ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

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Paper ID #14947

Impact of Elementary School Teachers' Enacted Engineering Design-Based Science Instruction on Student Learning (Fundamental)

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Impact of elementary school teachers' enacted engineering design-based science instruction on student learning

Introduction

Engineering design is viewed as a vehicle through which scientific knowledge and real-world problem-solving skills can be constructed, refined, and enhanced. With the adoption of new national science standards in the U.S. [1,2] teachers, specifically elementary school teachers, are faced with the daunting task of learning how to integrate engineering design and, more importantly, facilitate student learning of science through design. Considerable strides at the national level have been made to integrate engineering design for inservice elementary science teachers.[3,4,5,6,7] Programs such as the Boston's Museum of Science's *Engineering is Elementary,* Purdue University's *Science Learning through Engineering Design (SLED) Partnership,* The John Hopkins University's *STEM Achievement in Baltimore Elementary Schools (SABES),* and University of Minnesota's *Engr: TEAMS* are grounded in the delivery of high-quality, content-rich, engineering design-based experiences for inservice elementary science teachers. Results from the SLED Partnership, for example, show strong proof-of-concept that elementary teachers can develop deep conceptual knowledge of engineering practices and effectively translate engineering basics into the classroom environment.[3,4] However, how elementary school teachers' direct instruction of engineering design impacts student learning of science has yet to be examined. The purpose of this study was to explore elementary school teachers' enactments of engineering design-based science instruction and to assess the impact of their instruction on students' science learning.

Research questions

This study was guided by the following research questions: a) How do elementary school teachers enact engineering design-based science instruction? b) What is the fidelity of teachers' implementation? c) What knowledge do students learn when engaging in engineering design-based tasks? and d) To what extent does the fidelity of instruction correlate with students' science learning?

Theoretical framework

This study is grounded in the theoretical construct of situated learning theory where learners (teachers and students) become part of a community of practice in which they learn from others (university STEM faculty, more knowledgeable peers) through an apprenticeship approach and advance from simple to more complex tasks until becoming full-fledged participants of the community. Based on Lave and Wenger's (1991) concept of situated learning, teachers learn how to utilize and implement new science-teaching practices through experienced teachers (e.g., master science teachers or STEM faculty).[8] As they continue to attend more professional development, they become more active in the community. This process where the newcomer moves from the periphery to the community's center is known as legitimate peripheral participation. Through this progression, the newcomers become old-timers. Thus, learning occurs in social interactions within context, activity, and culture; this concept is known as "situated learning." Within situated learning, knowledge is socially distributed. Lave and Wenger (1991) assert that learning is useless unless it is applied within the context that is intended for.[8] The success of the science teacher depends on his/her social interactions with others within the community. Therefore, learning takes place within a social setting. This setting is known as a community of practice, and it offers teachers in situated learning a chance to collaborate with other community members, which has been found to have a positive influence on teacher and student learning.[9,10]

In this study, we utilize the construct of situated learning to paint the landscape of how a university-school partnership and its related professional development activities fostered a sense of collaborative learning among elementary school teachers. By immersing fifth and sixth grade teachers in authentic, ill-structured design problems, STEM faculty helped teachers to learn firsthand how to utilize design thinking and reasoning as a way of developing their own understanding of and emerging practice for engineering design-based science instruction. Simultaneously we leveraged the role of experienced SLED teachers as master teachers to facilitate engineering design-based science instruction during the summer professional development and within SLED schools.

As the teachers integrated various curricular activities grounded in the engineering design process, they merged key science ideas, concepts, and skills with children's use of everyday technology (e.g., simple machines at home and in school), children's ideas of current science issues and topics (e.g., water conservation and purification), and children's abilities to work collaboratively in a social setting modeling the engineer's workplace. When learning is composed of authentic tasks, we hypothesize that there is a greater probability of engagement with the task and also with the information and ideas involved with the tasks.[11,12,13] Authentic engineering learning tasks are more likely to hold the attention and interest of students and lead to deeper levels of engagement than other similar but more traditional (less authentic) classroom tasks.[14] Students will gain new knowledge over time and will share this knowledge among fellow community members to form a productive community of practice.

Participants of the study

The context of this study is a large, multi-year university school partnership that includes the participation of over 200 elementary/intermediate school teachers, 3,000 students, 25 STEM faculty and educational researchers. For the purpose of this study, a sub-sample of ten individual cases (five Grade 5 teachers and 180 students, and five Grade 6 teachers and 224 students) were purposefully selected from the larger population. These cases represented individual classroom teachers and their students who provided consent, completed all research-related activities, and implemented a series of similar engineering design-based science tasks over the course of one year. The teacher participants included eight females and two males. All were White, Caucasian with a range of teaching experience from at least five years to over thirty years (see Table 1). The demographics of the entire sample of student participants included the following: 205 females and 199 males; 246 White/Caucasian (61%); 64 Hispanic or Latino (16%); and 24 Black or African American (6%). The classrooms represented students from grade 5 (46%) and grade 6 (55%) (See Table 2). The demographics in this study aligned reasonably well with the larger U.S. school age population; the national percentage distribution of enrollment in public elementary schools is reported as White/Caucasian (57.8%); African American (17%); and Hispanic (21.1%). [15,16,17]

Table 1. Demographic profile of teacher participants*

Teacher [Pseudonyms]	**School setting**			**Number of years teaching**				
	Urban	**Suburban**	**Rural**	**5 to 10**	**11 to 15**	**16 to 20**	**21 to 30**	**31+**
Grade 5								
Karina	x						x	
Anita	x						x	
Barry	x					x		
Nadia	x							x
Susan		x			x			
Grade 6								
Cassandra	x			x				
Matthew	x			x				
Olive	x						x	
Lauren	x			x				
Helen			x		x			

*Pseudonyms are used to protect the anonymity of the participants.

