

Infusing Design into the G7-12 Curriculum—Two Example Cases*

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This paper focuses on Engineering and Education faculty and students, and middle and high school science and mathematics teachers who collaborated on a project to investigate strategies to infuse engineering design into the Grade 7–12 curriculum using hands-on design projects. The experience in the design and classroom testing of two projects is reported. It was found that students liked the hands-on exemplars, but resisted the design aspects of the task, such as working under constraints. Boys generally reported higher self-efficacy than girls and showed different patterns of interest than girls. Projects that were not directly relevant to improving test scores were difficult to implement because of resistance from teachers and administrators.

Keywords: motivation; design; self-efficacy; hands-on projects

INTRODUCTION

THE GROWING COMPLEXITY and influence of technology make it imperative that we integrate technological literacy into the pre-service and teacher training curriculum, in addition to integrating it into the K-12 curriculum directly [1, 2]. In 2001, Wulf [3], President of the National Academy of Engineering, defined technological literacy as consisting of three components: a body of knowledge and the artifacts that come from that knowledge, a process called engineering, and a process of innovation or commercialization called commerce. He pointed out that in most cases teaching the process, or ‘engineering,’ is more important than teaching ‘technology,’ the body of knowledge. Additionally, he wrote, ‘Right now our country is profoundly technologically illiterate on essentially all three dimensions. At the same time, some of the most important public policy issues facing us require an understanding of technology in order to discuss them intelligently. I think it’s the responsibility of the engineering community to own that problem and do something to fix it.’

Collaborations between colleges of Engineering and colleges of Education are needed to address these issues effectively. A paradigm shift is taking

place in engineering education driven by changing expectations of employers, the rapidly changing state of the art of pedagogy, and higher education’s new emphasis on student-centered learning [4, 5]. This and the fact that disciplines such as engineering depend on the pipeline of high school matriculates who are well prepared in science, math, and technology [6], make it imperative that meaningful relationships be developed with the K-12 system in order to satisfy the expectations of the modern workplace. We need to start recruiting students to engineering in middle school or before because by the time they leave middle school, they have often not taken the appropriate mathematics and science courses to be prepared for engineering [7].

This article focuses on a specific part of the experience of our team, which consisted of Engineering and Education faculty and G7-12 science and mathematics teachers in the area of Columbia, Missouri. We collaborated on a National Science Foundation Bridges for Engineering Education (BEE) grant during 2003 to investigate strategies to infuse engineering design into G7-12 curriculum using hands-on design projects, referred to below as ‘exemplars.’ Previous research shows that such design activities inspire student interest in engineering [8].

Before beginning to work on the project, our team wanted to know to what degree high school

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students learn about engineering and design concepts in high school. The team designed a survey and administered it to 104 first year mechanical engineering students at the University of Missouri-Columbia. The survey revealed a lack of attention to engineering in their high school experience. For example, over 50% indicated that they had had no high school experience that led to their interest in engineering. Approximately 50% indicated that their high school science and mathematics courses did not illustrate engineering concepts, and 55% indicated that they learned nothing about engineering design in high school. Over 80% of the same students reported that they generally enjoy mathematics and science. This is encouraging because mathematics and science form the basis of engineering education. Hence, exposing students before college to the fundamentals and challenges of engineering, and to the connections between science, mathematics, and engineering design, could increase interest in engineering significantly.

Six undergraduate engineering students and six undergraduate education students were paired into six teams of one education student and one engineering student who developed 12 exemplars (see www.missouri.edu/~engk12) to provide engineering design experiences in the classroom. These exemplars were selected from a large assortment with input from six science teachers who were part of our team. Examples include paper airplanes (compare flight times and distances), columns (compare designs that can support weight), and a crash car (compare designs that protect an egg during a crash). Each team developed two exemplars with attention to the following issues:

- Does the exemplar present engineering design problems that allow for brainstorming and teamwork? Will it generate discussion on alternate ways of solving design problems?
- Is there ample opportunity for hands-on activities?
- Do the learners need to consider data collection, problem solving, economic constraints, human factors, and new designs?

The engineering/education student teams wrote lesson plans and linked them to relevant standards described by professional organizations (*Principles and Standards for School Mathematics* published by the National Council of Teachers of Mathematics, and *Standards for Technological Literacy: Content for the Study of Technology* published by the International Technology Education Association), and by the state of Missouri curriculum and proficiency test guidelines. Linkage to standards proved to be a difficult and complex task. Teams generated matrices to help them keep track of the various standards and of overlap among the standards and guidelines. They pilot tested the exemplars first with our team of teachers and then with junior high school students.

