



Evidence of Students' Engineering Learning in an Elementary Classroom

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Over the past decade there has been an increased emphasis on improving the teaching and learning of Science, Technology, Engineering, and Mathematics (STEM) disciplines. There has also been an increased emphasis on engineering education at the K-12 level. Most academic science standards at the state-level, as well as the Next Generation Science Standards (NGSS) include some form of engineering^{1, 2}. As schools and teachers incorporate standards that include engineering into their science instruction, it has been found that many teachers feel uncomfortable, underprepared, and under resourced when teaching science at the elementary level^{3, 4} and that these feelings are increased when teachers also have to think about teaching and integrating engineering into their elementary classrooms^{5, 6}. Engineering integration at the elementary level is still relatively recent. There is a need for research in the area of engineering education to examine how these national documents and policies emphasizing the integration of engineering are being translated into classroom practice and what factors support or hinder successful inclusion of engineering at the elementary level.

An additional challenge that elementary teachers are facing in the wake of this increased emphasis for the inclusion of engineering in their science instruction is that there is currently very little instructional time for science with the accountability pressures for reading and mathematics^{3, 7}. Integration of STEM subjects has been suggested as a way to address the challenges of diminishing instructional time while providing students with the opportunity for engaging in realistic and multidisciplinary contexts that reflect real world problems. With many states adopting the NGSS⁸, curricula for integrating engineering with an explicit focus on teaching science are needed.

PictureSTEM is a curricular development project aimed at creating STEM integration modules with an explicit focus on engineering design, as well as standards-based mathematics and science, for grades K-5. The PictureSTEM units were developed to meet this need for explicit STEM integration modules that meaningfully teach each of the STEM disciplines. The theoretical framework guiding the development of the PictureSTEM modules was the STEM integration research paradigm, which is defined by the merging of the disciplines of science, technology, engineering, and mathematics in order to: (1) deepen student understanding of STEM disciplines by contextualizing concepts, (2) broaden student understanding of STEM disciplines through exposure to socially and culturally relevant STEM contexts, and (3) increase student interest in STEM disciplines to expand their pathways for students to entering STEM fields⁹. Additionally, the units were built from the Framework for Quality STEM Integration Curriculum, with each unit intentionally including a motivating and engaging context, meaningful mathematics and science content, student-centered pedagogies, an engineering design task, teamwork and communication skills¹⁰. Each of the units includes science and mathematics picture books, STEM activities, and an engineering design challenge to integrate STEM learning. This provides students with contextual activities that engage learners in specific STEM content as well as integrate concepts across traditional disciplinary boundaries. The engineering and literacy contexts are important features within these STEM integration units that facilitate the authentic and meaningful integration of multiple STEM disciplines.

This study explores the student learning of engineering design practices and engineering thinking skills as a result of one commonly suggested model for implementation, which includes integrating engineering content and practices with science, mathematics, and/or STEM instruction^{5, 11, 12}. The research question that is guiding this study is: *What evidence of students' engineering learning is present during the implementation of an elementary literacy and STEM integration unit?*

Background

STEM integration in the classroom is not yet a well-defined construct. For this research, we take STEM integration to require that engineering is the integrator of the STEM subjects and that each subject has a meaningful role in the STEM integration curriculum. Engineering design-based STEM integration learning environments have the potential to allow students to see problems more like they are in their real world environments¹³. Our definition of meaningful STEM integration includes that quality STEM integration uses engineering, which requires purposeful and meaningful understanding and application of mathematics and science through the use and development of relevant technologies¹⁴. Today, there are many academic pushes towards an integration of engineering in the precollege education. Both state and national standards are adding engineering^{1, 2, 8}, and national documents^{11, 12, 15} are supporting this integration. One of the most common environments that has seen a change due to this increasing emphasis for integrating engineering into science instruction has been K-12 classrooms.

As a result of that push to integrate engineering into K-12 classrooms, there has been an increase in the amount and type of curriculum, programs, and specialized schools that have emerged to meet this need for integrating engineering^{16, 17}. However, while progress has been made with the publication of the Next Generation Science Standards and the Framework for K-12 Science Education: Practices, Crosscutting Concepts and Core Ideas¹², there is still no common model of what K-12 engineering education should include or accomplish in the K-12 setting⁵. For example, the NGSS chose to include engineering practices and engineering design in their model of what K-12 students should understand, and the document states that the goal was not to be an inclusive of all engineering. Additional recommendations for K-12 engineering instruction have come from the 2009 NAE/NRC report, which state that engineering at this level should emphasize engineering design, incorporate developmentally appropriate mathematics, science and technology skills and promote engineering habits of mind¹¹. The engineering “habits of mind” mentioned in this document refers to the values, attitudes and thinking skills associated with engineering and these include: (1) systems thinking, (2) creativity, (3) optimism, (4) collaboration, (5) communication, and (6) attention to ethical considerations¹¹. Therefore, as more K-12 schools and teachers are integrating engineering into their classrooms, there continues to be a need for a more clear definition of what types of engineering practices, values, and skills teachers should be including in their classrooms in order to ensure that students are learning about and practicing what engineers do.