Table 2. Demographic profile of student participants

Teacher [Pseudonym]	**# of Students**	**Male**	**Female**	**Hispanic or Latino**	**Black or African American**	**Asian**	**White Caucasian**	**American Indian or Alaska Native**	**Native Hawaiian or Other Pacific Islander**	**More than 1 Race Reported**	**Not Reported**
Grade 5											
Karina	44	20	24	11	5	0	23	0	0	4	1
Anita	39	17	22	13	2	0	19	0	0	5	0
Barry	39	17	22	1	1	1	28	1	0	6	1
Nadia	43	25	18	9	4	0	22	0	0	8	0
Susan	15	8	7	2	0	0	11	2	0	0	0
Grade 6											
Cassandra	42	17	25	7	0	0	30	0	0	3	1
Matthew	40	21	19	10	4	0	18	1	0	5	2
Olive	40	20	20	7	5	0	23	1	0	3	1
Lauren	27	14	13	1	0	1	22	0	0	1	2
Helen	75	40	35	3	3	0	50	6	0	12	1

Design tasks

SLED tasks include a series of standards-, engineering design-based science tasks that reinforce one or more key grade level science concepts (See Table 3 for examples): a complete list is available at https://stemedhub.org/groups/sled/design_resources). The design-based tasks were developed by multi-disciplinary teams of STEM faculty, who were recruited to participate in the project and worked in a community of practice with classroom teachers to create standards-based, age-appropriate materials.[21] Each design challenge is viewed as a competition in which technical teams compete, not with each other, but to meet the design specifications (i.e. client's needs, goals, and constraints). A design goal such as, "Can you devise a way to trap a wolf using simple machines?" provides a challenge, dares the students to test their skills and their knowledge, and sees if they can design a prototype of a trap that fulfills all the requirements. Accompanying each challenge are exercises including concept-mapping, journaling through the use of "design notebooks," and oral reporting – designed to help students construct their personal meanings.

Table 3. Examples of Grade 5 and 6 SLED design tasks

Grade Level	***Task***	***Description***	***Core science concept***
5	Prosthetic Limb	Design a model of a prosthetic leg for a young child that can kick a soccer ball.	mass, volume, density, musculoskeletal system
	Water Filter	Design a device to remove as much sediment (dirt) as possible from dirty water in the shortest amount of time.	weight, volume, properties of materials
6	Solar Tracker	Develop a solar panel system that can be easily moved to track the sun in the sky during different times of the day and different seasons.	inclination of the earth, direct and indirect light rays, seasons
	Roller Coaster	Design and construct a roller coaster model that results in the greatest total loop diameter at the lowest cost.	potential and kinetic energy

Data collection and analysis

The research team employed a mixed methods approach, collecting quantitative and qualitative data concurrently throughout the course of the study (Creswell, 2002). What follows is a description of methods and analytic procedures employed for data gathered among both teacher and student participants.

Table 4. Overview of data collection methods

Research questions	**Data collection methods**	
	Qualitative	***Quantitative***
How do elementary school teachers enact engineering design-based science instruction?	Interviews Classroom Observations	
What is the fidelity of teachers' implementation?	SLED Engineering Design-based Classroom Observational Rubric	
What knowledge do students learn when engaging in engineering design-based tasks?		Pre-/post-Knowledge Tests
To what extent does the fidelity of instruction correlate with students' science learning?	SLED Engineering Design-based Classroom Observational Rubric	Pre-/post-Knowledge Tests

Teacher participant data

Interviews. Semi-structured interviews (n=20 total) were conducted at the beginning and end of the school year to identify and characterize teachers' perceptions of engineering design, expectations and reflections of task implementation, and challenges they experienced throughout the year. Analysis and interpretation of teacher interviews involved the use of grounded theory.[18] During this process, members of the research team focused on identifying indicators of concepts and categories that fit the data. Repeatedly appearing categories, concepts, and events helped the research team construct assertions based on the events leading up to the teachers' conceptions of engineering design, plans for integrating engineering design-based tasks, and the actual implementation of engineering design tasks.

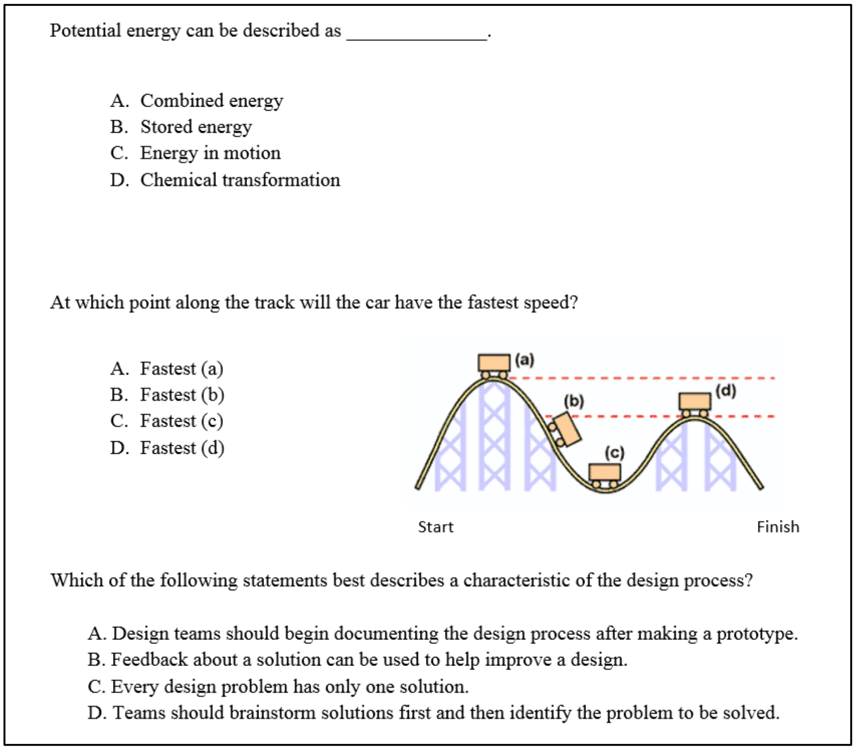
Classroom observations. The aim of classroom observations was to observe and characterize design-informed pedagogical methods employed by SLED teachers. Initially, members of the research team conducted informal classroom observations that included open field notes focusing on the teacher; specifically, his/her instructional practices exhibited during a given lesson. Based on early field notes and a review of existing classroom observational protocols (e.g., RTOP, STAMM, and ATI) and science education reform documents, the research team elected to employ a modified-version of the Inquiring into Science Instruction Observation Protocol (ISIOP) developed by Minner and DeLisi (2012).[20] Members of the research team adapted the ISIOP protocol to address engineering practices as depicted in the NGSS by adding a series of engineering design-based instructional codes.[4, 19, 20] Examples of codes included PROB/DEF indicating that the teacher encouraged students to identify the problem statement and essential features of the design brief; PLAN/IND or PLAN/TEAM indicating individual and team planning, respectively; and CONSTRUCT and TEST representing the creation and testing of a design. Observation data were independently coded and the codes were then compared for agreement. Inter-rater reliability for the observers yielded an inter-reliability of 0.88 for the observation protocol.

