Understanding and Improving K-12 Engineering in the United States

Project Summary for Public Comment

Committee on K-12 Engineering Education

National Academy of Engineering
National Research Council

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INTRODUCTION

This report summarizes key activities of the Committee on K-12 Engineering Education. The committee operates under the auspices of the National Academy of Engineering (NAE; www.nae.edu) and National Research Council Board on Science Education (www7.nationalacademies.org/bose), both part of The National Academies (www.nationalacademies.org). The 24-month project is funded by NAE member Stephen D. Bechtel, Jr., with additional support from Parametric Technology Corp., Inc.

The committee is in the preliminary stages of writing its final project report and seeks input and comment on its work from those interested in the topic of K-12 engineering education. Under the rules of the Academies, the committee is not permitted to publicly discuss its findings and recommendations until publication of its own report, scheduled for early in 2009. Therefore, this summary does not include findings and recommendations.

This document provides background information on the project; presents the committee's working definition of engineering and related terms; describes the project's curriculum analysis effort; outlines the committee's effort to survey the literature on engineering concept and skill development; briefly reviews evidence for the impact of K-12 engineering initiatives; and lists a number of pre-college engineering education initiatives in other countries.

The report concludes with a brief discussion of key issues and questions. While the committee welcomes comment on any aspect of the project, it particularly welcomes responses to these questions.

All of the material presented here should be considered preliminary. The committee is working to finalizing its findings, conclusions, and recommendations. The committee's final report may differ in important respects from the contents of this public summary.

Comments on the summary report should be submitted via e-mail no later than May 15 to: k-12engineering@nae.edu. This document may be downloaded at: www.nae.edu/k-12engineering.

PROJECT BACKGROUND

Over the past 10-15 years, a number of efforts to include engineering in the educational experiences of U.S. K-12 students have been launched. While most are relatively small in terms of pupils reached, a few have grown to considerable size. These programs are motivated by several factors. Industry and government are concerned about the size, diversity, and quality of the U.S. engineering workforce. In addition, a basic understanding of engineering and its relation to science, mathematics, and technology is considered an important attribute of both scientific and technological literacy. And 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 and engagement.

The variety and relative immaturity of initiatives to introduce engineering concepts and practices in the K-12 classroom suggest a number of challenges. At the level of practice, individual schools and teachers are faced with accommodating additional content in an already crowded curriculum. Curriculum developers, for their part, often try to create content connections between engineering and other subject areas, in the absence of information about appropriate learning outcomes or effective strategies for conveying engineering concepts. Policy makers concerned about K-12 student achievement in mathematics and science must consider the potential value of engineering education with little information to assist such decision making.

Project Goals and Objective

The goal of this project is to provide carefully reasoned guidance to key stakeholders[1] regarding the creation and implementation of K-12 engineering curricula and instructional practices, focusing especially on the connections among science, technology, engineering, and mathematics education.

The project has the following objectives:

1. Survey the landscape of current and past efforts to implement engineering-related K-12 instructional materials and curricula in the United States and other nations.
2. Review evidence related to the impact of these initiatives, to the extent such information is available;
3. Describe the ways in which K-12 engineering content has incorporated science, technology, and mathematics concepts, used these subjects as context to explore engineering concepts, or used engineering as a context to explore science, technology, and mathematics concepts; and
4. Report on the intended learning outcomes of K-12 engineering education initiatives, taking into account student age, curriculum focus (e.g., science v. technology education), program orientation (e.g., general education v. career/vocational education), and other factors.

Guiding Questions

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[1] The stakeholder group includes the U.S. K-12 science, mathematics, and technology education communities; engineering and science practitioners involved in K-12 education; education policy makers at the local, state, and national level; and industries concerned with the quality and composition of the U.S. science, engineering, and technician workforce.

In meeting the goal and objectives, the project will focus on three key issues and three related guiding questions:

1) There are multiple perspectives about the purpose and place of engineering in the K-12 classroom. These points of view lead to emphases on very different outcomes.

    QUESTION: What are realistic and appropriate learning outcomes for engineering education in K-12?

2) There has not been a careful analysis of engineering education within a K-12 environment that looks at possible subject intersections.

    QUESTION: How might engineering education complement the learning objectives of other content areas, particularly science, technology, and mathematics, and how might these other content areas complement learning objectives in engineering education?

3) There has been little if any serious consideration of the systemic changes in the U.S. education system that might be required to enhance K-12 engineering education.

    QUESTION: What educational policies, programs, and practice at the local, state, and federal levels might permit meaningful inclusion of engineering at the K-12 level in the United States?

The Academies Study Process

For more than 140 years, the National Academies have been advising the nation on issues of science, technology, and medicine. The 1863 Congressional charter signed by President Lincoln authorized this non-governmental institution to honor top scientists with membership and to serve the nation whenever called upon. Today, the National Academies—the National Academy of Sciences, National Academy of Engineering, Institute of Medicine, and the National Research Council—continue that dual mission.

The National Academies enlist the nation's foremost scientists, engineers, health professionals, and other experts to address the scientific and technical aspects of some of society's most pressing problems. Each year, more than 6,000 of these experts are selected to serve on hundreds of study committees that are convened to answer specific sets of questions. All serve without pay.

Federal agencies are the primary financial sponsors of the Academies' work. Additional studies are funded by state agencies, foundations, other private sponsors, and the National Academies endowment. The Academies provide independent advice; the external sponsors have no control over the conduct of a study once the statement of task and budget are finalized. Study committees gather information from many sources in public meetings but they deliberate in private in order to avoid political, special interest, and sponsor influence.