Even though there is not a widely accepted model for integrating engineering into K-12 classrooms, commonly seen approaches include the integration of engineering into science instruction or the addition of engineering through a STEM integration model. This particular study, uses engineering-based STEM integration as the model for the inclusion of engineering in

K-12 classrooms. As the emphasis on engineering-based STEM integration is translated into practice in K-12 classrooms^{8, 17}, it is important to continue to develop the research base on K-12 STEM education to gain a better understanding of the impact of these efforts and how they are playing out in the classroom.

Initial research has identified a number of factors found to be important in determining whether STEM integration can be done in ways that produce positive outcomes for students, which include: the expertise of educators working in classrooms, the approach and implementation of the integration, and the kinds of supports that are provided throughout the instruction^{17, 18}. Additionally, research suggests that high quality STEM integration and curriculum should have the following six characteristics¹⁰. First, there should be a context that is both motivating and engaging to the students to help develop personal connections and investment in the activities⁵. Second, students should be actively engaged in an engineering design challenge that develops students' problem-solving, creativity, and higher-order thinking skills¹⁹. The third characteristic is that lesson activities should provide students with opportunities to learn from failure and engage in redesign²⁰. Fourth, the main objectives of the lesson must include meaningful mathematics and/or science content^{17, 21} that are enhanced by the engineering design challenge and activities. In addition, the meaningful mathematics and science content lessons that incorporate non-STEM content, such as reading or social studies, are highly encouraged^{12, 22}. Fifth, teachers should implement student-centered pedagogies to develop a deep understanding of mathematical and scientific knowledge²³. Finally, STEM integration lessons should help students to build and incorporate teamwork²³ and communication skills^{12, 24}.

However, research in this area has also shown that K-12 teachers are limited in their ability to develop and implement quality STEM lessons for use in their classrooms¹⁸ making it difficult for teachers to integrate STEM into their current curriculum. Additionally, as engineering is a large part of many models of STEM integration and included in the NGSS^{8, 17, 25}, it has been found that even after participation in a year-long professional development focused on integrating engineering, teachers struggled with the integration of engineering into their science curriculum¹⁸.

Therefore, as STEM and STEM integration are gaining exposure and becoming more commonplace in elementary classrooms, it is important to look at how teachers are implementing STEM lessons in their classrooms, and how teacher educators can help elementary teachers to successfully implement STEM lessons in their classrooms. Research in this area will help to better understand the transition of STEM integration research into classroom practice and inform the teacher development of pre-service and in-service teachers in terms of the implementation of STEM integration in elementary classrooms. The study reported here adds to that research base regarding K-12 STEM education by examining engineering learning in an elementary classroom.

Methodology and Methods

To understand the actions and interactions occurring during implementation of an elementary engineering unit that contribute to engineering student learning, this study uses A Framework for Quality K-12 Engineering Education (FQEE-K12) as the basis for the analysis of video data and student work artifacts²⁶. The framework offers a structure for understanding key elements that

are the essential elements of a K-12 engineering education. These elements need not be present in every engineering lesson or unit, but should be addressed throughout the K-12 engineering curriculum. The key indicators and their descriptions are shown in Table 1.

Table 1: A Framework for Quality K-12 Engineering Education (FQEE-K12)^{2, 26}

Key Indicator	Description
Process of Design (POD)	Design processes are at the center of engineering practice. Solving engineering problems in an iterative process involving preparing, planning, and evaluating the solution.
Problem & Background (POD-PB)	Identification or formulation of engineering problems and research and learning activities necessary to gain background knowledge.
Plan & Implement (POD-PI)	Brainstorming, developing multiple solutions, judging the relative importance of constraints and the creation of a prototype, model, or other product.
Test & Evaluate (POD-TE)	Generating testable hypotheses and designing experiments to gather data that should be used to evaluate the prototype or solution, and to use this feedback in redesign.
Apply Science, Engineering, & Mathematics Knowledge (SEM)	The practice of engineering requires the application of science, mathematics, and engineering knowledge, and engineering education at the K-12 level should emphasize this interdisciplinary nature.
Engineering Thinking (EThink)	Students should be independent and reflective thinkers capable of seeking out new knowledge and learning from failure when problems within engineering contexts arise.
Conceptions of Engineers & Engineering (CEE)	K-12 students not only need to participate in an engineering process, but understand what an engineer does.
Engineering Tools & Processes (ETool)	Students studying engineering need to become familiar and proficient in the processes, techniques, skills, and tools engineers use in their work.
Issues Solutions & Impacts (ISI)	To solve complex and multidisciplinary problems, students need to be able to understand the impact of their solutions on current issues and vice versa.
Ethics	Students should consider ethical situations inherent in the practice of engineering.
Teamwork (Team)	In K-12 engineering education, it is important to develop students' abilities to participate as a contributing team member.
Engineering Communication (Comm-Engr)	Communication is the ability of a student to effectively take in information and to relay understandings to others in an engineering context.

