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Approaches to Integrating Engineering in STEM Units and Student Achievement Gains

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Abstract

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Keywords

STEM, engineering, integration, achievement gains

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Approaches to Integrating Engineering in STEM Units and Student Achievement Gains

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Abstract

This study examined different approaches to integrating engineering practices in science, technology, engineering, and mathematics (STEM) curriculum units. These various approaches were correlated with student outcomes on engineering assessment items. There are numerous reform documents in the USA and around the world that emphasize the need to incorporate engineering into science education. The authors of this study contend that different approaches to integrating engineering in STEM units correlate to larger student achievement gains in engineering, based on assessment items developed from the Framework for Quality K–12 Engineering Education (Moore, Glancy, Tank, Kersten, & Smith, 2014). The goal of this work is not to establish one singular working definition for how to integrate the disciplines of STEM but rather to focus on characteristics of integrating engineering within STEM curricular units that are associated with higher student achievement gains in engineering for the students involved in this study. The results indicate that when engineering is introduced at the beginning of the unit to provide context for the learning, and revisited throughout the duration of the unit, student achievement gains with engineering assessment items are greater than when engineering is incorporated only at the end of the unit as a design challenge in the form of a culminating project.

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Introduction

Recent national reports (e.g., Carnegie Corporation, 2009; National Commission on Mathematics and Science Teaching for the 21st Century, 2000; National Research Council [NRC], 2012; National Science Board, 2007; President's Council of Advisors on Science and Technology, 2010) call for improvements in the quality of science, technology, engineering, and mathematics (STEM) education to address the pressing needs for more STEM professionals and maintain global competitiveness for the United States. These reports argue that the United States' ability to prepare students in STEM fields and stay at the cutting edge of technological solutions that drive further innovation in STEM will promote the country's future competitiveness in the global market. STEM education initiatives strive to meaningfully incorporate learning across the fields of science, mathematics, and engineering while using technology to prepare students for the complex and information-rich demands of the 21st century. The workforce of the 21st century will need to know how to utilize technology

to solve complex and multidisciplinary problems. The NRC (2012) states that STEM education in primary and secondary education can serve as a means for integrating learning across content areas to prepare students for the skills and knowledge required to participate as informed members of society (Honey, Pearson, & Schweingruber, 2014).

The Committee on Integrated STEM Education (Honey et al., 2014) released a report in which they stated that they were unable to come to a consensus on a precise and useful definition of STEM integration. There are various integrated STEM education approaches and the effectiveness of those approaches depends on the content being taught, students' previous experiences with integrated STEM, and teachers' comfort level with using different pedagogical strategies. However, as Bybee (2010) argues, "if STEM education is going to advance beyond a slogan, educators in the STEM community will have to clarify what the acronym actually means for educational policies, programs, and practices" (p. 30). The goal of this work is not to develop a singular interpretation of STEM integration but to examine how different approaches to incorporating engineering in STEM units can correlate to various student outcomes on engineering assessment items. The notion of STEM education is still in development; however engineering is the least developed of the STEM domains in the K–12 classroom setting (Honey et al., 2014). In order to bring clarity to how engineering is incorporated in the K–12 education setting, the various approaches to using engineering in the K–12 classroom context need to be further examined. The Next Generation Science Standards (NGSS Lead States, 2013) demonstrate an emphasis on STEM integration as well as the inclusion of engineering standards across multiple grade bands, representing engineering as one of several core disciplines. Thus, teachers are being held accountable for teaching science with a more interdisciplinary approach that is highly inclusive of engineering, while little is known about how this approach facilitates students' understandings of science or engineering, particularly engineering as a new focus in K–12 education. Thus, this study examines how various approaches to integrating engineering in STEM curricular units correlate to students' learning outcomes related to engineering. The research question guiding this work is: *In what ways does the type of engineering integration in STEM curricular units correlate to gains in student achievement in engineering?*

Theoretical Grounding and Review of the Literature

The theoretical grounding for this work comes from a perspective on learning from a situated cognition framework (Brown, Collins, & Duguid, 1989). This framework requires the social and cultural components of the learning space and considers the activities and contexts in which students' knowledge is developed as an integral part of

what is ultimately learned. Learning and cognition are fundamentally situated and cannot be separated from the social, cultural, and experiential nature of the learning environment (Brown et al., 1989). Brown et al. (1989) claim, "too often the practices of contemporary schooling deny students the chance to engage the relevant domain culture, because that culture is not in evidence" (p. 34). In other words, students learn science by doing science, as it would be practiced in authentic contexts. Students need to have opportunities to engage in scientific practices that require them to use their scientific knowledge and skills to answer empirical questions through inquiry and realistic practice. Engineering can provide context for the problems posed in STEM units that are similar to problems that engineers might encounter in life, thus providing a more authentic approach to problem solving. Engineering often involves teams of individuals working together to meet the needs of a client and this social approach to learning and problem solving also aligns with the principles of situated cognition.

