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Building Up STEM: An Analysis of Teacher-Developed Engineering Design-Based STEM Integration Curricular Materials

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Abstract

Improving K–12 Science, Technology, Engineering, and Mathematics (STEM) education has a priority on numerous education reforms in the United States. To that end, developing and sustaining quality programs that focus on integrated STEM education is critical for educators. Successful implementation of any STEM program is related to the curriculum materials used. Educators increasingly recognize the challenge of finding quality curriculum materials for integrated STEM education. In this study, 48 teachers participated in a year-long professional development program on STEM integration, and they designed 20 new engineering design-based STEM curriculum units. Each STEM curriculum unit includes an engineering challenge in which students develop technologies to solve the challenge; each unit also integrates grade level appropriate mathematics (data analysis and measurement) and one of the three science content areas: life science, physical science, or earth science. A total of 20 STEM integration units were assessed using the STEM Integration Curriculum Assessment (STEM-ICA) tool. Comparisons among the STEM units showed that the context or the engineering activities in physical science focused STEM units were more engaging and motivating comparing to the authentic contexts used in life science and earth science focused STEM units. Moreover, mathematics integration and communicating mathematics, science, and engineering thinking were not found to strongly contribute to the overall quality of the STEM units. Implications for designing effective professional development on integrated STEM education will be discussed.

Keywords

Engineering curricula, STEM integration, curriculum development, curriculum evaluation, teachers as curriculum designers

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Building up STEM: An Analysis of Teacher-Developed Engineering Design-Based STEM Integration Curricular Materials

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Abstract

Improving K–12 Science, Technology, Engineering, and Mathematics (STEM) education has a priority on numerous education reforms in the United States. To that end, developing and sustaining quality programs that focus on integrated STEM education is critical for educators. Successful implementation of any STEM program is related to the curriculum materials used. Educators increasingly recognize the challenge of finding quality curriculum materials for integrated STEM education. In this study, 48 teachers participated in a year-long professional development program on STEM integration, and they designed 20 new engineering design-based STEM curriculum units. Each STEM curriculum unit includes an engineering challenge in which students develop technologies to solve the challenge; each unit also integrates grade level appropriate mathematics (data analysis and measurement) and one of the three science content areas: life science, physical science, or earth science. A total of 20 STEM integration units were assessed using the STEM Integration Curriculum Assessment (STEM-ICA) tool. Comparisons among the STEM units showed that the context or the engineering activities in physical science focused STEM units were more engaging and motivating comparing to the authentic contexts used in life science and earth science focused STEM units. Moreover, mathematics integration and communicating mathematics, science, and engineering thinking were not found to strongly contribute to the overall quality of the STEM units. Implications for designing effective professional development on integrated STEM education will be discussed.

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Building up STEM: An Analysis of Teacher-Developed Engineering Design-Based STEM Integration Curricular Materials

Over the years there have been numerous calls for advancing Science, Technology, Engineering, and Mathematics (STEM) education in the United States (National Academy of Engineering [NAE] & National Research Council [NRC], 2014; NRC, 2009, 2011, 2012, 2013). Improving STEM education is described as a high priority in recent education reports because of its potential to (1) increase the number of students who pursue advanced degrees and careers in STEM fields, (2) expand the STEM-capable workforce, and (3) increase STEM literacy for *all* students (NAE & NRC, 2014; NRC, 2011). These outcomes are critical to enhance the competitiveness of the U.S. in the global economy.

Although STEM subjects have traditionally been taught separately in K–12 schools, the new initiatives share a focus on integrated approaches to teaching STEM (NRC, 2012, 2013). For example, the recently released *Next Generation Science*

Standards (NGSS Lead States, 2013) addressed the need for explicit integration of science with engineering. Science teachers are expected to teach intersecting concepts and core disciplinary science using scientific and engineering practices. The integration of mathematical reasoning, problem solving, and technological literacies to scientific and engineering practices are grounded in NGSS as well. Making learning of STEM subjects more relevant to students' lives and helping them to see connections between and among STEM subjects represents an integrated approach, which can increase motivation to learn science, as well as enhance conceptual understanding of science (NAE & NRC, 2014).

Although curriculum integration in science education has been around for more than five decades (Berlin, 1994; Biological Sciences Curriculum Study [BSCS], 2000), integrated STEM education is new to many science teachers. Thus, implementing integrated STEM education approaches presents several challenges to science teachers (Dossey, 1991; Guzey, Tank, Wang, Roehrig, & Moore, 2014; Meier, Nicol, & Cobbs, 1998). One common challenge that science teachers face is the lack of guidance about how to integrate STEM subjects meaningfully. It is clear that without providing teachers with professional development for STEM integration and new curriculum materials, the intentions of the NGSS and other reform efforts are unlikely to lead to improvements in STEM education (Czerniak & Johnson, 2014; Guzey et al., 2014).

To address the need of supporting science teachers in teaching science while focusing on more and deeper connections among STEM subjects, we designed and delivered a year-long teacher professional development program. In this program, 48 science teachers participated in a three-week summer institute to explore integrated STEM education approaches and begin to develop their own integrated STEM curricular units. The rest of the year was dedicated to the improvement of the integrated STEM curricular units through an iterative process that involved multiple rounds of testing through classroom implementation and subsequent revisions. Our approach was unique in that we asked the participating science teachers to work in curriculum design teams. As a result, 20 STEM integration units were designed by teachers, and the present study focuses on these curricular units. Our primary objective in the present study was to add to the research base on the view of *teachers as curriculum makers* (Clandinin & Connelly, 1992) by examining the STEM units these science teachers developed.

Numerous studies have shown the positive influences of involvement in curriculum design for the professional growth of teachers (Clandinin & Connelly, 1992; Craig & Ross, 2008). However, currently, there is little research on science teachers' development and implementation of integrated STEM curricular units (Czerniak & Johnson, 2014; Guzey et al., 2014). Such research is essential to support efforts to improve integrated STEM education. To this end, the main research questions that guided this study were:

- What are the characteristics of the integrated STEM curriculum units that science teachers developed while participating in a professional development program on integrated STEM education?
- Are there any differences among the STEM curriculum units that integrate engineering design process with life science, earth science, or physical science?

Literature Review

STEM Integration

As addressed in the report entitled *STEM Integration in K–12 Education: Status, Prospects, and an Agenda for Research* (NAE & NRC, 2014), solving the critical problems we face in our society requires the use of knowledge across the domains of science, engineering, mathematics, and technology. Integrated STEM education provides authentic contexts for learning and enables students to make connections among the STEM disciplines, and it also supports “build[ing] knowledge and skill both within the disciplines and across the disciplines” (NAE & NRC, 2014, p. 5). Thus, integrated approaches prepare students to successfully find solutions to complex interdisciplinary problems.

Integration can take place in many forms. In a study of types of approaches for integrated science and mathematics education, Hurley (2001) presented five levels of integration: sequenced (science and mathematics taught sequentially), parallel (science and mathematics taught simultaneously), partial (science and mathematics partially taught together), enhanced (science or mathematics taught as the major discipline with the other one included to support teaching the major discipline), and total (science and mathematics taught together as two major disciplines). Hurley found different outcomes for science and mathematics learning depending on the type of integration. For example, student achievement effects were larger for science learning and smaller for mathematics learning in enhanced and total integration.

A similar continuum for integrated curriculum was developed by Jacobs (1989) for educators “as a planning tool to clarify their choices and combine option” (p. 13). Six types of integration were identified in the model: discipline based (separate subjects taught in separate classes), parallel disciplines (each discipline connected to the same theme or topic), multidisciplinary (some disciplines taught together), interdisciplinary units (deliberately making connections among disciplines), integrated day (taught disciplines under a theme or problem emerging from child's world), and complete program (totally integrated program, curriculum designed out of students' everyday lives). According to Jacobs, the greatest success comes when schools use a combination of the design options. Schools can begin improving their current program and then develop, adopt, and implement curricula that emphasize integration among several disciplines.