Through this careful study process, the National Academies produce 200–300 authoritative reports each year. Recent reports cover such topics as the obesity epidemic, the use of forensics in the courtroom, invasive plants, underage drinking, the Hubble Telescope, vaccine safety, the hydrogen economy, transportation safety, climate change, and homeland security. Many reports influence policy decisions; some are instrumental in enabling new research programs; others provide program reviews.

Study Committee

To oversee the project, the Academies appointed a 15-member study committee (Table 1) with a balance of expertise in research, practice, and policy related to STEM learning and teaching, with an emphasis on engineering. To account for the focus on teaching and learning in K-12 populations, the committee includes both individuals working at the classroom, school, and system level as well as those engaged in curriculum development and research. Expertise in the cognitive sciences is included so that committee deliberations are informed by findings from research on learning. Content expertise is present in several engineering disciplines (e.g., electrical, mechanical, systems), in the natural and physical sciences (e.g., environmental health, physics, biology, zoology), in mathematics, and in technology. To address the potential role of K-12 engineering in supporting a more STEM-talented workforce, members are included from industries with experience in K-12 outreach. To avoid the appearance of conflict of interest in its analysis of K-12 engineering programs, the committee membership does not include representatives from some of the larger such programs (e.g., Project Lead the Way, Infinity Project, Boston Museum of Science).

TABLE 1 Committee on K-12 Engineering Education

Linda Katehi (Chair)
Provost and Vice Chancellor for Academic Affairs
University of Illinois at Urbana-Champaign

Lynn Basham
Technology Education Specialist
Virginia Department of Education
Richmond, VA

M. David Burghardt
Professor of Engineering
Co-Director, Center for Technological Literacy
Hofstra University
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Kathleen Conn
Assistant Professor
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Alan G. Gomez
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Sun Prairie High School
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Craig Kesselheim
Senior Consultant
Great Maine Schools Project
Senator George Mitchell Institute

Portland, ME

Michael C. Lach
Director of Mathematics and Science
Chicago Public Schools
Chicago, IL

Rich Lehrer
Professor
Department of Teaching and Learning
Peabody College of Vanderbilt University
Nashville, TN

Deborah McGriff
Executive Vice President and Chief
Relations Officer
Edison Schools
New York, NY

Roland J. Otto
STEM Education Consultant
Berkeley, CA

Richard Schaar
Math and Science Education Policy Advisor
Texas Instruments
Plano, TX

Mark Schroll
The Kern Family Foundation
Waukesha, WI

Christian D. Schunn
Assistant Professor, Dept. of Psychology
University of Pittsburgh
Pittsburgh, PA

Jacquelyn F. Sullivan
Co-Director, Integrated Teaching and
Learning Program
University of Colorado – Boulder

Robin Willner
Vice President Global Community
Initiatives
IBM
Armonk, NY

Project Activities and Timeline

The study committee will have had five face-to-face meetings by the time the project ends. It met for the first time in April 2007 and will meet for the last time in early June 2008. Two of the committee's meetings were held in conjunction with information-gathering workshops. (Agendas for these workshops appear in an appendix to this report.) The committee's final report is expected to be published in early 2009.

Curriculum Analysis

A major component of the project has been the collection and analysis of some two dozen K-12 curricula that include major elements related to engineering (Table 2). The analysis is being led by Dr. Kenneth Welty, University of Wisconsin—Stout. Dr. Welty is a Co-PI at the NSF-funded National Center for Engineering and Technology Education. More detailed information on the analysis is presented in the section, Curriculum Analysis, below.

TABLE 2 Curricula Currently Being Considered in NAE/NRC Project on K-12 Engineering

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
7. Invention, Innovation, and Inquiry	International Technology Education Association
Middle School	
8. Design & Discovery	Intel Corporation
9. Engineering by Design	International Technology Education Association
10. Exploring Design & Engineering	The College of New Jersey
11. Gateway to Technology	Project Lead the Way
12. World in Motion	Society for Automotive Engineers
13. Technology Education: Learning by Design	Hofstra University
14. Learning by Design	Georgia Institute of Technology
High School	
15. Introduction to Engineering Design	Project Lead the Way
16. Engineering by Design	International Technology Education Association
17. Engineering the Future	Boston Museum of Science
18. Exploring Design & Engineering	The College of New Jersey
19. Designing for Tomorrow	Ford Partnership for Advanced Studies
20. Infinity Project	Southern Methodist University
21. Material World Modules	Northwestern University
22. What is Engineering	Johns Hopkins University
23. World in Motion	Society for Automotive Engineers
Other	
24. Teach Engineering (web-based)	Five-University Collaboration with ASEE

In addition to workshops and the curriculum analysis, the committee commissioned literature reviews in several areas of key importance to the project. These commissioned papers, described later in this summary, addressed the following topics:

- Conceptual Learning Related to Engineering
- Learning Design Skills in Engineering
- Impacts of K-12 Engineering Education
- Pre-University Engineering Education Initiatives Outside of the United States

NOTE: Any findings, conclusions, or recommendations presented in the summaries of the commissioned papers are those of the author(s), not the Committee on K-12 Engineering Education.

DEFINING KEY TERMS

Before the committee could intelligently consider issues related to K-12 engineering education, it had to first come to some agreement on what engineering is. A number of related words and terms, such as engineering design, modeling, and optimization, also warranted defining.