Situated cognition provides a strong basis for the development of authentic STEM environments in which students are faced with challenges that require peer collaboration that will prepare them for the problems they will likely encounter in the real world. These challenges are multidisciplinary and have a multiplicity of "right answers." Incorporating engineering into the science classroom allows for students to engage in learning science and mathematics content in authentic, situated contexts. By engaging in engineering design challenges, students are able to apply their scientific knowledge and skills in solving a real-world problem. Such authentic experiences that are socially and culturally situated and require students to process information as they will need to later in life are optimal for learning (Brown et al., 1989). Thus, STEM initiatives that aim to approach real-world problems with interdisciplinary approaches align well with this framework for learning and cognition.

Engineering in the Science Classroom

Recent national reforms such as the Next Generation Science Standards (NGSS Lead States, 2013) have a demonstrated commitment to interdisciplinary content integration and problem solving. The inclusion of engineering into the NGSS framework constitutes a commitment to science instruction that engages students in addressing real-world problems (NGSS Lead States, 2013). The NRC released the *Framework for K–12 Science Education* in which engineering has become an area of focus for science teachers. The NRC (2009) found promising early results that engineering could have a positive impact on learning science and mathematics. Wendell and Rogers (2013) also reported results that indicated adding engineering to the science curriculum increased students'

science achievement compared to traditional science-only instructional units. Riskowski, Todd, Wee, Dark, and Harbor (2009) found that when students were taught with more inquiry- and design-based approaches, compared to traditional passive content pedagogies, students' scores were significantly better in content knowledge measures and displayed more complex reasoning skills on assessment items. Lachapelle and Cunningham (2014) assert that engineering in school has the potential to improve mathematics and science achievement by making mathematics, science, and engineering more relevant to students. Similarly, Mehalik, Doppelt, and Schunn (2008) found that when design-based engineering practices were integrated into science units, compared to inquiry-based science units, greater learning in the science content was observed, and specifically greater achievement gains were noted for African American students. Lachapelle and Cunningham (2014) outline several reasons for incorporating engineering education in K–12 education. They discuss that children are naturally inclined to tinker and create and this provides a strong foundation for students to engage in engineering design tasks.

Engineering Beyond Design

Dym, Agogino, Eris, Frey, and Leifer (2005) discuss engineering education with a focus on the notion of design and design thinking. Those authors present findings that promote several dimensions to design thinking. They further offer a perspective on system dynamics in which designers are able to anticipate unintended consequences among multiple interacting parts of a system. They discuss the notions of teamwork and collaboration that are necessary to the design process. In addition, Dym et al. (2005) examine the use of project-based learning strategies to approach teaching the design process to students. The emphasis on design established by Dym et al. will be extended for this research study to include additional components of engineering as proposed by Moore, Glancy, Tank, Kersten, and Smith (2014). The elements of engineering education that were the focus of this study came from the Framework for Quality K–12 Engineering Education (Moore et al., 2014). This framework includes dimensions beyond the attributes previously listed. The framework does address the process of design in three general categories: problem and background, plan and implement, and test and evaluate, while including several other attributes. The complete framework is provided in Figure 1. It is important to consider how this framework defines engineering beyond just the scope of the design process. The framework is relevant to this study because the authors contend that the interpretation of how engineering is integrated into the science classroom can influence how students understand engineering. Secondly, the framework provides a theoretical map upon which the assessment items used in this study were based.

The assessment instrument used in the pretest and posttest score analysis was developed based on these domains of engineering education provided in the Framework for Quality K–12 Engineering Education.

Engineering Integration Approaches

The role that engineering can play in integrated STEM models can vary substantially. As early as 1991, a discussion regarding different models of integrating curriculum began to surface (Fogarty, 1991). In Fogarty's work, ten models of integrated curriculum were presented with varying types of overlap or reliance between content areas. Fogarty presented a continuum of interpretations for the notion of integrated curriculum, from threaded approaches in which one subject area leads to another and allows for a more natural progression between content instruction, to webbed curricular approaches where a theme or context drives the connections between subject areas, to more comprehensive models of full integration in which content spans disciplines and requires a truly interdisciplinary approach (Fogarty, 1991). Bybee (2013) discusses different notions of integrated STEM as well. The role that engineering plays in the different models of STEM integration presented by Bybee (2013) can be quite different. Bybee presents some cases where engineering is serving as the context for making connections between mathematics and science content. In other cases, science, technology, engineering, and mathematics are all treated as separate disciplines with equal weights. The way in which STEM is conceptualized will have implications for how engineering is situated in a learning progression. For the purpose of the study, three models of engineering integration will be explored: (1) engineering used as a culminating project for the unit, (2) engineering used at the beginning of the unit to frame the learning and at the end of the unit to assess mastery through design, and (3) engineering used consistently throughout the duration of the STEM unit.

While there is little consensus regarding how engineering should be incorporated into K–12 STEM or science classrooms, a few general approaches are more prevalent in the research literature. Many approaches to incorporating engineering into the science classroom cite using engineering and design as a context for a unit in which solving the problems requires the use of scientific knowledge and skills as well as mathematics (Kolodner et al., 2003; Penner, Lehrer, & Schauble, 1998). Kolodner et al. present the use of the curriculum Learning by Design in which engineering problems create the context for students to apply knowledge and skills drawn from the fields of science and mathematics. The approach is rooted in a problem-based learning and case-based reasoning model in which students are presented with relevant problems where they need to engineer appropriate solutions. This type of engineering integration would likely fall under the approach where

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

Figure 1. A framework for quality K–12 engineering education: research and development. From Moore et al. (2014).

engineering is introduced at the beginning of the unit to frame the unit and revisited throughout the unit with mini design challenges for exploring science content with a culminating engineering design project.

