Student Connections between Engineering Contexts and STEM Content

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Middle School Student Connections Between Engineering Contexts and STEM Content

Abstract

Integrated STEM (science, technology, engineering, mathematics) curriculum can potentially increase student motivation because it provides a real-world context, promotes learning, and stimulates “higher-order” thinking. Curriculum developers designed the integrated STEM curricula for middle school students to utilize a problem-based learning approach in a science-focused lesson. Designers developed the curricula to incorporate STEM connections from all areas (science, technology, engineering, and mathematics) into each unit through a “real-world” engineering design challenge. The curricula employ engineering challenges that engage and motivate students to apply newly learned principles to an engineering design problem. The curriculum aims to support student autonomy and competence needs by giving students structured opportunities to make choices in an engineering design project. The goal is that integrated STEM will motivate students with varying interests because of its variety and support for their sense of autonomy, choice, and competence. This study will investigate a pedagogical strategy that asks students to anticipate the learning they need to engage in to prepare for implementing their engineering design solution; “What do you need to know in order to solve the problem?” We examined 150 middle-school student engineering notebooks to determine: 1. Do students correctly anticipate the presence of each type of STEM connection in the unit (science, technology, engineering, mathematics)? 2. Do students correctly anticipate the nature of the STEM connections in the unit? In answering these questions, we can discover if students determine that they must learn the very same STEM concept(s) for which the curriculum was designed. If students anticipate the correct connections, we have reason to believe this supports students’ feelings of autonomy, competence, and motivation. The answer to our questions provides the impetus for further investigation into how students perceive the variety and nature of connections inherent in STEM integration and how may lead to greater student motivation.

Introduction

The recent STEM education reforms in the U.S. call for authentic STEM learning activities that engage learners in STEM content and practices. Prior research demonstrates that integrated STEM education approaches promote learning [1] [2], increase engagement [3], and enhance problem-solving skills[4]. However, integrated STEM education is new to many teachers. Providing quality professional development programs and well-developed curriculum units is necessary to successfully implement integrated STEM approaches in K-12 classrooms.

In this study, a group of teachers partnered with engineering education researchers in a professional development program to create integrated STEM curricula for elementary and middle school levels. The integrated STEM curricula use motivating problems set in realistic contexts. They also employ self-regulated/self-directed learning techniques to build upon children's innate curiosity about the world. The curricula utilize engineering challenges that engage and motivate students to apply newly learned principles to an engineering design problem. Engaging students in problem-based engineering design with self-regulated/self-directed learning empowers them to be autonomous thinkers who seek solutions in a contemplative manner[5].

The curricula developers designed each unit to align specific Next Generation Science Standards (NGSS) and Common Core State Standards for Mathematics (CCSSM) while also involving technology and engineering principles [6]. These constraints in aligning the curricula to standards naturally limit students to the science and mathematics they must learn. This alignment could pose a problem to students' feelings of autonomy, which is essential to self-regulated/self-directed learning. The project curriculum units are designed for students to make connections across the STEM disciplines and, perhaps, broaden their appeal. Because integrated STEM curricula can include learning objectives from all STEM disciplines, it allows for differing student interests. It can provide greater motivation for students to engage in self-directed learning. However, little is known about how students make connections across the STEM disciplines. If they make connections, do they anticipate the right connections? If they anticipate the breadth of connections, we have a higher likelihood of each student finding something that intrinsically motivates them. If their anticipated connections are correct, we've supported feelings of competence, another motivating factor. For this study, we seek to determine if students recognize connections in the curricula to science, technology & engineering, and mathematics and if those connections align with the intention of the curriculum designers. We have two related but distinct questions: *1. Do students correctly anticipate the presence of each type of STEM connection in the unit (science, technology, engineering, mathematics)? 2. Do students correctly anticipate the nature of the STEM connections in the unit?* This research study is a precursor to investigating how STEM integration can foster student motivation.

