In-Service Secondary Teacher Training Program in Engineering Design
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Abstract
We have developed and implemented a comprehensive, three-year professional development program for in-service secondary teachers to prepare them to teach engineering design and problem solving, and to use design-based teaching approaches in their science curriculum. The program used a constructionist, immersion pedagogy and a three-phase learning cycle. The program consisted of intensive summer workshops followed by monthly one-day workshops, school visits, and support activities during the academic year. This paper describes the program philosophy and activities, and presents outcome results using both qualitative and quantitative data. Pre- and post-test results indicate the workshop pedagogy and program structure were successful in meeting the goals and desired outcomes of the program.

Introduction
According to the National Academy of Engineering and the National Research Council (NAE–NRC) Report, Engineering in K-12 Education, introducing engineering concepts into K–12 education has the potential to increase student engagement, improve learning in science and mathematics, increase technological literacy, provide a better understanding of what engineers do, and increase the number of students who pursue STEM careers [1]. However, the Report also notes that there is limited data to support these claims, in part because there are still few programs to study, and in part because of the variety of program types and their emphasis on different outcomes.

School administrators considering adding engineering to the curriculum face three questions: What engineering material or concepts should be included; what is the most effective way of introducing this material into the school curriculum; and who is qualified to teach them? Our program, the Rice Engineering Design
Experience (REDE), like most others, bases its content on the NAE–NRC Report Principles that K–12 engineering education should emphasize “the design process, the engineering approach to identifying and solving problems,” along with engineering habits of mind including systems thinking, creativity, collaboration, communication, and attention to social and ethical considerations in choosing technological solutions. Many believe these are the essence of technological literacy and essential skills for citizens in the 21st century [2]. Focusing on engineering design, problem solving, and habits of mind represents a useful pedagogical strategy in the absence of national learning standards for K–12 engineering.

There are several approaches to introducing engineering into secondary schools. A series of studies shows that replacing conventional science curriculum with design-based teaching of science concepts resulted in superior student knowledge gain, engagement, and retention compared to scripted-inquiry teaching [3-5]. The engineering design pedagogy was most helpful to low-achieving, traditionally underserved students. However, the school restructuring necessary for replacing curriculum is always difficult, and sometimes impossible, limiting its effectiveness and overall impact. Stand-alone engineering courses are another approach. Project Lead the Way, for example, claims significant gains with its sequence of engineering courses for middle and high school [6]. However, these courses require an expensive contract, are rigidly structured, and are usually offered as electives. Courses that cannot be adapted for local conditions, and that are not part of the core curriculum for all students have limited potential impact.

The REDE program is based on our belief that the benefits of incorporating engineering in secondary school can be achieved by infusing team-based design projects and engineering-oriented material into existing core science classes, thus reaching every child while avoiding school restructuring. However, this approach requires teachers with special skills. The REDE professional development program was designed to provide these skills.

**The Rice Engineering Design Experience**

The specific objectives of the REDE program can be grouped into three general goals:

- Give teachers the content and implementation skills to develop and integrate project-based learning lessons, open-ended activities, and design challenges into science courses to enhance student motivation and learning.
• Provide teachers with the experience, knowledge, and skills necessary to guide student teams through engineering design problems that integrate science and mathematics concepts aligned with state standards.

• Familiarize teachers with engineering professional practice, the content of the different engineering areas, and the nature of various engineering degrees and their requirements, so that they can advise students.

It is a rare secondary school teacher that has such a knowledge and skill set, necessitating a comprehensive professional development (PD) program. In addition to the training, the program provided teachers with instructional materials, online resources, and continuing support to implement effective teaching strategies and to develop a community of practice.

The Professional Development Challenge

Designing a PD program to meet the goals above is a challenge. Most teacher PD programs focus on improving or updating knowledge and skills in an area that teachers have already studied. Unlike for core subjects, there are no teacher credentialing standards for engineering, virtually no pre-service training programs [7], and in-service PD is rare and variable in content [8]. It is not surprising that there is a wide variation in what takes place in classrooms in the name of engineering education. For our program we could not assume any prior knowledge of engineering on the part of participants.

We believe that only a deep understanding of engineering design and problem solving by teachers can lead to transformational change in the classroom and the benefits claimed for incorporating engineering in secondary school. Open-ended design problems, unlike science or mathematical problems, have multiple “correct” solutions that represent different choices of how to meet the design goals within the problem constraints; guiding students through them and assessing the results from student teams requires specific skills. We firmly believe that the only way to understand and learn to apply the design process is to do it. Like learning to swim, one can read books, listen to lectures, and watch demonstrations, but eventually, one has to jump into the pool and actively struggle to master the skill. And as Kolb notes, “It is difficult, if not impossible, to teach in ways that one has not learned” [9].