> **Engineering** — a process for creating the human-made world, the artifacts and processes that never existed before. This is in contrast to science, the study of the natural world. Most often engineers do not literally construct the artifacts, they provide plans and directions for how the artifacts are to be constructed. Artifacts may be as small like a hand calculator or large like a bridge. They also design processes, the processes may be those used in chemical and pharmaceutical industries to create chemicals and drugs, to directing how components are put together on an assembly line, or indicating how checks are to be processed in banking.
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> **Engineering Design Process** — the iterative process for creation and manipulation of the human-made world. The process combines knowledge and skills from a variety of fields with the application of values and understanding of societal needs to create systems, components, or processes to meet human needs. Initialized by problem definition, followed by clarity of the specifications that the designed product must meet, the open-ended engineering design process optimizes competing needs and constraints, and uses modeling and analysis to drive the creation of new engineered solutions to serve humankind.
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> **Technology** — the artifacts of the human-made world (e.g., computers and software, aircraft, pesticides, water-treatment plants, birth-control pills, and microwave ovens). Technology also includes the knowledge and processes used

to create and to operate the artifacts—engineering know-how, manufacturing expertise, various technical skills, and so on—are equally important. An especially important area of knowledge is the engineering design process, of starting with a set of criteria and constraints and working toward a solution—a device, say, or a process—that meets those conditions. Technology also includes all of the infrastructure necessary for the design, manufacture, operation, and repair of technological artifacts, from corporate headquarters and engineering schools to manufacturing plants and maintenance facilities.

Technology Education — a subject of study in K-12 schools involving the investigation of the human-made world, its artifacts, and processes. One important goal of technology education is to produce students who are technologically literate, in the broad meaning of the term (e.g., as described in *Technically Speaking: Why All Americans Need to Know More About Technology,* National Academy Press, 2002).

Science—the study of the natural world and the knowledge gained from that study. Among the many science disciplines, physics, chemistry, and biology are most relevant to the practice of engineering. A central component of science is the process of inquiry, which involves making observations; posing questions; gathering information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations.

Mathematics—the body of knowledge centered on such concepts as quantity, structure, space, and change, and also the academic discipline that studies them. Among the many fields of mathematics, applied mathematics, which includes mathematical physics, probability, numerical analysis, optimization, fluid dynamics, and statistics, are most relevant to engineering.

Modeling — in engineering, a way to better understand what may happen to an actual device or system during its intended use. Models may consist of drawings or physical, three-dimensional renditions. Models incorporate assumptions about the device or system's size, shape, and physical properties, among other considerations. Using this representational model, the engineer may create a so-called free-body diagram, which shows the various forces—such as gravity, compression, and tension—acting on the device or system. From the free-body diagram, the engineer can develop a mathematical model based on laws of mechanics.

Predictive Analysis—the process of creating representational models of potential solutions and then mathematically characterizing them. This allows engineers to predict the behavior of technologies before they are built. The predictions can then be tested experimentally. The accuracies of the representational and the mathematical models determine how valid the predictions are. This process of predictive analysis is a central feature of engineering design.

Specifications—the performance requirements, or output requirements, the design solution must fulfill. The design specifications for toothpaste might include that it cleans plaque from teeth, tastes good, and can be squeezed easily out of a tube. A design specification for a certain type of car might be that it can accelerate from 0-60 mph in under 10 seconds. Design specifications often include safety considerations. Stating that a passenger elevator must have a safety factor ten times greater than the load it is expected to carry, or that the front of a car will not be damaged after a crash of 5 mph, are specifications the design must meet. Other common types of specifications relate to a technology's reliability, ergonomics, environmental considerations and manufacturability.

Constraints—the limitations imposed upon the design solution. Constraints are often related to resources such as the materials the designer is able to use, how much money a finished product can cost, or how much time can be devoted to producing it. Other limitations can relate to the availability of certain kinds of workers or the need to limit negative effects of the design on the environment. Constraints can also include socio-political factors, such as laws or regulations that place limits on the design, for instance, how much pollution or noise it can create, what materials it must or cannot use, and so on.

Optimization—the process of determining the best solution to a technical problem, while balancing competing or conflicting factors (constraints). Often, different alternatives will be better in different ways. For example, one material may be stronger, but a second material may cost less. Choosing the best solution normally requires trade-offs. That is, one must give up maximizing one desirable thing for another. In such cases, deciding which criteria are the most important helps in determining the best solution to the problem. The idea is to decide upon a design that best meets the specifications, fits within the constraints, and has the least number of negative characteristics.

CURRICULUM ANALYSIS

A major element of the project was the collection and analysis of curricula used to teach engineering concepts and skills in K-12 classrooms. This effort was intended to give the committee a sense of the K-12 engineering "landscape" in the United States. The committee recognizes that there are numerous efforts to introduce engineering to K-12 students outside of formal school settings, through websites, contests, after-school programs, and summer experiences. However, the charge to the committee did not include examining informal K-12 engineering education, and so these initiatives are not addressed in this summary.

As noted in the Introduction, the information provided in this section may differ in important ways from what finally appears in the committee's own report.

The initial identification of curricula for possible inclusion in the study was accomplished through the joint efforts of the curriculum researcher (Welty), committee, and project staff. The methods included review of Web sites of relevant professional organizations, government agencies, and corporations with an interest in engineering education, as well as searches of on-line curriculum clearinghouses and libraries. Additional curricula were identified in direct communication with engineering educators, technology teacher educators, supervisors from state departments of education, and principal investigators of known K-12 engineering education programs and projects.

Selection Criteria

In order to bound the analysis, the committee developed criteria to help guide the selection of curricula.

Design

To be included the analysis, a curriculum must engage young people in the study of design. This can be in the form of student participation in an engineering design process or it can involve student analysis of existing solutions to engineering design problems from the past. The treatment of design must address two or more of the following concepts.