Of the nine key indicators (and three sub-indicators), a subset were chosen for analysis in this study: Process of Design including Problem & Background, Plan & Implement, and Test &

Evaluate; Apply Science, Engineering, & Mathematics Knowledge; Engineering Thinking; Teamwork; and Engineering Communication (POD [POD-PB, POD-PI, POD-TE], SEM, EThink, Team, Comm-Engr). This subset of indicators is composed of those that have been found to be essential for successful K-12 engineering implementation²⁷.

Participants

The focus of this study was one 4th grade classroom's implementation of the Nature-Inspired Design module of the PictureSTEM engineering curricula²⁸. Twenty-three students (5 girls, 18 boys) participated from an accelerated self-contained classroom in a suburban area of the United States. During the engineering activity, these students were further subdivided into six groups (three groups of four students, two groups of three students and one group of five students). The classroom teacher and instructional support assistant were also observed during the study.

Nature-Inspired Design (NID) Module

This module was chosen due to the fact that it was designed as an integrated STEM curriculum that uses engineering design to facilitate science, mathematics, and engineering learning and therefore allows for the examination of students' engineering learning. It is a seven-lesson unit that is geared towards the upper elementary grades (4-5), but is also easily adaptable to middle school. The nature-inspired design module requires students to design a rainwater collection tank for families on an island in Panama using a series of lessons about nature-inspired design, measurement and data analysis of rainfall, and plant and animal adaptations. It connects learning in the areas of life science, geometry, measurement, data analysis, and engineering design through seven pairs of literacy and STEM integration activities, each with their own age- and activity-appropriate high-quality trade book as shown in Table 2. Implementation of the module extended over 12 sessions as shown in Table 3.

Table 2: Fifth Grade Unit Overview

Fifth Grade Unit Overview: Nature-Inspired Design							
	Lesson 1 – Biomimicry	Lesson 2 – Volume	Lesson 3 – Data Analysis & Volume	Lesson 4 – What are Adaptations?	Lesson 5 – Plant Adaptations	Lesson 6 – Planning your design	Lesson 7 – Nature- Inspired Design
Literacy Activities	Book: <i>Nature Got There First: Inventions Inspired by Nature</i> Strategy: Summarize informational text	Book: <i>For Good Measure</i> Strategy: Juicy Words- Vocabulary	Book: <i>Our World of Water: Children and Water Around the World</i> Strategy: Compare & Contrast	Book: <i>What Do You Do when Something Wants to Eat You?</i> or <i>Island: A Story of the Galápagos</i> Strategy: Making Predictions	Student research on biomes and plant adaptations Strategy: Research Skills	Book: <i>Biomimicry: Inventions Inspired by Nature</i> Strategy: Identify Important Details	Book: <i>A Cool Drink of Water</i> Strategy: Author's Message
STEM integration activities	Students explore an example of nature inspired design before sharing products with classmates	Students learn about volume, how to calculate volume using nets and the relationship between volume and liquid volume	Students use data analysis and average rainfall data to help inform the size/dimensions that they want to use for their storage tank	Rotate through stations, where students explore the advantages that different adaptations provide	Students research a biome and plant adaptations from that biome before sharing their findings with the class	Students review before the initial brainstorming & planning for engineering design challenge	Create prototype, present to the class and then improve the design

Table 3: Classroom Implementation Schedule

Classroom Session	1	2	3	4	5	6	7	8	9	10	11	12
Lesson	1	2	2	2	3	3	3	4	5	6	7	7

Data Collection and Analysis

The classroom was videotaped during module implementation as described by Mondada²⁹, offering a situated view of social conduct within the classroom context. The camera was kept stationary at the back of the room unless the entire class moved to one area of the room, such as the front, and captured the entire NID session each day throughout the implementation. This allowed for capture of the greatest quantity of data, sacrificing individual details of student group interactions for whole-class analysis throughout the classroom implementation. While some participants were aware of the camera at times as demonstrated by making faces or pausing, the class as a whole did not seem to alter their behavior due to the presence of the recording device. The videos were transcribed and reviewed during coding. Student classroom artifacts were collected and scanned. Two researchers coded all of the student artifact and video data. For the video, they used a part-to-whole deductive approach in viewing and re-viewing the data while recording instances of behaviors and discussion relating to the chosen framework³⁰. Data have been presented as descriptions of student work or observations along with supporting quotations; these quotations have been cleaned of filler sounds for presentation.

Evidence of Student Learning

This section discusses the findings of each of the 5 indicators mentioned in the previous section: POD, SEM, EThink, Team, and Comm-Engr. First, we have presented a table showing how evidence of engineering played out throughout the whole curriculum. Then, we have presented examples, organized by the key indicator of engineering in question, in order to provide a rich description of the types of evidence of student learning that are available to the teacher during classroom implementation of engineering design work.