Bybee (2013) also argued that integration cannot be accomplished quickly and requires development of a plan of action to improve STEM education. Bybee presented eight approaches for integration with a focus on STEM education. In these approaches, STEM refers to (a) science (or mathematics); (b) both science and mathematics; (c) science and the incorporation of technology, engineering, or mathematics; (d) a quartet of separate disciplines of science, mathematics, engineering, and technology; (e) science and mathematics that are connected by a technology or engineering program; (f) coordination across disciplines; (g) combining two or three disciplines; (h) complementary overlapping across disciplines; (i) a transdisciplinary course or program. Bybee pointed out that there may be other approaches to STEM education and that no one approach to STEM integration is always best; rather, each approach has its unique advantages and disadvantages. However, each approach must make the integration of the STEM subjects intentional and explicit to students (NAE & NRC, 2014).

The integration approaches presented by Hurley (2001), Jacobs (1989), and Bybee (2013) are useful to conceptualize integration at a high level, but they do not provide instructional guidelines or guidelines for developing curricular materials for integrated teaching, particularly integrated STEM teaching. Relatively little is known about the multidimensional nature of integrated STEM education and effective approaches to integrated STEM education (NAE & NRC, 2014). To address this need, the authors (Moore, Stohlmann, Wang, Tank, Glancy, & Roehrig, 2014) developed a framework for STEM integration through reviewing the literature on effective practices in STEM education. The framework conceptualizes STEM integration as “an effort by educators to have students participate in engineering design as a means to develop technologies that require meaningful learning and an application of mathematics and/or science” (p. 38). In this approach to integrated STEM education, content from all four disciplines of STEM can be emphasized in a lesson or curriculum unit, or one or two content areas can be the focus, whereas the others are used as contexts to support learning of the targeted content areas.

The framework for quality STEM education has six key elements that are required for meaningful integrated STEM teaching and learning (Moore et al., 2014). First, a unique feature of an integrated STEM curriculum is the use of a motivating and engaging context, which helps students make sense of the unit activities that are based on extensions of their own personal knowledge and experiences. The context of the curriculum needs to include a compelling purpose and involve current events and/or contemporary issues so that students can apply engineering processes in personally meaningful, partially or completely realistic situations (Brophy, Klein, Portsmore, & Rogers, 2008; Carlson & Sullivan, 2004; Frykholm & Glasson, 2005; Kolodner et al., 2003). Second, the STEM unit should

allow students participating in engineering design challenges to learn about engineering design processes and engineering practices. A good engineering design challenge allows students to explore or develop technologies to solve the problem and requires students to consider constraints, safety, risks, and alternative solutions (Kolodner et al., 2003; Morrison, 2006). Third, learning from failure is a critical part of an engineering design process and student learning (Kolodner et al., 2003; Wendell & Rogers, 2013). Fourth, the integrated STEM unit includes grade level appropriate science and mathematics content. Students participate in activities that allow them to learn, understand, and use fundamental science and mathematics concepts to solve the engineering challenge (Fortus, Dershimier, Krajcik, Marx, & Mamlok-Naaman, 2004; NAE & NRC, 2009; Penner, Lehrer, & Schauble, 1998). Fifth, the lessons and the activities in an integrated STEM unit should be student-centered. Previous research has shown that students develop better understanding and skills through active participation in learning activities (NRC, 2000; Smith, Sheppard, Johnson, & Johnson, 2005). Specifically, project-based or problem based approaches provide great opportunities for students for conceptual learning of complex systems and science concepts (Hmelo, Holton, & Kolodner, 2000). Sixth, teamwork and communication have to be at the core of the STEM activities. Students should work in teams to complete the engineering challenge and other science or mathematics activities as necessary (Carlson & Sullivan, 2004). Students need many opportunities to be involved in teamwork to improve their teamwork skills since it is a critical 21st century skill. The unit should foster communication skill development as well. Students need to communicate science concepts, mathematical thinking, and engineering thinking (Dym, Agogino, Eris, Frey, & Leifer, 2005; Roth, 1996). Together, these six elements help to ensure a useful integrated STEM learning environment.

The STEM integration framework (Moore et al., 2014) has elements for promoting student learning in integrated STEM classrooms. However, integrated STEM education is complex and brings challenges to the classrooms. Among the many challenges teachers face, often the most difficult is how to effectively integrate engineering and science. Content plays an important role. Many physical science concepts (e.g., force and motion, energy transfer) can be easily taught through engineering design. However, integrating life science concepts with engineering design in K–12 classrooms is more challenging. Most life science concepts are abstract and design activities in life science classes often require the use of technologies that are not commonly found in K–12 classrooms. Deep conceptual learning is another concern related to integration of disciplines. Researchers and educators still question whether integration improves deep conceptual learning in the disciplines. Learning outcomes differ depending on the nature of the integration and factors such as teachers’ pedagogical

content knowledge and students' prior knowledge and experiences. More research is needed to know about "how to organize curriculum and instruction so that emerging knowledge in different disciplines will mesh smoothly and at the right time to yield the kind of integration that supports coherent learning" (NAE & NRC, 2014, p. 53).

Curriculum Materials for STEM Integration

Although developing a plan of action for reforming STEM education may help teachers advance STEM education in their unique school environments (Bybee, 2013), teachers still face many challenges as they move through curriculum integration. Finding quality curriculum materials for integrated STEM education is currently a challenge for many teachers (Guzey et al., 2014). Several online resources provide teachers a variety of STEM activities, but the quality varies. For example, a quick search on the Internet for engineering activities for science classrooms yields many "hits," yet the majority of these engineering activities do not (a) include and emphasize engineering design, (b) incorporate important and developmentally appropriate science, mathematics, and technology knowledge and skills, or (c) promote engineering habits of mind which are the general principles of K–12 engineering education (NRC, 2009). In addition, due to the nature of the areas of the physical sciences, earth sciences, and life sciences, it is likely that more STEM activities can be used in physical science classrooms, as there are fewer design activities (e.g., designing an elbow, designing greenhouses) available for life science and earth science teachers (Guzey et al., 2014).

As noted above, integrated or interdisciplinary science curriculum is not a new concept (Berlin, 1994; BSCS, 2000; Drake & Burns, 2004); however, designing instructional materials for integrated STEM education is new for many teachers. Put simply, there are few resources available for teachers to help them develop integrated STEM curriculum materials (e.g., Jacobs, 1989; Vasquez, Sneider, & Comer, 2013), and designing curriculum materials is a complex process. The previous literature reveals that the strategy of teachers as curriculum designers provides teachers with rich opportunities for professional growth (Clandinin & Connelly, 1992). "[Teachers as curriculum makers] is a view in which the teacher is seen as an integral part of the curricular process and in which teacher, learners, subject matter, and milieu are in dynamic interaction" (Clandinin & Connelly, 1992, p. 392). A number of studies looked at teachers' experiences through curriculum development and outcomes of the curriculum development process on teachers' knowledge and practices (Schkedi, 1996; Shawer, 2010; Voogt et al., 2011). The experience of curriculum development offers teachers opportunities to analyze their teaching, reflect on their practices, and organize their materials focusing on student thinking and learning (Parke & Coble, 1997).