Literature Review

Students have diverse personal interests, and we can broaden and enhance their perception of engineering by allowing them ample freedom to engage in interest-based engineering challenges [7]. In addition, research demonstrates that self-regulated/self-directed learning encourages students' feelings of autonomy and motivation by allowing them to define their learning activities [5]. Thus at its furthest end towards freedom and self-directed learning, students engaged in engineering experiences that allow wide choice can experience a more significant amount of motivation to pursue their personal interests. However, such a model of freedom is not available in school learning because of the need to align with state and federal education standards. Integrated STEM can help bridge the gap between the motivating elements of complete freedom to pursue intrinsic interests and the constraints inherent in academic school-based curricula.

Integrated STEM curricula are tasked with developing challenges that ask learners to use science and mathematics concepts to create technology under the umbrella of engineering design [8]. Integrated STEM instruction utilizes a problem-focused learning approach to provide broad, motivating engineering design contexts for engaging students in STEM learning. By integrating engineering design into science and mathematics through integrated STEM curricula, the curricula provide a realistic engineering context that promotes student interest [9]. The integrated STEM curricula challenge students to solve open-ended problems, similar to problem- or project-based learning (PBL), encouraging students to be independent thinkers. Integrated STEM education provides opportunities for students to construct their knowledge and encourages their interests and identity development. Like PBL, a benefit of integrated STEM curricula is its potential to motivate students [10] because it involves a real-world context, promotes learning, and stimulates "higher-order" thinking [11].

Research has shown that learning activities that reinforce concepts help students understand the content they previously struggled to master [12]. This approach also improves their understanding of concepts, the principles that link concepts, and the linking of concepts and principles to conditions and procedures for application [13]. It is critical to allow students to relate concepts to their application by providing realistic scenarios for students to solve using their knowledge of STEM. Integrated STEM activities can foster self-regulated/self-directed learning in several ways. One is by prompting students for explanations via guiding questions, which help students reflect upon and integrate the knowledge they require to solve the problem [14]. For the integrated STEM curricula under study, educators used guiding questions to foster self-regulated/self-directed learning. Students are prompted with several guiding questions about the problem's importance, scope, end-users, and constraints. These guiding questions aim to support students' feelings of autonomy, competence, and motivation in alignment with self-regulated/self-directed learning.

Classroom environments that support feelings of autonomy and competence in their students facilitate greater intrinsic and extrinsic motivation and curiosity[15]. Because autonomy is reinforced by choice [16], one strategy to support the feeling of autonomy is to give students a choice in their learning. By giving students a sense of choice in their activities, teachers reinforce autonomy, contribute to increased intrinsic motivation in their students, and positively affect student engagement and feelings of competence [17] [18]. Students with self-efficacy who know they have successfully solved problems in the past believe in themselves and are more likely to succeed in future problem-solving opportunities [19]. The integrated STEM curricula developed for middle school students for the current study aim to support student autonomy and competence needs by giving students structured opportunities to make choices and reflect upon their decisions in an engineering design project [5]. By helping students feel independent and competent, we support students' intrinsic motivation. The curriculumdesigners' motivation for including the question under study was to simulate student autonomy and thus contribute to increased motivation.

We understand the importance of students' intrinsic motivation and the motivational benefits of self-directed learning, where students can pursue their own interests. However, studies have shown that intrinsic interest in school decreases from grades 3-9 [20]. When maturing and capable of greater autonomy and self-direction, middle school students experience less independence because of an increased focus on teacher control and discipline [21]. The lack of support for student autonomy and competence via increased teacher control can hinder students' intrinsic motivation [22]. We seek to maintain students' feelings of autonomy, choice, competence, and, thus, motivation at a time when such sentiments are in decline. Yet, absolute autonomy for each student to pursue their own interests is impossible, as academic standards mandate topics teachers must cover in middle school. How can we foster students' feelings of independence and competence through choice when limited choices are available due to topic coverage as prescribed by NGSS and CCSSM?