In the following sections, the experience related to the design and classroom testing of two exemplars is discussed: the boat exemplar and the bulldozer robot exemplar. General issues related to design projects and their implementation are then discussed, followed by conclusions.

TWO EXAMPLE CASES

Two exemplars were classroom tested. One of them, the boat exemplar, was constructed by the students according to the design specifications provided. The second, the bull dozer exemplar, was constructed from a commercial kit, and the students did not have to conform to any specifications or design the system.

The boat exemplar

The boat exemplar asks students to experiment with the properties of buoyancy, density and stability. The students were provided with an imaginary scenario to frame the design of their boat. Crisp-Crème has just released a request for proposals (RFP) to transport donuts 30 miles down a river. Your engineering design firm, Boats R Us, will provide a design and model. The overall goal of the project is to maximize the total mass that the craft can carry in order to move the 1800 lbs of donuts in a limited time frame to preserve freshness.

The design of the craft must incorporate several natural constraints of the river that include a bridge, a narrow channel, and a shallow area. Furthermore, Crisp-Crème is willing to spend a set amount of money for the project. Designers should take into consideration river regulations that allow only craft of less than 24 square feet in area. The constraints will be simulated with model boats floated in a plastic tub filled with water.

Design concepts

The students design a craft using a variety of materials such as Styrofoam, paper, duct tape, and wood. Students must factor the cost of each material into their model, and design concepts must be implemented in every stage of the project. Students are given the freedom to create their own design based on discoveries about material density, buoyancy, and displacement. This exemplar introduces a design vocabulary that may be new to students such as optimization, workable solutions, load, prototype, model, constraints, five steps of design process, and cost efficiency.

Connection to real world

This exemplar has many ties to the real world. Students acquire experience with the principles behind the flotation of boats and why some materials float better than others based on their densities. Students engage a problem that has no correct answer and create a boat that they believe

solves the problem. They then present a proposal that includes a cost analysis.

Promoting teamwork

This exemplar promotes teamwork in a variety of ways. Students can assume roles in their group of designer, builder, tester, financial officer, and so forth, and work together to produce the optimal product. Students need to work together and come to agreements about several key issues in the design process, such as the design of the boat, the materials of the boat, and how to weigh cost against performance.

Student presentations

At the end of the project the students present their project in front of the class, including a float test in a basin of water. During the float test, the boats are loaded with metal washers until they sink or capsize. Some issues that can be addressed include:

- Which type of craft held the most weight?
- What happens to the maximum weight as the area and volume of the craft increase?
- Which material was the most buoyant? Is that material consistent with your initial guess?
- Were your findings close to those of other groups?
- What connections do you see between this project and the real world?

School implementation of the boat exemplar

Two teachers at a junior high school chose to implement the boat building exemplar in five sections of their eighth and ninth grade science classes. The school serves middle and low income areas, and is predominantly white but includes a sizeable African American minority. The activity asks students in groups to build a model boat out of materials that were made available. Teachers gave each group \$600 in bogus money. Each set of materials cost \$100, e.g., four popsicle sticks or one block of Styrofoam. Thus the students must choose materials based on cost and purpose. This is intended to teach the sort of cost-benefit analysis that is required by design activities. The boat must float high enough in the water to pass over the shallows in the model river, and the superstructure must be low enough to pass beneath the bridge, and the cost cannot be over \$600. After students had designed and built the boat, they tried loading it with metal washers and floating it over shallows and under the model bridge. The activity required three to five 50-minute periods, depending on the class.

One teacher reported that she has been teaching buoyancy and Archimedes' principle for 5 years, and the classes that did this boat building activity showed greater understanding than any previous class.

106 of the students returned Individual Reflections designed by the teachers. When asked what

they liked about the boat activity, the most frequent responses were the following:

- Designing and building the boat (46)
- Being creative, having autonomy (29)
- Presenting and testing the boat on water (24)
- Working as a group (13)
- Novelty (6)

Perhaps of even more interest, the students responded to what was boring about the activity:

- Nothing (40)
- Presenting and testing the boat on water (24)
- Issues related to money and materials (e.g., limited money, limited materials, the process of planning and purchasing materials) (13)
- Paperwork (both drawing the boat and filling out the spreadsheet) (12)

Note that presenting and testing the boat on water was both the best aspect of the task for some students and the most boring for others. This appears to be because students liked being able to test their constructions and designs with a hands-on test, but they disliked—were bored by—watching other teams prepare and test their boats. Thus, students who were presenting and testing their own boat in the model river were very interested, but everyone else in the class was bored while they watched and waited. Our interviews with teachers confirmed the paradox of testing. The teachers only had one basin of water; it would be useful to have more than one in future use of the exemplar. In addition, testing could be modified so that it involves the whole class instead of one group while the others sit restless and bored.

