AC 2011-690: MAKING ELEMENTARY ENGINEERING WORK: LESSONS FROM

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Making Elementary Engineering Work: Lessons from Partnerships and Practice

Abstract

Infusing engineering into mainstream K-12 education—not merely as an elective or extracurricular activity—has been a strategic goal of the Center for Innovation in Engineering and Science Education (CIESE) at Stevens Institute of Technology since 2004. Since that time, CIESE has been working with school districts throughout New Jersey to promote the position that all children should experience engineering as an integral part of their K-12 education. From a small demonstration project in 2006 to the launch of an intensive five-year, statewide program targeting 400 Grade 3-8 teachers in 2010, CIESE has impacted more than 3,500 K-12 educators with exemplary engineering curricula and associated professional development. Approximately two-thirds of these teachers are elementary teachers, who have special opportunities and special challenges to the incorporation of engineering into the traditional school day. Lessons learned over six years through several federal, state, and corporate-sponsored programs show that: blending research-based engineering curricula and professional development with science inquiry and support for science content learning for teachers has significant impact on teacher learning and student learning; that elementary teachers, students, and other stakeholders embrace engineering once initial concerns are allayed through professional development and evidence on learning gains; that awareness of engineering careers and engineering/technology contributions to society increases; and that addressing the particular needs of various partners—corporations, government and funding agencies, policymakers, school administrators, parents, teachers, and students—up front, can reap important and even unanticipated benefits.

Rationale

The 2010 *Rising Above the Gathering Storm* update reinforced the earlier report's shocking statistic: although a primary driver of a robust economy and the concomitant creation of jobs will be innovation, based largely on advances in science and engineering, only four percent of the nation's work force is composed of scientists and engineers. This group disproportionately creates jobs for the other 96 percent.¹

Yet, the American public and private education systems have not met this urgent challenge. The 2009 National Academy of Engineering report on K-12 engineering education states that although there were more than 56 million pre-K-12 students enrolled in U.S. public and private schools in 2008, no more than 6 million students have had any kind of formal K-12 engineering education since the early 1990s.² The famous quote attributed to Albert Einstein, that the definition of insanity is doing the same thing repeatedly and expecting different results, appears quite relevant to this problem. Continuing the status quo in developing America's future technical workforce will not result in the increased human resource talent pool that is needed to sustain and grow the U.S. economy and that reflects the diversity of the U.S. population.

At CIESE, we have waged a multi-front campaign since 2004 to infuse engineering into mainstream K-12 education, not merely as an elective or extracurricular activity. We have posited that engineering: (1) presents opportunities for students to acquire critical 21st century

skills, such as problem-solving, creativity, innovation, and teamwork; (2) provides relevant problems and contexts which will motivate students to more deeply learn and apply science and mathematics; (3) promotes habits of mind, such as analytical thinking, that can be applied across a variety of problems, disciplines, and contexts; and (4) is a misunderstood and little-known career path that provides opportunities for intellectually and financially rewarding careers that can help society and improve quality of life.

The 2010 report *Strengthening STEM Education in the Early Years: A Strategic Report* acknowledges that most of the efforts to improve STEM education have focused on the middle and high school levels, even though there is growing consensus among educators that STEM education must begin earlier, starting as early as in Pre-K.³

Since 2004, through a series of small and large programs of varying scope, duration, intensity, and objectives, CIESE at Stevens has provided professional development to more than 3,500 K-12 educators, including classroom teachers and school and district administrators from public and non-public schools across New Jersey. Approximately 2/3 of these educators are elementary teachers. This focus on elementary educators is, at the same time, both deliberate and opportunistic. First, we believe that engaging young students in engineering may increase motivation and persistence in STEM study for larger numbers of students who may experience greater satisfaction with learning and therefore be less susceptible to negative stereotypes later in life. Second, the elementary classroom, despite high stakes testing pressures in mathematics and language arts/literacy, has the greatest flexibility and opportunity for infusion of engineering curricula that can connect with other core subjects such as science and reading. Although CIESE conducts STEM programming and education research across the K-20 spectrum, this paper will focus on elementary engineering initiatives.

Elementary Engineering Programs

Since 2004, planning for, implementation of, and research on learning outcomes of elementary engineering has grown substantially under a campaign launched as *Engineering Our Future NJ*. This initiative has had as its key goal to ensure that all students experience engineering as an integral part of their K-12 education, not merely as an elective or extracurricular activity. Under this umbrella initiative, several state-, federal- and corporate-funded programs, as well as fee-based school-supported programs, have been conducted that have included the following components:

- Teacher professional development
- Policy and advocacy, particularly around the inclusion of engineering in science standards
- Administrator programming, specifically awareness building of the “E” in STEM and engineering’s link to innovation and economic growth
- Parent outreach initiatives
- PR and media outreach
- Education research on learning outcomes on teachers and students in science, engineering and 21st century skills

- Guidance counselor professional development focusing on the breadth of engineering careers and academic requirements for admission into college engineering programs
- Classroom visits by practicing engineers/corporate volunteers

State-Sponsored Demonstration Project

The 2005-2006 *Engineering Our Future NJ* demonstration project included a pilot component focusing on elementary teachers. The goal of this pilot was to assess the impact of engineering curricula on student learning and interest in engineering and to investigate classroom implementation challenges and benefits. In this pilot, the *Engineering is Elementary* (EiE) curriculum modules were selected to align with many elementary schools' science curricula. Each EiE module contains lessons that integrate an elementary school science topic with a specific field of engineering and features hands-on activities that engage students in the engineering design process.

In addition to this research, a parallel goal was to create awareness and partnerships to build an infrastructure and support for K-12 engineering. In addressing this goal, the NJ Department of Education was invited to become a key partner to explore curricular alignment, ensure the broad representation of academically, socio-economically, and geographically diverse schools, teachers, and students in the pilot, and to consider the future implications of the pilot's results.

The two EiE modules selected for the pilot program were:

(1) Water, Water, Everywhere (Environmental Engineering)

This module (Figure 1) addresses the increasingly important issue of water quality through lessons that teach students about water contamination and the ways that people ensure the quality of their drinking water. Students plan, construct, test, and improve their own water filters.

Figure 1

(2) Catching the Wind (Mechanical Engineering)

This module (Figure 2) guides students to learn about wind and the ways engineers design machines to capture wind energy. Students explore different materials and shapes conducive to catching the wind. For the design activity, students create their own windmills that can lift a small weight.

Figure 2

Elementary Pilot Study Results

The EiE modules were used in 13 New Jersey schools to assess the impact of grade appropriate engineering curricula for elementary students. Evaluation of student learning associated with use of EiE modules, was conducted by the Museum of Science, Boston in the context of a national research effort to assess the impact of the EiE modules on student learning. The evaluation

involved administering five pre-post assessments to gauge student understanding of the core science concepts and examples of engineering. The key findings from this study included:

(1) Students significantly improved their ability to identify examples of technology and engineering. On the more difficult items to classify, students improved (between 11% and 50%) in their ability to correctly identify human-made items as examples of technology on the post-assessment.

(2) Students significantly improved their ability to answer questions about water filters, filter materials and the science involved with the water filter module. Students were asked eight questions about water filters and water filter materials and six science content questions.

(3) Students improved their ability to answer questions about windmills and blade materials. Students performed consistently better on post-assessments than on pre-assessments but not all changes from pre-test to post-test were significant.

Evaluators collected the reflections and observations of the teacher participants using informal surveys and classroom visits. A summary of teacher comments indicate:

- Teachers discovered that engineering concepts could be introduced at an early grade level.
- Teachers reported that students developed a better understanding of what engineers do.
- Teachers found the EiE lessons furthered objectives for science in the classroom and reinforced concepts already taught in class.
- Student understanding of science concepts improved as a result of interaction with the EiE materials.
- Teachers plan to integrate the EiE lessons into their existing science curriculum.
- Both teachers and students felt comfortable using the engineering design process.
- Students learned that there are different ways to solve problems.
- Students were active learners and motivation was positively affected; they were engaged and excited.⁴

Corporate-Sponsored Statewide Elementary Engineering Programs

This demonstration project succeeded in building awareness and interest among both educators and policy makers, and in producing research evidence of learning impact sufficient to expand the program. Through a major corporate grant from the Verizon Foundation, a statewide effort was launched in 2006. The goal of this program was to provide professional development on K-12 engineering education to 2,000 K-12 teachers throughout New Jersey, while working at the policy level on the issue of including engineering in the state science standards.⁵

To accomplish the goal of providing professional development on engineering curricula for 2,000 K-12 educators, it became critical to leverage existing collaborations and create new partnerships. CIESE at Stevens developed a request for proposals and provided “catalyst grants” of \$5,000 to six organizations to initiate, expand, or enhance teacher professional development programs to include engineering. These partner organizations ranged from community colleges to an elite, Ivy League institution, to a college of teacher education. In addition to these catalyst

grants, CIESE expanded other partnerships to provide opportunities to showcase engineering in different ways:

- guest lectures at colleges of teacher education in science methods courses
- a statewide conference for school and district administrators
- a speakers' briefing package to prepare engineering alumni interested in promoting engineering in K-12
- corporate engineer classroom visits, which generated media coverage for the corporation and for the schools

In this ambitious program, it became necessary to broaden the number as well as the content focus of the elementary engineering curricula we supported, in order to align with as many school and district curricula as possible. Instructors participated in training on all existing EiE modules and were prepared to offer them across the state. After the third year of the program, more than 3,300 teachers had participated in engineering-focused professional development, ranging from single day workshops to intensive, multi-year professional development programs.

The Verizon Foundation, which sponsored this program, was a key partner in several critical respects:

- Cooperating on creating visibility and media coverage of the program, including news articles on the grant announcement, classroom visits of Verizon engineers, and co-authoring opinion articles about the importance of engineering and innovation in the state's economy
- Lending the credibility, prestige, and leverage of a national, Fortune 50 company to policy efforts to bring engineering into K-12

In addition, the "catalyst grant" partners leveraged the mini-grants to engage new schools and districts in their local areas and, in some cases, bring in additional funding. Several institutionalized their elementary engineering programs in other ways. Brockway et al reported on quantitative and qualitative results of this program.⁶ To date, more than 3,500 teachers from 465 public school districts and 182 private schools in all NJ 21 counties have participated in K-12 engineering activities. Approximately 2/3 of these have been elementary educators.

Competitive Grant Funds: NJ Department of Education Math Science Partnership

During the period of Verizon funding and the implementation of the *Engineering Our Future NJ* initiative, CIESE at Stevens was awarded \$1.7 million for one of six state-administered U.S. Department of Education Math Science Partnership grants. This intensive, three-year program focused on increasing teacher learning and student learning in life and environmental science, earth science, and physical science through a coherent set of integrated inquiry-based science learning activities combined with appropriate engineering learning experiences. This program, known as PISA (Partnership to Improve Student Achievement in Northern New Jersey), worked intensively with a cadre of approximately 50 elementary teachers from six northern New Jersey school districts over three years. Each teacher participated in 124 hours of professional development each year for three years.

Macalalag et al have reported on significant teacher and student outcomes of this project, as measured through a quasi-experimental study.^{7,8} In each year for three years, teachers increased their own content knowledge of the targeted science domains (Year 1 was life and environmental science; Year 2 was earth science, and Year 3 was physical science) through inquiry-based science investigations; participation in engineering design activities; including *Engineering is Elementary* and others; development of model-based inquiry artifacts; reflection; and curriculum planning. In this study, students of teachers in the treatment group who used the engineering design process showed a greater increase in content knowledge and displayed higher levels of thinking on open-ended questions when compared to the comparison group. Importantly, both teachers and students have shown highly significant learning gains for the corresponding science content in the two years of the program. In Year 1, the mean score of the treatment group of *teachers* increased by 7.6 percentage points with respect to science content, while the comparison group gained 2.7 percentage points on average. This difference was statistically significant. Similarly, *students* of teachers in the treatment group had science achievement gains almost two times greater than the students of teachers in the comparison group⁹.

In the second year, which used the same model of teacher professional development with a nearly-identical cohort of elementary teachers and students and matched comparison teachers and students, we found that when the teachers' pre-test scores were held constant, the treatment *teachers* had higher post-test scores (M=18.074) than the comparison teachers (M=15.948). This difference in the post-test scores between the two groups was significant. Further, after students' pre-test scores were held constant statistically, the treatment *students* had higher post-test scores (M=11.624) than the comparison students (M=10.535). Further, teachers' knowledge of and use of inquiry-based science instruction also increased from pre- to post-surveys: teachers were more comprehensive in their description of scientific inquiry. In addition, there were notable increases in their identification of scientific practices such as generating models, conducting a series of observations or experiments, analyzing data, explaining results based on science, revising models, and presenting models¹⁰.

Further analysis of teachers' and students' test scores revealed that teachers' post-test scores were a significant predictor of their students' post-test scores. This suggested that the test itself could be better tied to the content being taught by teachers. Analysis of teacher implementation surveys indicated that over half of the treatment teachers implemented ten or more of the 27 lessons presented during the summer workshops. Teachers mentioned that the science and engineering activities, through scientific inquiry and engineering design process, promoted problem solving, critical thinking, collaboration, and communication in their classrooms, which are crucial skills for students to learn to compete in the global economy of the 21st century. Finally, the number of engineering activities to which the students were exposed in the classroom was a significant predictor of their science post-test scores.¹¹

Competitive Grant Funds: NSF Math Science Partnership

Based on lessons learned and teacher and student outcomes of the PISA program, CIESE at Stevens won a competitive National Science Foundation Targeted Partnership five-year grant, one of a very few engineering-focused MSP programs funded in the last two yearsⁱ.

This program, known as PISA², (Partnership to Improve Student Achievement in Physical Science: Integrating STEM Approaches) is a collaboration with 12 socio-economically, geographically, and academically diverse school districts throughout New Jersey. Its goal is to significantly increase the quantity, quality, and diversity of teachers who are prepared to teach physical science, in Grades 3-8 through an integrated STEM approach to teaching and learning, by the presentation of science concepts in the context of relevant societal issues such as climate change and energy, and by the infusion of learning sciences research.

Five three-credit graduate science content courses are being developed for this program. These courses are based on the AAAS Benchmarks for Science Literacy Clusters, specifically in three topics: the Physical Setting, the Designed World, and the Nature of Technology¹². The courses are also being correlated with the 2009 New Jersey Core Curriculum Content Standards in science, which have an interdisciplinary STEM approach and a problem-based learning emphasis.¹³

Each of the five courses are to be introduced through the perspective of a contemporary issue in which science and engineering play a paramount role, such as energy consumption and climate change. Scientific inquiry and the engineering design process will be embedded within each course and will be used as vehicles to promote 21st Century Skills, particularly problem solving, innovation and creativity.

Each course will engage teachers as learners in what the National Research Council describes as the four strands of science learning¹⁴:

- Understanding Scientific Explanations
- Generating Scientific Evidence
- Reflecting on Scientific Knowledge
- Participating Productively in Science

Teachers need to know science in ways that are particularly suited for instruction...they don't just need to know the subject matter—they need to know how to teach the subject matter. They need to understand the strands of science learning in a student-learning context. This “pedagogical content knowledge” combines the fundamental understanding of a discipline with an understanding of how students learn.