Specifically, the project curricula incorporate several strategies to ease the autonomy constraints inherent in delivering specific science and mathematics content and increase student feelings of metacognitive competence with new material. This study will investigate the usefulness of a strategy that asks students to anticipate the learning they need to engage in to prepare for implementing their engineering design solution; "What do you need to know in order to solve the problem?" In answering this question, we want students to make connections with one or more STEM topics that could meet their interests. We also desire that students determine they must learn the very same concept(s) for which the curriculum was designed. We want students to believe it was their own idea to learn this content because this can boost feelings of autonomy and competence. If students' answers correspond to the STEM content they will be taught, we have contributed to supporting student autonomy, competence, and motivation. Students will feel they have exercised some agency in determining their next learning steps. We want them to feel like they have a choice and a voice in their learning because they have already predicted their need to know the topics the unit will eventually cover. Examining students' STEM connections is the first crucial step in evaluating the effectiveness of our pedagogical strategy.

Project Background

Researchers developed and tested different integrated STEM education models. These models vary based on STEM learning goals, learning contexts, and learning theories being used [23]. Our synthesis of the body of literature focusing on integrating STEM disciplines for learning and teaching highlights several critical elements of integrated science and engineering instruction: (1) using motivating and engaging context, (2) having students participate in engineering design challenges of relevant technologies, (3) including main learning objectives from science and/or mathematics, (4) using student-centered pedagogies, and (5) involving students in teamwork and communication.

The resulting integrated STEM curricula were part of a multi-year effort that involved education researchers and pre-college teachers in two Midwestern states. The project aimed to develop curricular units that utilized integrated STEM education to teach state science and mathematics standards to upper elementary and middle-school students. Thirteen units focused on topics of Earth Science, Physical Science, and Life Science. The curricula designers identified the connections they aimed for each curriculum to teach students. Each unit identified science, mathematics, and technology & engineering connections that students should have learned upon completing the unit [24]. The six units designed for middle school science classrooms are the focus of this study. Although the topics in each curriculum varied, all curricula followed the same basic format. Each curriculum presented a design challenge in the early lessons, followed by several content lessons. The design challenge and science, mathematics, and technology & engineering connections for each middle-school unit are outlined in Table 1 [6]. The connections outlined correspond to NGSS and CCSSM for middle school.

Each of the six middle-school curricula introduced students to the engineering design process using communication and teamwork to work through six pre-defined steps: Define the problem, learn about the problem, plan a solution, try a solution, test a solution, and decide whether the solution is good enough. To motivate students and foster intrinsic motivation, each unit began with a letter from a "client," often a university or company, asking this group of young scientists and engineers to help them solve a problem with real-world environmental and societal impact. The next 4-7 lessons in the unit focused on interactively introducing STEM concepts. These STEM concepts equipped students with the background knowledge to develop design solutions, followed by a Design lesson for creating prototypes, a Test lesson for making hypotheses about the design's effectiveness and testing them, and a Redesign lesson for making design changes based on test results. Finally, the last lesson allowed students to present their solutions to the client through a poster, presentation, or memo.

Teachers provided students with an engineering design notebook for the unit's duration. The notebooks prompted students to make observations, collect data, plan for their design, and serve as a reference for the newly learned information. Notebook prompts also asked students to justify their design decisions with the mathematics and science concepts learned during the unit and to reflect on what they had learned about engineering design at the end of the unit. These notebooks reflect professional engineering notebooks and contribute to the concept that the student's work is important. Teachers collected these notebooks at the end of each class to assess learning throughout the design process, and some chose to give feedback according to the provided rubrics.

Table 1: Middle-School Curricular Units

Unit Name	Design Challenge	Science Connections	Technology & Engineering Connections	Mathematics Connections
Ecuadorian Fishermen (Grades 6-8)	Create a cooker container for the fishermen to use at the fish market.	• Heat transfer • Convection • Conduction • Radiation • Temperature • Thermal energy • Heat	• Use of thermometers • Complete full engineering design process • Problem scoping (define and learn about the problem) • Solution generation (plan, try/build, test, decide about a solution) • Redesign • Communication of final design to the client	• Collecting data • Plugging points in the Coordinate system • Making interpretations from graphs • Measuring temperature • Using data tables
Got GMOs? (Grades 6-8)	Evaluate the efficacy of a barrier that reduces cross-contamination of non-GMO corn fields from GMO corn fields and develop a strategy to test for cross-contamination.	• Cells contain DNA. • Genes are located in DNA. • Genes carry information about traits. • Asexual reproduction, single parent • Sexual reproduction, two parents • Environment	• Ethical and practices uses of technology • Technology used in science and engineering. • Engineering design • Frame scientific learning through engineering	• Population from a sample • Draw inferences about a population from the data • Variation in estimates and predictions • Probability • Statistics