The REDE program began in 2009 as a two-year program with a single cohort of participants taking part in extended summer workshops and academic year meetings, with over 100 contact hours per year. Later the program was extended for a third year. Some teachers joined during the course of the program, and a few became inactive because they left teaching or changed subjects. The program
ended with about 20 participants. In addition to an immersion in engineering design, the program incorporated characteristics that have proven to promote teacher learning [10]: a focus on engineering content and a pedagogy that builds on the teachers’ existing subject skills; a well-defined image of effective classroom learning and teaching; in-depth, active learning experiences; opportunities for reflection and collaboration that engage teachers as adult learners, and an extended duration of formal training followed by ongoing support and continuing education.

**Program Activities**

Each year of the REDE program consisted of an extensive summer workshop, 5–10 full-time days, plus academic year meetings for about one full day per month. The initial 2009 summer workshop provided a ten-day immersion in the design process for the beginning participants. Teams of teachers were asked to design, build, and demonstrate a prosthetic hand using a rapid-prototyping materials (LEGOS NXT systems). The workshop led the teams through the ten steps of the design process using an innovative three phase learning cycle, illustrated in Fig. 1.

![Fig. 1. The Three-Phase Learning Cycle](image)

First, Building the Knowledge Base, (BKB) developed content knowledge through reading, lectures, and activities. For example, for design Step 5: Develop Multiple Concepts and Solutions, the BKB material covered brainstorming, conceptual blocks to innovative solutions, and how to break those blocks. During the second phase, the Challenge, the teacher-teams implemented that content knowledge to devise multiple solutions for their design problem. During their active experimental work they were supported and mentored by course staff and instructors to build confidence, keep forward momentum, and insure
success. In this stage teachers developed their experiential, *intrinsic knowledge* of design.

The third phase was Advancing Classroom Technique (ACT). Teachers came together to reflect on and share their experiences in working on the project. Guided by master teachers and the instructors, they discussed how to implement this step of the design process in their classroom, how to integrate design into the STEM subjects they teach, how to guide students through it, and how to deal with anticipated problems. This stage provided *pedagogy skills* and knowledge. The class then moved on to the next step in the design process, repeating the BKB, Challenge, and ACT cycle.

All through the steps, the teams wrote reports documenting their progress. Such reports were an essential component of the design process, but they also served as formative assessment tools for the instructors to modify the pace or content of the workshop as necessary. At the end of the workshop, the teams presented and demonstrated their solutions to the Challenge, and together the teachers had a final ACT phase to discuss the entire design process, and its curricular implications.

The 2010 summer workshop challenged the participants to test and develop several Design Teaching Kits (DTK). A DTK is a set of hands-on activities, plus a design contest, to supplement the teaching of a specific set of science topics. It does not replace curriculum but enhances it. It also provides information for students on the engineering design process, the difference between science and engineering, and engineering disciplines and practice. The REDE DTKs were based on activities developed at the University of Virginia as senior engineering design projects [11-13]. For example, the *Save the Penguins* DTK supplements lessons on the nature of heat, radiation, convection, and conduction, and insulating materials. Teams of students make observations about heat flow, measure the insulating properties of different materials, and then design an enclosure, an “igloo,” to minimize the melting of a penguin-shaped ice cube in a heated environment. Teachers in the workshop tested and modified the activities, aligned them with state science standards, and wrote scaffolding information for teachers. These kits were subsequently supplied to the teachers. Another kit focused on solar energy, solar cells, electric measurements and motors, and torque and gears.

The final 2011 summer workshop included a review of the design process with a short team design project, as several new participants had joined the program. A particular focus of the workshop was how to tailor projects to the ethnic, gender, and cultural diversity of the student body, and to incorporating
English language proficiency activities into design projects. A key point is that technical communication and the vocabulary of engineering and design is a “foreign language” to virtually all students, not just English language learners, and activities and techniques were shared that help all students develop good oral and written communication skills.

All during the program, the monthly academic year meetings provided review of the summer workshop material, and support for the teachers using design projects in class. These meetings also covered the majority of material on engineering professional practice, the content of the different engineering areas, and the nature of various engineering degrees and their requirements. Most meetings included a talk and laboratory tour by an engineering faculty member, to help put an engineering discipline in concrete terms. All the material from the workshops and meetings is archived in an online collaboration site available to the participants and other interested teachers. The site also provides tools for communication between participants, forums, blogs, and a wiki. This resource will remain in place after the end of the project to facilitate ongoing work and community building.