Another approach to integrating engineering is to use the design challenge at the end as a culminating project for the unit. This approach utilizes the design challenge and engineering as an additional component to the science unit. The Engineering is Elementary (EiE) curriculum series presents engineering design challenges that can be paired with science instruction. The engineering lessons are intended to supplement the science instruction to allow students to apply the science concepts as a culminating engineering

design project for the unit. The unit addresses elementary science topics and a field of engineering (i.e., package, environmental, chemical, etc.) (Lachapelle and Cunningham, 2014).

The Type of Integration Matters

The Next Generation Science Standards (NGSS Lead States, 2013) promote strong connections between science content and engineering integration in order to ensure that students will need to utilize their science knowledge to solve the design problems. There are a few studies that have examined the effects of different implementation

approaches for STEM integration on student learning. For example, Schnittka (2012) found that when one teacher was implementing the same STEM curriculum unit to two classes, one advanced class and one standard class, the implementation of the unit differed dramatically based on the teacher's expectations of what students in each setting would be able to do. The teacher gave fewer opportunities for students in the standard class to discuss their design ideas and explore science content through demonstrations and discussion, compared to the advanced class. These alterations potentially influenced the level of science content learning between the two groups. A commitment to the design process and giving students sufficient freedom in the unit to be creative seems to be an important component to the success of STEM units, which is largely directed by teachers' expectations of what students can do. This study sheds light on the notion that the implementation of engineering practices in the unit and teacher expectations can influence the learning that students experience as well.

Methods

Context

The context of this study is the EngrTEAMS Project (NSF-#1238140) that aims to promote STEM integration in the classrooms in grades 4–9. This project provides three weeks of extensive professional development for teachers during the summer focused on learning around K–12 engineering and using engineering design tasks to support learning in science and mathematics, specifically data analysis and measurement. The end product from the summer professional development is new STEM integration units designed by teams of teachers supported by a graduate student coach from the partnering university. Teachers pilot their team's curriculum in a university summer camp and use this experience to revise their curriculum based on this pilot before implementing the unit in their classroom during the academic year.

Data Collection – Data Sources

The data collection period for this research was from August of 2013 through June 2014, while the units were developed during the summer of 2013 prior to the implementation school year. Forty-eight teachers participated in the project in which they designed and implemented their new STEM units over the course of the year. Implementation of the units took 3–4 weeks and classroom observations were conducted during the classroom implementation. The data collection measures during these observations that were utilized in this study were: a report log indicating the lesson focus (science, mathematics,

engineering, or technology) for each day and observation notes from each lesson conducted by the research team, as well as pretest and posttest engineering content assessment scores from students experiencing the units. The report logs served as the primary predictor in the linear model for this analysis. The report log files included information about the content focus of the lesson, type of instruction used in the lesson, and time spent on each STEM discipline. Thus, the log files provide detailed information about each teacher's implementation of the units and insight into how engineering was integrated in the scope of the unit.

The second data source was the content tests that students completed before and after the implementation of each unit. These project-constructed assessments captured achievement in engineering, science, and mathematics and were designed to be sensitive to the engineering design-based science curricula that teachers developed and taught. These assessments were developed, scaled, and validated following the process described in the Standards for Educational and Psychological Testing (American Educational Research Association, 1999). For the purpose of this analysis, only the questions relating to engineering were used. These data were the primary focus of the study to ensure alignment to the research question, which aimed to explore specifically how curriculum integration approaches impacted engineering understandings for students. The elementary exam consisted of 10 multiple-choice questions and the middle school exam consisted of 15 multiple-choice assessment items. There were two assessments, one for middle school and one for elementary school, to account for the developmental differences between the grade levels. This required the analysis to be conducted on pre/post assessment percentages in the regression model. It is important to note that the assessment items were driven by engineering, as presented in the Framework for Quality K–12 Engineering (Moore et al., 2014) across both the elementary and middle school exams.

Participants

A quantitative approach served as the primary methodology for this study, utilizing multiple linear regression. The regression equation modeled data from posttest scores by pretest scores and the type of engineering integration in the unit. The data were collected from 2,530 students across grades four through nine of the teachers participating in the project. Student demographics are provided in Figure 2 for the 2,530 students in the study. There were 48 teachers present in the study in which each was categorized as using a particular type of engineering integration approach in their STEM unit. The 48 teachers were practicing in classrooms across three different districts: one urban district, one inner ring (also called a first ring suburb in that it has slightly higher urban density than a suburb

Figure 2. Demographic information for the students involved in the study.

and has a closer proximity to the city center), and a suburban district.

