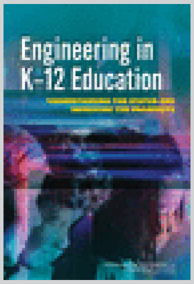

Engineering in K-12 Education: Understanding the Status and Improving the Prospects

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Linda Katehi, Greg Pearson, and Michael Feder, Editors; Committee on K-12 Engineering Education; National Academy of Engineering and National Research Council

Engineering in K–12 Education

UNDERSTANDING THE STATUS AND IMPROVING THE PROSPECTS

Committee on K–12 Engineering Education

Linda Katehi, Greg Pearson, and Michael Feder, *Editors*

NATIONAL ACADEMY OF ENGINEERING *AND*
NATIONAL RESEARCH COUNCIL
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Preface

This report is the final product of a two-year study by the Committee on K–12 Engineering Education, a group of experts on diverse subjects under the auspices of the National Academy of Engineering (NAE) and the Board on Science Education at the Center for Education, part of the National Research Council (NRC). The committee's charge was to determine the scope and nature of efforts to teach engineering to the nation's elementary and secondary students. In fulfilling that charge, the committee considered a number of specific questions, such as What types of curricula and teacher professional development have been used? How does engineering education "interact" with science, technology, and mathematics? And what impact—on student learning, interest in engineering, and other outcomes—have various initiatives had?

Engineering education is a relatively new school subject in U.S. K–12 education. Up to this point it has developed in an ad hoc fashion, and its spread into classrooms has been fairly modest. Even so, the presence of engineering in K–12 classrooms is an important phenomenon, because it casts new light on the very important issue of STEM (science, technology, engineering, and mathematics) education. There is broad agreement today among educators, policy makers, and industry leaders that the teaching of STEM subjects in American K–12 schools must be improved. Many of the concerns about STEM education tie to worries about the innovation capacity of the United States and its ability to compete in the global marketplace.

This report will be of special interest to individuals and groups interested in improving the quality of K–12 STEM education in this country. Engineering educators, policy makers, employers, and others concerned about the development of the country's technical workforce will also find much to ponder. The report should prove useful to advocates for greater public understanding of engineering, as well as to those working to boost citizens' technological and scientific literacy. Finally, for educational researchers and cognitive scientists, the document exposes a rich set of questions related to how and under what conditions students come to understand engineering.

The committee met five times, sponsored two data-gathering workshops, and solicited online input from the public midway through the project. The committee also commissioned an analysis of a number of existing K–12 engineering curricula; conducted reviews of the literature on areas of conceptual learning related to engineering, the development of engineering skills, and the impacts of K–12 engineering education initiatives; and collected preliminary information about a few pre-college engineering education programs in other countries. Beyond this data gathering, the report reflects the personal and professional experiences and judgments of committee members.

Linda P.B. Katehi, *Chair*
Committee on K–12 Engineering Education

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

William F. Bertrand, Bureau of Teaching and Learning Support, Division of Standards and Curriculum, Pennsylvania Department of Education
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Yannis C. Yortsos, Viterbi School of Engineering, University of Southern California

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by William G. Agnew, Retired Director, Programs and Plans, General Motors Corporation, Corrales, New Mexico. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

In addition to the reviewers, many other individuals assisted in the development of this report. Anthony J. Petrosino and Vanessa Svihla, University of Texas at Austin, and Sean Brophy, Purdue University, prepared a commissioned paper examining cognitive science research related to engineering skills; Eli M. Silk and committee member Christian D. Schunn, University of Pittsburgh, prepared a commissioned paper examining cognitive science research related to core concepts in engineering; Vanessa Svihla, Jill Marshall, University of Texas at Austin, and Anthony J. Petrosino prepared a commissioned paper examining the impacts of K–12 engineering education efforts; Jonson Miller, Drexel University, prepared a commissioned paper reviewing the history of engineering and technical education in the United States; and Marc J. de Vries, Eindhoven University of Technology/Delft University of Technology, The Netherlands, prepared a commissioned paper examining pre-college engineering education initiatives outside the United States.

Thanks are also due to the project staff. Maribeth Keitz managed the study's logistical and administrative needs, making sure meetings and workshops ran efficiently and smoothly. Christine Mirzayan Science & Technology Policy Graduate Fellow Carolyn Williams did extensive research on pre-college engineering education programs outside the United States, work that led to the commissioned paper by Marc de Vries. Freelance writer Robert Pool helped write several chapters of the report. NAE Senior Editor Carol R. Arenberg substantially improved the readability of the report. Special thanks are due to Kenneth Welty, University of Wisconsin, Stout, who conducted an extensive analysis of K–12 engineering curricula that substantially informed the committee's work. Michael Feder, at the NRC Board on Science Education, helped guide the project from its inception. Greg Pearson, at the NAE, played a key role in conceptualizing the study and managed the project from start to finish.

Contents

*Appendix C is reproduced on the CD (inside back cover) and in the PDF available online at http://www.nap/edu/catalog.php?record_id=12635.

List of Acronyms

AAAS	American Association for the Advancement of Science
ASCE	American Society of Civil Engineers
ASEE	American Society for Engineering Education
AWIM	A World in Motion®
CAD/CAM	computer-aided design/computer-aided manufacturing
CLT	cognitive load theory
CD	compact disk
CO_2	carbon dioxide
DPS	Denver Public Schools
DSST	Denver School of Science and Technology
DVD	digital video disk
EPICS	Engineering Projects in Community Service
FBS	function-behavior-structure
FIRST	For Inspiration and Recognition of Science and Technology
HSCE	Higher School Certificate in Engineering

INSPIRES	INcreasing Student Participation, Interest, and Recruitment in Engineering and Science
ITEA	International Technology Education Association
K–12	kindergarten through grade 12
M/S/T	mathematics/science/technology
MWM	Material World Modules
NAE	National Academy of Engineering
NAEP	National Assessment of Educational Progress
NAGB	National Assessment Governing Board
NCETE	National Center for Engineering and Technology Education
NCLB	No Child Left Behind
NSF	National Science Foundation
PD	professional development
PLTW	Project Lead the Way
SAE	Society of Automotive Engineers
SBF	structure-behavior-function
SMET	science, mathematics, engineering, and technology
STEM	science, technology, engineering, and mathematics
TCNJ	The College of New Jersey
TIMSS	Trends in International Mathematics and Science Study
TISD	Texarkana Independent School District

Summary

Although K–12 engineering education has received little attention from most Americans, including educators and policy makers, it has slowly been making its way into U.S. K–12 classrooms. Today, several dozen different engineering programs and curricula are offered in school districts around the country, and thousands of teachers have attended professional development sessions to teach engineering-related coursework. In the past 15 years, several million K–12 students have experienced some formal engineering education.

The presence of engineering in K–12 classrooms is an important phenomenon, not because of the number of students impacted, which is still small relative to other school subjects, but because of the implications of engineering education for the future of science, technology, engineering, and mathematics (STEM) education more broadly. Specifically, as elaborated in the full report, K–12 engineering education may improve student learning and achievement in science and mathematics; increase awareness of engineering and the work of engineers; boost youth interest in pursuing engineering as a career; and increase the technological literacy of all students. The committee believes engineering education may even act as a catalyst for a more interconnected and effective K–12 STEM education system in the United States. Achieving the latter outcome will require significant rethinking of what STEM education can and should be.

In recent years, educators and policy makers have come to a consensus that the teaching of STEM subjects in U.S. schools must be improved. The focus on STEM topics is closely related to concerns about U.S. competitiveness in the global economy and about the development of a workforce with the knowledge and skills to address technical and technological issues. To date, most efforts to improve STEM education have been concentrated on mathematics and science, but an increasing number of states and school districts have been adding technology education to the mix, and a smaller but significant number have added engineering.

In contrast to science, mathematics, and even technology education, all of which have established learning standards and a long history in the K–12 curriculum, the teaching of engineering in elementary and secondary schools is still very much a work in progress. Not only have no learning standards been developed, little is available in the way of guidance for teacher professional development, and no national or state-level assessments of student accomplishment have been developed. In addition, no single organization or central clearinghouse collects information on K–12 engineering education.

Thus a number of basic questions remain unanswered. How is engineering taught in grades K–12? What types of instructional materials and curricula have been used? How does engineering education "interact" with other STEM subjects? In particular, how has K–12 engineering instruction incorporated science, technology, and mathematics concepts, and how has it used these subjects as a context for exploring engineering concepts? Conversely, how has engineering been used as a context for exploring science, technology, and mathematics concepts? And what impact have various initiatives had? Have they, for instance, improved student achievement in science or mathematics or stimulated interest among students in pursuing careers in engineering?

In 2006 the National Academy of Engineering and National Research Council Center for Education established the Committee on K–12 Engineering Education to begin to address these and other questions. Over a period of two years, the committee held five face-to-face meetings, two of which accompanied information-gathering workshops. The committee also commissioned an analysis of existing K–12 engineering curricula; conducted reviews of the literature on areas of conceptual learning related to engineering, the development of engineering skills, and the impact of K–12 engineering education initiatives; and collected preliminary information about a few pre-college engineering education programs in other countries.

The goal of the project was to provide carefully reasoned guidance to key stakeholders 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 had these specific objectives:

- 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;
- Review evidence related to the impact of these initiatives, to the extent such information is available;
- 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
- Report on the intended learning outcomes of K–12 engineering education initiatives, taking into account student age, curriculum focus (e.g., science vs. technology education), program orientation (e.g., general education vs. career/vocational education), and other factors.