Collaborative curriculum development also allows educators to learn from each other (Schkedi, 1996; Schneider & Pickett, 2006; Voogt et al., 2011). Each teacher brings unique experiences and has knowledge in different areas of teaching and learning; thus collaborations can contribute to the design of more effective curriculum materials. However, studies also report that teachers often do not have curriculum design expertise, which influences the quality of curricula designed by teacher teams (Huizinga, Handelzalts, Nieveen, & Voogt, 2014). Professional development programs that focus on curriculum design are valuable resources for teachers to foster their curriculum design knowledge and skills (Parke & Coble, 1997).

Building on previous research, we argue that engaging teachers in professional development of curriculum design is critical for improving integrated STEM education. Considering the fact that integrated STEM education requires teachers to have enough knowledge of each of the STEM disciplines to effectively design and teach STEM activities, collaborating with other teachers, educators, scientists, and engineers in a professional development program could help teachers to develop integrated STEM activities aligned with the characteristics of the STEM integration framework (Guzey et al., 2014) and new reform efforts (NGSS Lead States, 2013). Furthermore, approaches to STEM education chosen by teachers and/or schools could be unique to schools; thus, curriculum materials locally designed by teachers would allow teachers and schools to better achieve the goal of improving integrated STEM education.

Methods and Procedures

The study uses a conversion mixed method design in which qualitative data are analyzed using quantitative approaches (Teddlie & Tashakkori, 2009). This design approach allowed the researchers to investigate the characteristics of the units qualitatively and also to evaluate the quality of the units quantitatively. The reason for transforming qualitative data to quantitative data is to rank the curriculum units to investigate the similarities and differences among them. This transformation of qualitative data to quantitative data provides new insights and statistically based interpretations.

Context

The context of this study was a professional development program for 4–8 grade science teachers. The professional development program aimed to:

- Increase teacher understanding of engineering and engineering design,
- Increase teachers' confidence in integrating mathematics and technology in science teaching,
- Promote curricular design that allows content to be taught more meaningfully in the same or less time as

more standard ways of approaching the teaching of science.

In this study, 48 science teachers from three large school districts in a Midwest state participated in the professional development program. Years of teaching experience varied from 1 to 17 years. Only few teachers expressed that they previously participated in a professional development program focused on engineering integration. All the participating teachers were willing to join our program. They received materials they need to implement STEM units in their classroom and a stipend for their time and effort they devoted to their professional development.

In the first week of the three-week summer institute, teachers learned about engineering design, engineering practices, and data analysis and measurement. Teachers completed a variety of design challenges such as building a table-top wind turbine that generates the most electrical energy, an artificial dialysis machine that functions effectively, and a rainwater collector system that collects the most rainwater for people who do not have access to clean and reliable water. Each design challenge asked teachers to use an iterative engineering design process to solve the challenge. Teachers identified the engineering challenge, did background research, planned a solution, created a prototype, tested the prototype, presented it to others, and redesigned the prototype to improve it.

At the end of the first week of the summer institute, teachers chose one of the three science content areas to focus on for the second week: life science, physical science, or earth science. Teachers chose their focus content area based on their teaching assignment (e.g., sixth grade physical science). In week two, teachers explored science concepts in their chosen area of science through STEM integration activities. The physical science group focused on heat transfer and properties of matter; the target science concepts for the earth science group were erosion and plate tectonics; and the life science group focused on ecosystems. Teachers completed two more design activities to explore the targeted science concepts in week two. In life science group, for example, these engineering tasks were designing and building small scale artificial floating islands for habitat restoration in a small pond and designing nests for pelican eggs for a large pelican colony in a breeding area destroyed by farmers in the area.

In the third week of the summer institute, teachers explored curriculum design for STEM integration. We introduced the STEM integration framework (Moore et al., 2014) and provided a lesson plan template for the teachers. Teachers were also asked to form curriculum design teams based on their science content focus chosen for the second week of the summer institute. A science teacher who attended the earth science session in week two, for example, teamed up with one or two other teachers who attended the same session; thus, the science content of their STEM unit focused on earth science. Several types of teams were

formed: (1) teachers from the same school, (2) teachers from different schools in the same district, and (3) teachers from different schools in different districts. Since the majority of the teachers did not have previous experience with designing integrated STEM curriculum units, the project team worked with each curriculum design team and provided feedback on content goals, context for the engineering challenge, and mathematics integration during the curriculum design process.

A coach or mentor was assigned to each curriculum design team. The coach started to work with his/her team in the summer and continued to support teachers during the academic school year. Each team met monthly to discuss their STEM integration efforts, revisions their STEM unit need, and areas that the teachers want to improve in their instruction. Since coaches had previous coaching experiences and knew about integrated STEM education they were able to facilitate professional development of teachers. Coaches also support teachers during the implementation of the STEM units.

Data Collection and Analysis

To assess the curriculum units, we developed a STEM Integration Curriculum Assessment Tool (STEM-ICA) that relied on a deductive-inductive approach. We used the STEM integration framework (Moore et al., 2014) and the literature on curriculum design and evaluation (e.g., Keiser, Lawrenz, & Appleton, 2004) to develop the first draft of the STEM-ICA. This first draft was sent to three STEM education and assessment experts. Afterwards, a refined draft was sent to 20 teachers and PhD candidates in STEM education for their feedback. The reviewers commented on items that were confusing and suggested alternative wordings. As a result of these reviews, we reworded several items. When developing measurement tools such as STEM-ICA, validity is critical. The use of a group of experts in STEM education and assessment allowed the researchers to ensure that items accurately measure what they are intended to measure.

The final version of the STEM-ICA was composed of nine items: motivating and engaging context, engineering design, integration of science content, integration of mathematics content, instructional strategies, teamwork, communication, assessment, and organization. The STEM-ICA closely aligns with the framework for quality STEM integration (Moore et al., 2014). Each of these nine constructs was operationally defined to pull out components of student learning. Here we present two of the constructs in detail: motivating and engaging context and engineering design. Motivating and engaging contexts were defined to include realistic situations, address issues of personal meaningfulness to students, incorporate issues that are relevant to students with a variety of backgrounds, and provide a compelling purpose for doing the STEM

integration activity (including global, environmental, social contexts and/or current events or issues). Engineering design was operationalized by addressing a complete engineering design cycle to develop a relevant technology while working for a client, allowing students to learn from failure and redesign, providing the students with opportunities to think like engineers (e.g., use engineering habits-of-mind and engineering tools and processes), and exposing students what engineering is and what engineers do at work. For more detail, the STEM-ICA in its entirety is provided in the appendix.

There are two constructs in the STEM-ICA that were added beyond the constructs laid out in the STEM integration framework: assessment and curriculum organization. We included assessment in the STEM-ICA since assessment is critical for effective curriculum design. The use of different types of assessments provides students with opportunities to produce evidence of understanding and abilities in different ways through performance tasks (NAE & NRC, 2014; NGSS Lead States, 2013; Wiggins & McTighe, 2011). Since the STEM units emphasize more than one disciplinary content area and require students engage in design challenges, it is necessary to use effective assessment tasks that capture student learning of both content and practices. Organization of the activities and lessons was also added as it is a core component of a curriculum unit. In an effective STEM unit, lessons flow in a logical and sequential order so they build on each other. In order for students to see the connections among different disciplines, every single learning activity needs to be coherent and tied to the engineering challenge in a STEM unit. It is also important that each lesson presents clear learning objectives and goals (Wiggins & McTighe, 2011).

Each item in the STEM-ICA is rated on a 5-point scale from 0 to 4 (0: not present, 1: weak, 2: adequate, 3: good, 4: excellent). Each item also includes several yes and no questions to help the reviewers reflect on specific elements of the curriculum unit and to help them understand the intent of the rubric question. Thus, overall, the reviewers are asked to answer some yes or no questions, provide a rating of quality, and give evidence to support the ratings.