		al influences on traits • Organisms		
Laser Security System (Grades 6-8)	Create a laser security system to protect artifacts in a traveling museum exhibit.	• Light • Waves • Color spectrum • Reflection • Refraction • Absorption • Transmission	• Engineering design process • Lasers • Computer simulations	• Angles • Measurement
Loon Nesting Platforms (Grades 6-8)	Create a loon nesting platform and choose a suitable lake	• Food chain energy flow • Food web or food chain • Human impact on the environment • Lake ecosystem components	• Engineering design process cycles • Tools and technology for data analysis • Testing and evaluating prototypes	• Data analysis and measurement • Graphing • Percentages • Area • Proportional reasoning
Mineral Mayhem (Grades 7-8)	Design a process to efficiently sort a variety of minerals that have fallen into a lake and been mixed.	• Mineral properties • Methods of identifying minerals • Non-renewable resources	• Engineering design process • Environment al engineering • Civil engineering • Process design • Process modeling • Process-flow diagrams	• Proportional reasoning • Scatterplots • Best fit lines • Slope of a line • Density • Volume

Methods

Students in the middle-school classrooms utilized engineering notebooks as part of the integrated STEM unit. The notebooks contained student responses to curricular prompts designed to capture their thinking, decisions, and grasp of the science, mathematics, and technology & engineering content. We employed qualitative coding methods to examine how closely student answers resemble the integrated STEM connections the curricula designers identified for the unit. The terms used as connections reflect the NGSS and CCSSM that align with each unit. Table 1 [6] contains the wording we searched for in the student answers. For example: in the Loon Nesting Platforms curriculum for science connections, we looked for the words "food chain energy flow," "food web," "food chain," "human impact on the environment," and "lake ecosystem components." We coded the student response as a science connection if students expressed any of these main idea words, phrases, or themes. If the student mentioned data analysis, measurement, calculating graphing, percentages, or area; or explicitly discussed proportional reasoning, we coded their response as a mathematics connection. Three researchers examined 150 middle-school student notebooks across the five science curricula delivered by nine different teachers. We analyzed students' answers to the reflection prompt, "What do you need to know in order to solve the problem?" For this prompt, students were asked to provide an individual answer and then discuss it with their teammates through a think-pair-share activity to create a team answer. Because of the teachers' implementation differences, we grouped individual and team responses during our coding. One researcher coded one unit, and two researchers coded two units each. We coded a sample of units independently, then discussed our coding process and results to ensure consistent application of the coding framework. We then coded the remaining notebook prompts independently, followed by a group discussion of the results. Even if a student identified more than one term or phrase listed for a topic connection, we only counted this as having made one connection in that category. We performed coding in two passes. During the first pass, we adhered closely to the connections outlined in each lesson, looking for words and phrases that closely matched the terminology used by the curricula developers for each unit. We analyzed our findings to discern whether asking students to engage in metacognitive construction of their own learning goals showed that their intentions corresponded to the prescribed NGSS and CCSSM learning objectives.

During our second coding pass, we looked for recurring themes in students' answers and other connections related to science, mathematics, or technology & engineering but were not explicitly aligned with NGSS or CCSSM outlined by the curriculum developers. The new science connection gleaned from this process stated "signs of cross-pollination," "signs of cross-contamination," "how GMOs are contaminated," and "how far pollen can travel.". Also, during our second pass, we expanded our approach to include word synonyms. For example: In the Laser Security System curriculum, if the student mentioned "mirror" but not "reflection," we coded this as a science connection, whereas we did not code it as such in the first pass because the student did not use the exact word "reflection." The results of our completed analysis appear in the Results section.

Results

Upon completing analyses of student notebooks, we found 138 connections made by 150 students (Table 2). Considering our coding process, whereby we coded each student's response for at most one science connection, one technology & engineering connection, and one mathematics connection, there were a total of 450 connections that the 150 students could have made. Science connections were undoubtedly the most prevalent, representing 66% of all coded connections.