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

- 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?
- 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?
- 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 educa-

tional 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 committee believes this report will be of special interest to individuals and groups interested in improving the quality of K–12 STEM education in this country. But engineering educators, policy makers, employers, and others concerned about the development of the country's technical workforce will also find much to ponder. The report should prove useful to advocates for greater public understanding of engineering, as well as to those working to boost citizens' technological and scientific literacy. Finally, for educational researchers and cognitive scientists, the document exposes a rich set of questions related to how and under what conditions students come to understand engineering.

GENERAL PRINCIPLES FOR K–12 ENGINEERING EDUCATION

The specifics of how engineering is taught vary from school district to school district, and what takes place in classrooms in the name of engineering education does not always align with generally accepted ideas about the discipline and practice of engineering. This is not to suggest that K–12 students should be treated like little engineers, but when a school subject is taught for which there is a professional counterpart, there should be a conceptual connection to post-secondary studies and to the practice of that subject in the real world.

The committee set forth three general principles for K–12 engineering education.

Principle 1. K–12 engineering education should emphasize engineering design.

The design process, the engineering approach to identifying and solving problems, is (1) highly iterative; (2) open to the idea that a problem may have many possible solutions; (3) a meaningful context for learning scientific, mathematical, and technological concepts; and (4) a stimulus to systems thinking, modeling, and analysis. In all of these ways, engineering design is a potentially useful pedagogical strategy.

Principle 2. K–12 engineering education should incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills.

Certain science concepts as well as the use of scientific inquiry methods can support engineering design activities. Similarly, certain mathematical concepts and computational methods can support engineering design, especially in service of analysis and modeling. Technology and technology concepts can illustrate the outcomes of engineering design, provide opportunities for "reverse engineering" activities, and encourage the consideration of social, environmental, and other impacts of engineering design decisions. Testing and measurement technologies, such as thermometers and oscilloscopes; software for data acquisition and management; computational and visualization tools, such as graphing calculators and CAD/CAM (i.e., computer design) programs; and the Internet should be used, as appropriate, to support engineering design, particularly at the high school level.

Principle 3. K–12 engineering education should promote engineering habits of mind.

Engineering "habits of mind"[1] align with what many believe are essential skills for citizens in the 21st century.[2] These include (1) systems thinking, (2) creativity, (3) optimism, (4) collaboration, (5) communication, and (6) attention to ethical considerations. Systems thinking equips students to recognize essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behavior of individual subsystems. Creativity is inherent in the engineering design process. Optimism reflects a world view in which possibilities and opportunities can be found in every challenge and an understanding that every technology can be improved. Engineering is a "team sport"; collaboration leverages the perspectives, knowledge, and capabilities of team members to address a design challenge. Communication is essential to effective collaboration, to understanding the particular wants and needs of a "customer," and to explaining and justifying the final design solution. Ethical considerations draw attention to the impacts of engineering on people and the environment; ethical considerations include possible unintended consequences

[1]The committee has adopted the term "habits of mind," as used by the American Association for the Advancement of Science in *Science for All Americans* (1990), to refer to the values, attitudes, and thinking skills associated with engineering.

[2]See, for example, The Partnership for 21st Century Skills, *www.21stcenturyskills.org*.

of a technology, the potential disproportionate advantages or disadvantages of a technology for certain groups or individuals, and other issues.

These principles, particularly Principle 3, should be considered aspirational rather than a reflection of what is present in current K–12 engineering education efforts or, indeed, in post-secondary engineering education.

THE SCOPE OF K–12 ENGINEERING EDUCATION

No reliable data are available on the precise number of U.S. K–12 students who have been exposed to engineering-related coursework. With a few notable exceptions, the first formal K–12 engineering programs in the United States emerged in the early 1990s. Since that time, fewer than 6 million students have had some kind of formal engineering education. By comparison, the estimated enrollment for grades pre-K–12 for U.S. public and private schools in 2008 was nearly 56 million.

No reliable data are available on the number of teachers involved in K–12 engineering education. The committee estimates that only about 18,000 teachers have received pre- or in-service professional development training to teach engineering-related coursework. The relatively small number of curricular and teacher professional development initiatives for K–12 engineering education were developed independently, often have different goals, and vary in how they treat engineering concepts, engineering design, and relationships among engineering and the other STEM subjects.

Although engineering education represents a relatively small slice of the K–12 educational pie, activity in this arena has increased significantly, from almost no curricula or programs 15 years ago to several dozen today. The future of K–12 engineering education will depend, at least in part, on whether it continues to be taught as a separate subject or whether engineering becomes a catalyst for more interconnected STEM education.

IMPACTS OF K–12 ENGINEERING EDUCATION

A variety of claims have been made for the benefits of teaching engineering to K–12 students, ranging from improved performance in related subjects, such as science and mathematics, and increased technological literacy to improvements in school attendance and retention, a better understanding of what engineers do, and an increase in the number of students who pursue careers in engineering. Only limited reliable data are available to support these claims. The most intriguing possible benefit of K–12 engineering education relates to improved student learning and achievement in mathematics and science, but even here, the paucity and small size of studies and their uneven quality cannot support unqualified claims of impact. For engineering education to become a mainstream component of K–12 education, there will have to be much more, and much higher quality, outcomes-based data.

RECOMMENDATION 1. Foundations and federal agencies with an interest in K–12 engineering education should support long-term research to confirm and refine the findings of earlier studies of the impacts of engineering education on student learning in STEM subjects, student engagement and retention, understanding of engineering, career aspirations, and technological literacy.

RECOMMENDATION 2. Funders of new efforts to develop and implement curricula for K–12 engineering education should include a research component that will provide a basis for analyzing how design ideas and practices develop in students over time and determining the classroom conditions necessary to support this development. After a solid analytic foundation has been established, a rigorous evaluation should be undertaken to determine what works and why.

THE NATURE OF K–12 ENGINEERING EDUCATION

Based on extensive reviews of the research literature and curricular materials, the committee concluded that there is no widely accepted vision of what K–12 engineering education should include or accomplish. This lack of consensus reflects the ad hoc development of educational materials in engineering and that no major effort has been made to define the content of K–12 engineering in a rigorous way.

Curriculum Content

The committee's review of curricula revealed that engineering design, the central activity of engineering, is predominant in most K–12 curricular and professional development programs. The treatment of key ideas in engineering, many closely related to engineering design, is much more uneven and, in some cases, suggests a lack of understanding on the part of curriculum developers. These shortcomings may be the result, at least in part, of the absence of a clear description of which engineering knowledge, skills, and habits of mind are most important, how they relate to and build on one another, and how and when (i.e., at what age) they should be introduced to students. In fact, it seems that no one has attempted to specify age-appropriate learning progressions in a rigorous or systematic way; this lack of specificity or consensus on learning outcomes and progressions goes a long way toward explaining the variability and unevenness in the curricula.

Curriculum Connections

Although there are a number of natural connections between engineering and the three other STEM subjects, existing curricula in K–12 engineering education do not fully explore them. For example, scientific investigation and engineering design are closely related activities that can be mutually reinforcing. Most curricula include some instances in which this connection is exploited (e.g., using scientific inquiry to generate data that can inform engineering design decisions or using engineering design to provide contextualized opportunities for science learning), but the connection is not systematically emphasized to improve learning in both domains. One option, which was evident in several of the curricula we reviewed, is to use engineering as a pedagogical strategy for science laboratory activities.

Similarly, mathematical analysis and modeling are essential to engineering design, but very few curricula or professional development initiatives reviewed by the committee used mathematics in ways that support modeling and analysis. The committee believes that K–12 engineering can contribute to improvements in students' performance and understanding of certain mathematical concepts and skills.

RECOMMENDATION 3. The National Science Foundation and/or U.S. Department of Education should fund research to determine how science inquiry and mathematical reasoning can be connected to engineering design in K–12 curricula and teacher professional development. The research should cover the following specific areas:

- the most important concepts, skills, and habits of mind in science and mathematics that can be taught effectively using an engineering design approach;
- the circumstances under which students learn important science and mathematics concepts, skills, and habits of mind through an

engineering-design approach as well or better than through science or mathematics instruction;

- how engineering design can be used as a pedagogical strategy in science and mathematics instruction; and
- the implications for professional development of using engineering design as a pedagogical tool for supporting science and mathematics learning.

Finally, our review of curricula showed that technology in K–12 engineering education has primarily been used to illustrate the products of engineering and to provide a context for thinking about engineering design. There were few examples of engineering being used to elucidate ideas related to other aspects of technological literacy, such as the nature and history of technology and the cultural, social, economic, and political dimensions of technology development.

Professional Development Programs

Compared with professional development opportunities for teaching other STEM subjects, the opportunities for engineering are few and far between. Nearly all in-service initiatives are associated with a few existing curricula, and many do not have one or more of the characteristics (e.g., activities that last for at least one week, ongoing in-classroom or online support following formal training, and opportunities for continuing education) that have been proven to promote teacher learning.

The committee found no pre-service initiatives that are likely to contribute significantly to the supply of qualified engineering teachers in the near future. Indeed, the "qualifications" for engineering educators at the K–12 level have not even been described. Graduates from a handful of teacher preparation programs have strong backgrounds in STEM subjects, including engineering, but few if any of them teach engineering classes in K–12 schools.