From the recorded classroom observations, each instance of key engineering indicators was coded. Presence of indicators is presented by lesson in Table 4. While no single lesson of the module contained all key engineering indicators, all of the indicators are present when considering the module as a whole. Each lesson built upon the last to create a quality engineering experience as defined by Kersten²⁷.

Table 4: Indicators of engineering present in NID module lessons

		Framework						
		POD			SEM	Ethink	Team	Comm-Engr
		PB	PI	TE				
Lesson	1	X	X		X	X	X	X
	2	X			X	X	X	X
	3	X	X		X	X	X	X
	4		X				X	
	5				X	X		
	6		X				X	
	7		X	X	X	X		X

The Process of Design is present throughout the engineering module, following a reasonable flow. Instances of Problem and Background (POD-PB), or identifying the problem and building the necessary knowledge to solve it, are seen in early lessons but not later ones. Planning and Implementation (POD-PI) occurs throughout the module as students create, revise, and implement their engineering solutions. Testing and Evaluation (POD-TE) comes at the end of the module, where students evaluate their proposed solution in an objective manner. The application of science, engineering, and mathematics knowledge (SEM) occurs throughout the module as students learn, review, and apply the content knowledge necessary for successful engineering solutions to the engineering challenge. Similarly, students employ Engineering Thinking (EThink), Teamwork (Team), and Engineering Communication (Comm-Engr) throughout the module as they work in teams to create engineering solutions.

Table 4 and the subsequent explanation provide an overview of the engineering indicators that were present during the implementation of this NID module, where they appear, and how they fit together. The following section will describe each indicator in detail, presenting evidence of student learning and a discussion of classroom observations.

Process of Design (POD)

Following the FQEE-K12 framework, we discuss the first of the five indicators identified by Kersten (2014) as essential for quality engineering, which was Process of Design. This indicator is comprised of three sub-indicators, POD-PB, POD-PI, and POD-TE, that are mentioned in more detail above. Evidence of this indicator was seen multiple times throughout the unit as the teacher offered background information to the students. Building on this background information, the students worked on their implementation, and followed this with the testing and evaluation phase including redesigning. Examples that capture instances where each of the sub-indicators were seen during the classroom implementation have been presented and discussed in the sections below.

POD-Problem and Background

The Problem and Background sub-indicator of POD requires that students participate in problem scoping and exploring of the background knowledge needed to solve the problem. In this case, the teacher introduces the challenge right at the start of the first lesson as a “real-life type of situation” that helps students to understand the context for the problem they are trying to solve. This also helps to situate the science and mathematics learning that will be necessary for solving the engineering problem that is being posed to students. In regards to the mathematics learning, students had the opportunity to discuss measurement strategies and analyze rainfall amounts, which gave them an insight on important factors to consider for the selection of their storage tank. In terms of the science content, students used their newly acquired knowledge of plant adaptations to help provide a source of inspiration for the design for their water storage tank. In addition to participation in science and mathematics learning experiences that would provide content background for their engineering design, it is important for students to be able to identify the problem and what information they might need to solve this problem. More evidence of student learning of this first sub-indicator, *POD-Problem and Background*, can be seen in the following student work examples from Team 2 and Team 6. In these examples, the teacher has

asked students to identify the problem, solution, client, and source of inspiration that they are addressing in this engineering design challenge:

Team 2:

Problem Statement: *On Popa Island there isn't enough Fresh water during the dry season*

Solution: *Design a filter that also stores and collects fresh water*

Client: *Popa Island people*

Biomimicry idea is: *Porcupine stores water in spikes*

Team 6:

Problem Statement: *Popa Island cannot find fresh water during the dry season unless walking a long distance.*

Solution: *Inventing a bin that can collect water during the rainy season so they have water in the dry season*

Client: *People of Popa Island*

Biomimicry idea is: *Tree has droopy branches so water drips off.*

From the statements provided in these examples, students were able to construct their own description of the engineering problem they were attempting to solve, how they were solving this problem and what background knowledge they were using as inspiration for their design. Note that while the actual source of inspiration for Team 2 included incorrect knowledge, the students were correctly applying the idea that animal adaptations could serve as sources of inspiration for engineering design.

POD-Plan and Implement

The next sub-indicator of POD is the planning and implementing phase of a design cycle, which involves brainstorming ideas, developing multiple solutions, considering constraints, and creating a prototype. The NID curriculum guides the students through these processes. The most important aspect of this process is idea generation and content understanding. This curriculum addresses this by explicitly offering plant and animal adaptations to offer several conceptual ideas of what can be used in their design. Each team was able to successfully generate ideas and offer a solution for this project. Evidence of student brainstorming possible solutions and discussing their prototype design can be seen in many instances throughout the module implementation.

