Leveraging Simple Problems to Introduce Engineering Principles and Ways of Thinking

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ABSTRACT

This study sought to test the merits of "engineering simple things in sophisticated ways" under the auspices of integrated STEM education. The inquiry employed pre- and post-assessments to gauge students' conceptions of engineering, the work that engineers do, and the nature of engineering design. It also included an analysis of classroom observations, teacher testimony, and students' work in the interest of triangulation. The findings suggest the nature of engineering can be portrayed with surprising richness with an extremely simple problem. More specifically, they suggest engineering a simple object in a rich manner can weaken the misconception that engineers fix things, increase student awareness of design in engineering endeavors, and enable students to recognize the importance of testing in the design process. Lastly, an emphasis on reverse engineering and redesigning a simple object within a few lessons can capture and retain student interest.

Keywords: STEM, Conference Proceedings, Engineering Education

INTRODUCTION

The study of science, technology, engineering and mathematics, commonly referred to as STEM education, has become a pervasive topic in education journals, conferences, and legislation. It has been the impetus for establishing charter schools, launching curriculum projects, and funding new initiatives. It is a fashionable catch phrase for marketing everything from instructional materials to textbooks and computer software to laboratory equipment. It has become a popular subject for keynote addresses, graduate courses, and professional development workshops. Much of the discourse portrays STEM as four discrete disciplines that warrant additional attention in response to the rapid pace of science and technology developments, the imminent growth in global competition, the demands of economic development, and a perceived shortage of domestically trained scientists and engineers. An alternative view espouses the potential for synergy among the STEM disciplines (Sanders, 2009). Unfortunately, the study of technology and engineering are not as prominent as science and mathematics in the public school curriculum. The following narrative will present the results of a modest line of inquiry that examined the potential roles that reverse engineering everyday objects and engineering simple things could play in STEM education.

PROBLEM

Numerous curriculum initiatives have addressed engineering principles and ways of thinking for elementary and secondary education (Welty, 2008). The National Academy of Engineering commissioned a descriptive study of K-12 engineering education in the United States. The goal of this study was to gather and present information about the approaches used to introduce the study of engineering to our nation's young people. More specifically, it examined the mission, goals, content, and learning activities of prominent curricula to characterize their treatment of engineering concepts, such as design, analysis, modeling, systems, and constraints; and the inclusion of mathematics, science, and technology. The findings suggest the potential of studying engineering in K-12 education has not been fully realized (Katehi, Pearson & Feder, 2009; Welty, 2008).

One of the lessons learned during the curriculum review process is the development of STEM materials is often driven by considerations other than engineering education. Some of the materials are all about engaging students in more scientific inquiry. Others are all about engaging students in problem solving for the sake of problem solving. Still others are about teaching technology as a subject. Very few are genuinely dedicated to teaching young people about the nature of engineering and its contributions to civilization and the human condition.

Conventional wisdom suggests the study of engineering should start with simple topics and progress to more sophisticated ones as students accumulate knowledge and skill. Furthermore, the complexity of the engineering tasks associated with these topics would also evolve as students gain know-how. A review of prominent STEM curricula will uncover a wide range of approaches to the study of engineering. Many engage students in engineering relatively sophisticated things in rather simplistic ways. For example, *Engineering the Future* by the Museum of Science, Boston (2008) challenges students to address the problem of urban sprawl by designing a building that provides housing while fulfilling at least one other function (e.g., offices space, retail stores, manufacturing facilities). Addressing this problem in an authentic manner is extremely complex. The amount of domain knowledge required to compose a modest proposal for a new building is far beyond the scope of a simple unit of instruction. In an effort to make the problem more manageable the authors focus on heat loss. Despite their efforts to narrow the problem, calculating the heating requirements of a multi-function building involves numerous variables that warrant attention (e.g., insulation systems and materials, thermal conductivity of building materials, interior and exterior air films, infiltration rates, size and composition of windows and doors, projected air changes per hour, solar orientation, design temperature, foundation systems, the thermal conductivity of soil at various depths, sources of heat other than climate control systems). Calculating heat loss for a building, especially one that is being designed to address more than one purpose, is far more complex than figuring heat loss for a small-insulated box. Thus, the learning activity asks students to engineer a rather sophisticated system in a relatively simple way. In fairness to the curriculum in question, it appears the authors only tried to provide students a sampling of the work that engineers do.