RECOMMENDATION 4. The American Society for Engineering Education (ASEE), through its Division of K–12 and Pre-College Education, should begin a national dialogue on preparing K–12 engineering teachers to address the very different needs and circumstances of elementary and secondary teachers and the pros and cons of establishing a formal credentialing process. Participants in the dialogue should include leaders in K–12 teacher education in mathematics, science, and technology; schools of education and engineering; state departments of education; teacher licensing and certification groups; and STEM program accreditors. ASEE should consult with the National Center for Engineering and Technology Education, which has conducted research on this topic.

Diversity

The lack of diversity in post-secondary engineering education and the engineering workforce in the United States is well documented. Based on evaluation data, analysis of curriculum materials, anecdotal reports, and personal observation, the committee concluded that lack of diversity is probably an issue for K–12 engineering education as well. This problem is manifested in two ways. First, the number of girls and underrepresented minorities who participate in K–12 engineering education initiatives is well below their numbers in the general population. Second, with a few exceptions, curricular materials do not portray engineering in ways that seem likely to excite the interest of students from a variety of ethnic and cultural backgrounds. For K–12 engineering education to yield the many benefits its supporters claim, access and participation will have to be expanded considerably.

RECOMMENDATION 5. Given the demographic trends in the United States and the challenges of attracting girls, African Americans, Hispanics, and some Asian subpopulations to engineering studies, K–12 engineering curricula should be developed with special attention to features which appeal to students from these underrepresented groups, and programs that promote K–12 engineering education should be strategic in their outreach to these populations. Both curriculum developers and outreach organizations should take advantage of recent market research that suggests effective ways of communicating about engineering to the public.

POLICY AND PROGRAM ISSUES

Although many unanswered questions about K–12 engineering education remain, engineering is being taught in K–12 schools around the country, and it appears that the trend is upward. Thus it is imperative that we begin to think about ways to guide and support engineering education in the future. An underlying question for policy makers is how engineering concepts, skills, and habits of mind should be introduced into the school curriculum. There are at least three options—ad hoc infusion, stand-alone courses, and interconnected STEM education. These options vary in terms of ease of implementation:

- Ad hoc infusion, or introduction, of engineering ideas and activities (i.e., design projects) into existing science, mathematics, and technology curricula is the most direct and least complicated option, because implementation requires no significant changes in school structure. The main requirements would be (1) willingness on the part of teachers and (2) access to instructional materials. Ideally, teachers would also have a modicum of engineering pedagogical content knowledge to deliver the new material effectively. The ad hoc option is probably most useful for providing an introductory exposure to engineering ideas rather than a deep understanding of engineering principles and skills.
- Stand-alone courses for engineering, an option required for implementing many of the curricula reviewed for this project, presents considerably more challenges for teachers and schools. In high schools, the new material could be offered as an elective. If that is not possible, it would either have to replace existing classes or content, perhaps a science or technology course, or the school day would have to be reconfigured, perhaps lengthened, to accommodate a new course(s) without eliminating existing curricular material. Stand-alone courses would also require teacher professional development and approval of the program at various levels. This option has the potential advantage of providing a more in-depth exposure to engineering.
- Fully integrated STEM education, that is, using engineering concepts and skills to leverage the natural connections between STEM subjects, would almost certainly require changes in the structure and practices of schools. Research would be necessary to develop and test curricula, assessments, and approaches to teacher professional development. New integrated STEM programs or "pilot schools" might be established to test changes before they are widely adopted.

These three options, as well as others that are not described here, are not mutually exclusive. Indeed, the committee believes that implementation should be flexible, because no single approach is likely to be acceptable or feasible in every district or school.

Whichever options are implemented, planners must take into account the "technical core" of education, that is, what happens in the classroom between the teacher, the student, and the content. One way to access the technical core is to work toward "coherence" by creating educational systems with standards, curricula, professional development, and student assessments and school leadership that supports the need for change.

RECOMMENDATION 6. Philanthropic foundations or federal agencies with an interest in STEM education and school reform should fund research to identify models of implementation for K–12 engineering education that embody the principles of coherence and can guide decision making that will work for widely variable American school systems. The research should explicitly address school populations that do not currently have access to engineering studies.

The need for qualified teachers to teach engineering in K–12 classrooms raises a number of policy and program issues. The current ad hoc approach of mostly in-service training may not be adequate to train enough teachers, if K–12 engineering continues to grow. A variety of traditional and alternative mechanisms should be evaluated as part of the initiative suggested in Recommendation 4.

INTEGRATED STEM EDUCATION

During the course of this project, the committee focused increasingly on the potential of using engineering education as a catalyst for improving STEM education in general, about which serious concerns have been raised among policy makers, educators, and industry managers. So far, the role of either technology education or engineering education has rarely been mentioned in these concerns. The STEM acronym is more often used as shorthand for science or mathematics education; even references to science and mathematics tend to be "siloed," that is, treated largely as separate entities. In other words, as STEM education is currently structured and implemented in U.S. classrooms, it does not reflect the natural connections among the four subjects, which are reflected in the real world of research and technology development.

The committee believes the "siloed" teaching of STEM subjects has impeded efforts to increase student interest and improve performance in science and mathematics. It also inhibits the development of technological and scientific literacy, which are essential to informed citizens in the 21st century. The committee believes that increasing the visibility of technology and, especially, engineering in STEM education in ways that address the interconnections in STEM teaching and learning could be extremely important. Ideally, all K–12 students in the United States should have the option of experiencing some form of formal engineering studies. We are a long way from that situation now.

In the committee's vision for STEM education in U.S. K–12 schools, all students who graduate high school will have a level of STEM literacy sufficient to (1) ensure their successful employment, post-secondary education, or both, and (2) prepare them to be competent, capable citizens in our technology-dependent, democratic society. Because of the natural connections of engineering education to science, mathematics, and technology, it might serve as a catalyst for achieving this vision. The committee was not asked to determine the qualities that characterize a STEM-literate person, but this would be a worthwhile exercise for a future study.

RECOMMENDATION 7. The National Science Foundation and the U.S. Department of Education should support research to characterize, or define, "STEM literacy." Researchers should consider not only core knowledge and skills in science, technology, engineering, and mathematics, but also the "big ideas" that link the four subject areas.

Pursuing the goal of STEM literacy in K–12 schools will require a paradigm shift by students, teachers, administrators, textbook publishers, and policy makers, as well as by the many scientists, technologists, engineers, and mathematicians involved in K–12 education. However, the committee believes that, as a result of that shift, students would be better prepared for life in the 21st century and would have the tools they need to make informed career decisions or pursue post-secondary education. In addition, integrated STEM education could improve teaching and learning in all four STEM subjects by forcing a reevaluation of the currently excessive expectations for STEM teachers and students. The committee is not suggesting a "dumbing-down" process. On the contrary, this is a call for more in-depth knowledge in fewer key STEM areas and for more time to be devoted to the development of a wider range of STEM skills, such as engineering design and scientific inquiry.

Meaningful improvements in the learning and teaching of engineering—and movement toward integrated STEM education—will not come easily or quickly. Progress will be measured in decades, rather than months or years. The necessary changes will only happen with a sustained commitment of financial resources, the support of policy makers and other leaders, and the efforts of many individuals in and outside K–12 schools. Despite these challenges, the committee is hopeful, the potential for enriching and improving K–12 STEM education is real, and engineering education can be the catalyst.

1

Introduction

In the past 15 years a consensus has emerged about the need to improve K–12 education, particularly in science, technology, engineering, and mathematics, the so-called STEM subjects. The lengthening list of groups and agencies calling for improvements includes the National Science Board, U.S. Department of Education, American Association for the Advancement of Science, National Academies, and many, many others (NSB, 2007; DOEd, 2008; AAAS, 1993; NAS, NAE, and IOM, 2007). In response, some legislative action, such as the 2007 America COMPETES Act (P.L. 110-69), has been taken to strengthen K–12 STEM education.

Many concerns about the quality of STEM education are related to the challenges facing the nation in an increasingly interconnected, increasingly competitive world. The general belief is that improving K–12 STEM education can help the country meet those challenges in two important ways. First, it will keep the "pipeline" of students prepared to pursue careers in various scientific and technical fields full. Second, it will raise the level of scientific and technological literacy in the general population. Ultimately, these changes should improve our ability to compete successfully in the global marketplace, defend ourselves against various non-economic threats, and improve our overall quality of life.

Based on those beliefs, a tremendous amount of attention has been paid to the question of how to improve the teaching and learning of science and mathematics in elementary and secondary schools. In fact, this has been the focus of grants by federal agencies, presidential commissions, initiatives by professional organizations, and studies by think tanks. Improving technology education (the "T" in STEM), however, has received significantly less attention.

By contrast, almost no attention has been paid—at least on the national level—to the issue of engineering education (the "E" in STEM) in grades K–12. The goal of this report is to begin to fill that gap by providing an overview of the current state of K–12 engineering education in the United States and a discussion of what we must do in the coming years to make engineering a more effective component of the STEM equation.

CURRENT K–12 STEM EDUCATION

The STEM acronym is a relatively recent innovation (Cavanagh and Trotter, 2008). Until 2001, the common shorthand was SMET, science, mathematics, engineering, and technology. The National Science Foundation (NSF) was the first to begin referring to this collection of subjects as STEM, reflecting a change in philosophy. Up to that point, NSF's K–12 programs had targeted mostly high-achieving students who were the most likely to pursue careers in science, mathematics, and engineering. In the past decade, however, the agency has focused more resources on broad-based programs to appeal to the entire student population.

The STEM acronym has since become ubiquitous, which might lead one to conclude that the four subjects (Box 1-1) represent a well connected system of learning. However, in reality, in most elementary and secondary schools, STEM subjects are taught with little or no connection among them. Students learn mathematics in one classroom, science in another, and technology and engineering—if they learn them at all—in yet other classrooms.