Three Approaches to Integrating Engineering in STEM Units

The codes for the type of engineering integration present in the curriculum were developed from report logs in which teachers or coaches reported each day's lesson as having an emphasis on engineering, mathematics, science, or a combination of these. Thus, these codes came from documentation of the daily implementation of the STEM units, not from curriculum documents. Patterns over the course of the unit were analyzed by the researchers to classify the types of engineering integration based on frequency in the unit and placement of engineering tasks within the unit to better understand how the engineering components of the STEM unit were situated in the overall structure of the unit. The researchers incorporated both frequency and position of engineering tasks to develop a sense for how engineering was being incorporated into the unit when assigning codes for the type of engineering utilized. The engineering integration was then assigned a category. The first type of engineering integration was when engineering was used as a *Culminating Project* where engineering was introduced only at the end of the STEM unit as a design challenge or project. The second approach for integrating engineering was *Implicit* integration, in that the teachers generally tried to integrate engineering early and use the engineering design challenge to provide context and framing to the unit as well as using the design challenge at the end of the unit as a culminating project, but engineering tasks or engineering thinking was not consistently revisited throughout the duration of the unit. The third approach was *Explicit* integration. In this category teachers purposefully introduced the engineering design challenge in lesson one and revisited engineering in some way almost every day to continually situate engineering as foundational to the unit goals that eventually culminated with an engineering design challenge. It is important to note that teachers were not required to implement a specific engineering integration

strategy nor were they explicitly advised of these different categories. Rather, teachers used a particular strategy naturally based on how they deemed most appropriate to incorporate engineering with their disciplinary content area and the research team then disaggregated results based on their observed approach.

Three Examples for Each Engineering Integration Approach

Here we present three life science units to provide an example for each category: (1) culminating project, (2) implicit, and (3) explicit approaches to integrating engineering in the unit.

Integrating Engineering as a Culminating Project—Plants and Space

In this unit, students completed several science experiments to explore photosynthesis, to compare and contrast the roles of organisms (producers/consumers/decomposers) in ecosystems, to study biotic and abiotic factors that influence populations in an ecosystem, and to explain water absorption of plants. Science lessons were designed to promote skills and background knowledge that would prepare students for the engineering design challenge, which was introduced to students after the completion of the science activities. The design challenge was adapted from NASA and required students to design a simple hydroponic system with a small container that would hold water and a membrane or layer that allowed plants to grow on it as it held soil without falling through but allowed water go through it. The curriculum unit included ten lessons and took four weeks to complete. This approach introduced many science-only lessons initially to front load the background knowledge students would need, which then led to an engineering design challenge at the end of the unit to tie it all together. In this way, engineering was treated as a culminating project to bring the unit ideas together through an activity that was primarily built on science knowledge.

Implicit Integration Approach—Fit Fish

In this unit, students explored natural selection, researched fish and fisheries management, and were then asked to design a prototype for a fish fitness-testing device using the data from their research. The engineering design challenge was introduced in the first lesson of the unit and used to frame the subsequent research they would be doing. Students explored engineering concepts such as design and constraints before they started any of the science activities. After the completion of the science activities, students participated in the engineering design challenge. Additional constraints for the engineering design challenge were presented after the initial design and prototype construction. Students redesigned after the initial build trying to make adjustments to their solutions that would fit the constraints. The unit included six lessons and took three weeks to implement. In this example, the engineering design challenge was presented at the onset of the unit and used to frame the research in science topics that students would be doing. Then, the engineering design challenge was revisited at the end of the unit. In this way, engineering was used initially to frame the learning experience and visited again at the end, but most of the lessons in the middle of the unit were strictly science lessons with little tie-in to the engineering process of design.

Explicit Integration Approach—Genetically Modified Organisms

This unit started with the introduction of the engineering design challenge and a brief introduction to genetically modified organisms (GMOs). Students then engaged in a number of science experiments and inquiry lessons to explore cells, to consider the relationship of the structure and function of DNA, to study sexual and asexual reproduction, and to explain basic heredity patterns found in nature. At the outset of the unit, students were introduced to GMOs and the client, a Midwestern University's Agricultural Extension Office, which had been asked to design a barrier that effectively reduces cross-contamination of non-GMO cornfields from GMO cornfields. These lessons concluded with a discussion that provided students with a summary of the content knowledge they had learned during the lesson. Prior to, during, or immediately following each lesson, the students were asked to consider ways in which the content related to the engineering design challenge. Finally, students were asked to write a final letter, including their designs and using evidence-based reasoning, to pitch their design to the client. The unit included eight lessons and took five weeks to complete. This approach is different in that the design challenge was mentioned at the end of each lesson during the unit and continually revisited to ensure students were connecting the science they were learning to ultimately be able to apply towards a design product. The engineering design challenge was anchoring

the science learning toward a useful application throughout the unit.

The above examples show three different strategies to integrating engineering into life science units. Note the differences in approach for how engineering was placed and treated in the units described above. Engineering was introduced at the end of the unit in the *Plants and Space* unit, which would be considered a *Culminating Project*. In the second unit described, *Fit Fish*, engineering was introduced early in the unit but the challenge and discussions around engineering concepts only appeared again at the end of the unit, which is an example of *Implicit* integration. In the third unit described, *GMOs*, engineering was integrated throughout the life science unit starting from the first lesson where science and engineering lessons built on each other, thus representing the *Explicit* integration approach. More engineering concepts were discussed throughout the *GMO* unit, allowing for students to engage in engineering practices more often and root their science experiences into this practice with engineering design. In all of these units, mathematics was used to analyze and make sense of data that students collected in somewhat similar ways across all three units described. Thus the factor that differed across the units was the ways in which engineering was approached. These examples provide more information to describe the differences in approaching how engineering was used across the three units.