**Results**

The effectiveness of our program was assessed using both quantitative and qualitative measures. Pre- and post-tests were written and graded by the project directors. These were used as formative assessment during the program to guide meeting activities, and as a final summative assessment of the program. Independent external evaluators surveyed participants after workshops and meetings, held focus groups, and visited classrooms to observe and interview students. Finally, the state granting agency is conducting a uniform program-wide assessment involving classroom evaluations using a standardized instrument. The state assessment, and our evaluator’s final report is not available at this writing, but we can give our summative results and earlier qualitative results from our evaluators.

The pre-and post-tests consisted of a combination of 16–17 open-ended questions and multiple choice items. Pre-and post-test items differed by changes in the ordering of the items, wording changes, and different questions. We identified eight specific outcomes or objectives of interest for our program, as shown in Table I. Each objective was associated with one or more questions on the pre- and post-tests. Over the three year program, participants took both tests a variable number of times, depending on when they were active in the program. For our summative evaluation we compared the first pre-test score of a
participant with their last post-test score, and computed a participant average (arithmetic mean) for each objective, and for all the objectives.

### Table I. Program Objectives and Test Score Averages

<table>
<thead>
<tr>
<th>Objective Description</th>
<th>Pre-Test</th>
<th>Post-Test</th>
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<tbody>
<tr>
<td>A Develop, integrate, &amp; implement design-based, open-ended activities for science classes.</td>
<td>44%</td>
<td>70%</td>
</tr>
<tr>
<td>B Explain the engineering design process, &amp; compare it to the scientific inquiry process.</td>
<td>61%</td>
<td>77%</td>
</tr>
<tr>
<td>C Organize, develop, &amp; guide student design teams.</td>
<td>70%</td>
<td>85%</td>
</tr>
<tr>
<td>D Apply appropriate formative &amp; summative assessment to team project outcomes.</td>
<td>48%</td>
<td>85%</td>
</tr>
<tr>
<td>E Be able to describe engineering practice &amp; discipline areas.</td>
<td>50%</td>
<td>93%</td>
</tr>
<tr>
<td>F Be able to advise students about educational paths into STEM careers.</td>
<td>64%</td>
<td>71%</td>
</tr>
<tr>
<td>G Explain engineering ethics, responsibility to the public, &amp; consideration of social values in design choices.</td>
<td>58%</td>
<td>81%</td>
</tr>
<tr>
<td>H Develop student communication skills through documenting team design projects.</td>
<td>38%</td>
<td>52%</td>
</tr>
<tr>
<td><strong>Average for all objectives:</strong></td>
<td><strong>54%</strong></td>
<td><strong>77%</strong></td>
</tr>
</tbody>
</table>

As shown in Table I and Fig. 2, post-test scores were higher for all objectives, and increased over pre-test scores an average of 23 percentage points.
In surveys and focus groups administered by the external evaluators at the end of our first year and its in-depth design workshop, all of the participants indicated that the training was the correct length, the pacing was appropriate, and there was enough individualized help for the hands-on activities. The participants rated the usefulness of various components of the training with assisting them with understanding the design process and helping with classroom implementation. The components Defining Engineering Design and Overview of the Design Process were rated as most useful (5 on a scale of 1 to 5), by at least 88.9 percent of participants. None of the participants rated any component lower than a 3. Participants also rated the different aspects of the training from Poor to Excellent. At least 85 percent of the participants rated networking opportunities, communication of available resources (web), and overall quality of the training as Excellent. None of the participants rated any aspect as poor or average.

Respondents were asked what was most beneficial about the training. Some responses related directly to the structure of the workshop and the learning cycle used, such as, “Getting the student perspective on working as a member of a team on a design project...,” “The connections to the real world. The structure was modeled in the way we should do it in class,” and “The most beneficial part was designing the prosthetic hand.” Later surveys and focus groups were
consistent with these results, although we do not have a comprehensive summary yet.

During the second year our evaluators visited participant classrooms to observe activities and survey students. Most students said they liked doing the design contests (98.7%): “It was really fun coming up with different ideas ... that would help mankind.” “I found ... hands on projects is the way I learn best.” “Usually students do not get the chance to build creations at this level.” “We learn new skills from these projects.” Most students, 87%, also said they planned on taking STEM classes in college, and 75% said they were planning a STEM major in college and a STEM career, with 24% mentioning engineering as a possible career choice.

Conclusions

These results, taken together, indicate the workshop pedagogy and program structure were successful in meeting the goals and desired outcomes of the program although the final evaluation data is not yet available. Furthermore, it is not clear if we will be able to get data to indicate whether infusing engineering into these classes improved the students’ science and mathematics skills and achievement.

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Citations