Infusing real engineering problems and practices into the curriculum under the auspices of STEM tends to be more complicated and problematic than first envisioned. To make engineering ways of thinking accessible to students, the *Design and Discovery* curriculum by the Intel Corporation (2004) poses the challenge of designing a new paper clip. The subtle complexities of this problem include the strength, malleability, and elasticity of different metals, the holding power of various geometric shapes, and the grip of different configurations relative to the thickness of paper being bound. However, the curriculum only scratches the surface of how a simple problem can be leveraged to illuminate the nature of engineering. For example, students can use mathematical reasoning to confront the tradeoffs associated with the holding power of different designs relative to the cost of the wire, the amount of wire used, and the number of bends in the manufacturing process.

The merit of "engineering simple things in sophisticated ways" needs to be explored in more detail. Therefore, the purpose of this pilot study was to explore how a relatively simple problem, like designing a better paperclip, can be leveraged to engage students in engineering design and engineering ways of thinking. More specifically, the following study sought to address the following questions: (1) To what extent can a simple engineering design problem affect middle school students' conceptions of engineering? (2) To what extent will middle school students engage in guided inquiry in the context of a simple problem? (3) To what extent will a simple engineering design problem retain the attention of middle school students?

METHODOLOGY

The authors partnered with a rural school district in Wisconsin to test the merits of "engineering simple things in sophisticated ways" under the auspices of integrated STEM education. The population for this pilot study was seventh and eighth grade students enrolled at Spring Valley Middle School (N = 110). The sample was 18 eighth graders and 19 seventh graders enrolled in technology education classes during the second trimester. The sample featured 13 females and 24 males. The courses in question are required classes and the sample was representative of the middle school population.

This inquiry used a single group pretest-posttest design. It also included classroom observations, teacher testimony, and an analysis of students' work in the interest of triangulation. The pre- and post-assessments used an interview schedule featuring a series of open-ended questions that were designed to gather information about the students' conceptions of engineering. More specifically, they were asked what the word engineering means to them, what they think engineers do, what engineers think about, what makes something a good design, and how many ideas lead up to one that will work the best.

The questions were projected onto a smart board at the front of the classroom and read out loud to each class. The students recorded their answers on index cards to make handling the data easier during the coding process. All of the data was in the form of simple sentences and short statements written by the students in their own words. The researchers reviewed the students responses to each question, identified the salient themes embedded in each response, coded the themes based on their similarity with other students response, and determined their frequency before and after the treatment. Given the size of the sample, a Fisher's exact test was used to determine if the differences between the pre- and post-assessment were statistically significant.

The treatment took the form of a series of tasks that utilized guided inquiry to engage students in reverse engineering and engineering design activities. For the purpose of this study, the guided inquiry involved giving students a specific problem to address along with procedures for addressing the problem without disclosing any outcomes. The procedures and questions engaged students in a set of predetermined investigations that were designed to uncover variables, as well as relationships between variables, that could be used to inform the solution to the problem posed. In this case, students were challenged to design a better paperclip. Under the auspices of reverse engineering they examined the basic features of a common paperclip, tested its holding power relative to different quantities of paper, determined the amount of contact made by the paperclip relative to different quantities of paper, and measured the strength, elasticity, and fatigue of the wire used to manufacture common paperclips. The reverse engineering process culminated with drawing conclusions about the performance and limitation of common paperclips.

Under the auspices of engineering design, the students were asked to define a problem with the common paperclip that they would like to address. They were also asked to specify the requirements that need to be met in order to solve the problem they identified. Subsequent design processes included generating alternative designs; evaluating alternative designs based on form, function, simplicity, and cost; testing and selecting best material for their new paperclip; making and testing a prototype; and lastly, reflecting on the design process.

FINDINGS

During the pre- and post-assessments students were told, "The word engineering means different things to different people." They were then asked, "What does the word engineering mean to you?" Their responses suggest middle school students associated the word engineering with a variety of salient themes (see Table 1). The most prominent themes were building, making, designing, creating, and inventing. The most notable difference between the pre-assessment and the post-assessment was an increase in the number of references to designing, creating, and inventing. Another noteworthy addition was the number of students that recognized redesigning things and improving things were engineering endeavors. However, these modest gains were not statistically significant.