As a first step in assessing the consistency of ratings, the STEM-ICA was used by six graduate researchers pursuing a PhD in STEM education to evaluate three STEM curriculum units (Save the Seabirds [Schnittka, 2009];

Greenhouse Design [NSTA, 2013]; and Invent a Wheel [City Technology]). Researchers/reviewers first participated in a two-hour workshop to learn about the STEM-ICA. They then rated the three sample STEM units individually using the STEM-ICA. Forty-seven percent of the ratings were in perfect agreement, and 80% were within one point of agreement. All the reviewers discussed the scores in a second meeting and came to a consensus in all scores.

It is important to note that STEM-ICA or the evaluation techniques were not shared with the teachers during the summer program. After teachers submitted the 20 STEM integration units developed as a part of the project, and reviewers started to assess, with two reviewers rating each STEM unit. Reviewers rated the units individually and then met to discuss their scores and to agree on final scores. Eighty-five percent of the ratings provided by each pair of reviewers were in perfect agreement. Afterwards, an “expert” reviewer, the first author of the paper, randomly chose five curriculum units and rated them using the STEM-ICA. Expert ratings and the final ratings from the reviewers matched 91% of the time. These results supported the consistency of ratings of the STEM-ICA. Next, to answer the research questions, Kruskal-Wallis tests were conducted on the ranked ratings (Marascuilo & McSweeney, 1977). The Kruskal-Wallis test is a nonparametric analog of one-way ANOVA.

Results

In this study, 48 science teachers developed 20 STEM curriculum units as a part of a professional development program that focused on integrated STEM education. Among the 20 STEM curriculum units, seven focus on life science (ecosystems), seven address earth science topics (plate tectonics or erosion), and six focus on physical science (heat transfer or particle theory). Each unit includes five to ten lessons and takes about one to four weeks to implement. The analysis of the units shows that each unit uses a unique authentic context such as solar oven design, freezer design, animal nest design, and park design (see Table 1). Each curricular unit asks students to engage in a real-world related problem in which they design, build, test, and re-design an artifact to apply the science and mathematics concepts that are being studied. The units ask students to work in teams and follow an iterative design

Table 1.
Overview of the STEM curriculum units.

Science area focus	Unit title	Grade focus
Life Science	Butterfly puddles, Eco house, Pollutants in the pond, Greenhouse	Elementary school
	Loon nesting platforms, Plants and space, Save the moose	Middle school
Earth Science	Planet Andoddin, Mississippi park planning, Rockin' good times	Elementary school
	Soil solutions, Earthquakes, EnerGreen house, Mineral Mayhem	Middle school
Physical Science	Chill out, Rocket-powered delivery SySTEM, Keep it cool	Elementary school
	Ecuadorian fishermen, Solar ovens, Water desalination: Survival style	Middle school

process to solve the engineering challenge. All of the units include characteristics defined in the STEM integration framework (Moore et al., 2014) and STEM-ICA. However, the curriculum units use different approaches to STEM integration, and the level of integration of each characteristic in the units varies.

With the exception of a single unit, in all the curricular units, students are asked to solve the engineering challenge after completing the science and mathematics lessons. This exception is an earth science unit, *Mississippi park planning*, which introduces students to the engineering challenge in the first lesson and requires students to complete their first design without any pre-teaching of the fundamental science and mathematics concepts. Students redesign after learning necessary science and mathematics concepts. This engineering design challenge is also different than the engineering challenges present in other units. The *Mississippi park planning* unit requires students to create a land-use proposal for a new park located on the Mississippi river. Engineering challenges in the other 19 curriculum units ask students to design and build a physical artifact.

A total of 20 STEM curriculum units were rated using the STEM-ICA to further investigate the characteristics of the units and the differences among them. Table 2 shows the scores of the curriculum units. As shown in Table 3, no statistically significant difference in the ratings among life science, earth science, and physical science focused STEM units was found using the Kruskal-Wallis test ($H(2) = 5.88, p = 0.74$). The Kruskal-Wallis test ranks the raw scores and then calculates each sum of ranks; this value is labeled as H . When the p value associated with H is smaller than the level of significance, the null hypothesis is rejected. The null hypothesis for this test is that the mean ranks for groups are the same.

The Kruskal-Wallis test also showed that there was no difference in rank rating means between STEM curricula for Items 2 (engineering challenge), 3 (science integration), 4 (mathematics integration), 5 (instructional strategies), 6 (teamwork), 7 (communication), 8 (assessment) and 9 (curriculum organization), meaning that on average the same pattern of (rank) ratings were assigned regardless of curriculum type (see Table 3). However, there were statistically significant differences between groups on Item 1, motivating and engaging context. Physical science units had significantly higher mean ranks for Item 1 compared to both life science and earth science units. In the following paragraphs we discuss scores for each STEM-ICA item in more detail.

Context

From seven physical science focused STEM units, two of them were scored a four for the motivating and engaging context (Item 1). The *Chill out* unit, for example, presents a highly engaging context, which is about the need for safely

Table 2.
STEM-ICA scores.

	Item #1				Item #2				Item #3				Item #4				Item #5				Item #6				Item #7				Item #8				Item #9				Overall																																						
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4																														
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ES	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*										
PS	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

NOTES: LS: Life science, ES: Earth science, PS: Physical science. * represents a curriculum unit. For example, 2 Life science units were scored a one for item #1

Table 3.
Results of the Kruskal-Wallis test for STEM curriculum units.

	Item #1	Item #2	Item #3	Item #4	Item #5	Item #6	Item #7	Item #8	Item #9	Item #9
	Context	Engineering	Science	Math	Pedagogies	Teamwork	Communication	Assessment	Organization	
<i>H</i>	9.25	3.50	2.93	2.46	3.36	0.63	2.96	1.95	1.07	1.07
<i>df</i>	2	2	2	2	2	2	2	2	2	2
<i>p</i>	0.01*	0.17	0.23	0.29	0.18	0.72	0.22	0.37	0.58	0.74

* $p < 0.05$, $N = 20$

storing vaccines. In this unit, fourth graders review the concept of disease prevention via vaccinations and follow the engineering design process as they explore the roles of conductors and insulators in heat transfer. Students design, build, test, evaluate, and redesign model vaccine coolers. The context has a compelling purpose, and it involves a current event. The teachers designed this unit for their students in a state where very high rates of whooping cough have been seen in recent years. The best way to prevent whooping cough is to get vaccinated, and this requires large amount of vaccines in the state. The engineering scenario emphasizes the need for finding better ways to maintain vaccines at the correct temperature. The context uses a realistic situation and is highly relevant to students' personal knowledge and experiences.

The remaining physical science units' contexts were scored a three. For example, the *Ecuadorian fishermen* unit uses the following story as a context: A group that works with small businesses in Ecuador has discovered that some of the Ecuadorian fishermen need help. These fishermen take their small boats over to the Galapagos Island, which has many unusual and tasty fish. They need to bring ice with them in a cooler that will stay cold long enough to bring the fish back unspoiled. Once back to their fish markets in Ecuador, the fishermen need a small cooker to cook the fish in so they can be sold for the greatest profit. In this unit, students are asked to build a cooler and a cooker. The context of this unit provides a realistic situation; however, it does not have high potential to motivate students from different backgrounds.