<u>Analysis</u>	A systematic and detailed examination that is used to define problems, predict performance, determine economic feasibility, evaluate alternatives, or investigate failures.
<u>Constraints</u>	The physical, economical, political, social, ethical, aesthetic, and time limitations that are inherent to or imposed upon the design of a solution to a technical problem.
<u>Modeling</u>	A graphic, physical, or mathematical representation of the essential features of a system or process that aids in facilitating the engineering design process.
<u>Optimization</u>	The pursuit of the best possible solution to a technical problem in which there are competing or conflicting factors that involve the balancing of trade-offs.
<u>Systems</u>	Organized collections of discrete elements (e.g., parts, process, people) that are designed to work together in interdependent ways to fulfill one or more functions.

Mathematics and Science

Each curriculum must feature an explicit treatment of mathematics and/or science in the context of addressing engineering problems.

Engineering, Technology, and Society

Each initiative must also include at least one of the following attributes to be included in the study:

1. Engages young people in addressing authentic problems that are derived from situations in everyday life or work outside of school.
2. Engages young people in understanding, developing, or improving technology (i.e., human-made objects; systems for the creation and production of human-made objects; knowledge related to the creation, production, and use of human-made objects).
3. Engages young people in an examination of the positive or negative impacts, including those that were anticipated and unanticipated, that engineering endeavors have on individuals, society, and the environment.

General Considerations

The following general considerations were used to screen the selection of the curricula that were analyzed.

<u>Size</u>	The curriculum was designed to be used by people and organizations outside the group that is responsible for its initial development.
<u>Maturity</u>	The curriculum contains one or more salient pieces that have undergone field testing and subsequent revision and are no longer being identified as "drafts."
<u>Rigor</u>	The development of the curriculum involved a review of the initial concept, pilot or field-testing, iterations based on feedback, and some form of external evaluation.

Review Process

The 24 curriculum projects being examined as part of the project represent over 10,000 pages of materials that include lengthy narratives downloaded off the web, distributed on compact disks, assembled in three-ring binders, and bound in the form of textbooks.

The review process was overseen by Dr. Ken Welty with help from graduate fellows at the National Center for Engineering and Technology Education. The reviews began with a detailed content inventory of each curriculum. The inventory identified salient instances of engineering, technology, mathematics, and science concepts and skills. The researchers also examined the curricula for their stated goals, pedagogical strategies employed, prominent activities, and treatment (if any) of content standards. To the extent such information was available, the researchers also attempted to document the extent of the curricula's implementation and any findings related to impact. The curricula's authors were contacted, as needed, to provide relevant background information, clarify certain details of the materials, or confirm the researcher's findings.

Dr. Welty prepared a summary report for each curriculum analysis. The committee divided into three subgroups, each of which reviewed and discussed one-third of the summary reports. Each subgroup then reported its conclusions to the committee as a whole.

Preliminary Observations[2,3]

The curriculum materials collected and analyzed for this project are extremely diverse in their focus, content, and requirements for implementation. 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; others required large capital investments for specific and elaborate pieces of laboratory equipment.

Purpose for Engineering

The purposes for developing curricula that embraced the study of engineering are as varied as the materials themselves. Some materials (e.g., City Technology, Engineering is Elementary) were developed at least in part to encourage technological literacy, as

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[2] As of the writing of this summary, only about half of the curriculum analyses had been completed. Thus, the following sections may not represent the full range of possible observations about the curricula.

[3] Some of the information in this section is adapted from a paper presented by Dr. Ken Welty at the 94th annual Mississippi Valley Technology Teacher Education Conference in Rosemont, Illinois, November 8-9, 2007.

described in such reports as *Technically Speaking: Why All Americans Need to Know More About Technology* (National Academy Press, 2002). Another prominent purpose was to enhance the study of mathematics and science (e.g., Materials World Modules, A World in Motion). Some curricula focused on using engineering design as a way to encourage problem-solving skills in students (e.g., Gateway to Technology, Design and Discovery). Still others aimed to prepare young people for further education and, possibly, careers in engineering (e.g., Introduction to Engineering, Ford PAS, Infinity Project). In some instances, the curricula appear to have multiple purposes.

Conceptual Frameworks

Curriculum developers used a wide range of strategies to frame the study of engineering. These included using traditional fields of engineering (e.g., civil, mechanical, electrical, environmental, biomedical) as content organizers (e.g., *Engineering is Elementary*); the design process as the central theme (e.g., *Design and Discovery, Technology Education: Learning by Design*); prominent industrial enterprises as the inspiration for interdisciplinary thematic units (e.g., Children Designing and Engineering); and interesting topics to package curricula into manageable chunks and programs of study (e.g., *City Technology., The Infinity Project, Material World Modules)*.

Presence of Engineering

Most of the curricula engage students in doing design. The majority of 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.

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 uncovered only isolated instances where analysis was used to define and clarify the problem, to make informed design decisions, or to predict and assess performance.

The physical, economic, political, social, ethical, aesthetic, and time limitations inherent to or imposed upon the design of a solution to a technical problem were considered to be constraints. Most of the attention given to constraints in the curriculum materials, such as finite supplies, storage space, or time, was attached to the learning activities in contrast to being integral to the design process.

Any graphic, physical, or mathematical representation of the essential features of a system or process that aids in facilitating the engineering design process is considered to be modeling. 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 pursuit of the best possible solution to a technical problem in which there are competing or conflicting factors that involve balancing trade-offs is optimization. However, most of the curriculum materials equate 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.

Attention to systems included any reference to organized collections of discrete elements (e.g., parts, processes, 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.

Presence of Science, Mathematics, and Technology

The most common science topics found in K-12 engineering curricula related to materials, mechanisms, electricity, energy, and structures. Most of the science content was presented in the form of encyclopedia-like explanations. A majority of inquiry activities students conducted was dedicated to making design decisions in contrast to uncovering, illuminating, or validating laws of nature.