When asked for suggestions of how to improve the activity, students' most common suggestions were the following:

- more money and more materials (35)
- more time to plan and build the boat (25)
- fewer constraints on building and testing the boat (20)
- Nothing (11)
- better materials and tools (9)

Note that the list of what students found boring and of what they recommend to improve the project suggests that at least some students resist the design process. That is, they want a greater variety of materials without price constraints or river constraints. They find the real world design process difficult. Providing more money and more materials would make the task easier, but would undermine teaching the design-under-constraints nature of real world problem solving.

Bulldozer kit-based exemplar

When we asked for volunteer teachers to implement a classroom exemplar, one teacher chose to assemble battery-powered wire-remote bulldozers from kits. The students assembled the remote control box, wiring, wooden frame, plastic gears,

and plastic tracks, and inserted three motors. The class was composed of 15 students in a small high school in a small rural town. All students were white except one African American. Previous researchers have implemented robots in undergraduate classes and also among secondary school students [19]. The students worked on the projects for 6 days, one 50 minute period per day.

Some of the patterns that were easily observable included the following:

- The students self-selected into four completely sex-segregated groups, two groups of girls and two of boys.
- In the boy groups, only one boy did not seek to handle the materials, while in the girl groups several did not. In addition, more girls than boys disengaged from the task for periods of time.
- The students did not seek to understand how the bulldozer worked. In fact, at one point, a girl asked, ‘What are we making?’ She had to look at the picture on the kit box top to remember. The bulldozer had three motors, one for the right track, one for the left, and one to raise and lower the bucket. When the observer asked each group why there were three motors, no student could answer (though they were able to figure out the answer). It was apparent they had not thought about how the kit parts worked together.

The observer, who observed for four class periods, reported that the student were on-task much more than during typical academic activities. For example, on the second day of the activity, when the students entered the classroom, they gathered in their groups immediately, without teacher reminders or supervision. They immediately started where they had left off the previous day’s work. This occurred each day of observation. This is not typical high school student behavior. High school students commonly attempt to delay the class as much as possible in order to avoid work. While students worked on assembling their robots, there was very little off-task commentary, though the observer heard a few comments about prom, Johnny Depp, and *The Da Vinci Code*.

We were interested in what students remembered across time, and their beliefs and attitudes. About a month after the bulldozer building activity, we administered a survey that included an 11 item test of content related to the dozer exemplar. There were 10 multiple choice items and one fill in the blank. None of the items were rote memorization. All required some level of inference. On the average, the eight boys scored higher than the seven girls, but the scores did not differ significantly (7.75 versus 6.43, respectively).

Self-efficacy refers to one’s confidence that one can carry out actions necessary to attain a desired performance [10]. Self-efficacy is a key construct because it predicts people’s willingness to engage activities, their persistence in those activities, and their actual performance. In the realm of science, technology, engineering, and math (STEM) activities, girls tend to show lower self-efficacy than boys, which affects their tendency to take STEM courses and to pursue STEM careers. We created a self-efficacy scale that was designed to assess efficacy to learn about electricity (5 items), math (3), hands-on building (2), and to become an engineer (1). Students were asked to rate on a scale of 1 (could not do it) to 10 (could definitely do it) their confidence that, if they took a class, they could learn to do relevant activities like ‘wire batteries and lights together so the lights work’ and ‘understand Ohm’s law of electricity,’ and that they could ‘become an engineer if you wanted to.’

Boys and girls differed significantly in self-efficacy for learning science and mathematics activities, with boys reporting higher self-efficacy (see Table 1). Both boys and girls showed low efficacy for what they apparently viewed as complex topics, notably Ohm’s law (item 5) and calculus (item 8).