Coded observation data (n=200 hours) were then assessed against an analytical rubric having 10 major categories representing the following: (a) a specific phase within the engineering design process as depicted in the SLED's design model and the literature in engineering education, and (b) one or more NGSS engineering practices (See Appendix A).[4] For example, the first phase of the design process is problem identification which is referred to as problem scoping in engineering and this phase aligns well with NGSS Practice 1 – Asking questions and defines features of an engineering problem.[1,22] Each category within the rubric consists of five levels of performance with a 0-, 1-, 2-, 3-, or 4- point value. Four denotes the highest fidelity to the SLED's model for engineering design-based instruction (very descriptive), whereas 0 denotes the lowest, indicating no evidence or occurrence. The mean of each category rather than the total score was reported in order to highlight the findings. Therefore, a 3 or higher was indicative of engineering design-based teaching. Thus, a teacher with a high degree of fidelity to the SLED model would obtain a mean score of 3 or higher, while a teacher with a low degree of fidelity would obtain a score of 2 or lower.

Student participant data

Students' development of content knowledge was assessed using identical pre- and post-instruction tests. The tests, which were developed by the project team, were composed of multiple-choice items that were designed to probe for different levels of comprehension using low, medium, and high cognitive demand items covering both science and engineering content. Each test focused on the specific science and engineering content that was addressed in the corresponding unit design task. Example items from one of the tests are shown in Figure 1. Tests were analyzed for item validity, and an overall Cronbach alpha reliability was calculated based on the post-test administration of the test. In grade 5, the test for the prosthetic limb task consisted of 12 items (9 science and 3 engineering), and it had a Cronbach alpha reliability of 0.56. The test for the water filter task also consisted of 12 items (9 science and 3 engineering), and it had a Cronbach alpha reliability of 0.59. In grade 6, the test for the solar tracker task consisted of 14 items (8 science, 2 math, and 4 engineering), and it had a Cronbach alpha reliability of 0.71. The test for the roller coaster task also consisted of 14 items (11 science and 3 engineering), and it had a Cronbach alpha reliability of 0.68.

The pre-instruction knowledge tests were administered at the beginning of the school year, and the post-instruction knowledge tests were administered within two weeks of the completion of the corresponding design task in the participating classrooms. Raw scores were converted to percentiles, and basic descriptive statistics were calculated for each test by classroom. To determine if students showed significant knowledge gains from pre-test to post-test, paired sample t-tests were used to compare the post-test to the pre-test means within and across teachers. To assess whether there was a relationship between the fidelity of teachers' implementation of the design-based lessons and student performance on the knowledge tests, Pearson product moment correlations were calculated between teachers' mean observational rubric scores and students' scores on the corresponding post-test. All statistical analyses were conducted using SAS 9.4 (SAS Institute, Inc.).



Potential energy can be described as ______________.

A. Combined energy
B. Stored energy
C. Energy in motion
D. Chemical transformation

At which point along the track will the car have the fastest speed?

A. Fastest (a)
B. Fastest (b)
C. Fastest (c)
D. Fastest (d)

Which of the following statements best describes a characteristic of the design process?

A. Design teams should begin documenting the design process after making a prototype.
B. Feedback about a solution can be used to help improve a design.
C. Every design problem has only one solution.
D. Teams should brainstorm solutions first and then identify the problem to be solved.

Figure 1. Example test assessment items (Source: SLED Roller Coaster task)

Triangulation

To determine the consistency of our findings from both the teacher and student data sets, we first reviewed fidelity of implementation results from the teacher's first and second implementations. As noted above, we then correlated the teachers' implementation scores with results from students' performance on the post- instruction tests. To confirm emerging patterns in these correlations, we used teacher interview data and original observation field notes to verify and validate assertions.

Results

Teachers' Enacted Attempts at Engineering Design-Based Instruction

Tables 5 and 6 show a breakdown of the mean scores for the ten key elements within the rubric for the ten teachers' first and second implementations.

Grade 5

The overall mean score or rating for the Grade 5 teachers' first implementation was 2.60. A rating of 2 indicates low fidelity of implementation of the SLED's model for engineering design-based science instruction. The mean score for one teacher, Anita, indicated low fidelity (2.00) while three teachers, Karina, Barry, and Nadia, indicated relatively high fidelity of implementation with mean scores ranging from 2.70 to 3.30. A closer look at the Grade 5 teachers' first implementation scores suggests that the teachers placed more emphasis on identifying the problem and generating both individual and team plans and less emphasis on comparing, communicating, and optimizing performance results.