Most of the mathematics in engineering curricula involved taking measurements and gathering, organizing, and presenting data. Very little attention was given to using mathematics to solve for unknowns (i.e., algebra). Little attention was given to the power of mathematical models in engineering design or in the use of mathematics to deal with economic issues encountered in doing design activities.

In most cases, curricula used the study of technology as domain knowledge. In a few 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.

COMMISSIONED PAPERS

In order to inform its deliberations, the committee commissioned literature reviews in three areas: conceptual learning related to engineering, the development of engineering skills, and evidence of impact of K-12 engineering education initiatives. The scope of each of these reviews is described below.

Conceptual Learning Related to Engineering

Based on a review of relevant literature, including national content standards in science and technology, the authors of this commissioned paper organized the "big ideas" of engineering into two broad categories: systems and optimization (Table 3). The literature analysis was intended to answer two questions: 1) What is challenging for students to understand and at what grade levels? and 2) What is the nature of the experiences that extend or build understanding?

TABLE 3 Engineering Concepts Organized Under the Big Ideas of Systems and Optimization

Systems	Optimization
Structure-behavior-function	Multiple Variables
Emergent properties	Trade-offs
Control/feedback	Requirements
Processes	Resources
Boundaries	Physical laws
Subsystems	Social constraints
Interactions	Cultural norms
	Side effects

The bulk of cognitive research related to systems examined either the structure-behavior-function relationship or the concept of emergent properties. In the latter category, concepts related to multiple variables and trade-offs were treated in the literature. In the case of optimization, the cognitive and learning science literature did not directly address what was difficult about these concepts for K-12 students in terms of engineering. As a result, the authors chose to focus on concepts that are relevant to the idea of optimization but may not be discussed in the same terms as they are in engineering contexts.

Structure-Behavior-Function

Structure-behavior-function is a framework for representing a system and can be used to describe both natural and designed systems. It relates the system's components (structures) to the purpose of those structures within the system (functions) and the mechanisms that enable the structures to achieve their function (behaviors).

Based on their review of the literature, the paper's authors concluded that students at a young age are unlikely to spontaneously consider the causal mechanisms that underlie a system. Students are much more likely to consider surface features, even when prompted. One primary method for advancing students' ideas about structure-behavior-function (SBF) seems to be engaging in active design of models. In addition, the iteration of successively complex models may be especially beneficial, since the first models tend to focus on superficial features and structural aspects, and many constructive ideas are raised in revision and refinement of the models. Furthermore, the supports provided by the teacher appear to have a large influence in making model-building activities productive toward understanding SBF. In particular, teacher questions that help students to focus on the connections between the design and the questions that are being asked, as well as helping to make step-wise and pragmatic goals for each revision, help students to understand SBF in a deeper way. With considerable supports by a teacher, early elementary students and older students are able to move toward a conceptual understanding that highlights functions, which is more characteristic of experienced designers. Despite this apparent opportunity, there are still many challenges that remain in understanding the behavior aspect of systems, presumably because the causal mechanisms underlying system behavior are more general and dynamic while also being less visible.

Emergent Properties

Not all systems are appropriately analyzed in terms of simple causal behaviors or a direct, linear sequence of events. Another prominent framework for understanding systems focuses on the behaviors that emerge from the dynamic interactions between components within the system. Emergent behaviors occur when the global, aggregate, or macro level behavior of a system emerges from the local, simple, or micro level interactions of the individual elements or components within the system. In these cases, the aggregate level behavior is not just a sum of the individual component behaviors, but is qualitatively distinct. Complex systems, and thus emergent behaviors, are a central part of many engineered systems that are commonly found today, including highways, the Internet, and the US power grid. Emergent properties are also characteristic of certain foundational science concepts. For instance, basic physics concepts such as force, light, heat, and electricity are often thought of by novices as material substances rather than being more appropriately represented as emergent processes.

Based on their review of the literature, the paper's authors concluded that what students find difficult and what helps them to build their knowledge of emergent properties highlights the importance of using tools to effectively analyze situations at multiple levels. Engaging in analysis at multiple levels may make the concept of emergent properties particularly demanding for elementary-age students, but there is not enough research to support that claim right now. With effective simulations that are properly motivated in the classroom context and make salient the connections between different levels, the strong tendency to use explanations that include central plans and single causes may be effectively transitioned to a perspective more consistent with conceptions of emergent properties.

Multiple Variables

The goal of engineering design is primarily about designing products or processes that result in predictable outcomes, often maximizing those outcomes as outputs given constraints on resources as inputs to the design. But in all real-world products or processes in need of an engineering solution, there are almost always a large number and wide range of input variables that can be manipulated in the design of an effective solution. Knowing which of those variables have a causal effect on the outcome is thus of central importance in engineering design.

Based on their review of the literature, the paper's authors concluded that the large number of variables that are involved in most engineering contexts easily overwhelm the limited cognitive resources of all individuals, including adults, even though adults have slightly more developed general cognitive resources. Meta-level knowledge about the nature of causality and the goal of testing can help students be systematic in learning about design. In addition, strategies for simplifying tasks by focusing on sub-problems, and utilizing external representations (physical and mathematical) are important things that students in K-12 setting can be taught.

Trade-Offs

In all optimization tasks, trade-offs occur both when considering the input variables of a system, those that can be manipulated in the system design, and the outcome variables, those that are used to judge the quality of the design. A trade-off of an input variable occurs when a choice to modify the level of one variable impacts the effect of another variable on the outcome. Thus, trade-offs refer not just to a case when multiple variables combine to influence an outcome in an additive way, but it refers to the more specific case when those variables are opposing each other. A similar case occurs when a particular variable will have a particular effect only under certain conditions. Trade-offs also occur when weighing the different outcomes of a design, such as when considering the cost of a design compared to its effectiveness. Trade-offs are an important aspect of all real-world engineering design.