Of seven earth science focused STEM curriculum units, two of them were scored a three and five of them were scored a two for the contexts that they use. For example, the *Rockin' good times* unit was scored a three for its context. In this unit, students select a site to safely build and anchor an amusement park ride in an earthquake prone area. Specifically, students choose a site based on stability of the underlying earth materials, while also considering other area concerns (e.g., distance of location from existing roads, housing). Once the site is chosen, students test various anchoring systems attached to a model amusement park ride. Cost constraints are added, so students have the realistic challenge of working within a budget. The students use an iPad seismometer app, which gives them the opportunity to see how seismic waves are instantly

measured and graphed. Pictures of existing anchoring systems and websites posting earthquake activity as it happens reinforce the real world context of the problem. On the other hand, the *Planet Andoddin* unit was scored a two for its context. In this unit students are tasked with working for a hypothetical multi-million dollar, multi-national corporation that has discovered resources on an exoplanet, Andoddin. Students utilize all available data on the planet, including types of resources, map analysis, design/build, and data analysis. Using the engineering design process, students create tools to mine wood, sand/gravel, and iron ore. Although the context of this unit would motivate some students, it does not have a compelling purpose.

For the life science units, finding an engaging context seemed more challenging. Within seven life science units, two units were scored a three, three units were scored a two, and two units were scored a one for the context they use. The *Loon nesting platforms* unit was scored a three. In this unit, students learn about ecology and ecosystems through the construction of loon nesting platforms. Students find a good location for their platform based on characteristics of the loon habitat and the dietary needs of loons. After incorporating food chains and food webs, students make an educated decision as to where to place their platform. Students explore prey/predator relationships during the construction of their nesting platform and have the opportunity to improve the platform's design. Because the loon is commonly found in the region in which this curriculum was implemented, this unit provides a realistic context for the students. However, the unit is limited in engaging students from different backgrounds. A life science unit that scored a one for its context, *Butterfly puddles*, focuses on the butterfly species Karner blue. This species is listed federally as an endangered species due to human land use altering their specialized habitat of sandy barrens and savannas where wild blue lupine grows from Maine to northern Iowa. Some butterflies, including blues, get needed minerals by drinking at mud puddles. The engineering design of the *Butterfly puddles* unit challenges fifth grade students to design mud puddles that evaporate slower than natural puddles to maintain in listed managed areas for the Karner blue butterfly. Similar to the *Loon nesting platforms* unit, this unit also focuses on an animal that students are familiar with; however, the latter involves simply puddle-making without providing students

opportunities to apply engineering processes in a realistic situation.

An Engineering Design Challenge

Only one unit was scored a four for the engineering design challenge (Item 2). The *Chill out* unit addresses all the elements for a quality engineering design challenge identified in the STEM-ICA. The engineering design challenge of this unit, which asks students design coolers for vaccines using physical science concepts, requires students to follow an iterative design process. Students are asked to identify the problem, conduct background research, plan and design their cooler to safely keep vaccines, build their prototype, test and evaluate their prototype, and finally redesign, retest, and reevaluate their model vaccine cooler. The research phase involves testing a variety of materials (e.g., aluminum foil, bubble wrap, cotton balls, wax paper) to find if they are good insulators. Students are also asked to work under budget constraints. The cooler needs to keep the vaccines cool but should cost no more than \$50.00. Thus, students need to choose materials that are good insulators but also think critically and creatively to avoid over-budgeting. After students decide which materials they need to use and how to use them in their vaccine cooler, they create their prototype. To test the cooler, students first weigh an ice cube and put the ice cube inside their model vaccine cooler and then place the cooler under a heat lamp. Students take the ice out of their cooler ten minutes later and weigh it again. They calculate how much the ice (vaccine) is melted. Students receive a score based on the amount of ice melted in their cooler. This score and the cost score are added together and used to evaluate the designs. In this design challenge, students work for a client, an engineering company. They record all their observations, designs, and test results and write a report to the client. The unit also promotes understanding about what engineering is and what engineers do at work. The first lesson of the unit introduces these concepts to the students to help them better understand the client and the context.

All the other STEM units include an engineering design challenge; however, they do not include one or more of the critical elements of an effective engineering design. Of seven earth science units, three units were scored a three and four units were scored a two for the engineering challenge. The *Planet Andoddin* unit, for example, was scored a three. There are two parts to the engineering design challenge in the unit. First, students create their own mining tool to extract a specific resource. The second part of the design challenge is to analyze data from four different mining sites on the exoplanet. When analyzing the data, students are asked to consider the cost of mining, the amount of time spent mining, and the environmental impact. The missing elements in this unit are the lack of emphasis on what engineering is and what engineers do at work and the engineering habits of mind (e.g., creativity, systems thinking).

Of the seven life science units, one unit was scored a three, three units were scored a two and three units were scored a one. The *Butterfly puddles* unit was scored a one for the engineering design challenge for several reasons. The engineering challenge asks students to design puddles for butterflies and the students follow a design process, but students do not have opportunities for redesign. The unit also does not provide any information about engineers and engineering. Finally, students do not explore and develop any technologies in this unit; the unit promotes design as an art and craft activity.

Science Integration and Mathematics Integration

Within 20 STEM curriculum units, none of them were scored higher than a three in the categories of science integration (Item 3) or mathematics integration (Item 4). There were eight units (four physical science, two earth science, and two life science) that were scored a three for science integration. Further, six units (four physical science and two earth science) were scored a three for mathematics integration. Of those units, five of them were scored a three for both science and mathematics integration. The *Solar ovens* unit is a physical science unit and was scored a three for both mathematics and science integration. Mathematics integration in this unit involves data analysis and measurement. Students collect and analyze data, create graphs and study relationships between angles formed by intersecting lines as they explore scientific data. Science concepts include conduction, convection, and radiation. Students are asked to use knowledge of science and mathematics concepts to build a solar oven using an engineering design process. A life science unit, *Pollutants in the pond*, and an earth science unit, *Soil solutions*, were scored a three for science integration but received a one for mathematics integration. Both units fail to focus enough on integrating mathematics into the science and engineering activities. In the *Pollutants in the pond* unit, students conduct science experiments to measure water pollution in a pond over a period of time, and they design a barrier to stop or slow fertilizer from running off into the pond. Mathematics could have been included into the unit by asking students to create graphs to display data from the experiments or to analyze the water pollution data of the pond collected over the past several years (which is available).

A total of six units (one physical science, four earth science, and one life science) received a rating of two for science integration. Further, five units (four earth science and one life science) were scored a two for mathematics integration. From those units, four of them were scored a two for both science and mathematics integration. Curriculum units within the score range of two demonstrate that the curriculum unit does not address the appropriate science and mathematics standards and does not promote conceptual understanding of science and mathematics. Further,

four curriculum units were scored a one for both science and mathematics integration. These units miss several elements for effective science and mathematics integration. In the life science group, the *Butterfly puddles* unit, for example, was scored a one for both science and mathematics integration. Activities in this unit were designed with the goal of students making connections between ecosystem interactions, organism adaptations, and energy transfer in food chains to the need of humans to positively impact the natural environment; however, the connections were loose and no science content application is necessary to solve the engineering challenge. In addition, no single mathematics lesson is included in the unit. Students are asked to calculate rates of evaporation of water when changing surface area as a part of a science experiment. There are five units (one physical science, one earth science, and three life science units) that received a rating of one for science integration, and eight units (two physical science, three earth science, and three life science units) were scored a one for mathematics integration. Only one life science unit does not provide enough information to identify the science and mathematics concepts addressed in the unit; therefore, this unit was scored a zero for both science and mathematics integration.

Instructional Strategies/Pedagogies

For Item 5, instructional strategies, the lessons in each unit were analyzed to find out if they are student-centered. A student-centered lesson requires students to complete and analyze information and data before arriving at a solution and embeds STEM ideas to be learned in multiple modes of representations (e.g., manipulatives, pictures, symbols) with an emphasis on transitions within and between modes. Only two physical science units and one earth science unit were scored a four for instructional strategies. The physical science unit, the *Chill out* unit, was scored a four since students participate in several demonstrations to explore heat transfer: metal vs. plastic spoon conductors, metal vs. wooden tray conductors, and pop-in-sock insulators. Students are asked to make predictions, observations, and explain what they observe. Students also complete two lab activities adapted from the FOSS water kit: the surface area melting and hot/cold water activity. Multiple modes of representations (e.g., real life situations, models, pictures) are embedded into these activities.