The students were asked to brainstorm ideas and provide supporting details of the ideas that might inspire their design. Many students came up with more than two ideas. From their readings on biomimicry, teams came up with different natural artifacts from which they might draw inspiration, such as shaping and cutting of wood can be inspired by the work of the beaver and bracing and supporting with strength can be inspired by bird rib cages which are spaced far apart but have great strength.

The students were then asked to plan for their design. The following images (Figure 1) show how the students were representing their plan.

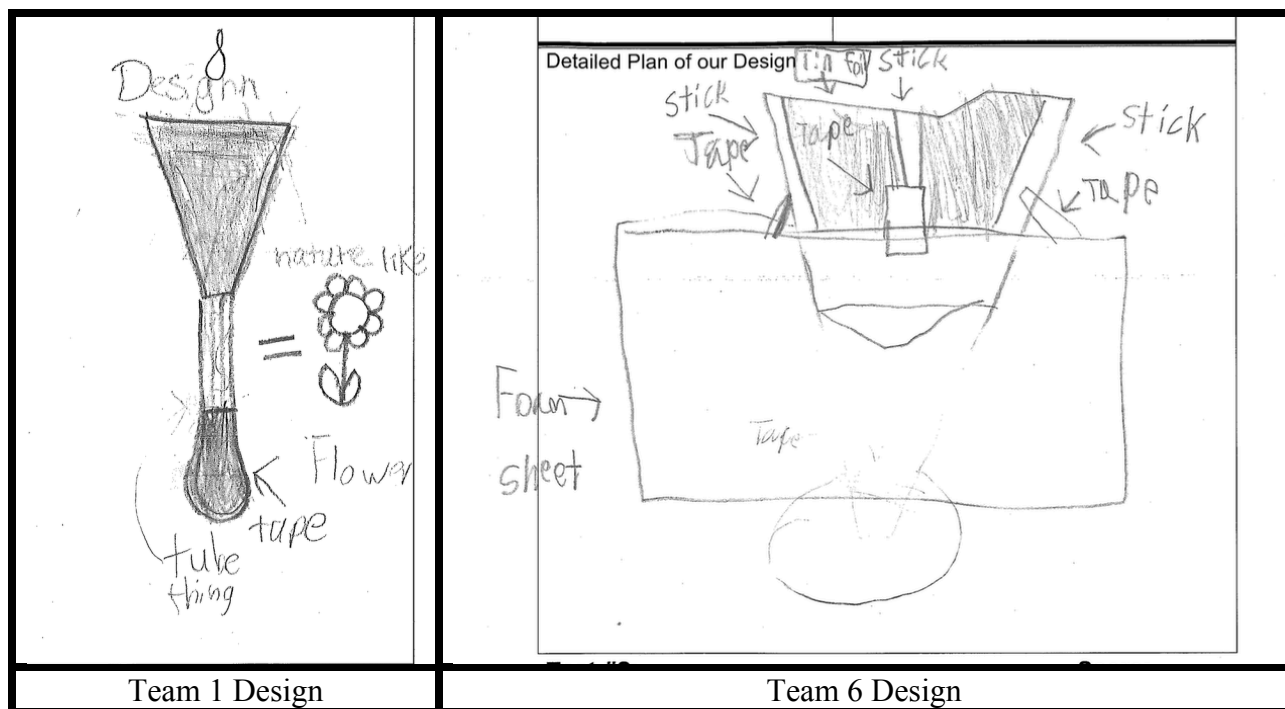


Figure 1: Teams 1 and 6 detailed plans of their designs they would implement.

After the brainstorming session, students adapted their best ideas into their prototypes and moved into the testing phase.

POD-Test and Evaluate

Once the implementation phase results in a prototype, students test and evaluate their design. The testing and evaluation phase is also as important to the engineering design process because it allows the students to analyze their design, make readjustments, or redesign. The NID unit explicitly builds in a redesign to ensure students experience an iterative engineering design cycle. During the implementation phase of their design, students were asked to consider the following while redesigning their prototype designs: (1) potentially change materials to bring down the cost of their design, and (2) redesign their prototype to collect more water. In addition, they were asked to keep in mind that they have to use something from nature to inspire their design. Students can be observed testing their storage tank and going back to evaluate the design at their tables to make corrections and retest.

After testing their designs, students were asked to fill out a test form to capture their findings and help them evaluate their designs prior to the redesign. The example below is an excerpt from Team 1's Nature Inspired Test form.

1. What happened when you tested?
It held water for most of the time then leaked a little.
2. How was your design inspired by nature?
It was based off a flower. How the flower sends its water down to the root and the straw gets water from the funnel.
3. What worked well with your design?

The funnel helped our design by allowing us to get more water in it.

4. What didn't work well with your design?

Crevices in the aluminum foil. Because it allowed the water to get out.

5. What did you see in another group's design that you liked?

I liked how the one of the other teams made their design look like a boat because it makes it interesting and worked.