Table 1: Perceptions regarding the meaning of Engineering

	Seventh Grade (n = 19)		Eighth Grade (n = 18)	
Salient Themes	Pre-assessment	Post-assessment	Pre-assessment	Post-assessment
Building or making things	10 (53%)	9 (47%)	9 (50%)	8 (44%)
Designing, creating, or inventing things	4 (21%)	9 (47%)	4 (22%)	8 (44%)
Doing something with machines or engines	3 (16%)	2 (11%)	5 (28%)	1 (6%)
Developing new ideas	1 (5%)	2 (11%)	4 (22%)	6 (33%)
Testing ideas, models, or things		2 (11%)	2 (11%)	2 (11%)
Redesigning and improving things		3 (16%)	1 (6%)	4 (22%)
Fixing things	1 (5%)	2 (11%)	3 (17%)	1 (6%)
Building, making, or fixing cars	3 (16%)		2 (11%)	1 (6%)

Note: The pre-assessment also rendered one or two references to "working," technology," "making things out of metal," using computers," "making money," "leading," "learning something," and "running something."

Students were also told, "Jobs can be described with simple words." The idea "teachers plan, teach, supervise, and grade" was provided as an example. They were then asked, "What words do you think describe what engineers do?" Once again, the students provided a wide array of ideas that included words like build, create, design, fix, plan, and test (see Table 2).

Furthermore, the number of student that used the word “design” to describe the work of engineers increased significantly from four to 12 ($p < 0.05$). Similarly, the number of students that included “testing” in their description rose significantly from one incident to 11 ($p < 0.025$). Lastly, the number of students reporting engineers “fix” things dropped significantly from 16 to four ($p < 0.025$). This finding suggests the design activity helped dispel the misconception that engineers repair things.

Table 2: Perceptions of What Engineers Do

Prominent Words	Seventh Grade (n = 19)		Eighth Grade (n = 18)	
	Pre-assessment	Post-assessment	Pre-assessment	Post-assessment
Build	9 (47%)	6 (32%)	10 (56%)	9 (50%)
Plan	4 (21%)	2 (11%)	7 (39%)	8 (44%)
Design		5 (26%)	4 (22%)	7 (39%)
Create	7 (37%)	6 (32%)	7 (39%)	5 (28%)
Think	3 (16%)	4 (21%)	3 (17%)	4 (22%)
Test		7 (37%)	1 (6%)	3 (17%)
Invent	5 (26%)	5 (26%)	4 (22%)	2 (11%)
Work	1 (5%)	2 (11%)	4 (22%)	4 (22%)
Fix	13 (68%)	4 (21%)	3 (16%)	
Make	3 (16%)	2 (11%)	1 (6%)	2 (11%)
Ideas		2 (11%)	1 (6%)	2 (11%)
Improve	1 (5%)	1 (5%)	2 (11%)	1 (6%)
Draw			1 (6%)	2 (11%)

The next question posed was, “What do you think engineers think about when they are designing something new?” The most common answers dealt with how well designs performed, the extent to which a design will be useful, and how to make something better. The number of students citing these themes increased between the pre- and post-assessment (see Table 3). However, these gains were not statistically significant.

The students were reminded, “Engineers design things” and then they were asked, “What do you think makes a new design a ‘good design?’” The students generated a variety of ideas on both the pre- and post-assessments (see Table 4). They reported that a good design should be easy to use, it should look good or cool, it should be new or original, and it should work well. The differences between the pre- and post-assessments were not statistically significant. However, the notion that a design must be new or original dropped from 10 students to four after the design activity.

Table 3: Perceptions of Engineering Thinking

	Seventh Grade (n = 19)		Eighth Grade (n = 18)	
Prominent Questions	Pre-assessment	Post-assessment	Pre-assessment	Post-assessment
Will it work or perform? Will it work under certain conditions or during testing?	5 (26%)	8 (42%)	6 (33%)	9 (50%)
It is useful? Will it benefit people? Will it make things easier?	2 (11%)	4 (21%)	5 (28%)	7 (39%)
What already exists? How to make it better? How can it be improved?	2 (11%)	6 (32%)	5 (28%)	6 (33%)
How much will it cost? How much money can be made?	3 (16%)	3 (16%)	3 (17%)	4 (22%)
Can it be made? How is it going to be built or made? What materials?	8 (42%)	6 (32%)	3 (17%)	2 (11%)
What will it look like? How will it turn out?	3 (16%)	3 (16%)	4 (22%)	2 (11%)
Is it going to be unique, cool, or awesome?	4 (21%)	1 (5%)		2 (11%)
Will it solve the problem or achieve the goal?	2 (11%)		4 (22%)	
What do people like, need, or want? What is in style?	2 (11%)	4 (21%)	1 (5%)	1 (5%)
What is good for the environment?	1 (5%)		2 (11%)	1 (5%)