Classroom observation ratings for engineering design-based instruction were noticeably different in the Grade 5 teachers' second implementation. The overall mean score for teachers' second implementations was 3.10. All five teachers demonstrated growth in mean scores with gains ranging from 0.30 to 0.80. Mean scores for Karina, Barry and Nadia indicated high fidelity of implementation with scores ranging from 3.30 to 3.70, while Anita and Susans' mean scores increased to 2.30 and 2.70, respectively. The scores also indicate increased emphasis on comparing performance results, revising, and improving designs.

Grade 6

The overall mean score for the Grade 6 teachers' first implementation was 2.28. This was lower than the mean score for the Grade 5 teachers' first implementation. The mean score for Cassandra was the highest (2.70) while Matthew and Helen had the lowest mean scores with 2.00 and 2.10, respectively. Like the Grade 5 teachers, the Grade 6 teachers' first implementation scores suggest that the teachers focused primarily on the early phases of the design process, including problem identification and planning.

Results from Grade 6 teachers' second implementation indicated moderate gains in mean scores. The overall mean score for teachers' second implementation was 2.46. Cassandra demonstrated considerable growth with a gain of 0.70 while Olive, Lauren, and Helen demonstrated limited gains and Matthew scored lower in his second implementation. Grade 6 teachers' second implementation scores indicated that more emphasis was placed on team planning, testing, and using data to evaluate the refine design solutions.

Table 5. Mean scores from the Engineering Design-based Classroom Observational Rubric for Grade 5 teachers (n = 5 teachers)

Key Element		First Implementation Mean Score *Prosthetic Limb*					Second Implementation Mean Score *Water Filter*				
		Karina	Anita	Barry	Nadia	Susan	Karina	Anita	Barry	Nadia	Susan
1	Ask questions and define features of an engineering problem (i.e., criteria, constraints, goal, end user, client and client's needs)	4.00	1.00	3.00	3.00	4.00	4.00	2.00	4.00	4.00	4.00
2	Express individual ideas in writing using models or drawings.	2.00	2.00	3.00	2.00	1.00	3.00	2.00	4.00	3.00	2.00
3	Share individual ideas orally and express group ideas in writing.	2.00	2.00	3.00	2.00	3.00	2.00	3.00	4.00	3.00	3.00
4	Collaborate with one or more peers throughout the design process for the selection of the most promising solution.	3.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00	3.00	3.00
5	Use of and access to a range of tools and manipulatives to construct and test a promising solution.	2.00	2.00	3.00	3.00	3.00	4.00	2.00	4.00	3.00	3.00
6	Collaboratively develop a model using an analogy, example, or abstract representation to describe a design solution that aligns with essential features of the engineering problem.	3.00	2.00	4.00	3.00	3.00	3.00	2.00	4.00	4.00	3.00
7	Test proposed solution of a design. Use data and scientific concepts to evaluate and refine design solutions.	3.00	2.00	4.00	3.00	2.00	4.00	2.00	4.00	4.00	3.00
8	Communicate clearly and persuasively the ideas, final design solutions, and related performance results using relevant evidence about how it meets the criteria and constraints of the problem.	4.00	2.00	3.00	3.00	2.00	4.00	2.00	3.00	3.00	2.00
9	Compare performance results, revise, and improve designs.	1.00	2.00	4.00	2.00	0.00	2.00	3.00	3.00	4.00	2.00
10	Teacher as facilitator	3.00	2.00	3.00	3.00	2.00	4.00	2.00	3.00	4.00	2.00
Overall mean		***2.70***	***2.00***	***3.30***	***2.70***	***2.30***	***3.30***	***2.30***	***3.70***	***3.50***	***2.70***

Table 6. Mean scores from the Engineering Design-based Classroom Observational Rubric for Grade 6 teachers (n = 5 teachers)

Key Element		First Implementation Mean Score *Solar Tracker*					Second Implementation Mean Score *Roller Coaster*				
		Cassandra	Matthew	Olive	Lauren	Helen	Cassandra	Matthew	Olive	Lauren	Helen
1	Ask questions and define features of an engineering problem (i.e., criteria, constraints, goal, end user, client and client's needs)	3.00	2.00	2.00	3.00	3.00	4.00	1.00	2.00	3.00	4.00
2	Express individual ideas in writing using models or drawings.	4.00	2.00	2.00	3.00	2.00	3.00	2.00	2.00	4.00	2.00
3	Share individual ideas orally and express group ideas in writing.	4.00	2.00	2.00	2.00	2.00	3.00	2.00	3.00	4.00	2.00
4	Collaborate with one or more peers throughout the design process for the selection of the most promising solution.	4.00	2.00	3.00	3.00	3.00	4.00	1.00	2.00	3.00	3.00
5	Use of and access to a range of tools and manipulatives to construct and test a promising solution.	3.00	3.00	3.00	3.00	2.00	3.00	2.00	3.00	4.00	3.00
6	Collaboratively develop a model using an analogy, example, or abstract representation to describe a design solution that aligns with essential features of the engineering problem.	3.00	2.00	3.00	3.00	3.00	4.00	2.00	2.00	4.00	3.00
7	Test proposed solution of a design. Use data and scientific concepts to evaluate and refine design solutions.	2.00	3.00	2.00	2.00	2.00	4.00	2.00	3.00	2.00	2.00
8	Communicate clearly and persuasively the ideas, final design solutions, and related performance results using relevant evidence about how it meets the criteria and constraints of the problem.	1.00	3.00	3.00	3.00	2.00	3.00	1.00	3.00	2.00	1.00
9	Compare performance results, revise, and improve designs.	0.00	0.00	0.00	0.00	0.00	3.00	1.00	0.00	0.00	0.00
10	Teacher as facilitator	3.00	1.00	2.00	2.00	2.00	3.00	1.00	3.00	3.00	2.00
	Overall mean	***2.70***	***2.00***	***2.20***	***2.40***	***2.10***	***3.40***	***1.50***	***2.30***	***2.90***	***2.20***

Assessment of Students' Content Knowledge

Tables 7 through 10 show a breakdown of the students' mean scores on the pre- and post-knowledge tests for the two engineering design activities that were implemented at each grade level. Tables 7 and 8 show the results for grade 5 students, and tables 9 and 10 show the results for grade 6 students.

Table 7 shows the knowledge test results for the Prosthetic Limb task. Across all grade 5 teachers, on average, students scored about 52% on the pre-test and about 68% on the post-test, a gain of about 16%. This gain was statistically significant ($t = 10.93$, $p < .0001$), which suggests that the grade 5 students developed their understanding of content knowledge related to scientific and engineering concepts as a result of their participation in the design-based lesson. In examining the gains across different teachers' classrooms, variability in student performance is apparent. While students across all classes improved from pre-test to post-test, gains within particular teachers' classrooms varied from a low of 4.63% (Anita) to a high of 27.78% (Nadia). Paired samples t-tests indicated that the gains for the students in the classes of Karina, Barry, and Nadia were statistically significant, while the gains for students in the classes of Anita and Susan were not statistically significant. (Note: the relatively low number of students in Susan's class may have contributed to the lack of significance.)

Table 8 shows the knowledge test results for the Water Filter task. The findings are similar to those for the Prosthetic Limb task. Across all grade 5 teachers, on average, students scored about 58% on the pre-test and about 69% on the post-test, a gain of about 11%, which was statistically significant ($t = 8.08$, $p < .0001$). Gains within particular teachers' classrooms varied from a low of 3.05% (Susan) to a high of 21.37% (Nadia). Statistical tests indicated that the gains for the students in the classes of Karina, Barry, and Nadia were statistically significant, while the gains for students in the classes of Anita and Susan were not statistically significant.

Table 9 shows the knowledge test results for the solar tracker task. Across all grade 6 teachers, on average, students scored about 68% on the pre-test and about 78% on the post-test, a gain of about 10%. This gain was statistically significant ($t = 8.35$, $p < .0001$), which suggests that the grade 6 students also developed their understanding of content knowledge related to scientific and engineering concepts as a result of their participation in the design-based lesson. Variability in student performance again was apparent across teachers, although these results were less variable than those of the grade 5 classrooms. Gains within particular teachers' classrooms varied from a low of 6.38% (Olive) to a high of 12.60% (Lauren). Paired samples t-tests indicated that the gains for the students in all of the classes were statistically significant, except for those in Olive's class, which approached significance at the $p = .05$ level.

Table 10 shows the knowledge test results for the roller coaster task. Across all teachers, on average, students scored about 52% on the pre-test and about 67% on the post-test, a gain of about 15%, which was statistically significant ($t = 11.29$, $p < .0001$). These results showed some variability across teachers' classes; gains varied from a low of 13.16% (Olive) to a high of 20.82% (Matthew). Statistical tests indicated that the gains for the students in all of the classes were statistically significant. So, there was uniformly better performance across classes for this particular task.

Overall, the results suggest that students developed their understanding of content knowledge related to scientific and engineering concepts as a result of their participation in the design-based lessons. Pre-test to post-test performance of students showed increases across all tasks. However, for several of the tasks, there was variability in student performance by teacher. This observed variation in student performance may relate to the fidelity with which teachers implemented the lessons.

Table 7. Students' Pre- and Post-instruction Knowledge Test Scores by Grade 5 Teacher for Prosthetic Limb Task

Teacher	**n**	**Pre-test Mean**	**Pre-test SD**	**Post-test Mean**	**Post-test SD**	**Gain**	**t**	**Prob (t)**
Karina	42	49.21	15.04	63.89	19.71	14.68	5.86	< .0001
Anita	36	53.24	15.21	57.87	15.43	4.63	1.58	0.1220
Barry	35	64.59	13.99	81.18	9.12	16.66	6.97	< .0001
Nadia	39	43.80	15.26	71.58	13.34	27.78	10.74	< .0001
Susan	14	56.54	24.72	66.66	9.25	10.13	1.64	0.1256
Overall	166	52.74	17.34	68.27	16.69	15.61	10.93	< .0001

Table 8. Students' Pre- and Post-instruction Knowledge Test Scores by Grade 5 Teacher for Water Filter Task

Teacher	**n**	**Pre-test Mean**	**Pre-test SD**	**Post-test Mean**	**Post-test SD**	**Gain**	**t**	**Prob (t)**
Karina	43	53.09	17.54	63.96	16.74	10.86	5.16	< .0001
Anita	32	64.21	15.02	69.01	15.43	4.17	1.35	0.1869
Barry	36	73.38	12.25	81.71	9.72	8.33	3.16	0.0032
Nadia	39	44.45	15.22	65.82	16.09	21.37	7.91	< .0001
Susan	11	61.34	24.52	64.40	22.69	3.05	0.51	0.6204
Overall	161	58.38	19.01	69.41	16.76	10.98	8.08	< .0001

Table 9. Students' Pre- and Post-instruction Knowledge Test Scores by Grade 6 Teacher for Solar Tracker Task

Teacher	**n**	**Pre-test Mean**	**Pre-test SD**	**Post-test Mean**	**Post-test SD**	**Gain**	**t**	**Prob (t)**
Cassandra	35	81.23	11.89	90.83	8.24	9.60	5.06	< .0001
Matthew	11	63.64	14.45	74.68	12.11	11.04	3.56	0.0052
Olive	28	69.13	16.74	75.51	17.11	6.38	1.95	0.0616
Lauren	25	71.14	14.51	83.73	13.92	12.60	4.58	0.0001
Helen	57	58.65	19.32	70.06	19.06	11.41	4.81	< .0001
Overall	156	67.95	18.32	78.22	17.44	10.26	8.35	< .0001

Table 10. Students' Pre- and Post-instruction Knowledge Test Scores by Grade 6 Teacher for Roller Coaster Task

Teacher	**n**	**Pre-test Mean**	**Pre-test SD**	**Post-test Mean**	**Post-test SD**	**Gain**	**t**	**Prob (t)**
Cassandra	34	58.19	13.63	75.16	7.52	16.97	6.59	< .0001
Matthew	13	41.22	17.77	62.04	13.78	20.82	5.01	0.0003
Olive	33	53.47	15.87	66.62	17.00	13.16	4.51	< .0001
Lauren	23	63.03	16.91	77.90	10.10	14.87	4.31	0.0003
Helen	65	46.70	16.75	60.06	18.25	13.36	5.76	< .0001
Overall	168	52.17	17.26	67.00	16.49	14.83	11.29	< .0001

Relationship of Teacher Implementation to Student Performance

To assess whether there was a relationship between teachers' implementation of the design-based lessons and subsequent student performance, Pearson product moment correlations were calculated between the overall mean scores on the teachers' observational rubric instrument, which measured the degree to which teachers' lesson implementations showed evidence of the engineering design practices encouraged by the project, and students' scores on the content knowledge post-tests for each design task. The results are shown in Table 11 (for grade 5 tasks) and Table 12 (for grade 6 tasks).

The results indicate that there were small to moderate positive correlations between teachers' implementation rubric scores and students' knowledge post-test scores in both grades 5 and 6. These correlations ranged from a low of r = 0.14254 (for the relationship of teachers' Water Filter implementation scores and students' Water Filter post-test scores) to a high of r = 0.45466 (for the relationship of teachers' Solar Tracker implementation scores and students' Solar Tracker post-test scores). These results indicate that there was a relationship between teachers' implementation of the design-based lessons and subsequent student performance. Students who were in the classrooms of teachers who had higher scores on the lesson implementation rubric had higher scores on the content knowledge post-tests. Of course, correlation does not imply causation, but these results suggest that how the teachers implemented the design-based lessons had an impact on their students' subsequent learning performance.

Table 11. Correlations of Grade 5 Teachers' Average Rubric Scores with Student Post-test Scores

Grade Level Rubric Score	**Student Prosthetic Limb Post-test Score**	**Student Water Filter Post-test Score**
Grade 5 Teacher Rubric Score for Prosthetic Limb Task	r = 0.44778 p < .0001 n = 166	r = 0.25445 p = 0.0011 n = 161
Grade 5 Teacher Rubric Score for Water Filter Task	r = 0.41282 p < .0001 n = 166	r = 0.14254 p = 0.0713 n = 161

Table 12. Correlations of Grade 6 Teachers' Average Rubric Scores with Student Post-test Scores

Grade Level Rubric Score	**Student Solar Tracker Post-test Score**	**Student Roller Coaster Post-test Score**
Grade 6 Teacher Rubric Score for Solar Tracker Task	r = 0.45466 p < .0001 n = 156	r = 0.37284 p < .0001 n = 168
Grade 6 Teacher Rubric Score for Roller Coaster Task	r = 0.42407 p < .0001 n = 156	r = 0.36167 p < .0001 n = 168

Discussion

The results from teachers' enactments of engineering design-based science instruction suggest relatively high fidelity of the SLED model for design for Grade 5 teachers and somewhat lower fidelity for Grade 6 teachers. Results from first to second implementations also suggested that both Grade 5 and 6 teachers initially focused on the early phases of the design process including problem identification and planning. By the second implementation, teachers focused more on testing, comparing test results, and improving designs. Correlations between teachers' implementations and student performance on the associated knowledge tests indicated that how teachers implemented the respective design tasks had an impact on students' learning of the relevant science and engineering knowledge.

From the situated learning perspective, teachers developed a shared repertoire of curriculum resources, classroom experiences, and best practices for engineering design-based science learning and teaching.[8] We conclude that all SLED teachers engaged in the process of becoming active participants in the community with some teachers developing a higher level of proficiency or expertise (high fidelity) than other teachers. Consequently, their students demonstrated competency as well. As learners, the teachers and their students inevitably participated in the SLED community of practice and their mastery of knowledge and skill is evidenced by their full participation in the engineering design-based learning and teaching activities.

There are several possible explanations that can account for the disparity in the fidelity of implementation among the elementary school teachers profiled in this study. First, the nature of the design task must be considered. Design tasks, such as Water Filter and Prosthetic Limb, allowed for more opportunities for students to manipulate materials, construct prototypes, and gather data from testing. Other tasks, such as Roller Coaster and Solar Tracker, involved more time on constructing and creating design artifacts and limited the amount of data collected from testing. Hence, the teachers' scores reflected emphasis on some design phases versus other phases based on the type of task. We did not anticipate, nor did the data reveal, high fidelity across all phases of the design process and across all teachers. Consistent mean scores for one or more teachers suggest a level of expertise and/or comfort with using design-based instructional strategies.

The results from the student knowledge assessments suggest that students learned science and engineering content as a result of participating in all of these design tasks. When looking at student performance across all classes, we observed significant gains in students' scores from pre-test to post-test, showing that students were learning as a result of engagement in these design-oriented lessons. However, we also observed variations in student performance by teacher for most of the design activities. To determine if these variations might relate to the observed variations in fidelity of implementations, we correlated teachers' implementation rubric scores with students' knowledge post-test scores. Indeed, we observed positive and, in most cases, statistically significant relationships. These results indicate that students' performance was related to the fidelity of teachers' implementation. Students in the classrooms of teachers who demonstrated higher fidelity of implementation performed better on the knowledge tests. This suggests that the effectiveness of an engineering design-based approach to science learning is dependent, at least to some degree, on how well the teacher enacts the tenets of a design-based approach. While perhaps not a surprise, these results confirm the importance of what the teacher does in the classroom.

Conclusion and implications

The purpose of this study was to examine teachers' attempts at integrating engineering design-based science instruction and the impact their instruction had on students' learning. Results from this study suggest that how teachers integrate engineering design-based pedagogies influences how students' construct new knowledge.

There are several limitations to this study. One limitation was the design of the study. Missing from this study was a carefully matched or randomly assigned control group, allowing the research team to conduct secondary analysis and correlations relative students' performance on instructional knowledge tests. Another limitation is the sample size, in particular the class size across multiple classrooms. The class sizes for the total sample ranged from 15 to 75 students for each respective teacher. The last limitation includes demographics of the students as learners. We can only speculate that some of teachers may have had more homogeneous classes than other teachers' classrooms or perhaps a higher or lower representation of high performing students.

Implications of this study suggest that there is fertile ground for studying the integration of engineering practices in the elementary science classroom. Consideration must be given to strategically examining how elementary school students engage in design and apply core disciplinary concepts. To what extent do students utilize and connect science concepts to develop and test their designs and how enduring are these concepts? Attention must also be given to how teachers orient their existing science teaching practices to engineering design? How do they mediate their existing teaching strategies with relatively new pedagogies? What does teacher expertise in engineering design-based science instruction look like and how does this impact student learning? From these studies we can learn more about the different ways elementary school teachers and their students engage in and learn from new reform efforts in engineering education.

References

[1] Next Generation Lead States. (2013). *Next Generation Science Standards*. National Academies Press: Washington DC.

[2] National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: National Academies Press.

[3] Capobianco, B., Lehman, J., & Kelley, T. (2015, April). Learning to teach elementary school science through engineering design. A paper presentation at the American Educational Research Association Annual Meeting, Chicago, IL.

[4] Capobianco, B. M., & Rupp, M. (2014). STEM teachers' planned and enacted attempts at implementing engineering design-based instruction. *School Science and Mathematics, 114*(6), 258-270.

[5] Sargianis, K., Yang, S., & Cunningham, C. (2012). Effective engineering professional development for elementary educators. A paper presented at the Annual Meeting for the American Society of Engineering Education, San Antonio, TX. Retrieved from https://peer.asee.org/effective-engineering-professional-development-for-elementary-educators

[6] Yasar, S., Baker, D., Robinson-Kurpius, S., Krause, S., & Roberts, C. (2006). Development of a survey to assess K-12 teachers' perceptions of engineers and familiarity with teaching design, engineering, and technology. *Journal of Engineering Education, 95* (3), 205-216.

[7] Yoon, S., Dyehouse, M., Lucietto, Diefes-Dux, H., & Capobianco, B. M. (2014). The effects of integrated science, technology, and engineering education on elementary students' knowledge and identity development. *School Science and Mathematics, 114* (8), 380-391.

[8] Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation.* Cambridge, England: Cambridge University Press.

[9] Cochran-Smith, M., & Lytle, S. (1999). Relationships of knowledge and practice: Teacher learning in communities. *Review of Research in Education, 24,* 249-305.

[10] Vescio, V., Ross, D., & Adams, A. (2008). A review of research on the impact of professional learning communities on teaching practice and student learning. *Teaching and Teacher Education, 24,* 80-91.

[11] Fortus, D., Dershimer, C., Krajcik, J., Marx, R., & Mamlok-Naaman, R. (2004). Design-based science and student learning. *Journal of Research in Science Teaching, 41*(10), 1081-1110.

[12] Roth, M. W. (1996). Art and artifact of children's designing: A situated cognition perspective. *The Journal of the Learning Sciences, 5,* 61-94.

[13] Roth, M. W. (1997). Interactional structures during a Grade 4-5 open-design engineering unit. *Journal of Research in Science Teaching, 34*(3), 273-302.

[14] Roth, W. M. (1998). *Designing communities*. Dordecht, The Netherlands. Kluwer.

[15] Sable, J., & Noel, A. (2013). *Public Elementary and Secondary School Student Enrollment and Staff from the Common Core of Data: School Year 2012-13* (NCES 2013-305). National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education. Washington, DC.

[16] U.S. Census Bureau. (2014). *School Enrollment--Social and Economic Characteristics of Students: October 2014.* Retrieved December 12, 2015, from the U.S. Census Bureau: http://www.census.gov/hhes/school/data/cps/2014/tables.html

[17] U.S. Department of Education Institute of Education Sciences. (2015). *Digest of Education Statistics, 2015.* Retrieved December 12, 2015, from the U.S. Department of Education: http://nces.ed.gov/programs/digest/2015menu_tables.asp

[18] Strauss, A., & Corbin, J. (1998). *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*. Thousand Oaks, CA: Sage.

[19] DeLisi, J., McNeill, K., & Minner, D. (2011). Illuminating the relationship between inquiry science instruction and student learning: Results from three case studies. A paper presentation at the annual meeting of the National Association of Research for Science Teaching.

[20] Minner, D., & DeLisi, J. (2010). Inquiring into science instruction observation protocol (ISIOP) Grades 9-12. Newton, MA: Education Development Center.

[21] Lehman, J. D., Kim, W., & Harris, C. (2014). Collaborations in a community of practice working to integrate engineering design in elementary science education. *Journal of STEM Education: Innovations and Research*, *15*(3), 21-28.

[22] Atman, C., Adams, R., Cardella, M., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education, 96*(4), 359-379.

APPENDIX A
Engineering Design-based Classroom Observational Rubric

Source: Capobianco, B. M., & Rupp, M. (2014). STEM teachers' planned and enacted attempts at implementing engineering design-based instruction. *School Science and Mathematics, 114*(6), 258-270.

Key elements		***0***	***1***	***2***	***3***	***4***	***Not observed***	***Score***
		Never occurred	←			→ ***Very descriptive***		
1	**Ask questions and define features of an engineering problem (i.e., criteria, constraints, goal, end user, client and client's needs).**	Teacher does not address nor discuss the essential features of the design brief.	Teacher verbalizes the essential features of the design brief to students. Entails a lot of teacher-directed instruction.	Teacher instructs students to identify or recall some of the essential features. Students are guided or coached through the protocol.	Teacher encourages students to identify or recall most of the essential features. Students need guidance and direction.	Teacher encourages students to identify or recall and record the problem statement, client, end user, criteria, constraints, and goal. Students appear self-directed and familiar with the protocol.		
2	**Express individual ideas in writing using models or drawings.**	Teacher does not allocate time for individual planning. Students do not express individual ideas.	Teacher provides a refined solution to individual students. Students are given possible solutions.	Teacher provides guidance or encouragement for students to develop individual solutions. Students are guided or coached through individual planning.	Teacher encourages students to generate and express practical, individual solutions that align with most of the essential features. Students require guidance and direction.	Teacher focuses students on developing individual feasible and detailed solutions that align with the goals, client's needs, criteria, and constraints. Students appear self-directed and cooperative.		
3	**Share individual ideas orally and express group ideas in writing.**	Teacher does not allocate time for team planning.	Teacher provides a refined solution to all student teams. Student teams are given refined solutions.	Teacher provides guidance or encouragement for students to negotiate and decide on one solution.	Teacher encourages student teams to develop one feasible solution that aligns with most of the essential features of the task. Student teams seek guidance from the teacher.	Teacher encourages teams to negotiate and decide on one feasible solution that aligns with the goals, client's needs, criteria, and constraints. Teacher and/or students encourage input from all team members. Group consensus is achieved by most teams.		
4	**Collaborate with one or more peers throughout the design process for the selection of the most promising solution.**	Students work individually or work independently in a team.	Teamwork is occasionally incorporated into the design lesson.	Teamwork is partially incorporated into the design lesson. Less than half of the student teams work as a unit; share ideas; or complete the task. There is little to no negotiation or compromise among team members.	Teamwork is frequently incorporated into the design lesson. The majority of student teams attempt to work as a unit; share some ideas; partially complete the task. There is some level of negotiation and compromise among team members.	Teamwork is incorporated throughout the design lesson. Student teams are high functioning; share and negotiate ideas equitably; share responsibilities; and complete the task.		
5	**Use of and access to a range of tools and manipulatives to construct and test a promising solution.**	Teacher does not allocate time for students to manipulate materials or tools.	Teacher limits the range of materials, tools, and the amount of time necessary to complete the task.	Teacher limits access to the materials and tools during individual or team planning. Teacher demonstrates the use of materials or tools with little to no student manipulation of materials or tools.	Teacher provides access to a range of materials and tools during individual/ team planning or construction. Students manipulate materials or tools.	Teacher provides multiple opportunities for students to observe, handle, or test out a range of materials and tools throughout planning and construction. Students use materials and tools to inform their design solutions.		

6	**Collaboratively develop a model using an analogy, example, or abstract representation to describe a design solution that aligns with essential features of the engineering problem.**	Creation of a design is incomplete.	Creation of a design is disorganized; unclear; and does not meet the client’s needs or constraints.	Creation of a design is somewhat disorganized; aspects of the design do not align with the design plans, client’s needs, or constraints. Teacher-student interactions are initiated and directed primarily by the teacher.	Creation of a design is somewhat organized; some aspects of the design align with the design plans; and meets some of the client’s needs and constraints. Teacher-student interactions are infrequent.	Creation of a design is organized, aligns with design plans, and meets the client’s needs and constraints. Teacher -student interactions are frequent and constructive.		
7	**Test proposed solution of a design. Use data and scientific concepts to evaluate and refine design solutions.**	Student teams do not conduct testing, evaluation or analysis of solutions.	Student teams conduct limited testing, evaluation, and analysis of solution performance.	Student teams conduct testing, evaluation, and analysis of solution performance.	Student teams test their solutions, collect and display data, and discuss overall results.	Teacher is focused on encouraging student teams to test their solutions, collect and analyze data, and explain the relationship between results and overall performance.		
8	**Communicate clearly and persuasively the ideas, final design solutions, and related performance results using relevant evidence about how it meets the criteria and constraints of the problem.**	Teacher does not facilitate opportunities for students to review, reflect or communicate performance results.	Teacher limits opportunities for students to review, reflect, and communicate performance results.	Teacher fosters communication of original ideas; final design; and performance results.	Teacher fosters communication of original ideas, final design, and performance results. Teacher encourages students to evaluate their designs based on what worked and what did not work with no reference to meeting the original goal, client’s needs, and constraints.	Teacher fosters clear and persuasive communication of original ideas, final design, and performance results; and elaborates on how designs met the goal, client’s needs, and constraints. Teacher explicitly encourages students to consider improvements to designs.		
9	**Compare performance results and revise and improve designs.**	Teacher does not encourage students to re-design.	Teacher limits opportunities for student to re-design, re-test or improve on the overall performance of the design.	Teacher encourages teams to improve and retest with minimal guidance. Teacher does emphasize a record of the revised solution, re-testing, or evaluation.	Teacher encourages teams to re-design one feature of the team’s design and record a revised solution. Teacher limits opportunity to re-test and evaluate the performance. The re-design does not make the solution better; however, it represents a plausible attempt.	Teacher encourages teams to re-design one or more feature(s) of the team’s design and record a revised solution. Students re-test and evaluate the performance. The re-design may make the solution better.		
10	**Teacher as facilitator**	Teacher-student interactions throughout the design lesson are absent.	Teacher is directive or prescriptive in teaching engineering design practices. Teacher-student interactions are minimal.	Teacher occasionally guides students by listening, observing, and questioning students. Responses are primarily teacher-directed or initiated.	Teacher guides students by listening, observing, and questioning students. Responses emerge from students’ ideas or questions. Teacher attempts to refocus students to essential elements of the design task.	Teacher guides students by listening, observing, and questioning students. Teacher builds the lesson around students’ ideas and questions while continually refocusing students to the essential elements of the design task.		