There are six units (two physical science, two earth science, and two life science) that received a score of a three and eight units (two physical science, three earth science, and three life science) that received a score of two for the instructional strategies. Thus, the majority of the STEM curriculum units (14 units) were scored a three or two, and these curriculum units do not have activities that include STEM ideas to be learned in multiple representations or the units include science lab activities with step-by-step

instructions. Further, two life science units and one earth science unit received a score of one because almost all the lessons in these units are very teacher-centered.

Teamwork and Communication

Teamwork (Item 6) was evident in all the 20 STEM curriculum units. All the curriculum units require students to collaborate with other students to complete the activities or to solve the engineering challenge. However, only the *Chill Out* unit was scored a four for teamwork. In this unit, the lessons and activities require students to collaborate with others and include elements of cooperative learning strategies (e.g., specific roles assigned to students). Only seven curriculum units (three physical science, two earth science, and three life science) received a score of three for teamwork since cooperative learning elements are not explicitly stated in the lesson plans. Further, eight curriculum units (two physical science, five earth science, and one life science) were scored a two for the teamwork. These units ask students to work in teams, but they do not provide opportunities for students to demonstrate individual responsibility while working in teams. These units also do not include cooperative learning elements. Finally, two units received a score of one for teamwork. *Save the moose* and *Greenhouse* are both life science units, and they received a two because the units weakly address teamwork. These units include statements such as “students will work in teams” without providing further details.

No single STEM curriculum unit was scored a four for communication (Item 7). There are eleven curriculum units (five physical science, three earth science, and three life science) that received a three. All of these units require students to communicate their engineering solutions through oral or written presentations; however, they do not require students to communicate science concepts or mathematics concepts. Six curriculum units received a two for communication. A common missing element in these units is the lack of information about student presentations of the engineering solutions or products. Only two units received a one since the communication was addressed weakly in the lesson plans. One of the life science units, *Butterfly puddles*, was scored a zero since the lessons do not include any information about students communicating science, mathematical, or engineering thinking.

Assessments

None of the STEM curriculum units was scored a four for assessment (Item 8). To receive a four, a curriculum unit should include formative and summative assessments, and these assessments should be closely aligned to the goals and objectives of the unit and state standards. Moreover, assessments should provide guidance to the teacher to improve the implementation of the unit. Only four units

received a score of three. Two of these units are physical science units, *Keep it cool* and *Solar ovens*. These two units include the storyboarding technique as a formative assessment. Students receive a large chart paper at the beginning of the unit and are asked to record information as they explore science and mathematics concepts and design and build engineering prototypes. This assessment technique provides opportunities to produce evidence of understanding. Two earth science units, *Mineral mayhem* and *Rockin' good times*, also received a score of three. The *Rockin' good times* unit, for example, includes a variety of formative assessments such as journal reflections and exit slips. However, the unit does not include a summative assessment. Also, information provided in this unit regarding assessments is not enough to identify if the performance and formative assessments are closely aligned with learning objectives and goals from the multiple disciplines of STEM. Further, four life science units received a two, and three units received a score of one. The *Loon nesting platforms* unit, for example, was scored a one since the lessons do not provide any specific information about the assessment strategies. Lesson plans include statements such as “teacher checks student progress as they are working on the activity” or “teacher will check group planning sheets for completeness and errors.”

Curriculum Organization

The organization of a STEM unit is critical. Only one unit, *Chill out*, was scored a four for the organization (Item 9). As shown in Table 4, each lesson in this unit flows in a logical and sequential order and is related to the engineering challenge. Students need to explore and apply the necessary science and mathematics concepts in order to solve the engineering challenge. Furthermore, the learning goals and objectives of the unit are all tied meaningfully to the standards.

Table 4.
Overview of the *Chill out* unit.

Lesson	Objectives
Intro whooping cough/pertussis, vaccination, vaccine	Analyze bar graph of whooping cough cases in MN in 2012 Set up the design challenge: Design and build a vaccine cooler Set up surface area/melting rate experiment
Intro heat, conductors	Observe, discover, understand that heat moves from warm to cold Observe, record, analyze surface area experiment in order to understand that greater surface area means more melting
Intro temperature, insulators	Observe, record, analyze, understand that some materials stop or slow heat from moving Test and evaluate possible insulators for the vaccine coolers
Intro Engineering and Design Process, design	Connect completed unit activities to the first steps of an Engineering and Design Process: Identify the problem, Explore/Learn more Outline requirement and constraints Begin the next steps: designing a solution, creating a model
Continue Engineering and Design Process	Review purpose of challenge: keeping vaccines at a safe temperature Analyze graph of whooping cough in the United States since the 1940s Review Engineering and Design Process so far Test the design. Collect data. Analyze data, evaluate the success of the design
“Completing” the Engineering and Design Process, redesign	Understand that any Engineering and Design process is cyclical Use evaluation of previous design to redesign an improved vaccine cooler Build, test, analyze and evaluate

Finally, the unit provides detailed guidance and instructions regarding each lesson. There are two life science units, two physical science units, and one earth science unit that were scored a three for organization of the unit. A common characteristic among these units is that they all include science and mathematics lessons and the engineering challenge; however, the activities do not really flow in a good logical or meaningful order. Further, one physical science, three earth science, and two life science units were scored a two. In these units, organization of the lessons was not clear. Lessons are not built on each other. The *Ecuadorian fishermen* unit, for example, includes science lessons that focus on density and heat transfer, and the engineering challenge requires students to design a cheap and non-electric cooler and cooker. Density lessons in this unit are not tied meaningfully to the engineering challenge.

A total of eight units (two physical science, three earth science, and three life science) were scored a one for the organization of the unit. The majority of these units do not provide instructional strategies for teachers who are not familiar with the unit, and lessons do not flow in a logical order. A life science unit, *Save the moose*, is an example that was scored a one. The unit uses a context in which bioengineers have developed a “tick-ti-cide” that effectively kills ticks, and the engineering challenge is to spread the “tick-ti-cide” to a large area effectively. The goals of the unit are not tied meaningfully to the standards, and the unit provides few instructional guidelines. Students complete the engineering activity at the end of the unit, and they do not need to apply any science knowledge they learn to solve the engineering activity.

Overall Quality

Reviewers were also asked to provide a rating for the overall effectiveness of each STEM unit. This rating was

not intended to be an average of all the previous ratings for nine items but rather the overall judgment of quality and likely impact of the curriculum unit. Of 20 STEM curriculum units, only five of them received a score of three for the overall quality. These units were: *Pollutants in the pond* (life science), *Rock' good times* (earth science), *Mineral mayhem* (earth science), *Chill out* (physical science), and *Solar ovens* (physical science). The majority of the units were received a two (ten units) or one (five units) for the quality. We grouped the units in two categories based on their overall scores: high-scoring group and medium-/low-scoring group. As shown in Table 5, the high-scoring group includes the five units that received a score of three for the overall quality. The medium/low-scoring group includes the 15 units that were scored a two or one for the overall quality. Analysis of the item scores of the two groups of units shed light on what makes STEM integration unique and high quality. We found that high scores in context, engineering, science integration, pedagogy (instructional strategies), teamwork, assessment, and organization were highly related to the overall score. Mathematics integration and communication did not play a major role in overall score. Quality of mathematics integration was varied across all curricula, and most curriculum units did well in implementing communication.