Science and Mathematics

Science and mathematics are the two STEM components with the longest histories in K–12 education. Both subjects have standards, curricula, and assessments, large numbers of textbooks and other teaching materials, and established courses of teacher education and professional development. Every student in every school in the country is expected to have a minimum level of proficiency in science and mathematics by the end of high school.

More important in the context of this report, student proficiency in both science and mathematics is widely recognized as important to individual

BOX 1-1
The Four STEM Subjects*

Science is the study of the natural world, including the laws of nature associated with physics, chemistry, and biology and the treatment or application of facts, principles, concepts, or conventions associated with these disciplines. Science is both a body of knowledge that has been accumulated over time and a process—scientific inquiry—that generates new knowledge. Knowledge from science informs the engineering design process.

Technology comprises the entire system of people and organizations, knowledge, processes, and devices that go into creating and operating technological artifacts, as well as the artifacts themselves. Throughout history, humans have created technology to satisfy their wants and needs. Much of modern technology is a product of science and engineering, and technological tools are used in both fields.

Engineering is both a body of knowledge—about the design and creation of human-made products—and a process for solving problems. This process is design under constraint. One constraint in engineering design is the laws of nature, or science. Other constraints include such things as time, money, available materials, ergonomics, environmental regulations, manufacturability, and repairability. Engineering utilizes concepts in science and mathematics as well as technological tools.

Mathematics is the study of patterns and relationships among quantities, numbers, and shapes. Specific branches of mathematics include arithmetic, geometry, algebra, trigonometry, and calculus. Mathematics is used in science and in engineering.

*See Chapter 2 for a more detailed discussion of relationships among science, technology, engineering, and mathematics.

success and to the success of the country. Thus the relatively poor showing of U.S. students in these subjects on national assessments (Grigg et al., 2006; Lee et al., 2007) and comparative international studies, such as the TIMSS (Trends in International Mathematics and Science Study) assessment of fourth- and eighth-grade students around the world (Martin et al., 2008;

Mullis et al., 2008), has led to numerous calls for improving science and mathematics education.

In 2007, for example, the National Academy of Sciences, National Academy of Engineering, and Institute of Medicine (together called the National Academies) published *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. The purpose of the report was to determine how the United States could maintain its competitiveness in the global marketplace, and the first recommendation was to "increase America's talent pool by vastly improving K–12 mathematics and science education" (NAS, NAE, and IOM, 2007). A variety of legislative initiatives at the state and federal levels have also addressed the issue. In addition to the recently enacted America COMPETES Act, the No Child Left Behind Act of 2001 (P.L. 107-110) specifically targets student achievement in science and mathematics by, for example, mandating testing in both subjects and providing funding for math and science partnerships between school districts and local colleges and universities (DoEd, 2008).

Technology Education

Although technology education has roots in the manual and industrial arts, over the past two decades the field has broadened to emphasize understanding of technology in its most general sense (Box 1-2). Technology education today is the study of the human-made world, including artifacts, processes, and their underlying principles and concepts, and the overarching goal of technology education is to equip students to participate effectively in our technologically dependent world (e.g., NAE and NRC, 2002).

Some of the specific goals of technology education are described in *Standards for Technological Literacy: Content for the Study of Technology*, a report published in 2000 by the International Technology Education Association (ITEA). To meet those standards, K–12 students must develop competencies in five areas: the nature of technology, technology and society, design, abilities for a technological world, and the designed world. The fourth competency, "abilities for a technological world," requires that students know how to use and maintain everyday technologies and be able to assess the effects of using different technologies on society and the environment. The fifth competency, "the designed world," requires an understanding of technologies in specific areas, such as medicine, agriculture, and information and communications.

Despite a sustained campaign by ITEA and others, technology education is only slowly gaining acceptance. Many people—including many

BOX 1-2
A Broad View of Technology

In the broadest sense, technology is the process by which humans modify nature to meet their wants and needs. Most people, however, think of technology in terms of its artifacts: computers and software, aircraft, pesticides, water-treatment plants, birth-control pills, and microwave ovens, to name a few. But technology is more than these tangible products. 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. 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 is a product of engineering and science, and science and technology are tightly coupled. A scientific understanding of the natural world is the basis for much of technological development today. Conversely, technology is the basis for a good part of scientific research. The climate models meteorologists use to study global warming, for example, require supercomputers to run the simulations. Technology is also closely associated with innovation, the transformation of ideas into new and useful products or processes. Innovation requires not only creative people and organizations, but also the availability of technology and science and engineering talent. Technology and innovation are synergistic. The development of gene-sequencing machines, for example, has made the decoding of the human genome possible, and that knowledge is fueling a revolution in diagnostic, therapeutic, and other biomedical innovations.

SOURCE: Adapted from NAE and NRC, 2002.

educators—confuse it with classes that train students to use computers. Today, classes in technology education are offered in a minority of school districts around the country, and only 12 states require completion of a technology education course by students graduating high school (Dugger, 2007). Consequently, there are far fewer technology education teachers working in U.S. schools than science or mathematics teachers, and far fewer students taking technology education classes than classes in science and mathematics. Finally, technology education has received very little attention from policy makers. Compared to science and mathematics, technology is still a small blip on the radar screen of STEM education.

Engineering

If technology education is a small blip on the STEM radar screen, engineering education is almost invisible. Few people even think of engineering as a K–12 subject, and nationwide, very few K–12 teachers are engaged in engineering education, and very few schools expose students to engineering ideas and activities. Engineering curricula that have been developed vary widely in focus, content, and requirements for implementation. Their purposes range from encouraging students to pursue careers in engineering to increasing technological literacy and improving student performance in science and mathematics. The conceptual frameworks of these curricula also vary greatly. No standards have been set for engineering education, no state or national assessment has been adopted, and almost no attention has been paid to engineering education by policy makers. In fact, engineering might be called the missing letter in STEM.

Connection among the STEM Subjects

Most K–12 schools in the United States teach STEM subjects as separate disciplines, sometimes called "silos"—a math silo, a science silo, perhaps a technology education silo, and, in rare cases, an engineering silo—with few connections in curriculum, in teaching, or in classroom activities. Thus opportunities for leveraging the benefits of interconnections, such as using science inquiry to support learning of mathematical concepts, are largely lost. Students are left with an implicit message that each discipline stands on its own.

This is a stark contrast to the real world of research and technology development, where scientists, engineers, mathematicians, and technologists—along with social scientists, business managers, and others—work together in teams to solve problems. Each STEM discipline brings unique capabilities and perspectives, but for the team to function effectively, each player must be able to draw on and use knowledge from all four disciplines. In some cutting-edge areas, such as nanotechnology, the line between scientists and engineers has all but disappeared.

Opportunity and Uncertainty

The near absence of engineering education in K–12 classrooms represents both opportunity and uncertainty. The opportunity lies in strengthening the engineering component of STEM education, which data presented in Chapter 3 suggest can simultaneously complement and improve learning in the other three disciplines. The uncertainty arises because there are still a great many unanswered questions about how engineering education should be incorporated into K–12 classrooms, as well as about the value of existing K–12 engineering education.

THE STUDY AND REPORT

The purpose of this study is to address three specific questions:[1]

- What are realistic and appropriate learning outcomes for K–12 engineering education?
- 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?
- What educational policies, programs, and practices at the local, state, and federal levels might lead to the meaningful inclusion of engineering in K–12 education in the United States?

The Study Committee

To answer these questions, in 2006 the National Academy of Engineering (NAE) and National Research Council Center for Education established the Committee on K–12 Engineering Education. The work of the committee was supported by a grant from NAE member Stephen D. Bechtel, Jr., and additional funds were provided by the Parametric Technology Corporation and NSF.

Study Objectives

The study had four objectives:

- 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.

[1]The complete statement of task appears in an annex to this chapter.

- Review the available information showing the impact of these initiatives.
- Describe how K–12 engineering content incorporates science, technology, and mathematics concepts, uses these subjects as context for exploring engineering concepts, or uses engineering as a context for exploring science, technology, and mathematics concepts.
- Report on the intended learning outcomes of K–12 engineering education initiatives, taking into account the age of the students, the focus of the curriculum (e.g., science vs. technology education), the orientation of the program (e.g., general education vs. career/vocational education), and other factors.

Although efforts have been made to introduce engineering to K–12 students in a variety of informal (non-school) settings, through websites, contests, after-school programs, and summer programs, this study focused only on formal K–12 activities.

Fact-Finding Process

To meet these objectives and answer the questions listed above, the committee spent two years studying K–12 engineering education in the United States. During this time, the committee held five face-to-face meetings, two of which accompanied information-gathering workshops.

To get a sense of the K–12 engineering "landscape," the committee commissioned an analysis of existing K–12 engineering curricula and reviews of the literature on conceptual learning related to engineering, the development of engineering skills, and evidence of the effectiveness of K–12 engineering education initiatives. Finally, the committee also collected preliminary information about a few pre-college engineering education efforts in other countries.

This report is based on these meetings, workshops, and analyses and reviews, as well as the expertise and experience of committee members.

Report Outline

Chapter 2 of the report addresses the question, "What is engineering?" Although many readers already have a clear idea of engineering, the committee believes that understanding the purposes of and approaches to K–12 engineering education requires understanding not only what engineering is but also the key concepts of engineering (e.g., optimization, systems, the design process) and the relationships between engineering and other disciplines, particularly science and mathematics.