Based on their review of the literature, the paper's authors concluded that conceptual understanding of trade-offs is cognitively demanding, and K-12 students are unlikely to have a normative understanding of interactions between variables in a general sense. Despite this, students can consider trade-offs by utilizing mathematical representations that make the relationships between variables more explicit and by engaging in successive iterations of design activities in which they are able to first consider variables in isolation and then together.

Learning Design Skills in Engineering

The commissioned authors conducted an integrative review of what is known about the development of core engineering skills over the grades K-12 period. The authors focused on skills related to design, because the most prototypical engineering process is design (and re-design). Thus, the most prototypical engineering skills are the component skills typically found in design processes (e.g., problem finding, requirements specification, system decomposition, solution generation, solution testing, modeling and analysis, sketching, visualization, alternative solution evaluation and optimization). The authors explored the development of design skills and their connections to learning engineering and science.

Early Competencies

A concern that pervades the literature is that the students will not have enough content knowledge to competently tackle design problems; this seems to be a reiteration of concerns that have been voiced about problem-based learning. However, learning of content has been demonstrated to occur synchronously with learning of problem-solving strategies.

The evidence reviewed by the authors illustrates that young children have the ability to develop the component skills of design. Children as young as second graders can grasp abstract principles such as ecological interdependence in a learning environment that supports social forms of inquiry. Children may appear to be concrete thinkers as an artifact of their status as novices; in fact, even adult novices rely on superficial features as compared to experts. Given sufficient familiarity with a situation, as in simple physical causality, even children aged 1-3 have been shown to rely upon structural principles. Children as young as 7 have been shown to apply the concepts of empirical and logical consistency to theory and to have personal theories that resemble scientific theories in term of coherence and explanatory power. These early competencies can provide the needed platform on which young children can develop engineering skills.

The authors point out that many developmental viewpoints present a deficit model of children, focusing on what they cannot do spontaneously. They suggest it is critical to consider a model of efficacy, focusing on what children bring and what they can learn to do with instruction. The literature reviewed by the authors suggests that children are much more capable, in terms of potential to engage in design activities, than predicted by Piaget's stages, particularly when students are scaffolded through the activities.

Drawing and Representation

The authors also conducted a more focused review of the engineering-related skills of drawing and representation. Studies of these skills have been prevalent in the developmental literature. While other skills may be just as important to the design process, reliable research into other skills has yet to emerge.

From their review of existing literature, the authors conclude that without deliberate intervention, children's drawings are unlikely to serve a function in design. The lack of connection between the drawing phase and the making and appraising phases leads to a view of design as linear rather than iterative, and the drawings serve little function in the cycle. Just as children's drawings may not be connected to design, other representations, such as models, without intervention, may preserve only the structural, superficial features. Alternatively, allowing young children to play with the materials they will be using can foster better design drawings, particularly when paired with discussion of how the drawings are to be used. Comparing drawings done before and after designing can highlight the role of the initial drawing. However the authors caution that while drawing and representing are useful ways to elicit nascent ideas, design representations tend to be highly contextualized and are therefore not likely to lead to abstraction or to be transferred to other situations

Teaching and Learning Engineering Skills in K-12

This same evidence was interpreted by the authors to suggest that for lower elementary students, design activities should include anchoring activities with the materials to be used. Specific instruction about the use of drawings in design is indicated. In order to support learning through design, it may be beneficial to frame design activity with a model of experimentation. Design-process models should emphasize the iterative nature of design and provide opportunities for reflection. As children develop more sophisticated design skills, reverse engineering or redesign activities could provide continued opportunity to develop greater competence with the design process. By beginning with a product in hand, the students have a shared anchor and can move from concrete to abstract. Mechanical dissection can provide connections to science and can still be used in an open-ended, problem-solving approach as students redesign the device. Engineering can be an effective means to support science learning, but only when framing of experimentation is scientific and evaluation encourages reflection.

Impacts of K-12 Engineering Education

One of the key elements of the charge to the committee was to determine the nature and extent of the impacts of efforts to teach engineering to K-12 students. The commissioned paper on this topic examined possible impacts in six areas:

- Awareness of engineering and the work of engineers
- Interest in engineering
- Science, Mathematics, and Technology Learning and Achievement
- Career Interest, Attendance, and Retention
- Understanding of design and the nature of engineering
- Equity issues in engineering education

Awareness

Based on a review of the literature, the paper's author concluded that young students, in particular, have little awareness of what an engineer is or does. Engineering activities may positively impact students' awareness of engineers, technology, and engineering, and this positive effect may be long lasting.

Interest

Based on a review of the literature, the paper's author concluded that some K-12 engineering programs have demonstrated significant increases in interest. However, this finding is rarely robust. Most studies reporting affective change rely on participants to report interest at the end of a program, and in almost all cases the participants have self-selected, meaning they may have already been interested.

SMT Learning and Achievement

Based on a review of the literature, the paper's author concluded, in some cases, achievement scores have been positively and significantly impacted. Design and scaffolded engineering problems afford greater learning opportunities than engineering science. Learning for understanding has been demonstrated and results from engineering design activities in which transfer is supported and scientific models of experimentation are employed. Competition may be motivating but may hinder learning because it privileges performance goals.

Career Interest, Attendance, and Retention

Based on a review of the literature, the paper's author concluded there are initial gender differences in interest in pursuing engineering as a career, but this gap may be narrowed by interventions. Interest is insufficient on its own to propel students to careers in engineering, as students may intend to pursue a degree yet still be ill-prepared to do so. Engineering framed as design rather than as science may positively impact attendance. Students who elect to participate in engineering extracurricular activities or who take engineering courses tend to continue to pursue engineering in college and to take a greater number of science and mathematics courses. This latter finding demonstrates that participating in engineering activities or courses may better prepare students who are already interested in engineering.