While the bulldozer building activity was highly engaging and apparently supported some learning (without a control group we could not assess whether the students would have done equally well on the test without the activity), it was apparent during classroom observation that the students were not learning all that they could. The

Table 1. Mean ratings of self-efficacy for boys and girls (10-point scale)

	Means (SD in parentheses)		<i>t</i> (df = 13)
	Male (n = 8)	Female (n = 7)	
1. Wire batteries and lights together so the lights work	8.8 (1.9)	4.9 (2.5)	-3.43**
2. Make an electric motor with wire and magnets	7.1 (2.5)	3.7 (2.2)	-2.76*
3. Repair the electrical parts of a desktop computer	6.4 (2.4)	2.6 (1.7)	-3.43**
4. Make a simple battery	7.3 (2.1)	5.4 (1.7)	-1.81
5. Understand Ohm’s law of electricity	5.5 (2.8)	5.1 (2.3)	-0.27
6. Use math to compute the volume of a room	6.6 (2.7)	4.3 (2.9)	-1.64
7. Use math to compute the acceleration of a car on a freeway	7.8 (1.4)	4.7 (2.6)	-2.85*
8. Learn calculus	4.9 (3.5)	3.6 (2.1)	-0.86
9. Build a model house with wood and screws	9.3 (1.2)	7.3 (2.1)	-2.25*
10. Build a 3-foot model bridge that you could stand on	8.5 (2.3)	6.3 (2.8)	-1.69
11. Become an engineer if you wanted to	6.1 (2.7)	4.0 (1.8)	-1.73
Total efficacy	7.1 (1.9)	4.7 (1.8)	-2.49*

Note: * $p < 0.05$; ** $p < 0.01$.

activity needed to be structured so that it is not just cookbook instruction-following, but so that it requires problem solving throughout. One mishap that required some problem solving occurred when two groups, a boy group and a girl group, glued the wood frame of the bulldozer on backwards. They had to soften the glue with water and cut the pieces apart with a razor knife. One of the girls had particular difficulty visualizing which part to remove and where to glue it back on. The observer thought that she demonstrated a lack of spatial ability.

SOME GENERAL ISSUES

Two issues that are related to the probability of students engaging in engineering design activities are student interest in engineering activities and the influence of state proficiency tests on the curriculum. We discuss these next.

Student interest in hands-on activities

As engineers and school personnel consider curriculum change, it is important to consider what interests students. Research suggests that hands-on activities tend to attract interest, but some activities are perceived as more interesting

than others [11]. It was apparent from classroom observations that the bulldozer robot assembly project was interesting to both males and females, but more so to males. It was also apparent that the students paid more attention to following instructions than to trying to understand what made the dozer work. We included a survey of interest in hands-on projects to find out which projects were most appealing to male and female students. Their ratings for 10 hands-on activities that teachers might use in classrooms are included in Table 2, along with comparisons between males and females. Based on the descriptions, boys most preferred hovercraft, crash test car, and bulldozer, while girls most preferred crash test car, indoor garden, and cool house. Boys least preferred indoor garden, paper airplanes, and water clock, while girls least preferred fire prevention, water clock, and paper airplanes. One can see strong similarities between boys and girls, such as a common interest in crash test car and dislike of paper airplanes and the water clock, and strong dissimilarities such as a female preference for indoor garden contrasted with a male dislike of indoor garden.

While the data reported here came from a small sample, they provide curriculum designers some guidance as to which activities are preferred by

Table 2. Mean student ratings of interest in hands-on activities for boys and girls

Instructions: We want to know what hands-on learning activities students prefer. Please rate each of the following activities for how much you would like to participate in them in class: 1 = no interest; 2 = slight interest; 3 = fair amount of interest; 4 = strong interest.

Activity	What you would do?	What you would learn	Male n = 8	Female n = 7	p
1. Paper airplanes	Build and fly paper airplanes.	Learn how to test what causes paper airplanes to fly better.	2.3 (0.9)	1.9 (0.7)	ns
2. Water clock	Build and test a water clock that tells time as water drips from one container to another.	Learn how the size and shape of the container affects drip rate and accuracy of time.	2.5 (1.1)	1.9 (1.2)	ns
3. Boats	Build toy boats that carry a load of metal.	Learn why things float and how to design something.	3.4 (0.5)	2.4 (1.0)	*
4. Cool house	Build a model house that stays cool inside. Test it with heaters and thermometers.	Learn how different materials insulate.	2.8 (1.3)	2.6 (0.8)	ns
5. Indoor garden	Build small garden boxes and grow plants indoors.	Learn how to test what makes plants grow better.	1.6 (0.7)	2.9 (0.9)	*
6. Hovercraft	Build a model hovercraft that hovers above the ground and can be guided by remote control.	Learn about electricity and air resistance.	3.8 (0.7)	2.4 (1.1)	*
7. Bridge	Build a model bridge that will hold as much weight as possible.	Learn what kind of bridge holds the most weight.	3.0 (0.9)	2.4 (0.8)	ns
8. Bulldozer	Build a remote-controlled bulldozer that can push objects around.	Learn about electricity, gears, and motors.	3.5 (0.5)	2.3 (1.0)	**
9. Crash-test car	Build a model car that protects an egg as the car crashes.	Learn about incline planes, force, acceleration.	3.5 (0.8)	3.0 (1.2)	ns
10. Fire prevention	Treat fabrics to see which treatments most reduce risk of fire.	Learn about fire. Learn about how to design a test of what burns most easily.	2.5 (1.1)	1.4 (0.5)	*