Lastly, students were asked, "How many ideas do you think engineers have come up with before they discover one that will work the best?" Almost all of the students reported the need to explore multiple ideas that ranged in number from several dozen to over one hundred. Despite this understanding, students had difficulty generating three designs or variations on a design in the context of designing a better paperclip. This suggests the middle school students recognized the need for exploring different ideas but did not possess the cognitive capacity or thinking strategies needed to generate alternative designs.

Table 4: Perceptions Regarding Design

	Seventh Grade (n = 19)		Eighth Grade (n = 18)	
Salient Themes	Pre-assessment	Post-assessment	Pre-assessment	Post-assessment
It works well	6 (32%)	4 (21%)	3 (17%)	4 (22%)
It is new and original	1 (5%)	1 (5%)	9 (50%)	3 (17%)
It looks good or cool	3 (16%)	5 (26%)	3 (17%)	1 (6%)
It is easy to use	1 (5%)	1 (5%)	1 (6%)	5 (28%)
What people want and will buy	3 (16%)	3 (16%)	3 (17%)	1 (6%)
It is helpful, useful, or practical	3 (16%)	2 (11%)	6 (33%)	5 (28%)
It is better, faster or more efficient	1 (5%)	5 (26%)	6 (33%)	7 (39%)
Makes life easier or less complicated	4 (21%)	2 (11%)		
It is good or high quality		2 (11%)	2 (11%)	1 (6%)
It is cheap or cost effective	1 (5%)		2 (11%)	5 (28%)
More dependable or durable			1 (6%)	6 (33%)
Good ideas and teamwork	2 (11%)		1 (6%)	
Considered all aspects of the product. Attention to details.	1 (5%)		2 (11%)	

Note: The pre- and post-assessments also rendered one or two references to "environmentally friendly," "fun," and "materials."

The treatment took the form of a series of learning activities that were implemented over the course of four days. All of the activities used a Socratic approach (questions) to guide students through the reverse engineering of a common paperclip and using their results to "design a better paperclip." Each session began with a brief introduction of the ideas and skills the students were going to address that day. The students were divided into teams of two and each team was given an engineering notebook that featured simple directions, color photographs, and places for recording measurements, sketching ideas, and answering questions. To perform the labs outlined in their notebooks, each team was also provided a fixture for testing the performance of paperclips as well as the material used to make them.

The first tasks asked students to examine the features of a common paperclip. The vast majority of students related the difference in the length of the loops to the holding power of the paperclip in contrast to facilitating its application. Other prominent observations included references to its composition (metal wire) and flexibility. Only a few teams noted the different sizes of the interior and exterior loops or lack of sharp angles in the design of a paperclip.

When prompted to test the holding power of the paperclip, students observed how paperclips behaved when holding different amounts of paper (20, 40, 60, and 80 sheets) while supporting a tethered weight. Most of the students recognized paperclips did not grip small (20 sheets) or large bundles (80 sheets) of paper especially well. Nearly half the students presented their answers in terms of trade-offs (e.g. "The more paper there was, the weaker the hold," "The more paper, the less the clip is touching the paper," "The ones with the least amount of paper and the most are the ones that seemed to have trouble holding...").

Students finished the analysis phase of a common paperclip by performing tests that revealed properties such as the strength, elasticity, and fatigue of the wire used to make paperclips. They were asked to record four statements in their notebooks that would summarize their observations. Although no instruction was given relative to vocabulary, all but four teams characterized their findings using the scientific terminology that was introduced in written directions to describe the product's performance (e.g. fatigue, strength, elasticity, limitations, durability).