6. What are some ideas for how you could improve your design for next time?

More tape to cover up crevices so the water doesn't leak out.

7. For our redesign we decided to change:

How we made the bottom and top so more water could get in and it wouldn't leak.

8. We think this will help because:

We got more water in there and it held more water. It also didn't leak as much because we had plastic wrap and duct tape to make sure water didn't get out of the bottom.

Summary of POD

The engineering design process begins by identifying problem or need, followed by a systematic path to reach one or more solutions that solves the stated problem³¹. The Process of Design (POD) was evident in this unit and was effectively implemented in the classroom. The students successfully went from generating a problem statement to implementing their design, testing, modifying, and retesting their design.

SEM Content

The next indicator from the five that were selected from the FQEE-K12 framework is the use of science, engineering, and mathematics content knowledge built into an engineering project in an interdisciplinary nature. This indicator emphasizes the importance of providing students with the opportunity to apply developmentally appropriate mathematics or science in the context of solving engineering problems. The following sub-sections provide examples of how this module presents students with the opportunity to apply both science and mathematics content in engineering contexts.

Science

During the implementation of the NID unit, students used their understanding of the structure and functions of nature (animals and plants) as inspiration for their designs. Focusing on learning the science topics around plant and animal adaptations in introductory lessons, and the use of adaptation station videos to help students understand the meaning of adaptation. Evidence of this application of science can be seen throughout the curriculum implementation. An example of this science content could be seen in the interaction between the teacher and the student after watching the Stickybot video – Robo Zoo:

Teacher: *How did the scientist in this film use nature to help solve their problem?*

Student 1: *They used the gecko's hands to see what it was using to stick on it, and they make something like that to climb on stuff.*

Teacher: *Alright, Yes.*

Student 2: *They used the hairs that they have... that the geckos have on their feet for a kind of like a velcro robot so that it would be able to climb and the feet also act like a vacuum.*

Teacher: *Okay. Yes.*

Student 3: *They basically observed a gecko and then the tiny hair leg things on their bodies and they recreated it. They put it on the stickybot and then they tested it. It worked.*

Teacher: *So it's definitely a situation of what could nature do? It could be answered in this, right?*

Student 4: *I mean, I think it would take a lot to build on, and it would take a long time. To find vertical surfaces and construct all that will take a really long time.*

Teacher: *Oh, I agree. (laugh)*

Student 4: *To find critical surfaces and to construct all that. It will probably take a really long time. So I don't think they are gonna let you come out with these in stores.*

Furthermore, examples of student learning of the adaptations of plants and animals were evident in the explanations of their designs. For example, Team 5 stated that their design was inspired by nature because “a plant in the jungle has a funnel-shaped top. Ours had 2 funnels on the top of it.” This team was drawing on the fact that the plant’s shape worked to direct water towards its roots.

Mathematics

In regards to the mathematics learning that the students did during this unit, they applied this learning during the discussion for the type of measurement they should use with their storage tank prior to selecting the storage base they wanted to use in their design. As part of this discussion, the students were talking about how to measure water or liquid as they started to form an understanding of the concept of volume. Students were then asked to calculate the volume and size of their containers and draw on their knowledge of water measurements to determine how much water to use in testing their prototypes. An example of using mathematics can be seen in the following interaction between students and the classroom support instructor on the topic of units of measurement needed for their designs:

Teacher: *What does milli mean?*

Student: *1000*

Teacher: *1000 you guys are [doing great]. Well, you don't need me. One thousand. You probably can't see that but you already know that right because there are 10 millimeters in a*

...

Student: *meter?*

Teacher: *Centimeter. Look at your ruler and look at the cm, it has how many of those tiny millimeters in it?*

Student: *10*

Teacher: *10. 10 x 100 gives you the thousand you are looking for. A millennium is how many years?*

Student: *A thousand.*

Teacher: *A million is a thousand what? Same thing.*

Student: *Centimeters?*

Teacher: *A thousand 100s. Who said it? There you go. A 1000 hundreds, that's how the Romans count it. Okay. So now, we go back to the milliliters. How many milliliters in a liter? Milli -*

Student: *A thousand.*

Teacher: *One thousand. So, this says 1000 mL. Which stands for?*

Student: *Milliliters*

The need for measurement in order to design the storage portion of their water collection tank drove the conversation above. The students in this class had not yet learned about volume, so this mathematics was a new concept for them. Yet the translation of the idea of water volume (mL) to tank volume (cm^3) was a concept that the students grappled with. This excerpt shows a student thinking deeply about how manipulative cm^3 blocks line up in a rectangular prism that represents the base of their water tank.