Understanding of Design and Nature of Engineering

Based on a review of the literature, the paper's author concluded that not all findings for studies of K-12 engineering programs demonstrate greater understanding of the nature of engineering. When no guidance is given on the design process, students tend not to progress beyond novice trial-and-error strategies, and even come to see these as the common tool of engineering. Authentic design experience fosters soft skills that are useful both within and beyond engineering.

Equity

Based on a review of the literature, the paper's author concluded that interventions specifically aimed at promoting intergroup relations may be beneficial in enhancing the participation of female students who are not members of majority culture friendship groups, although such interventions may cause discomfort and should be used with caution. (More study is needed to see whether this finding applies to boys as well as girls.) The addition of engineering modules to science and mathematics curricula may benefit underrepresented groups, possibly even more than majority students, as long as care is taken to ensure that the tasks are of genuine interest to the students. Students are generally unaware of the nature of careers in engineering. Providing such information explicitly may be beneficial to all students, particularly female students who may view engineering as relating only to machines and not people. Studies continue to show differential changes, both positive and negative, of outreach programs and other interventions on different subgroups. It is important to disaggregate data showing the effectiveness of interventions and also to compare participants to an appropriate control group in order to equitably assess outcomes.

Methodological Issues

The commissioned paper on impacts of K-12 engineering education uncovered a number of methodological shortcomings with the research literature. A number of studies, for example, provided post-intervention data but no other information, such as pre-intervention data or data from comparison groups. Many papers examined in the review provided data but no indication was given about the data's significance or inappropriate significance analyses were conducted. A number of papers reported that study participants perceived positive learning or attitude change, but study participants sometimes report positive results simply because they are in a study (the Hawthorne Effect). Many study populations consist of individuals who have chosen (self-selected) to participate in K-12 engineering activities, thus the relevance of these findings to the general population of students is unclear. Some studies provide only whole-group data, limiting their utility for understanding the impact of K-12 engineering on subgroups, such as under-represented minorities.

Pre-University Engineering Education Initiatives Outside of the United States

In order to gain some sense of the international situation related to pre-college engineering education, the committee commissioned research to investigate and describe such efforts outside of the United States. The criteria for selecting the international programs were generally the same used to select the U.S. curricula for analysis. The methodology consisted of doing Internet searches to identify candidate programs, downloading and printing curriculum materials, and engaging in e-mail or telephone discussions with people knowledgeable about the design and implementation of the materials. When available, information about the scale of implementation was collected. Due to time and funding constraints, no special effort was made to identify research studies examining the impacts of these international efforts.

Given the level of engineering education activity in India and China and the increasing innovation capacity of these two nations, the committee believes any information about pre-college engineering efforts in India and China would be very valuable. However, at the time this summary was prepared, the committee had not been able to identify any such initiatives.

The following initiatives were identified. Of these, only Pequeños Cientificos engaged younger (elementary age) students.

England and Wales: General Certificate of Education (GCE), Engineering
Australia (New South Wales): Higher School Certificate in Engineering Studies
Israel: ORT Innovative Science Track in Engineering Sciences
Germany: Junior-Ingenieur-Akademie (Academy for Junior Engineers)
South Africa: Further Education and Training in Electrical Technology
France: General Baccalauréat, Série Scientifique (General Baccalaureate, Scientific Series); Baccalauréat Technologique, Série Sciences et Technologies Industrielles (Technological Baccalaureate, Science and Industrial Technology Series)
Netherlands: "Technasium"
Colombia: Pequeños Cientificos (Little Scientists)

K-12 ENGINEERING AND STEM EDUCATION

The committee is currently in the process of drafting its report, which it hopes will provide useful information and advice to educators, policy makers, and others with an interest in improving U.S. K-12 education. Based on data collected through commissioned research, its review of curricula, and workshops, an overarching issue has emerged: the relationship of K-12 engineering to broader efforts to improve STEM education.

One view is that the true potential of STEM education will be realized only to the extent that there is synergy among all four subject areas. Currently, in most schools, science, mathematics, and technology are taught separately—by separate teachers, using separate curricula and instructional materials—and assessed, if at all, separately, too. However, engineering occupies a unique position relative to the other three STEM subjects. At the level of teaching and learning, it can be both an integrator and contextualizer. That is, K-12 engineering education can place mathematics, science, and technology in a meaningful, real-world context. This approach may not only motivate students and teachers, it may also address concerns of policy makers, industry, and higher education related to the effects of globalization, the need for innovative workers, and the desire to improve citizens' scientific and technological literacy.

Although there are tantalizing clues in the education research literature and in practice to support the vision of engineering as a catalyst for STEM, movement in this direction would not be easy or without complications. A central question is whether engineering can support quality STEM education at meaningful scale in an education system that inherently resists change. In considering this and other questions, the committee's report will likely address issues of teacher professional development, content standards, curriculum development, and accountability and assessment, among other topics.

INPUT TO THE PROJECT

As stated in the Introduction to this summary, the committee is seeking input from interested members of the public on its work. Any input is welcome and will be considered for including in the final report. The committee has several specific questions it would like readers to consider.

1. Has the project missed any curriculum projects that meet the criteria for inclusion (pp. 12-13) established by the committee?
2. Are there any examples of in-service or pre-service teacher professional development in engineering that the committee should be aware of that were not discussed in one of the committee's two workshops (included in the appendix)?
3. Are there instances of pre-college engineering education in other nations—particularly India or China—that are not described in this summary (p. 22)?
4. Are there other areas of research not described in this report that would be helpful to the committee's effort to answer the project's guiding questions (p. 5)?
5. Based on the information provided in this summary, does the idea of engineering as a catalyst for STEM education (pp. 22-23) seem compelling? If not, why not?