When looking at the individual curriculum units in Table 5, there were several interesting cases to pull out. We had three units (one life science and two physical science) that received mostly threes for all nine items in STEM-ICA, yet received a two for their overall scores. For example, the *Keep it cool* unit was scored low only for engineering and curriculum organization, which led to a lower overall score (two). Another interesting case was the *Chill out* unit, which received high scores for the context, engineering, instructional strategies, and organization. However, it received a two for assessment and a three for science integration. This unit received a three for the overall quality. As noted above, context, engineering, science integration, pedagogy (instructional strategies), teamwork, assessment, and organization are critical elements for effective STEM curriculum units.

We also ran a Kruskal-Wallis test to compare two groups of curriculum units (high-scoring group vs medium-/low-scoring group), and the results showed that there were statistically significant differences between the two groups of units in all nine STEM-ICA components except mathematics integration and communication (see Table 6). The high-scoring group received higher scores for the overall quality and seven items in STEM-ICA. As noted above, mathematics integration and communication did not play a significant role in effective STEM curriculum design.

Discussion

Key reform efforts advocate for integration of STEM subjects since interdisciplinary approaches can increase conceptual understanding within disciplines, support

Table 5. Groups of units based on overall scores.

Group	Item #1 Context				Item #2 Engineering				Item #3 Science				Item #4 Mathematics				Item #5 Pedagogies				Item #6 Teamwork				Item #7 Communication				Item #8 Assessment				Item #9 Organization																	
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4										
High (5)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*					
Middle/low (15)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Table 6.
Results of the Kruskal-Wallis test for two groups of STEM curriculum units.

	Item #1	Item #2	Item #3	Item #4	Item #5	Item #6	Item #7	Item #8	Item #9
	Context	Engineering	Science	Mathematics	Pedagogies	Teamwork	Communication	Assessment	Organization
<i>H</i>	5.46	4.70	4.50	1.22	9.45	4.91	1.84	6.45	5.10
<i>df</i>	1	1	1	1	1	1	1	1	1
<i>p</i>	0.019*	0.03*	0.03*	0.26	0.00*	0.02*	0.174	0.01*	0.02*

* $p < 0.05$, $N = 20$

interest development, and may “provide opportunities for students to engage in STEM in ways that potentially transform their identities with respect to STEM subjects” (NAE & NRC, 2014, p. 4). However, moving towards integrated STEM education is not easy; providing opportunities for teachers to learn about the nature and practices of STEM disciplines with which they have limited background is critical. Moreover, supporting teachers in curriculum design is essential, since the key to the success of a reform “is the development and wide acceptance of materials supporting that reform” (Dossey, 1991, p. 17).

In this study, we followed Clandinin and Connelly’s (1992) vision of teachers as curriculum makers, which views teachers as “an integral part of the curriculum constructed and enacted” (p. 363). The teachers participated in a professional development program in which they explored integrated approaches for teaching STEM subjects and formed teams of at least two teachers who collaboratively designed STEM curricular units. Findings of the study demonstrated that the teachers developed STEM integration curricular units that address the characteristics of the STEM integration framework (Moore et al., 2014) and STEM-ICA which are supported by the literature (e.g., Brophy, Klein, Portsmouth, & Rogers, 2008; Kolodner et al., 2003; Smith, Sheppard, Johnson, & Johnson, 2005) and new reform documents (NRC, 2009; 2014; NGSS Lead States, 2013). The application of integrated ways of teaching STEM subjects makes these curricular units unique. STEM curricular units developed in this study include a motivating engineering context, engineering design challenge, and grade level appropriate science and mathematics lessons. Moreover, the units ask students to work in teams, actively engage in their learning, and use an iterative design process to solve the engineering challenge. However, how well each unit addresses the above characteristics (e.g., context, engineering challenge) varies.

No statistically significant differences were found between the life science, physical science, and earth science STEM curricular units when the three groups were compared. However, group comparisons for each item on the STEM-ICA showed the difference among groups for Item 1, engaging and motivating context. The results showed that the contexts of the engineering activities developed by the physical science teachers were more engaging and motivating comparing to the authentic contexts used by life science and earth science teachers.

Using a motivating and engaging context is critical in integrated STEM education (Moore et al., 2014). Realistic contexts motivate students and help them engage in their learning (Kolodner et al., 2003). Additional support to life science and earth science teachers during the curriculum design process may assist them in creating more engaging contexts for their STEM curricular units. As shown in previous studies involving collaborative curriculum design teams, paying explicit attention to the areas that need to be improved can result in more positive outcomes in curriculum design (Voogt et al., 2011).

The results of the study illustrated that context, engineering challenge, science integration, instructional strategies, teamwork, assessment, and organization play a critical role in designing effective STEM curriculum units and strongly correlated to the overall quality of STEM units. However, teachers needed more support in some of these areas. For example, no single unit was scored a four for science integration. Designing STEM units that include grade level appropriate science content is critical (Guzey et al., 2014; NAE & NRC, 2014). Developing science lessons that are well connected to the engineering challenge seems challenging for the grades 4–8 teachers. Several units (e.g., *Chill out*) received a high score for engineering challenge but a lower score for science integration, and that resulted in a lower overall score. Similarly, assessment design for integrated STEM teaching was challenging, and only a few units received a score of three for including effective formative and summative assessments. Assessing student learning of multiple disciplines of STEM is difficult. Commonly used assessments such as quizzes and exams may not provide enough information about student learning of STEM (NGSS Lead States, 2013). Providing teachers just-in-time support in these areas in a professional development program may contribute to improving STEM curriculum design.

Scores of mathematics integration and communication did not strongly contribute to the overall score of the units. Quality of integration of mathematics and communication varied among the STEM curriculum units that teachers developed. Mathematics integration is difficult for most science teachers. A reason might be that science teachers do not have enough subject-matter knowledge to teach mathematics effectively. Furthermore, teachers might focus on mainly engineering and science integration, and mathematics was left out of the curriculum. Similarly,

communication tended not to be a major focus for the teachers for STEM curriculum design. One common concern associated with student communication is that presenting scientific, mathematical, and engineering thinking and design solutions requires class time. However, it has been shown that communicating scientific, mathematical, and engineering thinking fosters STEM learning (Dym, Agogino, Eris, Frey, & Leifer, 2005; Roth, 1996).

In this study, we used the STEM-ICA as a tool to assess STEM curriculum units. The assessment tool helped us to identify the similarities and differences among the STEM units. The STEM-ICA aligns with the STEM integration framework (Moore et al., 2014), which was developed through an iterative process that included a comprehensive literature review and testing. Recent studies emphasize the importance of providing tools and guidance for teachers to explore STEM integration (Czerniak & Johnson, 2014) and to learn about developing STEM lessons (Guzey et al., 2014). The STEM integration framework and the STEM-ICA can be used as a guide to develop effective STEM units and as a research tool. We will continue to use the STEM-ICA to evaluate the quality of the STEM units that will be developed during the next three years of the project. Studies around the new curricular units will provide additional support for the reliability and validity of the instrument.

Implications and Future Research

STEM integration has been a growing focus of nationwide efforts, and providing teachers with professional development opportunities for STEM curriculum development and implementation is critical. Teachers need opportunities to learn new knowledge and skills to implement integrated approaches and new curricular materials for implementing an integrated program. Professional development programs that focus on fundamental understanding and skills to teach integrated approaches and curriculum materials can provide teachers with a variety of ways to learn and implement effective integration.

Our future research focuses on reporting teachers' stories of the implementation of STEM units in their own classrooms. As we investigate their stories of development and implementation of integrated STEM units, we will be able to see and examine teachers' experiences closely. Stories of science teachers as STEM curriculum makers can help us, as researchers and educators, to find strategies for teachers to counter barriers to integration.