Teacher: *So, how many did you guys get? What did you get? How did you get it? How many are in there?*

Student: *We looked at ours and we had five on five for each floor and its 7 floors so we did 5 x 5. We had 25, then we did 25 x 7 which is 175 cubes.*

Here we see the students making sense of the how the cubes lined up in the rectangular prism and how one team thought about their counting strategies. This conversation between teacher and teams continued while other teams described their similar but different strategies for counting the cubes. Then the students explored other sizes of rectangular prisms and came up with counting techniques for these as well. Finally, the students were asked to make a generalized formula for a way to count the cubes in the rectangular prism which finalized in the volume formula of length x width x height.

Summary of SEM

The use and development of scientific and mathematical knowledge were critical to the implementation of this unit. Students used plant and animal adaptations while brainstorming for ideas and the use of inventions such as the Velcro helped student understand that inspiration can come from nature. The students had to justify their designs with ideas from nature using scientific argumentation. The mathematical content was necessary for the water storage device. Students needed to decide on the size of the tank to design and calculate it. This involved dealing with volume measurements of water and translating it into cubic length measurements. Then students had to scale lengths in order to make a prototype that they could create. This involved a deep development of the ideas of surface area as they related to volume.

Engineering Thinking (ETHINK)

ETHINK requires the students to use thinking skills that are important to those in the engineering profession. This includes the ability to use creativity, perseverance, seek new knowledge when necessary, and learn from failure. The students in this 4th grade classroom were successful in exuding ETHINK characteristics throughout this module through their discussions and questions, particularly during the design and redesign of their prototypes. Students can be observed discussing tradeoffs during their initial prototype designs, such as weighing cost of material, and during discussion of their redesign strategies. During a water measurement exercise, students were asked about how much water was in a bucket and how to measure it. The students came up with various possible answers independently and during a cube counting exercise, students explained their rationale for their findings on how many cubes could fit into a beaker, and explained their calculations; connecting their findings from their measurement experiment, tying it to specific measurement units.

Evidence of ETHINK can be seen in the following dialog with a student and teacher during lesson 2, when they are brainstorming about how to measure rainfall.

Teacher: *Tell me about this cloth you have in your hand, you just rung it out. You rung out a certain amount of water. If you put it in a measuring cup, you know how much you have. How much is in that towel? Is it all gone?*

Student: *No.*

Teacher: *How much is in there?*

Student: *We don't know.*

Teacher: *We don't know. So, is that an efficient way to measure? Even if we squeeze some out are we getting the most water for our people that need it?*

Student: *No.*

Teacher: *If you had a spectrum from the best way to the worst way, would you have that towards the best way or would you have it towards the worst way?*

Student: *Worst.*

Teacher: *Okay, so now we need to move along that line and try and get better. What's a better way than the towel?*

Student: *A bucket*

Teacher: *A bucket. I like the bucket. Buckets catch water.*

In this dialogue, the student acknowledges that it is difficult to measure water using the method that they first brainstormed and that it might not have been the best method. Instead of giving up and stating that they don't know how to measure water, the student suggested an alternative method. This idea of identifying an alternative method to test after testing their first method and realizing that it doesn't work is evidence that the student was learning from the failure of their first method.

Teamwork (Team)

Within engineering, there is an emphasis on the need for students to develop the ability to participate as a contributing member in a team setting. Evidence of this the teamwork indicator may include participation in collaborative groups that require students to demonstrate the ability to accept diverse viewpoints, exercise good listening skills, compromise, and include team members in the process rather than working alone through the process. An example of students working together in team setting can be seen on Day 6 when groups of students are working together to come up with the dimensions for their water storage tank. The following excerpt captures their conversation as members of a team practicing how to work together to help each other:

Student 1: *I'm forgetting stuff very quickly. How do you draw one of those?*

Student 2: *I'm really good at it. I'm not bragging. I can help you.*

Student 1: *Thank you. Can someone draw it?*

Student 2: *My way is kinda easier than yours. No offense.*

Student 3: *And make it a rectangular and not a square. Don't forget it's a rectangular prism and not a cube.*

In this example, the students are discussing a task assigned by the teacher. Evidence of their effective teamwork skills are seen as they are helping each other to proceed and complete the

task by helping each other and negotiating who will do which of these tasks based on their strengths and weaknesses.

Overall, in the NID curriculum students were arranged in teams early in the project and provided with multiple opportunities to work together throughout the unit. From the beginning of Day 2 - Lesson 2, students were divided into teams and worked together in groups for the duration of the design challenge. Before the formation of their design groups, students worked in groups to read, discuss, and generate nature inspired designs based on the book *Nature Got their First* (Day 1, Lesson 1). As students worked in groups, they showed evidence of teamwork by helping each other come up with the best way to proceed with the engineering design challenge. The team can be observed negotiating roles. Students also worked in team to come up with their problem statement for the people on the island in Panama and worked together to discuss what they would like to include in the background information for their design. And finally, they presented their prototype in teams.

Engineering Communication (Comm-Engr)

Communication in the engineering context means students present their ideas and are explicit in demonstrating their understanding of the project. Furthermore, students are able to assimilate information presented to them and effectively convey their interpretations of the content. In this NID curriculum, students used their engineering notebook, problem statements, artifacts, and presentations to communicate their design. In addition, students communicated to each other in their teams. They can be observed discussing tasks and making suggestions to one another. At the end of the unit, students presented their nature inspired design as a team to the class.