Chapter 3 provides a discussion of the available evidence showing the benefits of K–12 engineering education, such as improving learning in mathematics and science, improving technological literacy, and encouraging young people to consider careers in engineering or other technical fields, and the challenges to teaching engineering to K–12 students. Chapter 4 includes reviews of current K–12 engineering curricula, based largely on the commissioned analyses and reviews. In addition, the chapter reviews teacher education and professional development programs.

Chapter 5 discusses cognitive science research related to how students learn engineering concepts and skills and what this research suggests about the best approaches to teaching engineering in grades K–12. The committee's findings and recommendations are presented in Chapter 6.

Appendix A of the report provides biographical information for committee members; Appendix B contains short descriptive summaries of 19 curriculum projects that did not receive a detailed review by the committee; Appendix C, included on an accompanying CD inside the back cover of the report, contains detailed reviews of another 15 K–12 engineering education curriculum projects.

Intended Audiences

This report will be of special interest to individuals and groups interested in improving the quality of K–12 STEM education in this country. But engineering educators, policy makers, employers, and others concerned about the development of the country's technical workforce will also find much to ponder. The report should prove useful to advocates for greater public understanding of engineering, as well as to those working to boost citizens' technological and scientific literacy. Finally, for educational researchers and cognitive scientists, the document exposes a rich set of questions related to how and under what conditions students come to understand engineering.

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Annex

PROJECT STATEMENT OF TASK

The goal of this project, a collaboration between the National Academy of Engineering and the National Research Council's Center for Education, through its Board on Science Education, is to provide carefully reasoned guidance to key stakeholders 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.

Engineering is defined as "design under constraint," 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. Indeed, engineering is responsible for many of the most significant improvements in our quality of life. Engineers identify and then solve problems using a highly creative and iterative design process. While engineering requires the application of mathematics and scientific knowledge, it is this design process and the practical nature of the problems tackled that best distinguish engineering. What qualifies as engineering in the K–12 classroom, as contrasted with what engineering education is in post-secondary institutions, is something that this project will attempt to elucidate. In the early grades, "engineering" may be little more than a teacher-directed design activity, such as the construction of a balsa wood bridge, while in the later grades the design project may be considerably more open ended and involve the application of mathematics and science concepts to solve a specific problem.

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 vs. technology education), program orientation

(e.g., general education vs. career/vocational education), and other factors.

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?

Prior to the stage when the committee completes the preparation of its draft report for the institutional report review process, the committee will strive to obtain public inputs on key issues and on directions for the committee to consider in its recommendations.

2

What Is Engineering?

To understand approaches to and the potential benefits of K–12 engineering education, one must first have an understanding of engineering itself. The word engineer is derived from the Medieval Latin verb *ingeniare,* meaning to design or devise (Flexner, 1987). The word *ingeniare* is, in turn, derived from the Latin word for engine, *ingenium*, meaning a clever invention. Thus, a short definition of engineering is the process of designing the human-made world. In contrast, science is derived from the Latin noun *scientia*, meaning knowledge, and is commonly described as the study of the natural world. Whereas scientists ask questions about the world around us—what is out there, how do things work, and what rules can be deduced to explain the patterns we see—engineers modify the world to satisfy people's needs and wants. Of course, in the real world, engineering and science can not be neatly separated. Scientific knowledge informs engineering design, and many scientific advances would not be possible without technological tools developed by engineers.

Usually, engineers do not literally construct artifacts. They develop plans and directions for how artifacts are to be constructed. Some artifacts are small—a hand calculator, for example, or a computer chip—and some are large—a bridge, for example, or an aircraft carrier. Engineers also design processes, ranging from the manufacturing processes used in the chemical and pharmaceutical industries to create chemicals and drugs to procedures for putting components together on an assembly line.

One useful way to think about engineering is as "design under constraint" (Wulf, 1998). One of the constraints is the laws of nature, or science. Engineers designing a solution to a particular problem must, for instance, take into account how physical objects behave while in motion. Other constraints include such things as time, money, available materials, ergonomics, environmental regulations, manufacturability, repairability, and so on.

This somewhat sterile description belies the inherently creative nature of engineering and its contribution to human welfare. As noted in a recent initiative to develop more effective ways of communicating to the public about engineering, engineers "make a world of difference. From new medical equipment and safer drinking water to faster microchips, engineers apply their knowledge to improve people's lives in concrete, meaningful ways" (NAE, 2008).

This introduction to engineering includes a brief history of engineering and its importance to society, a discussion of some defining features of engineering, and descriptions of relationships between engineering, science, and mathematics. Throughout this chapter, the reader should keep in mind that although engineers are crucial to shaping technology, they collaborate with professionals in many other fields, including scientists, craftspeople who build devices, business people who market and sell products, and a variety of technicians and technologists who are responsible for the operation, maintenance, and repair of devices.

A BRIEF HISTORY OF THE ENGINEERING PROFESSION

Engineers have been important in every stage of human history, because people have always designed and built tools and other devices. Today, however, the word engineer is used in a more specific sense to refer to a member of the engineering profession, which has evolved over the past 300 to 400 years.[1]

Origins

Some of the earliest examples of activities we might call engineering can be found in the context of major building projects, such as the construction of the system of aqueducts in and around Rome from the fourth century B.C. to the third century A.D. (Aicher, 1995; Evans, 1994). The aqueducts

[1]Much of the following short history of engineering is taken from a commissioned paper by Jonson Miller, Drexel University, a consultant to the project.

carried water from the outskirts of Rome to the city itself via a system of pipes, trenches, bridges, and tunnels.

A project of this sort today would be largely the responsibility of engineers, but the historical records of Rome do not mention anyone who played that particular role. Much of the construction and maintenance of the aqueducts was under the supervision of a *curator aquarum*, or water commissioner, but he (and it was almost certainly a man) seems to have been considered more of an administrator than anything else. The individuals who actually built and maintained the aqueducts were architects, surveyors, craftsmen of various sorts, and manual laborers (generally slaves), but not engineers. The concept of an engineer as we know it today did not yet exist.

Engineering as a Formal Discipline

Engineering first emerged as a formal discipline during the Renaissance, with the design of military fortifications. Historically, artisans had been in charge of both planning and constructing fortifications, but by the middle of the sixteenth century a group of non-artisan specialists had appeared who used geometry and mathematics to design fortifications in a more rational way and who generally let craftsmen take care of the actual construction. These specialized military architects were the first true engineers in the modern sense of the word.

Over time military engineers expanded their purview to include other military work, such as designing siege engines, as well as civilian projects, such as designing and planning transportation systems. Engineering was first formalized and professionalized in France, with the establishment of training programs that required formal examinations in mathematics, drawing, engineering theory, and other subjects (Langins, 2004). The first formal engineering schools were established in the mid-eighteenth century, also in France, and included the École des Ponts et Chaussées (School of Bridges and Roads) and the École Royale du Génie (Royal School of Engineering).

Later, when colonists in the nascent United States needed a corps of military engineers, they looked to France. During the Revolutionary War the Continental Congress established the Corps of Engineers to help design fortifications and artillery. After the war, the corps was given a home at West Point, New York, as director of the new U.S. Military Academy (Reynolds, 1991).

One purpose of the academy was to develop military engineers by providing training in mathematics, as well as in military and civil engineering. During the first half of the nineteenth century a number of individual states, particularly southern states, started their own institutes, such as the Virginia Military Institute founded in 1839, that offered French-style engineering curricula. Most formal engineering training available in the United States up to the time of the Civil War was offered at these military academies.

Engineering as an Artisanal Craft

At the same time as a formal approach to engineering was being pursued in France, the United States and other countries adopted a second, more practical approach. The trend began in Great Britain with the advent of industrialization, when the country's artisans, who had a tradition of apprenticeships and on-the-job training, spearheaded the early design and development of the machinery and machine shops of the industrial age. The British transportation infrastructure was also developed by independent engineers who got their training through apprenticeships.

The apprenticeship tradition was transported to the 13 British colonies that would eventually become the United States, and the engineers who designed the machine shops and mechanized textile mills in the early days of this country had generally been trained in informal settings like those of typical British artisans and engineers (Calhoun, 1960; Reynolds, 1991). Similarly, many of the engineers who worked on road, bridge, and canal projects in the United States in the late 1700s and early 1800s were trained in this tradition—indeed, quite a few of them had learned their trades in Great Britain before coming to this country.

And so throughout much of the nineteenth century, engineers in the United States and elsewhere received their training in one of two very different ways—either a formal, theoretically oriented way that emphasized mathematics, science, and engineering theory, or a practical, hands-on way that favored on-the-job training.

The Rise of Professional Engineers

After the Civil War, engineering programs in the United States increasingly emphasized formal training, although on-the-job training remained important for a variety of engineering disciplines—particularly mechanical engineering—until the middle of the twentieth century. At the same time, in the years following the Civil War a number of engineering professional societies appeared: the American Society of Civil Engineers (ASCE) in 1865, the American Society of Mechanical Engineers in 1880, the American

Institute of Electrical Engineers in 1884, and so forth. These societies had a strong influence on how the various fields of engineering were developed. They influenced education and training programs for engineers, and they developed standards for industry as well as ethical codes for their members (Reynolds, 1991). Professional societies also helped define new fields of engineering, as when mining engineers split from the ASCE in 1871 to form the American Institute of Mining Engineers and when industrial chemists broke away from the American Chemical Society in 1908 to form the American Institute of Chemical Engineering.