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Appendix: STEM Integration Curriculum Assessment (STEM-ICA)

Reviewer Name:
Curriculum Name:
Date Curriculum Reviewed:

OVERVIEW

The rubric is for the evaluation of STEM integration curriculum. Elements of quality were identified in a literature review and analysis of the national and state level education standards. These quality indicators summarized and mapped to the rubric categories. There are nine separate rubric categories; however, they are closely related and connected to each other. There are two types of ratings: specific and overall.

The SPECIFIC RATINGS should be done first

Reviewers are asked to answer some yes or no questions, provide a rating of quality, and give evidence to support the ratings. **Reviewers will answer the questions first by marking no, somewhat, or yes for each item.** They are intended to help reviewers reflect on specific elements of the curriculum unit and to help them understand the intent of the rubric question. **They are meant to be representative of some important elements but not inclusive of all.**

The second item is an OVERALL RATING

- This is a summary assessment of the effectiveness of the curriculum unit in helping students learn the knowledge and skills and/or practices identified in national and state level education standards.
- Reviewers are asked to provide both a rating and the evidence to support the rating.

Rating Scale

- All items are rated on a **five-point scale from 0 to 4** describing the extent to which the unit meets the characteristics
 1. 0: Not present
 2. 1: Weak
 3. 2: Adequate
 4. 3: Good
 5. 4: Excellent

NA/DK

- Zero means none of the characteristics described in the question are reflected in the curriculum unit.
- Four indicates that all of the characteristics described in the question are reflected in the material.
- The NA means “Not Applicable” and DK means “Don’t Know.” These should only be used in rare circumstances.

SPECIFIC RATINGS

Please answer the Yes or No questions first by marking yes, somewhat, or no for each item before answering the rubric questions.

I. A Motivating and Engaging Context

Does the curriculum unit....	No	Somewhat	Yes
Allow students to make sense of the situation based on extensions of their own personal knowledge and experiences?			
Engage and motivate students from different backgrounds?			
Provide a context with a compelling purpose (what, why, and for whom)?			
Include global, economic, environmental, and/or societal contexts?			
Include current events and/or contemporary issues?			
Provide opportunities to apply engineering process in partially or completely realistic situations?			

1.1. To what extent does the curriculum unit use a motivating and engaging context?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings:

II. An Engineering Design Challenge

Does the curriculum unit...	No	Somewhat	Yes
Contain activities that require students to use engineering design processes? Address design elements of problem, background, plan, implement, test, evaluate (or other similar representation of the processes of design)?			
Allow students opportunities to learn from failure/past experiences?			
Allow students to redesign?			
Contain an engineering challenge that includes a client?			
Allow students to participate in an open-ended engineering design challenge in which they design and assess processes or build and evaluate prototypes/models/solutions?			
Contain an engineering challenge that requires students to consider constraints, safety, reliability, risks, alternatives, trade-offs, and/or ethical considerations?			
Promote engineering habits of mind (e.g., systems thinking, creativity, perseverance)?			
Requires students to explore or develop technologies (e.g., bridges, water filters, recycling plant processes) from the field of engineering (e.g., civil engineering, environmental engineering, industrial engineering) discussed in the engineering challenge?			
Promote understanding about what engineering is and what engineers do at work?			

2. To what extent does the curriculum unit allow students to learn engineering design by integrating an engineering design challenge?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings:

III. Integration of Science Content

Does the curriculum unit...	No	Somewhat	Yes
Address state standards in science at levels that match test specifications and beyond?			
Integrate science concepts that are grade level appropriate?			
Require students to learn, understand, and use fundamental science concepts and /or big ideas of science necessary to solve the engineering challenge?			
Promote coherent conceptual understanding of science?			
Provide opportunities to learn and implement different techniques, skills, processes, and tools related to science learning?			

3. To what extent does the curriculum unit integrate science content that are needed to solve the engineering challenge and support in-depth understanding?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings:

IV. Integration of Mathematics Content

Does the curriculum unit...	No	Somewhat	Yes
Address state standards in mathematics at levels that match test specifications and beyond?			
Integrate mathematics concepts that are grade level appropriate?			
Require students to learn, understand, and use fundamental mathematics concepts, particularly in data analysis and measurement, necessary to solve the engineering challenge?			
Promote coherent understanding of mathematical thinking?			

To what extent does the curriculum unit integrate mathematics content that are needed to solve the engineering challenge and support in-depth understanding?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings

V. Instructional Strategies

Does the curriculum unit...	<i>No</i>	<i>Somewhat</i>	<i>Yes</i>
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Contains lessons and activities that are student-centered – minds-on and/or minds-on/hands-on?

Contain some activities that require students to collect and analyze information or data before arriving at a solution?

Embed argumentation as a strategy to teach engineering and/or science (often data and data analysis provides the evidence for claims made)?

Include explicit connections to the overall design challenge/context in every lesson so that students understand why each lesson is important?

Involve students in activities that embed STEM ideas to be learned in multiple modes of representation (real life situation, pictures, verbal symbols, written symbols, manipulatives) with an emphasis on translations within and between modes?

4. To what extent does the curriculum unit support student centered teaching strategies?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings:

VI. Teamwork

Does the curriculum unit...	<i>No</i>	<i>Somewhat</i>	<i>Yes</i>
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Require students to collaborate with others?

Include opportunities for students to demonstrate individual responsibility while working in a team?

Build in instructional strategies that encourage positive team interactions and the five elements of cooperative learning?

Require that each member of the team is needed for completion of the activities/tasks?

6. How well does the curriculum unit enable students to develop teamwork skills?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings:

VII. Communication

Does the curriculum unit...	<i>No</i>	<i>Somewhat</i>	<i>Yes</i>
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Require students to communicate science concepts (e.g., oral, written, or using visual aids such as charts or graphs)?

Require students to communicate engineering thinking/engineering solutions/products (e.g., oral such as presentations to the client, written such as a memo to the client, technical communication, or with visual aids such as schematics)?

Encourage multiple modes of representation (real life situations, pictures, verbal symbols, written symbols, manipulatives/concrete models) within communication of learning?

Include a requirement for argumentation strategies?

7. How well does the curriculum unit enable students to develop communication skills in science, mathematics, and engineering?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings:

VIII. Performance and Formative Assessment

Does the curriculum unit include assessments that...	No	Somewhat	Yes
Are closely aligned with the learning objectives and goals and content from the multiple disciplines of STEM?			
Are tied meaningfully to state standards and test specifications and, when possible, go beyond these specifications?			
Provide students opportunities to produce evidence of understanding and abilities in different ways through performance tasks?			
Provide guidance to the teacher that could be used to improve implementation of the curriculum unit?			

To what extent do the assessments and required assignments in the curriculum unit measure students' knowledge and skills?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings:

IX. Organization

Does the curriculum unit...	No	Somewhat	Yes
Present clear objectives and learning goals from the multiple disciplines of STEM that are tied meaningfully to state standards and, when possible, go beyond these specifications?			
Include activities/lessons that flow in a logical and sequential order so they build on each other?			
Provide guidance and instructional strategies for teachers who are unfamiliar with the unit?			

9. How well is the curriculum unit organized?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings:

OVERALL RATING

Please rate the effectiveness of the curriculum unit in having students learn the knowledge and skills and/or practices identified in national and state education standards. Review the learning objectives of the curriculum once again before describing the evidence that supports your conclusions. ***This description is not intended to be an average of all the previous ratings, but your overall judgment of quality and likely impact of the curriculum unit. Please describe the evidence that supports your conclusions in the space provided.***

To what extent will the curriculum unit help students learn appropriate grade level knowledge, skills and/or practices of STEM subjects as identified in the national and state education standards?

NA/DK 0 1 2 3 4

Describe the evidence that supports your ratings: