AC 2008-873: ANALYSIS OF K-12 ENGINEERING EDUCATION CURRICULA IN THE UNITED STATES—A PRELIMINARY REPORT

Kenneth Welty, University of Wisconsin, Stout

Kenneth Welty is a Professor in the School of Education at the University of Wisconsin-Stout. He teaches a variety of undergraduate and graduate course in curriculum development, instructional methodology, and student assessment. He received his Bachelor's and Master's degrees from Illinois State University and earned his Doctor of Philosophy degree from the University of Illinois at Champaign/Urbana. Prior to joining the faculty at UW-Stout, he was a Visiting Professor in the College of Education at the University of Illinois, a Research Associate at Illinois State University, and a technology education teacher at Central Catholic High School in Bloomington, Illinois. His professional activities have included directing several curriculum development projects for the State of Illinois, researching people's attitudes towards technology, working with public schools to enhance their technology education programs, and serving as a curriculum consultant for the American Association for the Advancement of Science. He is currently an active member in the National Center for Engineering and Technology Education.

Linda Katehi, University of Illinois

Linda Katehi is the Provost and Vice Chancellor for Academic Affairs at the University of Illinois at Urbana Campaign, former Dean of Engineering and Professor of Electrical and Computer Engineering at Purdue University, and former Senior Associate Dean and Professor of Electrical Engineering and Computer Science at the University of Michigan. She chairs the National Academy of Engineering (NAE) and National Research Council Committee on K-12 Engineering Education. Prof. Katehi led efforts to establish the Purdue Department of Engineering Education, the first such department at a U.S. university to focus explicitly on engineering education. A key element of the department's work is research on K-12 engineering curriculum, standards, and teacher education. As a faculty member, Professor Katehi has focused her research on the development and characterization of three-dimensional integration and packaging of high-frequency circuits with particular emphasis on MEMS devices, high-Q evanescent mode filters and the theoretical and experimental study planar circuits for hybrid-monolithic and monolithic oscillator, amplifier, and mixer applications. Professor Katehi has been the author and co-author of 9 book chapters, she has published more than 550 articles in refereed journals and symposia proceedings, she owns 13 patents and has filed 7 patent applications. She is a member of the NAE, a fellow of the American Association for the Advancement of Science (AAAS), a member of the Nominations Committee for the National Medal of Technology, a member of the Kauffman National Panel for Entrepreneurship, a member of the NSF Advisory Committee to the Engineering Directorate, a member of the Engineering Advisory Committee for Iowa State University, a member of the NRC Army Research Lab Advisory Committee on Sensors and Electronics Division (SED), a member of the NSF Advisory Committee to CISE, a member of the NASA Aeronautics Technical Advisory Committee (ARAC), and a member of the DoD Advisory Group on Electron Devices. She recently served as a member of the NAE committee on the Future of Engineering Research.

Greg Pearson, National Academy of Engineering

Greg Pearson is a Senior Program Officer with the National Academy of Engineering (NAE) in Washington, D.C. In that role, he develops and manages new areas of activity within the NAE Program Office related to K-12 engineering education, technological literacy, and the public understanding of engineering. He currently serves as the responsible staff officer for three projects: Understanding and Improving K-12 Engineering in the United States, Exploring Content Standards for Engineering Education in K-12, and Developing Effective Messages for Improving Public Understanding of Engineering. He was the co-editor of the 2006 publication, Tech Tally: Approaches to Assessing Technological Literacy, and the 2002 publication, Technically Speaking: Why All Americans Need to Know More About Technology. Previous to this work, he oversaw an NAE review of technology education content standards developed by the International Technology Education Association. He works collaboratively with colleagues within and outside the National Academies on a variety of other projects involving K-12 science, mathematics, technology, and engineering education, and the public understanding of engineering and science. He has an undergraduate degree in biology from Swarthmore College and a graduate degree in journalism from The American University.

Michael Feder, National Research Council

Michael A. Feder is a program officer with Board on Science Education (BOSE) at the National Research Council. He is currently co-study director on three NRC studies: Understanding and Improving K-12 Engineering Education in the U.S, Learning Science in Informal Environments, and NASA K-12 Education Programs Review. He has a background in child development and education evaluation. His interests include applications of cognitive and social development theories to student learning, teacher development, research methods in education, and educational research to policy and practice dissemination. Prior to joining the NRC, Dr. Feder worked as an education program evaluator. During that time he contributed to various projects including the What Works Clearinghouse review of interventions for English language learners, and the evaluation of multiple state-wide Math and Science Partnership Programs. He has also evaluated the impact of subsidized non-Head Start daycare on the academic achievement of Hispanic children. Dr. Feder received his Ph.D. in Applied Developmental Psychology from George Mason University.

Analysis of K-12 Engineering Education Curricula in the United States--

A Preliminary Report[1]

Abstract

A number of initiatives in the United States have attempted or are attempting to develop or promote opportunities for K-12 students to learn engineering. For the most part, however, there is little evidence of what works, little agreement about how these efforts might be judged, and little understanding among the policy and practitioner communities about which initiatives sit on stronger or weaker theoretical foundations. This paper discusses preliminary observations from an analysis of nearly two dozen K-12 engineering curricula, conducted as part of a major study of K-12 engineering in the United States. Among other factors, the analysis examined the mission and goals of the curricula; the presence of engineering concepts, such as analysis, modeling, systems, and constraints; and the use of mathematics, science, and technology.

Introduction

Efforts to include engineering in the educational experiences of U.S. K-12 students are motivated by several concerns. For example, the engineering professional societies and many industries that depend on engineering talent have expressed concerns about both the number and quality of students graduating from engineering schools in the United States. Although experts disagree about the existence of a true engineering "shortage" in this country, there is no disagreement about the fact that women and certain minorities are seriously underrepresented in engineering studies and in the engineering workforce.[2] Nor is there disagreement about the desirability of making students more aware of science, technology, engineering and mathematics (STEM) career options. Thus one motivation for exposing children to engineering prior to college is the desire to correct imbalances in the engineering pipeline as well as make the pursuit of science and engineering careers more appealing. The problem-solving orientation and teamwork characteristics of engineering are also deemed desirable workplace attributes more generally,[3] suggesting another possible benefit of encouraging engineering thinking in the primary and secondary grades.

Many in the science and mathematics education communities believe that an engineering focus, particularly design activities, provides valuable context, application opportunities, and motivation for student learning as well as teacher engagement. [4 5] Design approaches to science teaching can focus student attention on solving specific problems, as in the Learning by Design (LBD) method developed by Kolodner et al.[6] LBD purposefully links the design aspects of problem solving with an "investigate and explore" phase, which in significant ways resembles and reinforces the process of science inquiry. Fortus et al.'s [7] design-based science units have a similar orientation. Modeling and design activities can also be used very deliberately to illustrate and make concrete science concepts, such as mechanical advantage.[8]

The technology education profession, for its part, is striving to respond to the new emphasis on engineering spelled out in the *Standards for Technological Literacy: Content for the Study of*

Technology.[9] Many in the profession believe technology education's historical emphasis on hands-on, project-based instruction is well suited to presenting engineering concepts and practices.[10]

This paper presents preliminary observations from an analysis of curriculum materials that are playing or might play a role in K-12 engineering education in the United States. The analysis was conducted as part of a larger project being conducted by the National Academy of Engineering and the National Research Council. Some of the materials explicitly espouse the study of engineering in their titles, while others do not aspire to teach engineering but are noteworthy because they utilize engineering contexts and design to make the core curriculum more authentic, interdisciplinary, or engaging for students.

For the purposes of this research, engineering was operationally defined as "design under constraint,"[11 12] where the constraints include the laws of nature, cost, safety, reliability, environmental impact, manufacturability, and many other factors. While science attempts to discover what is, engineering is concerned with what might be—with extending human capability through modifying the natural world. It is important to note that care had to be taken to discriminate between industrial design and engineering design. At the risk of oversimplification, industrial design was equated with design endeavors that draw heavily on aesthetic principles to inform a given design with an emphasis on form. In contrast, engineering design draws on mathematics and science to inform the development of a solution to a problem with an emphasis on function.

Curriculum Selection

In order to bound the analysis, criteria were developed for selecting the materials that would be studied. Several considerations played a role in the screening process. To be considered for inclusion in the study, each initiative had to engage young people in the study or practice of design. This could be in the form of guiding students through the engineering design process or it could involve an analysis of existing solutions to engineering design problems from the past. Furthermore, the treatment of design had to address two or more of the following engineering concepts: analysis, constraints, modeling, optimization, and systems.

Each initiative also had to feature an explicit treatment of mathematics and/or science in the context of addressing engineering problems. Finally, each initiative had to be of a scale, maturity, and rigor to justify the time and resources needed to conduct an analysis. More specifically, to be included in the study, each initiative had to be designed to be used by people or organizations outside the group responsible for its initial development. It also had to contain one or more salient pieces that have undergone field testing or external evaluation and subsequent revision and are no longer being identified as "drafts."

The K-12 engineering education initiatives that so far have met the selection criteria are listed in Table 1. It is possible that additional materials will be added to the analysis or that some currently listed will not receive a full review. At the time this paper was prepared, reviews for only about a third of the materials had been completed; another third were in some intermediate stage of review. Thus, the observations that follow must be considered preliminary in nature.

TABLE 1

Curriculum Title	Developer
Pre-K	
1. Young Scientist Series—Building Structures	Educational Development Center
Elementary	
2. City Technology/Stuff That Works	City College of New York
3. Children Designing & Engineering	The College of New Jersey
4. Engineering is Elementary	Boston Museum of Science
5. World in Motion	Society for Automotive Engineers
6. Full Option Science System	Lawrence Hall of Science
Middle School	
7. Design & Discovery	Intel Corporation
8. Engineering by Design	International Technology Education Assoc.
9. Exploring Design & Engineering	The College of New Jersey
10. Gateway to Technology	Project Lead the Way
11. World in Motion	Society for Automotive Engineers
12. Technology Education: Learning by Design	Hofstra University
High School	
13. Introduction to Engineering Design	Project Lead the Way
14. Engineering by Design	International Technology Education Assoc.
15. Engineering the Future	Boston Museum of Science
16. Exploring Design & Engineering	The College of New Jersey
17. Designing for Tomorrow	Ford Partnership for Advanced Studies
18. Infinity Project	Southern Methodist University
19. Materials World Modules	Northwestern University
20. What is Engineering	Johns Hopkins University
21. World in Motion	Society for Automotive Engineers
Other	
22. Teach Engineering (web-based)	Five-University Collaboration with ASEE

NOTE: Project Lead the Way has a number of high school units in addition to Introduction to Engineering Design. Due to time and resource constraints, only one unit was analyzed in this project.

Review Process

The curriculum review process was conducted by teams of doctorial fellows at the NSF-funded National Center for Engineering and Technology Education (NCETE) overseen by NCETE co-PI Ken Welty. The reviewers began by skimming of the curriculum documents, noting the topics being addressed, discovering how the contents were organized, and determining what was included in the curriculum and instruction. These cursory reviews indicated the presences or absence of things like objectives, standards, vocabulary terms, learning activities, design problems, projects, laboratory experiences, illustrations, examples, or assessment tools.

Each document then received a more careful reading, during which the noteworthy concepts, skills, or dispositions being addressed were tagged with color-coded strips. Special attention was paid to instances where mathematics, science, technology, and engineering concepts were mentioned. The reviewers also attempted to identify the basic principles of teaching and learning that underpinned each piece of the curriculum and instruction. Summary write-ups for each curriculum reviewed were then prepared.

Nature of K-12 Engineering Curricula

The search for K-12 engineering education curricula revealed an extremely wide variety of products. No two are alike in mission, content, format, or pedagogy. To date, the collection represents over 10,000 pages of curricula including lengthy narratives downloaded off the web, distributed on compact disks, assembled in three-ring binders, and bound in the form of textbooks. The sources of these materials include curriculum projects, government agencies, research initiatives, private corporations, professional organizations, and nonprofit foundations.

The depth and breadth of these materials range from 425 pages on a topic as narrow as gliders to a mere 46 pages on a topic as broad as biotechnology. The cost of the materials ranged from $1,100 for a series of 8 three-ring binders to a half-dozen large boxes of curricula and laboratory materials that were free upon request. The contents of these materials ranged from major curriculum initiatives that do not have a single objective to modest pieces of work that featured over 60. In some cases, the curricula can be implemented with everyday items at very little cost while others require large capital investments for specific and elaborate pieces of laboratory equipment or training.

Purposes for Engineering in K-12

The purposes for developing materials that embraced the study of engineering were as varied as the materials themselves. In some cases, the materials were developed, at least in part, to address the technological literacy needs of students. This was especially evident in the books written by the *City Technology* project. Their central focus was to "…engage elementary children with the core ideas and processes of technology (or engineering, if you prefer)." The *Engineering is Elementary* project set out to harness children's natural curiosity to promote "[the] learning of engineering and technology concepts." Similarly, the *Exploring Design and Engineering* initiative sought to "…help youngsters discover the 'human-made world,' its design and development." The *Engineering the Future* course was designed to "help today's high school students understand the ways in which they will engineer the world of the future — whether or not they pursue technical careers."

In other cases, the curricula were developed to leverage the hands-on and interdisciplinary nature of technology. For example, the *Children Designing & Engineering* project sought to "…develop innovative and unique contextual learning units that challenge students to think, act and share." Similarly, the *Ford Partnership for Advanced Studies* (*Ford PAS*) aimed to provide high school students with "…high-quality interdisciplinary learning experiences that challenge them academically and develop their problem-solving, critical thinking, and communication skills."

Another prominent thrust was to enhance thinking skills by engaging students in designing solutions to technical problems. For instance, one of the inspirations for Project Lead the Way's *Gateway to Technology* was "…to show students how technology is used in engineering to solve everyday problems." The *Engineering is Elementary* program set out to develop "…interesting problems and contexts and then invite children to have fun as they use their knowledge of science and engineering to design, create, and improve solutions." *Design and Discovery* "engages students in hands-on engineering and design activities intended to foster knowledge, skill development, and problem solving in the areas of science and engineering."

In many cases, the primary reason for including engineering was to enhance the study of science and mathematics. For example, the mission of the *Materials World Modules* was to improve science education by engaging students in the intellectual processes of inquiry and design. Consistent with this mission, the modules were designed to enhance the teaching of traditional science curricula by facilitating greater student awareness of the relationships between scientific and technological concepts and real-world applications. Similarly, the *Infinity Project* developed its materials to provide "… an innovative approach to applying fundamental science and mathematics concepts to solving contemporary engineering problems." *A World in Motion* designed its materials to facilitate a "…exploration of physical science while addressing essential mathematic and scientific concepts and skills."

Lastly, some of the materials were designed to prepare young people for further education and ultimately professional careers. *Ford PAS* "encourages and prepares students for success in college and professional careers in fields such as business, engineering, and technology." One of the central goals of the *Infinity Project* was to "help close the gap between the number of engineering graduates we currently produce in the United States, and the large need for high-quality engineering graduates in the near future."

Content Origins and Frameworks

Engineering is a significant human endeavor that permeates culture, underpins quality of life, and facilitates progress. It is a sophisticated enterprise combining different fields of study that interact to solve problems and advance technology. Unpacking the nature of engineering, identifying its salient attributes, and developing the lenses through which it can be studied and subsequently understood is fraught with complexity and compromise. Consequently, it was not surprising to discover that curriculum developers used a wide range of strategies to operationalize the study of engineering.

The only curriculum initiative to use traditional fields of engineering as content organizers was the *Engineering is Elementary* project. Most initiatives simply use interesting topics to package curricula into manageable chunks and compose programs of study (e.g., *City Tech., Exploring Design and Engineering, The Infinity Project, Material World Modules, Learning By Design*). Others clearly organized their curriculum and instruction around popular learning activities (e.g., *Gateway to Technology, A World in Motion*). Several sets of materials were organized around the design process with very little attention given to domain knowledge. This was especially evident in the *Design and Discovery* curriculum by the Intel Corporation. The *Children Designing and Engineering* project used prominent enterprises in their region as the inspiration for interdisciplinary thematic units that integrated content from different school subjects in authentic contexts.

Despite their different approaches to the study of engineering, there are some common threads that run through many of the materials in the collection. The most prominent thing that all the materials have in common is an emphasis on student engagement. Without exception they all feature rich learning activities that involve things like examining, designing, making, and testing.

Another common feature that can be found in most of the materials is the desire to engage students in "doing design." Most of the materials feature problems that have to be solved by gathering and processing information, generating and refining ideas, making and testing solutions, and presenting and defending the result to others. The role of design was especially prominent in the materials for *Engineering is Elementary*, *Children Designing and Engineering*, *Exploring Design and Engineering*, *Engineering the Future*, and *Design and Discovery*. The importance of inquiry to inform design decisions was very evident in the *City Technology*, *Material World Modules*, and *A World in Motion* materials.

Some of the materials gave deliberate attention to careers. This attention typically included description of the work that people in various occupations perform. The *Children Designing and Engineering* curricula had the greatest breadth of careers that included occupations beyond engineering. The *Engineering is Elementary* and the *Engineering the Future* materials focused more specifically on careers in engineering. These latter two curricula take great care to showcase under-represented and under-served populations as engineers.

Treatment of Engineering Concepts

One of the more salient indicators of engineering design was the presence of analysis. Evidence of analysis included any systematic and detailed examination that was used to define problems, predict performance, determine economic feasibility, evaluate alternatives, assess performance, or investigate failures. The review of the materials uncovered isolated instances where some form of analysis was used to define and clarify the problem, to make informed design decisions, or to predict and assess performance. For example, in several curriculum projects, students are asked to manipulate and test variables to discover patterns that can be used to inform or optimize a design. This form of inquiry was very evident in *A World in Motion*, *City Technology*, *Engineering is Elementary*, and the *Material World Modules*. However, analysis was rarely a reoccurring theme throughout a design process.

Another concept that was considered to be an integral part of engineering was constraints. Any attention given to the physical, economical, political, social, ethical, aesthetic, and time limitations inherent to or imposed upon the design of a solution to a technical problem was considered to be a constraint. Most of the attention given to constraints was attached to the learning activities in contrast to being integral to the design process. These constraints were attached to the materials that students used to address the problems for the purposes of managing finite supplies, storage space, or time. In other cases, the constraints were more authentic and they were embedded in the scenarios that contained the problems that the students were asked to address.

Modeling was another noteworthy element of engineering that warranted attention. For the purposes of this inquiry, a model was any graphic, physical, or mathematical representation of the essential features of a system or process that aids in facilitating the engineering design process. Most of the materials utilized some form of modeling to facilitate instruction. However, the use of models as tools in the design process was not as frequent. In most instances, models were student made artifacts that served as teaching tools. Furthermore, these models tended to be physical or graphical representations of design ideas. They were rarely mathematical or sources of data for making inferences.

The review was also attentive to the concept of optimization. Operationally, optimization was considered a pursuit of the best possible solution to a technical problem in which there are competing or conflicting factors that involve balancing trade-offs. However, most of the materials equated optimization with "think harder" and "make it even better" under the auspices of what is commonly associated with iteration and redesign. The improvement of a given design was often based on brainstorming in contrast to an analysis. Very little, if any, attention was given to trade-offs. Furthermore, very little attention was given to the roles that mathematics plays in optimization, especially when addressing the economic factors that influence design decisions.

The concept of systems was another variable that was sought in the curriculum review process. Attention to systems included any reference to organized collections of discrete elements (e.g., parts, processes, and people) that are designed to work together in interdependent ways to fulfill one or more functions. The treatment of systems was especially apparent in the curriculum initiatives that focused on domain knowledge. In these cases, systems thinking was often a subtle part of the storyline that explained how a technology in question works. In rare cases it was part of an analysis that explored why something failed or how something could be improved.

Treatment of Mathematics, Science, and Technology

For the purpose of this inquiry, mathematics was the patterns and relationships among quantities, numbers, and shapes. It also included arithmetic, geometry, algebra, trigonometry, and calculus. However, most of the mathematics in engineering curricula simply involved taking measurements and gathering, organizing and presenting data. Very little attention was given to using mathematics to solve for unknowns. Furthermore, little attention was given to the power of mathematical models in engineering design.

Science was defined as the study of the natural world. Operationally, it included the laws of nature associated with physics, chemistry, and biology. Any treatment or application of the facts, principles, concepts, and conventions associated with these disciplines was considered science. The most common topics found in K-12 engineering curricula were materials, mechanisms, electricity, energy, and structures. Most of the science content was presented in the form of encyclopedia-like explanations. A majority of the inquiries that students were asked to conduct was dedicated to making design decisions in contrast to uncovering, illuminating, or validating laws of nature.

For the purposes of this review, technology was the study of the human-made world from a macro perspective. More specifically, it is the knowledge, techniques, systems, and artifacts created by humankind in response to wants and needs. In most cases, the study of technology was simply domain knowledge. In other instances, technology was presented as a concrete example of a scientific principle. This was especially evident in curricula that deliberately used engineering ideas or context to enrich science and mathematics.

Final Comments

Because the curriculum analysis described in this paper is not yet complete, it is not possible to draw definitive conclusions about the nature and scope of efforts to introduce engineering to K-12 students in the United States. The larger study of which this research is a part will conclude at the end of 2008 with publication of a report, and that document will make more definitive statements about existing engineering curricula, teacher professional development efforts, and other salient issues.

What is clear even from this preliminary research is the great diversity—in content, organization, and purpose—of many of the curricular materials that have been developed to-date. This diversity reflects the complexity and breadth of modern engineering. At the same time, it poses challenges to educators and policy makers seeking to understand how—or whether—engineering can become a more regular part of U.S. pre-college education. The noticeably thin presence of mathematics, as well as of some key engineering concepts, such as modeling and analysis, raises additional questions about the difficulty of developing curricula that authentically represent the practice of engineering.

Another important question, not addressed in this paper but to be considered in the larger project's final report, is what impact K-12 engineering education has had on such things as student engagement and retention; achievement in mathematics, science, and technology; student understanding of engineering; and student intentions to consider engineering as a possible career path.

Bibliography

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[1] This paper is adapted from a paper presented November 8, 2007, by Ken Welty at the 94th annual Mississippi Valley Technology Teacher Education Conference in Rosemont, Ill.

[2] NSB (National Science Board). 2002. Science and Engineering Indicators 2002. January 2002. NSB-02-01C. Arlington, Va: NSB.

[3] See, for example, the core competencies described in the various reports of the Secretary's Commission on Achieving Necessary Skills (http://wdr.doleta.gov/SCANS/).

[4] deGarzia, J.L. 2001. Engineering Workshops for K-12 School Teachers. Paper from the 31st ASEE/IEEE Frontiers in Education Conference. Reno, Nev., Oct. 10-13, 2001.

[5] Kimmel, H, and R. Rockland. 2002. Incorporation of Pre-Engineering Lessons into Secondary Science Classrooms. Paper from the 32st ASEE/IEEE Frontiers in Education Conference. Boston, Nov. 6-9, 2002.

[6] Kolodner, J.L., P.J. Camp, D. Crismond, B. Fasse, J. Gray, J. Holbrook, S Puntambekar, and M. Ryan. 2003. Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design into practice. The Journal of the Learning Sciences, 12(4): 495-547.

[7] Fortus, D., R.C. Dershimer, J. Krajcik, R.W. Marx, and R. Mamlok-Naaman. 2004. Design-based science and student learning. Journal of Research in Science Teaching.

[8] Penner, D., Giles, N.D., Lehrer, R., & Schauble, L. 1997. Building functional models: Designing an elbow. Journal of Research in Science Teaching, 34, 135–143.

[9] International Technology Education Association (ITEA). 2002. Standards for Technological Literacy: Content for the Study of Technology. Reston, Va.: ITEA.

[10] Dearing, B.M., and M.K. Daugherty. 2004. Delivering Engineering Content in Technology Education. The Technology Teacher 64 (3): 8-11.

[11] American Association for the Advancement of Science. 1990. Chapter 3: The nature of technology, pp. 28-29, Science for All Americans. New York: Oxford University Press.

[12] Phal, G., W. Beitx, J. Feldhusen, and K.H. Grote. 2007. Engineering Design: A Systematic Approach. London: Springer-Verlag.