The professionalization of engineering continued through much of the twentieth century. One of the most important trends over the past 50 years has been the increasing emphasis on mathematics and science in the education of engineers. When the Soviet Union launched the Sputnik satellite in 1957, the U.S. response included a national effort to increase the number of scientists and engineers coming through the educational pipeline and to emphasize the teaching of science and mathematics. As a result, engineering education began to put much more emphasis on theory and mathematics (Lucena, 2005).

Over the past quarter century, as the national focus has shifted from the perceived Soviet military threat to concerns about globalization and U.S. competitiveness in the world economy, the emphasis in engineering education has shifted again. Today, engineering schools no longer focus exclusively on science, mathematics, and engineering theory. They also emphasize flexibility and being able to respond quickly to emerging challenges (e.g., NAE, 2004). Expectations for engineering students are now likely to include the ability to work well in teams, to communicate ideas effectively, and to understand other cultures and the effects of technology on societies and individuals. In short, as technology has evolved from a collection of mostly isolated devices and structures to a tightly interconnected global system, engineers—as the designers of this technological world—have also evolved. Today, they must be competent in far more than the traditional science- and math-oriented subjects.

Engineering, Industrial Arts, and Technology Education

The advent of formal engineering education with its emphasis on theoretical mathematics and science was accompanied by a growing recognition that aspiring engineers also needed manual skills. As early as 1870, Calvin M. Woodward, dean of the engineering department at Washington University, instituted shop training for his engineering students after he found that they were unable to produce satisfactory wooden models to demonstrate mechanical principles. John D. Runkle, president of the Massachusetts Institute of Technology, introduced a similar program after seeing demonstrations of Russian manual arts training at the 1876 Centennial Exposition in Philadelphia. Both men believed that shop skills were essential for engineers (Sanders, 2008).

In the 1880s, under the leadership of Woodward and Runkle, Washington University and MIT established schools for intermediate and secondary students that provided a combined program of liberal arts and manual training. Other schools, however, emphasized training in specific trades to provide skilled workers for specific industries. Both types of schools grew quickly.

By the early twentieth century, there had been a conceptual shift from "manual training" to "industrial arts." Contrary to what many people assume, industrial arts represented a shift away from vocational training toward general education for all (Herschbach, 2009). Students studied how industry created value from raw materials in the context of the developing industrial society in America. The curriculum required the ability to use industrial tools, equipment, and materials in a laboratory setting, but the "shop experience" was a means to an end, not an end in itself.

By the mid-twentieth century, industrial arts had become a standard component in the public school curriculum. However, it continued to be confused with vocational education, which was also on the rise during this period. By the end of the century, the teaching of industrial arts had expanded to include an understanding of technology in general. In 1985 the Industrial Arts Association of America changed its name to the International Technology Education Association (ITEA).[2]

Since the name change and, especially, since publication of *Standards for Technological Literacy: Content for the Study of Technology* (2000), technology education teachers have increasingly sought to teach engineering concepts and skills to students (Lewis, 2004). But this shift has not been universal, and technology education is still best thought of as a continuum of practice spanning traditional industrial arts ("shop") classes, career-focused indus-

[2]The shift is evident in a 2009 ballot measure to change the name of the International Technology Education Association (ITEA) to include the word engineering. A full 65 percent of voting members favored the name change (K. Starkweather, ITEA, personal communication, June 16, 2009). However, the association's bylaws require a 66 percent majority, so the measure did not pass.

trial technology, and technology education programs that include differing degrees of engineering content.

The varied implementation of technology education makes it difficult to clearly distinguish it from "engineering education" at the K–12 level. The distinctions are most apparent between the industrial arts model of technology education, with its emphasis on tool skills and fabrication of technological artifacts, and engineering education that focuses on the engineering design process as an approach to problem solving. Some analysts (McAlister, 2007) have pointed out that pre-service education for most technology teachers includes relatively few mathematics and science courses. Because engineering design, particularly modeling and analysis, relies on mathematics and science concepts, another emerging distinction between educators in technology and those in engineering may be their degree of preparation in science and mathematics.[3]

More broadly, there are indicators of growing interest in understanding and improving the connections between engineering and technology education. For example, the ITEA Council on Technology Teacher Education devoted an entire volume to the topic (CTTE, 2008); from 2004 to 2009, the National Science Foundation funded the nine-university National Center for Engineering and Technology Education (*www.ncete.org*), in part to grow these connections; and in 2004, the American Society for Engineering Education established a Division on K–12 and Pre-College Engineering, and some members of the division are from technology education.

The Demographics of Engineering Today

In 2006, the most recent year for which data are available, the United States had an engineering workforce of about 1.5 million people[4] (BLS, 2008a). About 37 percent of engineering jobs were in manufacturing industries, and 28 percent were in the professional, scientific, and technical services sector, primarily architectural, engineering, and related services. Many engineers also worked in the construction, telecommunications, and wholesale trades. In addition, federal, state, and local governments employed about 12 percent of engineers.

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[3]The importance of mathematics and science to engineering design is discussed at length in Chapter 4.

[4]This number does not include roughly 27,000 engineering teaching personnel who are employed by engineering schools (ASEE, 2007a, p. 28).

Although this chapter is focused on the history of engineering, it is important to recognize another significant component of the technology workforce, engineering technicians and technologists. Formal engineering technology programs, which were developed in the mid-twentieth century, provide students with a distinctly hands-on, practical education, in contrast to engineering programs, which focus more on theory and design (Grinter, 1984). Today, there are both two- and four-year engineering technology programs in the United States. Graduates of the former are often called engineering technicians; graduates of the latter are called engineering technologists. Engineering technologists typically implement designs created by engineers. They may be involved in making incremental design changes, building and testing products and processes, managing the installation of complex equipment, and developing maintenance procedures. Engineering technicians are primarily operators of technology, but they also have installation and maintenance skills beyond the capabilities of skilled tradesmen. In practice, there may be considerable overlap between engineering technologists and engineering technicians.

In 2006, 511,000 engineering technicians were working in the United States, a third of them electrical and electronics technicians (BLS, 2008b). The U.S. government does not collect employment data on engineering technologists in a separate job classification. However, the Engineering Workforce Commission estimates that there were about 10,000 bachelor's degrees in engineering technology awarded in 2007 (ASEE, 2007b).

Women and minorities are greatly underrepresented in engineering schools (both as students and faculty) and engineering jobs in the United States relative to their proportions in the population at large (Table 2-1). Although their participation has been increasing over the past two decades, the rate of increase has slowed—and for women the upward trend has recently reversed. This situation has many people in the engineering community worried about the future supply of engineers, especially as the U.S. population becomes increasingly diverse.

Some have expressed a concern that other countries—particularly China and India—have been outpacing the United States in the production of engineers. Although it is difficult to make comparisons because of differences in the methods of collecting data and differences in how engineers are defined, the trends are clear. The number of engineering bachelor's degrees awarded in the United States has increased gradually over the past seven years to slightly more than 74,000 in the 2005–2006 school year (ASEE, 2007a). This is a jump of about 20 percent since 1999. In China, by contrast, the number

TABLE 2-1 Selected Data for Women, African Americans, Hispanics, and Native Americans in Engineering

Women
Proportion of U.S. population, 2005 (est.): 50.7 percent
Proportion of students enrolled in degree-granting institutions, 2004: 57.4 percent
Proportion of bachelor's degrees in engineering, 2004: 20.5 percent
Proportion of tenured/tenure-track appointments on U.S. engineering faculties, 2005: 10.6 percent
Proportion employed as engineers, 2003: 11 percent

African Americans
Proportion of U.S. population, 2004: 12.8 percent
Proportion enrolled in degree-granting institutions, 2004: 12.5 percent
Proportion of bachelor's degrees in engineering earned, 2004: 5.3 percent
Proportion of tenured/tenure-track appointments on U.S. engineering faculties, 2005: 2.3 percent
Proportion employed as engineers, 2003: 3.1 percent

Hispanics
Proportion of U.S. population, 2004: 14.1 percent
Proportion enrolled in degree-granting institutions, 2004: 10.5 percent
Proportion of bachelor's degrees in engineering, 2004: 7.4 percent
Proportion of tenured/tenure-track professors on U.S. engineering faculties, 2005: 3.2 percent
Proportion employed as engineers, 2003: 4.9 percent

Native Americans
Proportion of U.S. population, 2004: 1 percent
Proportion enrolled in degree-granting institutions, 2004: 1 percent
Proportion of bachelor's degrees in engineering, 2004: 0.6 percent
Proportion of tenured/tenure-track professors on U.S. engineering faculties, 2005: 0.2 percent
Proportion employed as engineers, 2003: 0.3 percent

SOURCES: NSF, 2005a,b, 2006a,b; U.S. Census Bureau, 2002, 2005; U.S. DOEd 2006a,b.

of students graduating with four-year degrees in engineering, computer science, and information technology more than doubled between 2000 and 2004 (Wadhwa et al., 2007). A similar doubling occurred in India.

The committee did try to ascertain the level of pre-college engineering education in India and China. The various individuals we spoke with, including high-level education and industry officials in both countries, indicated there were no such efforts. We were told that Indian and Chinese students' first exposure to engineering ideas typically occurs in college. However, we could find no reliable evidence to confirm this.[5]

THE ROLE OF ENGINEERING IN MODERN SOCIETY

Over the past 400 years the role of engineers has expanded and diversified from a singular focus on military fortifications and engines to include products that affect almost every aspect of society and people's daily lives. Many of these are well known—engineers design both computers and the software that runs on them, both automobiles and the roads and bridges they travel on, and power plants and the transmission systems that carry power to the people who need it. In other respects, the accomplishments of engineers are not as widely recognized. For example, every piece of medical equipment, from the simplest thermometer to the most complex MRI device, was designed by an engineer, as were machines that are used to manufacture other machines and the equipment scientists rely on for work that often leads to scientific discoveries.