—Ready, Set, Science p. 156

Specifically, each course will require readings of science and engineering education research, such as *Ready, Set, Science, How People Learn* and current journal articles, to foster teachers' metacognition about their own and students' learning.

ⁱ In addition to the CIESE/Stevens award, the University of Texas at Austin and Purdue University are implementing the first NSF Math Science Partnership grants that focus on engineering.

As each course builds successively deeper, broader content knowledge for teachers, PISA² will build teachers' capacity to master concepts that are more complex and partner schools' ability to make available well-prepared teachers and research-based curricula.

A programmatic element and associated research question in this initiative is an effort to increase students' 21st century skills, particularly problem-solving and critical thinking and innovation and creativity.

In parallel, we are working with school and district administrators and other stakeholders to strengthen science leadership and build organizational capacity for STEM education. We also intend that the benefits to teaching and learning will accrue to the faculty who teach undergraduates in our own institution, such that research-based STEM teaching methods and knowledge of learning sciences research is integrated within the university teaching environment.

Over five years, 400 in-service teachers, 50 STEM undergraduates and 120 school and district administrators will benefit from PISA² programming:

- Five course graduate certificate program
- Intensive summer institutes leveraging graduate course content
- School-year PD and monthly classroom visits
- Pathways to Teaching Options for S&E undergraduates
- Leadership training/strategic planning/organizational capacity-building for district and IHE partners
- Science scope & sequence and curriculum workshops

Together, the 12 districts involved in PISA² serve more than 34,000 students in Grades 3-8 annually. Over the five years of the project, it is estimated that more than 87,500 grade 3-8 students will benefit. In addition, PISA² will impact an extended faculty community at Stevens Institute of Technology by augmenting an existing professional learning community around research and innovation in engineering education, by formalizing faculty development pathways to the designation of Master Teacher, and by providing credit in Stevens' promotion and tenure process for participation in related activities.

Fee-Based Programs

Ultimately, our and other organizations' efforts to influence the state's 2009 adoption of new science content standards to include engineering were ultimately not successful, due to a variety of political developments that presented themselves late in the process. Surprisingly, however, the outreach, visibility, and evidence of learning impacts of the various *Engineering Our Future NJ* and PISA programs, together with a higher national profile for STEM education (thanks in part to President Obama's advocacy), has created an unexpected demand for school-based engineering professional development.

Our current professional development catalog lists more than 50 workshop titles, most of which are engineering-focused or have an engineering component. These fee-based programs are

offered around the state to schools at the prevailing daily rate for workshops, which includes preparation and delivery of a workshop for up to 20 teachers. In 2010, school districts contracted for a combined 100 professional development days.

Discussion and Recommendations for Elementary Engineering Partnerships

The foregoing describes the growth and evolution of a statewide K-12 engineering education program that started with a pilot program involving 36 teachers in 2006 and has since garnered more than \$26 million in competitive grant funding. Much of this work has focused on elementary educators, both as the vehicle to positively influence the interest of students in engineering at a young age, and as a partner to advance research on teacher and student learning in science, engineering and 21st century skills.

Based on experience implementing K-12 engineering programs since 2006, we offer the following recommendations for expanding the reach and deepening the impact of elementary engineering education:

- Build a repertoire of workshops that include exemplary, research-based curricula such as *Engineering is Elementary*, *Design Squad* (PBS) and lessons from the *TeachEngineering* digital library, to facilitate as many connections with teachers' existing curricula and interests as possible.
- Promote and provide both standalone, single-day workshops, conferences, and longer-term, intensive professional development programs to raise awareness of “what engineering at the elementary level looks like” for both teachers and administrators.
- Use listservs and develop PD catalogs to keep former and current participants informed about new PD offerings, grant opportunities, and award opportunities related to engineering education and involve professional development specialists in encouraging and helping teachers to apply for grants and/or awards related to engineering education.
- Encourage teachers to join state and national technology associations such as ITEEA and ASEE and to present at professional conferences.
- Engage teachers as partners in research, as co-authors on papers and as members of project design committees and advisory boards. Enlist their help in disseminating findings and best practices to school and district audiences, parent groups, and local media.

In formulating partnerships to grow and sustain elementary engineering programs, we offer the following:

- Consider the particular interests, needs and incentives (the “what’s in it for me?”) of all stakeholders, from students to sponsors, administrators, teachers, education agencies, and even those within your own institution. Build in programming that provides for incentives and rewards for all stakeholders along the way, including financial rewards, if possible, but recognition in media, professional societies, and events. As an example, in the early stages of

the Engineering Our Future NJ initiative, we arranged for a U.S. Congressman to visit the school attended by the children of one of our corporate partner champions. This event provided media coverage that benefited the Congressman, the company, the school and the program! In addition, five teachers have received state and national recognition for their outstanding contributions and performance in the field of engineering education at the elementary level. One even received a \$10,000 cash award for her own use!

- Location, location, location! The *Field of Dreams* (“You build it and they will come”) adage does not necessarily apply to professional development for teachers, administrators, and guidance counselors. Find ways to reach educators where it is convenient to them, using both face-to-face and online communications. Our experience has shown that face-to-face programming has been much more popular than online programs, but we continue to explore and help teachers make use of online engineering resources, including social networking sites, to create awareness and visibility for your program and its participants.
- Select partners carefully. Know the “*what’s in it for me*” for all partners and make sure your goals and ways of operating are compatible. Choose partners that have the willingness and capacity to grow with you as your program expands.
- Consider sustainability and institutionalization within schools and districts. Long-term adoption and use of any innovation requires more than a single teacher’s enthusiasm. Build in programs to involve school and district administrators—principals, guidance counselors, curriculum supervisors, professional development supervisors, boards of education, parent representatives—in order to showcase highlights, accomplishments, learning outcomes, and student impact. Nothing works better than a combination of a compelling external evaluation study and a student presentation!
- Be creative, agile, flexible, and opportunistic. In the five years since the launch of our K-12 engineering programs, we have bootstrapped smaller programs into larger programs, involved local, regional, and national partners, and greatly expanded the footprint of K-12 engineering in NJ. We have paired engineering with other programs (science, art), and reached out to new educator constituencies, such as guidance counselors and boards of education. This has been the result of understanding the state and national education and policy landscape and funding opportunities.
- Lastly, listen to your “customer.” While some might object to the thought of teachers as “customers,” without them, we have no programs. Incorporate their feedback into new research questions and program improvements. Include them as co-presenters and co-authors. Nominate them for advisory boards and national recognition. Help them develop their “advocacy voice!” Your program’s impact is much more compelling coming from a “satisfied customer” than from the project director.

Conclusion

In the book, *Educating Engineers*, Sheppard et al¹⁵ articulate a vision of “networked engineering education,” in which students learn by experiencing an interconnected web of theoretical,

practical, contextual, and other knowledge, and which is designed to orient students to grapple with complex, ill-defined, problems that encompass technical and non-technical aspects. The authors describe the education needed to prepare “new-century engineers” as integrative, supporting synthesis of knowledge, requiring strong analytical skills, and cultivating mental habits of practical ingenuity, problem-definition, persistence, creativity, communication, and teamwork¹⁶.

Dr. Christine Cunningham said, “Just as it is important to begin science instruction in elementary school by building on children’s curiosity about the natural world, it’s important to begin engineering instruction in elementary school by building on children’s natural inclination to design and build things, and to take things apart to see how they work.....Children are born engineers. By encouraging these explorations in elementary school, we can keep these interests alive.”¹⁷

We believe that these types of learning experiences must begin in elementary grades or earlier, in order to create a technically-literate society and to build the technical workforce that our economy needs in the 21st century. This paper has attempted to describe some of the strategies for developing the programs to facilitate such experiences for all students starting in elementary grades.

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