During the engineering design phase the students were asked to use the results of their reverse engineering to identify an opportunity to improve the common paperclip. They were then asked to generate alternative designs, to test different types and thickness of wire, and to consider the cost of wire. Even though most of the students determined that using brass would cost nearly three times as much as steel, they were divided on the best wire to use. Nearly half chose steel and the others chose brass. In addition, despite the fact that 11 out of the 18 teams noted wire fatigue would be a factor under normal use, six groups cited resistance to breaking or fatigue to be factors in their material selection decision. Also, even though the idea of brainstorming was introduced as a way to generate new ideas, none of the groups produced more than five designs. Indeed, as mentioned earlier, nearly all of the groups had trouble developing three designs.

Lastly, teams were provided a pair of needle-nose pliers and directed to make and test a prototype using the wire that they selected. When finished, all but three of the groups were confident that they had designed a better paperclip because it could hold more paper when compared with the original design. Factors such as simplicity or cost were not cited as design strengths in the contexts of their prototype. When asked what they liked the most of their design, half of the teams declared they liked how it looked (e.g. cool design, attractive, swirls, pleasing to the eye). When asked what surprised them most about the engineering design process, they presented ideas like, "it was hard to come up with designs," "there is a lot of testing," "it takes a long time," and "your first sketch is not always the best."

CONCLUSIONS

The primary purpose of this inquiry was to test the merits of "engineering simple things in sophisticated ways" under the auspices of integrated STEM education. Towards that end, the researchers wanted to determine the extent to which a relatively robust treatment of a simple engineering design problem might affect middle school students' conceptions of engineering. There is evidence that suggests elementary children have misconceptions about the nature of engineering and the work that engineers do (Lachapelle & Cunningham, 2010). One of the more prominent misconceptions is engineers fix or repair things (e.g., automobiles). The results of this study suggest this misconception can persist into the middle school years if gone unchecked. More importantly, they suggest a rich treatment of a simple design problem can diminish this misconception. In contrast, the extent to which students equate engineering with design can increase. Lastly, students tended to overlook the importance of testing in engineering endeavors. Awareness of the roles that testing plays in design can be improved with a seemingly simple design problem that involves experimentation and analysis to inform design decisions and to evaluate a design's performance.

The researchers were also concerned about the extent middle school students would engage in guided inquiry in the context of a simple problem. Guided inquiry provides teachers with the opportunity to carefully plan classroom investigations that will help students build important understandings (Marzano, Pickering, & Pollack, 2001). The development of deep conceptual understanding takes time and there is evidence that it can be enhanced through questions, first-hand experiences, and scaffolding (National Research Council, 2005). When developing the instructional materials and physical manipulates for the subjects of this study, special attention was given to ensuring the documents featured clear images, utilized appropriate prose, and divided the reverse engineering and engineering design process into distinct, sequential, and culminating pieces that could be completed in the time allotted. The students' behavior, discussions, and written work suggested their immersion in the process of engineering took precedent over making the product itself.

Another concern going into this investigation was the extent to which a seemingly simple design problem would capture and retain the students' interest and attention. Conventional wisdom suggests the context of a design problem can be distracting. For example, in the case of designing solar hotdog cookers, the students' desire to cook hotdogs is competing with the need to control the angles of incidence and reflection to concentrate radiant energy onto a single focal point. Therefore, a deliberate effort was made to engage students in a problem with limited intrinsic appeal to draw attention to discovering, testing, and designing. To the researchers' surprise, almost all the students stayed on task throughout the reverse engineering and engineering design processes. All of the tasks and questions posed were addressed in thoughtful ways. Furthermore, the level of details presented in the students' written work was consistent, and in some instances, increased in sophistication as the unit progressed. The levels of engagement observed were especially noteworthy because the students' design experiences were interrupted by an unexpected cancellation of school due to snowfall, abbreviated by a pep rally, and suspended for one weekend.

CLOSING

Engineering is a significant human endeavor that permeates culture, underpins the quality of life, and facilitates technological progress. Young people preparing for life, work, and citizenship in a society inundated with technology can benefit from a fundamental understanding of the nature of engineering. A rich treatment of basic engineering principles and ways of thinking can help students translate seemingly sophisticated technologies into manageable sets of ideas, actions, outcomes, and consequences that can be understood and appreciated. The findings of this study suggest the nature of engineering can be portrayed with surprising richness with an extremely simple problem. Furthermore, the use of simple problems minimizes ambiguity, harnesses students' prior experience, reduces the need for domain knowledge, encourages iteration, and focuses attention on the nature of engineering. A rich treatment of a seemingly simple problem can also capture and retain students' interest.

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