One way to get a sense of the importance of engineering in modern society is to examine the list of 14 grand challenges for engineering produced by the National Academy of Engineering (NAE) in 2008 (Box 2-1). These challenges are major issues confronting society in the twenty-first century, and engineering will be crucial to addressing all of them.

For instance, sustainability is a major theme linking five of the grand challenges. As societies search for ways to maintain themselves in a sustainable way relative to the environment, engineers will have to find ways to provide clean water and economical solar power and energy from fusion and develop ways to remove carbon dioxide from the atmosphere, such as storing it in the Earth's crust. Engineers, working with doctors and medical researchers, can improve human health by developing better ways of storing, analyzing, and communicating health information and by designing more effective drugs. To avoid the misuse of powerful technologies, engineers will find ways to keep terrorists from obtaining and using nuclear materials and technologies and to secure cyberspace. Finally, engineers in the coming century will be crucial to improving human capacities by, for example, advancing personalized learning and engineering the tools that will enable scientific discovery.

[5]For a brief review of pre-college engineering efforts in countries other than India and China, see the annex to Chapter 4.

BOX 2-1
Grand Challenges for Engineering

On February 15, 2008, the National Academy of Engineering announced its list of 14 "grand challenges for engineering," examples of the types of challenges confronting societies in the twenty-first century. The solutions to these challenges will all have large engineering components. Although engineers cannot solve these challenges alone, neither can the challenges be solved without engineers.

The fourteen grand challenges are:

- Making solar power economical;
- Providing energy from fusion;
- Developing carbon-sequestration methods;
- Managing the nitrogen cycle;
- Providing access to clean water;
- Restoring and improving urban infrastructure;
- Advancing health informatics;
- Engineering better medicines;
- Reverse-engineering the brain;
- Preventing nuclear terror;
- Securing cyberspace;
- Enhancing virtual reality;
- Advancing personalized learning; and
- Engineering the tools of scientific discovery.

SOURCE: NAE, 2008.

DESIGN AS A PROBLEM-SOLVING PROCESS

Science, mathematics, and engineering all have domains of knowledge, process skills, and ways of looking at the world. Perhaps the most important for engineering is design, the basic engineering approach to solving problems. Using the design process, engineers can integrate various skills and types of thinking—analytical and synthetic thinking; detailed understanding and holistic understanding; planning and building; and implicit, procedural knowledge and explicit, declarative knowledge.

What Is Engineering Design?

Design is a deceptively common word that is used to describe what graphic artists do, what fashion designers do, what landscape architects do, and what flower arrangers do. But in the context of engineering, the word has a specific meaning. Design is the approach engineers use to solve engineering problems—generally, to determine the best way to make a device or process that serves a particular purpose. When electronic engineers design an integrated circuit chip, when transportation engineers design a subway system, when chemical engineers design a chemical processing plant, and when biomedical engineers design an artificial organ, they all use variants of the same basic problem-solving strategy—engineering design.

According to *Standards for Technological Literacy: Content for the Study of Technology* (ITEA, 2000), engineering design has a number of characteristic attributes. First, it is purposeful; a designer begins with an explicit goal that is clearly understood; thus design can be pictured as a journey with a particular destination, rather than a sightseeing trip. Second, designs are shaped by *specifications* and *constraints*. Specifications spell out what the design is intended to accomplish. Constraints are limitations the designer must contend with, such as costs, size requirements, or the physical limitations of the materials used. In addition, the design process is systematic and iterative. Engineering design is also a highly social and collaborative enterprise. Engineers engaged in design activities often work in teams, and communication with clients and others who have a stake in the project is crucial.

Over time, engineers have developed a variety of rules and principles governing the development of a design. Although the rules are not absolute, engineers understand that these principles are based on many years of accumulated experience and that without such rules engineers would be very much like tinkerers or amateur inventors.

Design is not a linear, step-by-step process. It is generally iterative; thus each new version of the design is tested and then modified based on what has been learned up to that point. Finally, there is never just one "correct" solution to a design challenge. Instead, there are a number of possible solutions, and choosing among them inevitably involves personal as well as technical considerations (ITEA, 2000, pp. 91–92).

Although there is no formula for engineering design that specifies step 1, step 2, and so on, there are a number of characteristic steps in a design process. One step, for example, is identifying the problem. As noted above, an explicit goal for a design is what distinguishes it from tinkering. A second step is generating ideas for how to solve the problem. Engineers often use research or brainstorming sessions to come up with a range of design alternatives for further development. Another step is the evaluation of potential solutions by building and testing models or prototypes, which provides valuable data that cannot be obtained in any other way. With data in hand, the engineer can evaluate how well the various solutions meet the specifications and constraints of the design, including considering the trade-offs needed to balance competing or conflicting constraints. Engineers call this process *optimization*.

These steps are repeated as necessary. For example, an engineer may go all the way back to step 1, identifying the problem, if the research and prototypes turn up something unexpected. Usually, however, the results of various tests lead to a round of improvements—complete with brainstorming ideas, testing new prototypes, and so on—and yet another round of improvements, until enough iterations have been performed that the engineer is satisfied with the result. Once the finished product has been tested and approved, it can be produced and marketed (ITEA, 2000, p. 99).

How Design Compares with the Scientific Method

Engineering design is often compared with scientific inquiry, the core problem-solving approach used in science, and, indeed, the two approaches have a number of similar features. But they also differ in significant ways. By identifying the convergences and divergences, one can get a better idea of how the two approaches might fit together in a school curriculum (Lewis, 2006).

The most obvious similarity, or convergence, is that both design and scientific inquiry are reasoning processes used to solve problems, "navigational devices that serve the purpose of bridging the gap between problem and solution" (Lewis, 2006, p. 271). For both scientists and engineers, some problems are relatively straightforward; challenging problems, however, are characterized by high levels of uncertainty that require a great deal of creativity on the part of the problem solver. In searching for solutions, engineers and scientists use similar cognitive tools, such as brainstorming, reasoning by analogy, mental models, and visual representations. And both require testing and evaluation of the product—the engineering design or the scientific hypothesis.

One point of divergence between engineering design and scientific inquiry is the role of constraints, which are common to both processes but are fundamental to engineering design. Budget constraints, for example, can limit scientific inquiry and perhaps even keep scientists from answering a particular question, but they do not affect the answer itself. For engineers, however, budget constraints can determine whether a particular design solution is workable. Another divergence is trade-offs. As Lewis notes (2006), trade-offs are a basic aspect of design but have essentially no part in scientific inquiry.

A related difference is the scientist's emphasis on finding general rules that describe as many phenomena as possible, whereas the engineer's focus is on finding solutions that satisfy particular circumstances. Scientific inquiry begins with a particular, detailed phenomenon and moves toward generalization, while engineering design applies general rules and approaches to zero in on a particular solution. In addition, judgments about the suitability of a design are inevitably shaped by individual and social values; thus the optimal design for one person may not be optimal for another. This is quite different from the scientific method; in the ideal scientific situation, answers are independent of values.

Another way to compare design with the scientific method is to consider the characteristics of the two problem-solving approaches (Box 2-2). *Science*

BOX 2-2
Characteristics of Scientific Inquiry and Engineering Design

Scientific Inquiry:
Demands evidence
Is a blend of logic and imagination
Explains and predicts
Tries to identify and avoid bias
Is not authoritarian

Engineering (or Technological) Design:
Is purposeful
Is based on certain requirements
Is systematic
Is iterative
Is creative
Allows many possible solutions

SOURCES: AAAS, 1989; ITEA, 2000.

for All Americans, published by the American Association for the Advancement of Science, identifies five characteristics of scientific inquiry that distinguish it from other modes of inquiry: science demands evidence; science is a blend of logic and imagination; science explains and predicts; scientists try to identify and avoid bias; and science is not authoritarian (AAAS, 1989). At first glance, these rather general statements seem to apply, at least partly, to engineering design. Certainly engineers also demand evidence, for instance, and they use a blend of logic and evidence in their design work. Conversely, there is little doubt that science can be a very creative endeavor, is systematic, and is purposeful. This overlap reflects the many similarities in the ways scientists and engineers go about their work.

Nevertheless, there are also important differences between the scientific method and engineering design. The distinguishing features of engineering design include taking into account specifications and constraints; dependence on iteration; and the embrace of multiple possible solutions. The differences in the two lists reflect the basic differences between science and engineering—scientists investigate and engineers create.

For example, although "purposeful" might describe a characteristic of the scientific method, it would certainly not appear near the top of the list. For engineering design, however, purposefulness is a fundamental characteristic—the first question that must be answered about any design is, "what is its purpose?" For scientists, however, the focus is on the particular questions they are investigating. Scientists may have an underlying purpose for investigating particular questions—for example, a geneticist studying the BCRA gene does so for the purpose of understanding breast cancer—but the day-to-day work of the scientist is driven by the question, not the purpose.

Similarly, specifications and constraints are not essential to answering scientific questions. Not every scientific question has a single "correct" solution, but there is no expectation in the scientific method that the process will inevitably produce multiple answers. These, however, are fundamental characteristics of design that set it apart from the scientific method.