APPENDIX

Committee on K-12 Engineering Education

National Academy of Engineering
National Research Council

Workshop
Oct. 22, 2007

Room 101
Keck Center of the National Academies
500 5th St., NW
Washington, D.C. 20001

Engineering Education in Grades K-5

Final Agenda

7:30 a.m. – 8:00 a.m.	**Breakfast –** Discussion of Meeting Goals
8:00 a.m. – 8:15 a.m.	**Welcome and Plans for the Day** *Linda Katehi, Chair*
8:15 a.m. – 9:30 a.m. **Development**	**TOPIC 1: Engineering Concept and Skill in K-5 Students** § Research on Skills (25 mins.) *Anthony Petrosino, Univ. of Texas—Austin* § Research on Concepts (25 mins.) *Chris Schunn, Univ. of Pittsburgh* § Examples of Student Classroom Learning (15 mins.) *Rich Lehrer, Vanderbilt University* Respondent: *Demetra Evangelou, Purdue Univ. (10 mins.)*
9:30 a.m. – 10:00 a.m.	**Committee Q&A** *Moderator: Craig Kesselheim*
10:00 a.m. – 10:15 a.m.	**Break**
10:30 a.m. – 11:30 p.m.	**TOPIC 2: Teacher Professional Development in Engineering K-5**

- Lessons Learned from “Engineering is Elementary (EiE) PD” (25 mins.)
  Christine Cunningham, Boston Museum of Science
- Adapting EiE PD to Encourage Open-Ended Mathematical Modeling (25 mins.)
  Heidi Diefes-Dux, Purdue University

11:30 a.m. – 12:00 p.m. **Committee Q&A**
Moderator: Dave Burghardt

12:00 p.m. – 1:00 p.m. **Lunch –** *Small group discussions with presenters*

1:00 p.m. – 3:00 p.m. **TOPIC 2 (cont.): Teacher Professional Development in Engineering K-5**

- Lessons Learned from “City Technology” *(25 mins.)*
  Jim Neujahr, City College of New York
- Lessons Learned from “Project Update” and “Children Designing and Engineering” *(25 mins.)*
  Ron Todd, The College of New Jersey
- Thoughts on Developing a Pre-Service Engineering Course for K-5 Teachers *(25 mins.)*
  David Crismond, City College of New York
- The M/S/T Education Major at TCNJ (25 mins.)
  Steve O’Brien, The College of New Jersey

3:00 p.m. – 3:15 p.m. **Break**

3:15 p.m. – 3:45 p.m. **Committee Q&A**
Moderator: Dave Burghardt

3:45 p.m. – 4:15 p.m. **TOPIC 3: Creating Educational Change**

- A Case Example: Efforts to Introduce K-12 Engineering in New Jersey
  Beth McGrath, Stevens Institute of Technology (25 mins.)

4:15 a.m. – 4:45 a.m. **Committee Q&A**
Moderator: Deborah McGriff

4:45 p.m. – 5:00 p.m.	**Final Comments and Thanks to Workshop Attendees** *Linda Katehi, Chair*
5:00 p.m.	**Adjourn**

Committee on K-12 Engineering Education
National Academy of Engineering
National Research Council

Workshop
February 25, 2008

Keck Center of the National Academies
Room 201

Final Draft Workshop Agenda

7:30 a.m. – 8:00 a.m.	**Continental Breakfast**
8:00 a.m. – 8:15 a.m.	**Introductions and Plans for the Day** *Linda Katehi, Chair*
8:15 a.m. – 9:00 a.m.	**TOPIC 1: The Theory and Practice of Systemic Educational Change** **Theoretical Models Appropriate to K-12 Engineering** • *Andrew Porter, University of Pennsylvania*
9:00 a.m. – 9:30 a.m.	**Committee Discussion**
9:30 a.m. – 10:30 a.m.	**Bringing K-12 Engineering To Scale: Case Examples** • *Richard Grimsley, Project Lead the Way* • *Tammy Richards, Infinity Project*
10:30 a.m. – 10:45 a.m.	**Break**
11:00 a.m. – 11:30 a.m.	**A Perspective from the National Academy of Engineering** *Charles M. Vest, NAE President*
11:30 a.m. – 12:30 p.m.	**Bringing K-12 Engineering To Scale: Case Examples (cont.)** • *Robert Chang, Northwestern University (Materials World Modules)* • *Matthew Miller, Society for Automotive Engineers (World in Motion)*

12:30 p.m. – 1:30 p.m.	**Lunch and Scalability Discussion** **Discussion Leaders** • *Mike Lach, Chicago Public Schools* • *Deborah McGriff (via telephone), Edison Schools*
	TOPIC 2: Professional Development for MS and HS Teachers of Engineering
1:30 p.m. – 2:00 p.m.	**In-Service Professional Development: Lessons Learned from a Multi-Institution Study** • *Dan Householder, National Center for Engineering and Technology Education*
2:00 p.m. – 3:00 p.m.	**Two Visions for Pre-Service Professional Development** • *Michael DeMiranda, Colorado State University* • *George Rogers, Purdue University*
3:00 p.m. – 3:30 p.m.	**Committee Discussion**
3:30 p.m.	**Workshop Adjournment**

*****CLOSED SESSION*****

3:45 p.m. – 5:00 p.m.	**Discussion of “Definitions”**
5:00 p.m.	**Committee Adjournment**
6:30 p.m.	**Committee Dinner** *Location TBD*