Findings and Data Analysis

To determine the extent that each type of engineering integration correlated to gains in student achievement on engineering, multiple linear regression was analyzed in which the posttest scores (percentages) were modeled on the following two predictors: the type of engineering integration (*Culminating Project*, *Implicit*, and *Explicit*) and pretest scores (percentages) as shown in Figure 3. The results of this study suggest that students perform better on engineering assessment items in STEM units when engineering is integrated using either an *Implicit* or *Explicit* approach than when there is a *Culminating Project* of engineering integration applied. In the context of these codes, when engineering is introduced at the beginning of the unit to frame the context as well as revisited with an engineering design challenge at the end of the unit (*Implicit*), student outcomes on engineering assessment items are more improved than when engineering is only used at the end (*Culminating Project*). Also, when engineering is referenced from the start and consistently throughout the unit (*Explicit*), student outcomes on engineering assessment items are significantly better than when engineering is only used at the end of the unit (*Culminating Project*) as indicated in Figure 3.

Table 1 provides the means, standard deviations, number of students, and confidence intervals for each integration approach in the regression model. For the 2,530 students in

Figure 3. A measure of predicted student posttest scores (percentage) in relation to pretest scores (percentage) of the participants and the type of engineering integration present in the unit.

Table 1.

Descriptive statistics for the data based on the approach for integrating engineering into the curriculum.

Type of engineering Integration	N	Pretest		Posttest	
		Mean (SD)	95% CI	Mean (SD)	95% CI
Culminating Project	587	45.8 (26.9)	44.3–48.0	46.5 (27.5)	44.3–48.7
Implicit	1461	59.0 (24.5)	57.7–60.3	63.9 (24.7)	62.6–65.2
Explicit	482	72.3 (20.8)	70.5–74.2	72.9 (22.5)	70.9–74.9

the study, 587 students experienced an approach to integrating engineering as a *Culminating Project*, 1,461 students experienced an *Implicit* approach, and 482 students experienced an *Explicit* approach to integrating engineering in their respective STEM units. The mean for the pretests scores for the *Culminating Project* approach was lowest at 45.8, with the *Implicit* pretest mean being 59.0 and the *Explicit* mean being 72.3. The posttest mean for the *Culminating Project* was 46.5, with an *Implicit* posttest mean of 63.9, and *Explicit* posttest mean of 72.9. Thus, the differences between pretest and posttest means within each integration approach were 0.7 percentage points for the *Culminating Project*, 4.9 percentage points for the *Implicit* approach, and 0.6 percentage points for the *Explicit* approach. The changes in students' scores between pretest and posttest were largest for the *Implicit* integration approach, which was also the category that had the largest number of students represented.

The assumptions of normality and homogeneity of variance were met. The *F*-statistic for this analysis was

$F(3, 2526) = 1,287, p < 0.001$ which corresponds to a *p*-value that was statistically significant at a Type I error rate of $\alpha = 0.05$. This provided strong evidence to reject the null hypothesis that type of engineering integration has no effect on posttest scores, while accounting for pretest scores. R^2 was 0.60, which implies that 60% of the variance was accounted for in the model. Thus, there was evidence to suggest that the type of engineering integration was positively correlated with student achievement on engineering assessment items.

Dummy-coded variables were applied to determine the nature of the effect for each of the three types of engineering integration. After analyzing the boxplots for the posttest and pretest scores, there was evidence to suggest that the inclusion of the pretest score as a predictor in the model was necessary because high pretest scores do not allow for as much growth as low scores.

In Figure 3 the *Implicit* integration approach to integrating engineering was associated with slightly higher posttest

Table 2.

Number of teachers assigned the different codes for types of engineering integration from the three districts involved in the study (percentage for each code within district).

District	Culminating Project	Implicit	Explicit
Urban	7 (26.9%)	17 (65.4%)	2 (7.7%)
Inner ring suburb	5 (41.7%)	6 (50.0%)	1 (8.3%)
Suburban	2 (25.0%)	4 (50.0%)	2 (25.0%)

scores than the *Explicit* integration approach. However, this difference was not statistically significant. Nonetheless, this was an unexpected finding and indicates that the types of engineering integration did not affect the outcome (posttest scores) with the same weight. The difference between *Explicit* and *Implicit* was not significant, while the difference between *Culminating Project* and *Explicit* was significant ($p < 0.001$) as well as the difference between *Culminating Project* and *Implicit* ($p < 0.001$). The regression equation for the model is given in Equation (1), in which the reference group was the *Culminating Project* integration level:

$$\widehat{PostTest} = 11.7 + 0.8(Pre) + 7.4(Implicit) + 6.3(Explicit) \quad (1)$$

Distribution of Codes

In looking at the codes for type of engineering integration utilized in the units, there was a somewhat common pattern for the distribution of codes across the three districts involved in this study in that for all three districts the largest proportion of the units were assigned the *Implicit* code with the code *Culminating Project* being the same or higher than the number of codes for *Explicit* integration within each district. Figure 2 demonstrates that the three districts represented different general demographics of students. Table 2 displays how different engineering approaches were coded across the three districts involved in the study. There were different approaches to integrating engineering across all three districts. This information provides information regarding how the different approaches to integrating engineering were applied throughout the three districts in the study.

