'm going to take the approach of teaching it sort of mid-way through the environmental science unit. The first learning set in the unit is looking at how water flows right and how the land affects the water so kind of taking a…just a very basic overview of watersheds…umm…and the second learning set asks us to think about water quality and what can affect it and how we can test it. And so that's where I'm choosing to insert it into the unit so that students are starting to think about if there is a problem with water what could we do to solve this problem. Right. We identify a problem now what? Kind of things…so I want to take a pause at that point in the unit and insert the EIE unit and thinking about engineers, thinking about technologies and it would also coincide nicely with the field trip we take to the waste water treatment plant where we're thinking already about technologies and engineering solutions to community problems. (Lisa, pre-interview).

The EiE lessons came immediately after students had been on the water treatment plant field trip, and she felt this was a great opportunity for integration. She stated:

> My goal was for them to do the EiE after having seen a more complex water treatment process, and kind of understanding stages of filtration and processing, so that then when they were applying, uh, the different, you know, media and things that they had available to them, they were thinking about getting out different contaminants at different stages of the process, so I wanted to put [EiE] in there before we got too much further in the unit (Lisa, post-interview).

A parent of one of the students in her class was an environmental engineer, and was able to get her class some extra materials (like activated charcoal) to use in their filter designs. This provided students with direct links to what they had seen at the water treatment plant, which helped further integrate their science learning with their engineering designs.

Conclusions and Implications

The findings of this study suggest integration of science and engineering contributed to more meaningful discussions of science ideas and that teaching engineering first can be a catalyst for integrating the STEM disciplines in elementary classrooms. How curriculum sequencing positions elementary students to engage meaningfully with content and disciplinary ideas certainly warrants more research. Because the curriculum units are still separate, they present challenges to integrating science and engineering. Whether engineering or science is taught first, this still shows a silo approach to the two content areas. What this study shows, however, is that by introducing students to engineering design before science content is taught could afford them opportunities for integration within and across curriculum units. The third model from this study in which the teacher alternated lessons between science and engineering warrants further study as another possible model for content integration.

This study will have implications for teacher education, professional development, and how teacher candidates are prepared to teach and integrate STEM in the classrooms. While this study includes a small sample size of teachers, it is a first step in understanding how they integrate science and engineering content and practices and how the sequence of instruction affects instruction implementation. While this study focused on the teachers and their curricular implementation and integration, further research from this project will look at student learning outcomes across the sequences of instruction.

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