Table 2: Connections identified in the students' notebooks.

Lesson	Science Connections	Tech & Engr Connections	Mathematics Connections	Total Students
Ecuadorian Fisherman	14	3	0	31
Got GMOs?	18	1	0	26
Laser Security System	14	27	12	40
Loon Nesting Platform	26	1	0	33
Mineral Mayhem	19	3	0	20
Total	91	35	12	150

Discussion

We noticed stark differences in each unit concerning the percentage of connections that students identified. The Lasers unit had higher technology & engineering connections than any other unit. It was also the only unit where students identified any mathematics connections. For the Mineral Mayhem unit, 95% of the students identified a science connection, as opposed to the Got GMOs unit, in which 11.5% identified a science connection. Noticing these differences, we analyzed the curricular content introduced to students before the question prompt under study; We revisited each client letter to determine precisely how the letter related to the connections and student notebook responses. We also sought differences in how those introductory materials aligned with the curriculum developers' science, technology & engineering, and mathematics connections.

Client Letters
For all curricula, before posing the question "What do you need to know in order to solve the problem?", the unit presents the engineering design process: Define, Learn, Plan, Try, Test, and Decide. Students view a video that sets the context for the design challenge. They also read a letter from the client outlining the design challenge they must solve. We examined the wording in the letter to see what terms and concepts it introduced.

Laser Security System: The client letter outlines that students must decide on the number and placement of museum artifacts in a room. It also discusses a requirement for the laser light to refract and reflect at least once, such that a thief would need to cross the laser light three or more times. Students for this lesson achieved connections within all three categories, primarily meeting the technology and engineering connection. Despite the STEM terms not being explicitly stated in the letter, students were engaged in the activity and mainly focused on security through engineering design. Many students focused on the size of the artifact or room and considered measurement a key design factor, which qualified as a mathematics connection.

Ecuadorian Fishermen: The client letter discusses their desire to teach villagers new methods to harvest, prepare, and market food. It states that the fishermen travel far to gather fish. It introduces the fishermen's access to solar ovens at the fish market. It presents the challenge of designing a cooker container to hold each fish as it cooks in the solar oven so that the fishermen earn more money at the market. Students focused on concepts around heat transfer and energy generation which fall under the science connection. While a few commented on the design process, they made zero mathematics connections concerning temperature, data points, and graphing. Students were engaged with the process of properly cooking the fish rather than the design process and data analysis.

Loon Nesting Platform: The Minnesota Department of Natural Resources (DNR) is the client for this lesson. The DNR informs students that loons have been affected by human activity on the shorelines of Minnesota's lakes and rivers. It states that loons require a new habitat to nest. The client asks students to choose a new nesting location and to design a floating nesting platform for their desired location. The science connection was strong for this lesson, with 79% of students discussing the food chain or ecosystem. Again, there was a lack of understanding that the engineering design process is a tool necessary to complete the task, as well as data analysis and proportional reasoning.

Mineral Mayhem: This lesson's client, Rock Rails Transport, states that while transporting valuable minerals across the country, their train derailed and dumped them into a lake. To avoid a complete loss of profit, they need help designing the most efficient method of identifying and sorting the minerals into their various types. Students recognized the importance of learning mineral properties and identification techniques with 19 out of 20 notebooks including a science connection. However, only three students noted that the design process was necessary, and zero discussed density or volume. Perhaps some students intended to include these ideas in their comments on mineral properties, but they could not specifically identify these mathematic concepts this early in the curriculum.

Got GMOs: The focus of this client letter includes what GMOs are and how they are used. The letter discusses the role of pollen in cross-contamination; Cross-contamination can lead to failure to meet strict regulations from the United States Department of Agriculture. The client asks students to use the engineering design process, science, and mathematics knowledge to develop a strategy that prevents cross-contamination and then tests whether it has occurred. Student responses focused heavily on the terms "cross-contamination," "cross-pollination," and "pollen travel," Which we coded as science connections during our second pass.. Despite the client letter specifically mentioning technology, engineering, and science, only one student made a technology & engineering connection, and no students made a mathematics connection. While the mathematics connections may have seemed obvious and not a tool needed to solve the problem, perhaps the technology & engineering concepts felt too advanced or misunderstood at the time for students to recognize their importance.