Below is the presentation from team one where they communicated the inspiration for their final design, cost, and what the team would like to improve on in a future design.

All: We are Team 1 and this is our nature-inspired design.

Student 1: Our design was complex for the materials we were given. A few of the materials we thought of followed through to the final design.

Student 2: Our final design was very simple: a funnel and storage tank.

Student3: Our other designs were prototypes. Our final design held the most water – 62%.

Student 4: We built the funnel out of tin foil. The teacher said, “we could not use the plastic funnel in our design”. So we thought outside of the box and used it as a mold to make our own funnel.

Student 3: We tried to keep the cost under \$350, and we did keep it less than \$350. The cost of the final design was \$114.

Student 1: Our design is inspired by a flower because of how it holds water in its roots.

Student 2: What we would improve on is the tank because it can leak.

Student1: Only our final design worked because all of our others leaked too much. The final design worked because we covered the bottom with tape so it didn’t leak as much.

Student 3: Our funnel shape helped us get water and pour the water back into a graduated cylinder. So we can get more water in the cylinder.

Engineering communication is in addition to both written and spoken language; many engineering ideas are also most effectively communicated using sketches, diagrams, graphs,

models, and products¹². On several occasions, student groups can be observed communicating and discussing the various exercises throughout the lessons, using these communication skills to help each other with calculations, measurements, and presentations. The students were able to communicate their problem statements in writing, present their ideas verbally, and create their prototype to convey their design physically. In general, they were observed communicating to their classmates, teacher, and the classroom support effectively.

Conclusion and Implications

Even though the curriculum was explicitly designed to be a STEM integration unit that uses literacy and engineering contexts to facilitate student learning in science and mathematics, it was unclear how this integrated model would impact students' learning in engineering when implemented in an elementary classroom. The analyses identified evidence of students' learning in all five of the indicators identified as essential for quality engineering instruction²⁷ throughout the unit. This was especially true of students' process of design learning, which was seen in varying degrees in almost every lesson and provided evidence that students were learning about engineering design as they progressed through the module and not just at the end when they engaged in the engineering design challenge. This is important because as teachers are thinking about how to integrate engineering into their classrooms, this study provides evidence that student learning of engineering design and engineering thinking can be woven throughout the unit, as described by Roehrig et al.⁹ and Guzey et al.¹⁸ During instruction of science and mathematics content, the evidence of student learning of engineering design was more heavily focused on the problem and background indicator that highlighted the problem scoping and necessary background information that students needed for the final design challenge. As the unit progressed, there was increased evidence of the plan and implement indicator which includes students brainstorming solutions and was largely seen through the students identifying how they could apply their learning to their design challenge. By introducing the context for the engineering design challenge at the beginning of the module, the students were able to make more connections to the final design challenge and therefore to engineering as they participated in the unit.

Another indicator from the FQEE-K12 that was seen throughout the unit was the application of science and mathematics knowledge within an engineering context (SEM). While the intention of this integrated STEM unit was to learn science and mathematics knowledge, it is also important for students to learn about how these concepts can be applied towards their engineering design challenge. This analysis provided evidence that students were making those connections throughout the module. This is important because it reinforces the idea that this is an integrated unit; the engineering learning is occurring at the same time that students are learning the required science and mathematics knowledge^{17, 21}. Additionally, this indicator emphasized that students were able to apply their science and mathematics learning within other contexts, such as engineering. Not only were students able to state how their mathematics and science learning could be applied in the future to their engineering design challenge, but they were also able to explain how they used the science and mathematics concepts that they had learned in their actual designs.

The professional skills of engineering such as the engineering habits of mind, teamwork, and communication are also important aspects of integrated STEM learning environments. Here we saw students using iterative thinking, making decisions based on evidence, learning from failure, learning to work in teams, and communicating in drawings and oral presentations. These aspects of engineering need to be highlighted at the elementary level. Students can capitalize on these ways of thinking and participating throughout their education³². These skills are the ones that will help students become STEM-literate citizens as well as aid them in other avenues in their life.

As the integration of engineering and STEM is becoming more commonplace in the elementary classroom, it is important to gain a better understanding of what evidence can be used to assess student learning of engineering at the elementary level. This study sheds light on the types of evidence that can be used to identify student learning and thinking in engineering, including young students working in teams effectively and pedagogical strategies that provide gains in STEM learning. This research aims to develop an understanding of student learning outcomes in engineering as teachers implement STEM integration curricular units in their elementary classrooms. As more schools and teachers are integrating engineering and STEM into their classroom instruction, it will be important for teacher educators and educational researchers to gain a better understanding of what factors are influencing this integration of engineering and what supports can be provided to facilitate successful teaching and learning at the elementary level.

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