Discussion

The findings of this research indicate that the placement of engineering within STEM units was correlated to different student learning gains with engineering for the students involved in this sample. Based on the results of this research, there is evidence that including engineering at the beginning of a STEM unit to frame the learning and provide context for the unit with engineering being revisited and used as a project at the end produced stronger engineering understandings for students compared to when engineering was used solely as a culminating project.

The initial hypothesis for this work was the notion that generally the more consistently engineering was used in the unit, the better the student outcomes would be with engineering assessment items. However, the *Explicit* and *Implicit* approaches showed no statistically significant difference. Furthermore, the model predicted slightly higher posttest scores for the *Implicit* level of integration compared to the *Explicit*. A possible explanation for this unexpected finding could be the average pretest scores for students not being equivalent across the three different types of engineering integration approaches. The pretest scores were lowest for the *Culminating Project* category and highest for the *Explicit* integration approach. This difference could be important, as students with higher initial scores have a smaller margin to improve than students with lower initial scores, which could account for some of the surprising results that were found with the *Explicit* integration approach. The authors acknowledge this limitation, while also noting that accounting for the changes in students' scores permitted student growth to be a factor and was therefore valuable to the model.

The statistical findings in this study provide support for the idea that the *Implicit* approach correlated to stronger engineering understandings than the *Culminating Project* approach. The *Implicit* approach was associated with a mean gain of 4.9 percentage points pretest to posttest, whereas the *Culminating Project* approach was associated with a 0.7 percentage point mean increase. The *Explicit* approach was associated with a 0.6 percentage point mean increase. Thus, while the results of this study are statistically significant, the educational significance for these different approaches needs to be further explored. The difference in means between the pretest and posttest scores for the *Implicit* approach was 4.9%, which is more meaningful within an educational context compared to gains of less than 1% for the other two integration approaches. According to the regression equation (Equation (1)), after accounting for a student's pretest score, student posttest scores would be predicted to be 7.4 points higher if taught with an *Implicit* approach and 6.3 points higher with the *Explicit* approach, than a student in the *Culminating Project* approach.

These results provide statistically significant evidence that utilizing different approaches to integrating engineering within the STEM units was associated with different learning outcomes for a large sample of students. Generally, including engineering at the beginning of the unit as well as at the end produced significantly higher learning outcomes for students with engineering assessment items. Frequently including engineering throughout the duration of the unit was also correlated to statistically significant higher learning outcomes for students compared to when engineering was only included at the end of the unit. However, the authors acknowledge the fact that effective engineering integration is not only about when to integrate engineering

but also strongly linked to how to integrate engineering. Studies show that engineering instruction and engineering-specific language (e.g., constraints, criteria) used by science teachers in instruction influence student learning of engineering and science (Guzey & Aranda, in press). The authors argue that students should engage in meaningful and purposeful engineering design and practices in their STEM experiences. Thus, simply adding an engineering design project to an existing science unit does not necessarily provide students with opportunities to practice and learn engineering and science in authentic and realistic ways. Effective instruction, including the discourses of engineering or language use in engineering education that recent reforms advocate (NRC, 2012; NGSS Lead States, 2013) are new to many teachers but they all are grounded in critical elements of a situated cognition approach to learning (Brown et al., 1989). Authentic learning activities, in which engineering practices are incorporated beyond superficial applications, are necessary for situated cognition to be most effective. The authors contend that the results of this study support the notion that engineering practices need to be consistently embedded in learning experiences in ways that are relevant to the content being learned in order to be authentically experienced by students.

Limitations and Implications for Future Study

The researchers acknowledge that there are several limitations to this quantitative study, and encourage future directions for this work. One limitation of this work was that there were relatively few codes assigned in the *Explicit* category. The different approaches to incorporating engineering in the STEM units were not assigned treatments in this study. Instead the integration of engineering was driven by the teachers themselves and examined by the research team at the conclusion of the units. This approach allowed the researchers not only to know how the practicing teachers were naturally inclined to incorporate engineering without researcher input, but also examine if there were correlations in student performance associated with those choices. As a result of this research design, the research team was not able to ensure that the codes were equally distributed across the three different types of engineering integration. This approach also limited the ability of the research team to ensure the pretest scores were equivalent across the different integration categories, which was a limitation to this work.

Another limitation of this study primarily centered on the assessment instrument utilized for data collection. The number of students included in the data is quite large ($n = 2,530$), which increases the power in the statistics. However, the strong statistical power comes at the cost of assessment alignment to what was taught by teachers in individual and varying STEM units. In other words, the large data set allows for assumptions that this population

was representative of a broader general student population, but compromises the level of specificity to assess individual unit objectives. The units covered varying engineering knowledge and skills; however, the assessment items needed to be consistent to allow for large-scale comparisons across units and therefore could not attend to all of those unique differences within units. The authors recognize the trade-offs in scale of the study and degree of alignment to specific unit learning goals. The authors also recognize that this study's emphasis on how engineering is positioned within the unit does not account for individual differences in engineering implementation quality across the sample of teachers.

Future investigation into the individual implementations of the integration methods would provide a more robust account to explore the educational significance of this work beyond the statistical significance that was found. A possible focus for future research might be a close examination of pedagogical approaches used by science teachers during implementation of the engineering design-based science units. Analysis of videotaped classroom instruction might help to reveal more about the complex relationship between instruction, curriculum unit, and student learning in the context of science and engineering teaching. The authors recognize that the statistical significance found in this study would be further supported by deeper qualitative study into these implementation and quality measures to support more robust pedagogical findings.

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APPENDIX

Elementary Engineering Test

(Indicators from Figure 1 provided in parenthesis for each item)

1. The zoo must move several animals from their habitats to the animal hospital. Which of the following is part of an engineering design process related to the movement of the animals? (*POD-PB, Ethics*)
 - A. Giving medicines to the zoo animals during the move.
 - B. Feeding the animals during the move.
 - C. Brainstorming different ideas of how to move the animals.
 - D. Cleaning the cages of the animals after the move.
2. Engineers are designing a bridge across a river. Some of the constraints that the engineers will consider are the time it takes to build the bridge, the cost of the construction of the bridge, and how much traffic will cross the bridge. Which of the following is also a very important constraint that the engineers would need to consider? (*ISI, Ethics*)
 - A. The population of fish in the river.
 - B. The types of plant life living in the river.
 - C. The pollution levels in the river.
 - D. The wearing away of the river.
3. When engineers test their designed product, which of the following is something they must consider in order to know if the product works? (*POD-TE*)
 - A. How many team members were needed to design the product.
 - B. How much of the allowable money to design the product was used.
 - C. How many ideas they came up with during the brainstorming phase.
 - D. How well the product meets the client's needs.
4. Which of the following would NOT be a part of the job of an environmental engineer? (*CEE, ISI, and Ethics*)
 - A. Design a technology to clean up a pollutant.
 - B. Investigate the source of underground soil pollutants.
 - C. Pollute a stream to test the effect on the environments.
 - D. Make recommendations to a community on how to clean up river pollution.
5. A team of engineers are designing an earthquake-resistant building. They make a list of construction

materials and build a prototype of their earthquake resistant building. They decide to use a “shake table” to help them with their design. Shake tables such as the one shown below provide conditions representative of actual earthquakes. (*POD-TE*)

Engineers will use the shake tables to:

- A. Test the color of the materials used to build their earthquake-resistant prototype.
 - B. Find the cost of the materials to build the actual earthquake-resistant building.
 - C. Test their prototype earthquake-resistant building.
 - D. Display the prototype of the earthquake-resistant building.
-
6. Ava is an engineer who investigates soil and rock properties on and below planned construction areas. Today, she is investigating an area where a chain grocery store is to be built. What should she do if she finds the planned construction area has a high risk of earthquakes? (*POD*)
 - A. Approve the design of the grocery store as originally designed.
 - B. Deny construction of any building on the area.
 - C. Suggest a redesign of the building that can tolerate movement.
 - D. Approve the construction of a building and then investigate the soil and rock properties of the area again after the building is built.
 7. Jayson is working on his design of a video game. He has redesigned his video game several times. His problem is that the game stops working in level 3 each time he tests it. In order for Jayson to think creatively his next redesign, he should: (*POD-TE*)
 - A. Test his current design again to see if the problem goes away.
 - B. Use an old way of solving the problem.
 - C. Look at his problem in only one way.
 - D. Look at his problem in a new or different way.
 8. Which of the following statements about engineers is NOT true? (*SEM, Team, CEE, and ETool*)
 - A. Engineers usually work in teams but they are also independent thinkers.
 - B. Engineers use only science to solve problems.
 - C. Engineers manage constraints, risk, and safety factors.
 - D. Engineers use a variety of tools, skills, and processes at work.

9. Kellie needs to design and build a speaker for a class project. After completing the construction of her speaker, she tested it. She found a failure in her design. What does she need to do next? (*POD*)
 - A. She needs to start working on a completely different design.
 - B. She should evaluate her design, identify strengths and weaknesses, and then use this feedback in redesign.
 - C. She does not need to make any changes on her design.
 - D. She should stop working individually and start working with a friend on a new design.
10. Engineers use a variety of tools such as 3D modeling programs in their work. Why do you think using 3D modeling programs helps engineers in their work? (*ETool*)

3D modeling programs help engineers to:

- A. Design and test their prototype.
- B. Build a prototype that is physically identical to the end product.
- C. Reduce product development time by 50% or more.
- D. Eliminate all the risks associated with the end product.

Middle School Engineering Test

1. Which of the following activities is most important to the work of an engineer? (*CEE*)
 - A. Using power tools to fix broken things.
 - B. Using power tools to build things.
 - C. Developing understanding about what makes things break.
 - D. Fixing broken things for people.
2. Engineers are designing a bridge across a river. Some of the constraints that the engineers will consider are the time it takes to build the bridge, the cost of the construction of the bridge, and how much traffic will cross the bridge. Which of the following is also a very important constraint that the engineers would need to consider? (*ISI, Ethics*)
 - A. The population of fish in the river.
 - B. The types of plant life living in the river.
 - C. The pollution levels in the river.
 - D. The erosion of the river.
3. Which of these statements describes something that an engineer would do as part of his or her job? (*CEE* and *POD-PB*)
 - A. Figure out what materials to use to make bridges strong.
 - B. Operate cranes.
 - C. Build chimneys out of bricks.
 - D. Pour concrete or cement for new roads.
4. When engineers test their designed product, which of the following is something they must consider in order to know if the product works? (*POD-TE*)
 - A. How many team members were needed to design the product.
 - B. How much of the allowable money to design the product was used.
 - C. How many ideas they came up with during the brainstorming phase.
 - D. How well the product meets the client's needs.
5. Which of the following would NOT be a part of the job of an environmental engineer? (*CEE, ISI* and *Ethics*)
 - A. Design a technology to clean up a pollutant.
 - B. Investigate the source of underground soil pollutants.
 - C. Pollute a stream to test the effect on the environments.
 - D. Make recommendations to a community on how to clean up river pollution.
6. You are working as an engineer in a food storage container company and find out that one of the company products contains a potentially harmful chemical. What should you do? (*ISI* and *Ethics*)
 - A. Tell your boss so that the product can be taken out of stores and customers can return them for full refund of their money.
 - B. Change the name and packaging of the product so that no one knows it is the same.
 - C. Test the products on people to see if they get sick.
 - D. Sell the products that are already on the shelves, but stop making new ones.
7. Which of the following statements represents something that an engineer would do as part of his or her job? (*CEE*)
 - A. Repair the engine in a car that will not start.
 - B. Improve your truck by putting new wheels on it.
 - C. Figure out how to improve the safety of cars.
 - D. Drive cars in racing competitions.
8. When designing a bridge, which of the following measures will help the engineers make a decision about the safety of the bridge? (*POD, SEM*, and *ETool*)

- A. The color of the paint on the bridge.
 - B. The brands of cars that will cross the bridge.
 - C. The amount of weight the bridge can hold.
 - D. The final destinations of the people crossing the bridge.
9. A team of engineers are designing an earthquake-resistant building. They make a list of construction materials and build a prototype of their earthquake-resistant building. They decide to use a “shake table” to help them with their design. Shake tables such as the one shown below provide conditions representative of actual earthquakes.

Engineers will use the shake tables to:

- A. Test the color of the materials used to build their earthquake-resistant prototype.
 - B. Find the cost of the materials to build the actual earthquake-resistant building.
 - C. Test their prototype earthquake-resistant building.
 - D. Display the prototype of the earthquake-resistant building.
-
10. Kai is working on a solar oven design. A solar oven is a device that uses the energy from direct sunlight in order to cook food. Kai's main goal is to cook the food quickly. Which of the following should Kai focus on when designing his solar oven? (*POD-PB* and *SEM*)
- A. How to design a solar oven to heat the air inside the oven.
 - B. How to design the solar oven so it is easy to carry.
 - C. How to design the least expensive solar oven.
 - D. How to design the solar oven to be the smallest.
11. Ava is a geotechnical engineer who investigates soil and rock properties on and below planned construction areas. Today, she is investigating an area where a chain grocery store is to be built. What should she do if she finds the planned construction area has a high risk of earthquakes? (*POD*)
- A. Approve the design of the grocery store as originally designed.
 - B. Deny construction of any building on the area.
 - C. Suggest a redesign of the building that can tolerate movement.

- D. Approve the construction of a building and then investigate the soil and rock properties of the area again after the building is built.
12. Nina needs to design and build a water filter for her science fair project. She brainstormed different filter materials that she could use in her design, tested them, and decided on which materials she would use. What should she do next? (*POD*)
- A. Build her filter design and test it.
 - B. Keep brainstorming different filter materials.
 - C. Ask questions of her teacher about water pollution.
 - D. Draw a plan of her filter design.
13. Jayson is working on his design of a video game. He has redesigned his video game several times. His problem is that the game stops working in level 3 each time he tests it. In order for Jayson to think creatively his next redesign, he should: (*POD-TE*)
- A. Test his current design again to see if the problem goes away.
 - B. Use an old way of solving the problem.
 - C. Look at his problem in only one way.
 - D. Look at his problem in a new or different way.
14. Which of the following statements about engineers is NOT true? (*SEM, Team, CEE, and ETool*)
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 - B. Engineers use only mathematics to solve problems.
 - C. Engineers manage constraints, risk, and safety factors.
 - D. Engineers use a variety of tools, skills, and processes at work.
15. Kellie needs to design and build a speaker for a class project. After completing the construction of her speaker, she tested it. She found a failure in her design. What does she need to do next? (*POD*)
- A. She needs to start working on a completely different design.
 - B. She should evaluate her design, identify strengths and weaknesses, and then use this feedback in redesign.
 - C. She does not need to make any changes on her design.
 - D. She should stop working individually and start working with a friend on a new design.