boys, which are preferred by girls, and which are highly rated by both without a significant difference between them. Those that are highly rated by boys and girls without a significant difference between them are most appropriate for most classroom activities; they include crash test car, bridge, and cool house. However, it is important to note that changes in wording activity descriptions might change preferences. The topic of what are interesting hands-on activities, to our knowledge, has not been empirically investigated.

We were interested in knowing whether students experience school-prompted interest, that is, become so interested in a topic that they learn more about it outside of school. Research shows that high school students sometimes experience school-prompted interest, but not at a high rate [12]. The purpose of school should not be just to prepare for tests, but should create long-lasting interest in students for at least some topics [13]. We asked whether students had experienced school-prompted interest during the previous two weeks related to history, science, and the dozer-building activity. For history, 12 students said that they had experienced school-prompted interest, which was primarily manifest as watching a show on the History Channel. For science, only three students reported school-prompted interest (two from television). For the target dozer activity, only one student reported school-prompted interest.

Effects of proficiency testing on curriculum

In the U.S., most states have adopted some kind of proficiency testing. As we attempted to test exemplars in the classroom, we found that additional projects that were not directly relevant to improving test scores were difficult to implement. Teachers and administrators are under considerable pressure to improve test scores. They did not want to use classroom time for projects that they believed were unlikely to raise test scores. We found that classes that were electives, like technology classes, were more likely to welcome new projects into their curriculum than were core courses that were required for all students and that were viewed as crucial for success on proficiency tests.

CONCLUSION

Engineering and engineering design principles are seldom part of the pre-college curriculum. Our survey of first-year engineering students found that few had been exposed to any engineering or design concepts during their high school years. Similarly, the pre-teacher curriculum could also benefit from the incorporation of hands-on design projects. Our team developed hands-on

exemplars that can be implemented in grades 7–12 to introduce students to engineering design. The exemplars are congruent with the guidelines of relevant learned societies and with the published state standards. As we tried to introduce the exemplars into schools, we found that schools in the United States are increasingly under pressure to raise proficiency test scores in order to comply with No Child Left Behind legislation. This is very important for engineers who may wish to introduce engineering and design principles into the K–12 curriculum. Anything that competes with or displaces a curriculum that prepares students for proficiency tests is likely to be rejected. Those who would introduce new material into the curriculum must be prepared to show that the material will be likely to enhance test scores. Electives like technology classes are more likely to embrace new hands-on engineering activities than are core classes that prepare students for proficiency tests.

We found that when students assembled bulldozers following directions, they were highly engaged and motivated, but they were not engaged in figuring out how the mechanisms worked, nor did they have to deal with constraints or design. In contrast, when students designed model boats that had to conform to design constraints, they were highly engaged and motivated, but also learned more about design and about the scientific principles that form the basis for the design, in this case, buoyancy.

We also surveyed students about their preferences for hands-on activities and found that a few activities were reported as equally attractive by both boys and girls. In the effort to address gender equity in the classroom and to attract more women to engineering, it is important to provide activities that girls find at least as attractive as do boys. The activities that were rated equally by boys and girls were crash test car, building a bridge, and constructing a model house that would stay cool.

Finally, a key motivation difference between boys and girls is their self-efficacy for doing STEM activities. Our classroom survey found that boys generally had higher self-efficacy than girls. Teachers need to provide successful mastery experiences that can enhance girls' efficacy for STEM activities. It is anticipated that, in the long term, involvement with engineering design will lead to improved academic performance as students engage in meaningful engineering design experiences. We believe that the emphasis on engineering in the classroom would also lead to an increase in the number of students who enroll in engineering degree programs.

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