Reasons for Various Connections

Curriculum designers intended the concept of designing an engineering solution for a client to be an engaging and motivating factor for students to participate in the lessons. Therefore, it would be logical for students to rely on the introductory invitation from clients when answering their reflection prompt on what they need to solve the problem. For the Got GMO's lesson, we found a strong relationship between the terminology used in the initial client letter and the students' answers to the reflection prompt. This relation revealed itself in students' ideas regarding the science connections of cross-contamination and cross-pollination. Students' use of the letter as an initial resource could explain why, in the GMOs lesson, students' answers more closely reflected the science terminology used in the letter, as opposed to the NGSS aligned science connections identified by curriculum developers.

For the Lasers lesson, we sought to understand why students could identify the breadth of connections involved. We revisited the wording for the technology & engineering, mathematics, and science connections and students' answers for their words that matched the desired links. In most cases, students used the word "lasers," which counted as a technology & engineering connection. They also referred to elements of the engineering design process, which counted as a technology & engineering connection. The fact that "lasers" counted as a technology & engineering connection could account for the prevalence of this connection in student responses. For the mathematics connections, students predominantly referred to the need to measure various aspects involved in the context, such as the entrance, room, and artifact sizes. For the science connections, students mainly mentioned the concepts of reflection and refraction, terms included in the client letter.

In addition, while the lesson plans provided to science teachers are over 80 pages long, each teacher had a different method of disseminating information to their classroom. This external factor, as well as students' attention, individual classroom variables, and previous knowledge of the subject may have also contributed to differences in connections made. For example, students are likely to be familiar with cooking, so creating a cooking device for the Fisherman lesson may be easier to list science background knowledge for than why GMO cross-contamination is important in agriculture.

When asked the reflection question, students may make assumptions about what the correct answer "should" be, which may explain why they made very few mathematics connections. Students understand the importance of learning new terminology and mastering concepts that relate to science because the content is delivered in a science class. However, mathematics connections such as measurement and graphing may seem obvious. Suppose students did not understand that this question was designed for them to consider topics in each STEM area. In that case, it could have led to them focusing on science instead of each topic area individually.

Conclusion/Future Directions

The curriculum developers identified all the units' science, mathematics, and technology & engineering connections that aligned with NGSS and CCSSM. However, for most of the lessons, the science connections dominated student responses. In the future, curriculum developers could consider encouraging students to better grasp all areas' roles in STEM integration by making those connections more explicit. For example, the questions prompt could specifically ask about the science, mathematics, and technology & engineering knowledge they anticipate needing to solve the problem, regardless of whether or not students will need to learn this information or if it is prior knowledge.

While asking the question, "What do you need to know in order to solve the problem?" prompts the students to think and build autonomy, there was no opportunity for them to reflect on how much knowledge they had gained in this area at the end of the unit. When students were asked this question during the early stages of the unit, they had only a preliminary amount of information. This question could be asked a second time at the end of the unit, rephrasing it to, "What did you need to solve the problem?" Once answered, teachers can compare the two responses and encourage students to reflect upon the terminology, concepts, and design skills they now possess which were gained during the unit.

This study has shown that there is reason to believe students can correctly anticipate science learning topics that the curricular units will cover. We confirm the correspondence between what students believe to be their learning idea and the learning they will actually participate in for the unit. However, students mainly identified science connections, minimal technology & engineering, and mathematics connections for most units. Therefore, the results also show that integrated STEM curricula designers could make more effort to highlight the integration of technology & engineering, and mathematics in the introductory materials and guiding question prompts contained in the curricula. These results show the potential for our desire to support students' feelings of autonomy, competence, and motivation in the area of science. For future studies, we are interested in directly measuring levels of student motivation that occur within the context of the project's integrated STEM classes. We are also interested in the impact on student motivation from emphasizing the integrated nature of learning to students.

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