IMPORTANT CONCEPTS IN ENGINEERING

In addition to specifications and constraints, a number of other concepts are key to understanding what engineers do and how they do it. The list may vary depending on who compiles it, but certain concepts will appear on most lists (e.g., AAAS, 1993; Burghardt, 2007; Childress and Rhodes, 2006; Childress and Sanders, 2007; ITEA, 2000; Sneider, 2006).

One crucial idea that appears regularly on the engineering list, but also on the science list and lists for many other areas of study, is the concept of *systems*. In very general terms a system is a collection of interacting pieces. The collection of all trains, planes, and automobiles, along with railways, airports, roads, and everything else involved in getting people and things from one place to another makes up one type of system—the country's transportation system. The various components of an iPod constitute another kind of system. The machines and their operators in an automobile plant make up another kind of system.

In most cases a system is more than the sum of its parts, and understanding a system involves not only understanding the individual parts but also understanding how the parts interact. Most of the "things" engineers design are systems of one kind or another, and in many cases those things function as part of a larger system. Thus engineers must have a good grasp of how systems work and the factors that influence the performance of the system (AAAS, 1993).

Engineers use *modeling* as a way to understand what may happen when an actual artifact or process is used. In the case of a wooden plank used as a footbridge across a stream, for instance, an engineer might be asked to predict the weight of the heaviest person who could cross the plank without breaking it. The engineer creates a *representational model* of the plank, which may consist of drawings or physical, three-dimensional renditions. The model incorporates assumptions about the size and physical properties of the plank and about how it is secured on the banks of the stream.

Using the representational model, the engineer creates a free-body diagram, which shows the various forces that act on the plank, and from the free-body diagram develops a *mathematical model* based on laws of mechanics. By creating the representational models of potential solutions and then mathematically characterizing them, engineers can predict the behavior of technologies before they are built, and the predictions can be tested experimentally. The accuracy of the representational and mathematical models—often calculated with the assistance of computer programs and/or computer simulations—determines the validity of the predictions. This process of *predictive analysis* is another central feature of engineering design.

Very sophisticated software programs have been developed for predicting the performance of integrated circuit chips, for example. Without these programs, it would be essentially impossible to design the highly sophisticated chips that are manufactured today (EDAC, 2008). Because of the importance of mathematical modeling and predictive analysis to engineering design, mathematics is essential to engineering, and engineers must be comfortable using mathematical tools.

As mentioned above, one step in design is understanding the requirements, or *specifications* and *constraint*s, of the design. The specifications are key features and elements of the product and what it is supposed to do. Constraints are limitations on the design—physical, financial, social, political, environmental factors, and so on. It is almost never possible to meet all of the specifications and accommodate all of the constraints simultaneously. Determining the best solution to a technical problem requires balancing competing or conflicting factors; this process is called *optimization*. Often different alternatives are better in different ways. One material may be stronger, for instance, but a second material may cost less. Choosing the best solution normally requires *trade-offs*, that is, deciding not to maximize one desirable thing in order to maximize another. Deciding which criteria are the most important is essential to determining the best solution to a problem. The idea is to decide upon a design that comes closest to meeting the specifications, that fits within the constraints, and that has the least number of negative characteristics (AAAS, 1993).

THE RELATIONSHIP OF ENGINEERING TO SCIENCE AND MATHEMATICS

Engineering is intimately related to science and mathematics. Engineers use both science and mathematics in their work, and scientists and mathematicians use the products of engineering in their work. In every field of engineering, an understanding of the relevant science is a prerequisite to doing the job. Chemical engineers must understand chemistry, bioengineers must understand molecular biology, petroleum engineers must understand geology, electronics engineers must understand how electrons behave in various materials, nuclear engineers must understand how the nuclei of atoms behave, and so on. Indeed, science is so fundamental to what engineers do that, in a very real sense, engineering can be thought of as putting science to work.

Mathematics is as fundamental to engineering as science. Engineers use mathematics both to describe data (e.g., graphs showing the strength or other properties of a material under varying conditions) and to analyze them (e.g., the flow rate of fluids through the pipes of a chemical plant). As noted above, engineers use science and mathematics most obviously in building and analyzing models.

Conversely, engineering is essential to science and mathematics. Scientists depend upon the products of engineers—everything from space telescopes to gene sequencers—to perform various manipulations and measurements in exploring the natural world. And although many mathematicians still require little more than chalk and a chalkboard for their studies, a growing number of them now take advantage of increasingly powerful computers—a gift from engineers—to perform mathematical explorations. Thus the relationship between engineering and science and mathematics is a two-way street.

ENGINEERING IN THE TWENTY-FIRST CENTURY

A description of engineering would be incomplete without addressing the challenges the field faces in the coming decades. Of course, looking into the future is always a tricky proposition, but several trends in engineering provide a basis for extrapolating and predicting some things about the future of engineers and engineering.

An Increasingly Diverse Workforce

As shown in Table 2-1, the engineering workforce in the United States today includes relatively few women and minorities compared to the percentages of these groups in the general population and the overall workforce. These numbers indicate that the potential contributions of women and minorities to the engineering workforce are not being realized. Addressing this underrepresentation will be critical to the future of engineering in light of the changing demographics in the United States.

Projections based on current trends indicate that by 2050 minorities will make up almost half of the U.S. population and a corresponding percentage of the U.S. workforce (U.S. Census Bureau, 2002). Thus even if minorities are still underrepresented in the engineering workforce, they will likely account for a much larger percentage of the workforce in coming years. The hope is, of course, that the engineering workforce of the future will be far more diverse and representative than it is today.

Adaptation to a Changing World

The kinds of jobs engineers are being asked to do and the skills they are expected to have are changing (Duderstadt, 2008). A major factor driving changes in the demands on U.S. engineers is increasing global competition. U.S. engineers increasingly find themselves competing for work with engineers from other countries, who are often paid much less—in some countries as much as 80 percent less. To succeed in this environment, U.S. engineers will need not only the analytic skills—high-level design, systems thinking, and creative innovation—that are taught in engineering courses, but also a variety of skills that are often overlooked in engineering education. These include communications and leadership skills, the flexibility to adapt to changing conditions, the ability to work in multicultural environments, an understanding of the business side of engineering, and a commitment to lifelong learning (NAE, 2004).

Implications for K–12 Engineering Education

As noted in Chapter 1 and discussed at greater length later in the report, one of the purposes of at least some K–12 engineering education programs is to encourage more young people to consider engineering as a career pathway. It is unrealistic to expect that the challenges facing U.S. innovation can be addressed solely by boosting the number and diversity of K–12 students interested in technical and scientific fields. But broadening the appeal of engineering and related careers to American pre-college students will almost certainly be part of the solution.

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3

The Case for K–12 Engineering Education

Proponents have put forth a number of reasons for adding K–12 engineering education to the school curriculum (Box 3-1). Their arguments are similar to arguments for improving STEM education. Both cases are based on changes in the world—increasing complexity, interconnectivity, competitiveness, and technology dependence—that pose new challenges for individuals and for nations that cannot be met by continuing education as usual. We will need a steady supply of well-trained engineers, scientists, and other technical workers, as well as a technologically and scientifically literate general public, to succeed and prosper in the twenty-first century (Augustine, 2007; BSCS, 2007).

In this chapter, we present a detailed discussion of the case for K–12 engineering education, focusing on various aspects of the argument and on supporting data.

THE BENEFITS OF K–12 ENGINEERING EDUCATION

The potential benefits to students of including engineering education in K–12 schools can be grouped into five areas:

- improved learning and achievement in science and mathematics;
- increased awareness of engineering and the work of engineers;
- understanding of and the ability to engage in engineering design;

BOX 3-1
Statements from Selected K–12 Engineering Education Programs

The "Engineering by Design"™ Program is a model used by schools developing themes in the STEM and IT Clusters that are seeking to increase all students' achievement in technology, science, mathematics, and English through authentic learning.

ITEA
http://www.iteaconnect.org/EbD/ebd.htm

"The Infinity Project" is helping 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. For our next generation of college graduates to be competitive in the global world of technology, we need to take steps now to encourage more young students to pursue engineering.

Southern Methodist University
http://www.infinity-project.org/infinity/infinity_hist.html

The "Engineering is Elementary" project aims to foster engineering and technological literacy among children.

Boston Museum of Science
http://www.mos.org/eie/index.php

- interest in pursuing engineering as a career; and
- increased technological literacy.

Although only a small percentage of students has had an opportunity to study engineering in elementary and secondary schools in the United States, a number of curricula for teaching engineering have been developed—many of which are described in Chapter 4. Curriculum developers, cognitive scientists, and others have studied the effects of these curricula and other K–12 engineering initiatives on student learning, interests, and attitudes. Based on their research, it is possible to assess the evidence for these benefits.

The remainder of this chapter provides the highlights and key findings of a commissioned review of the relevant research literature, which includes articles published in peer-reviewed journals, conference papers, program evaluations, and unpublished documents such as dissertations (Svihla et al., unpublished).

Overall, the review turned up limited evidence for many of the benefits predicted or claimed for K–12 engineering education. This does not mean that the benefits do not exist, but it does confirm that relatively few well-designed, carefully executed studies have been conducted on this subject. This issue is discussed in greater detail at the end of this chapter and in Chapter 6.

Improved Learning and Achievement in Science and Mathematics

One of the claims most often made about K–12 engineering education is that it improves learning and achievement in science and mathematics. This is a particularly compelling claim because, for the past two decades, many concerted efforts have been made to improve K–12 science and mathematics education in the United States. By most accounts those efforts have had relatively unimpressive results (Box 3-2).

How might engineering education improve learning in science and mathematics? In theory, if students are taught science and mathematics concepts and skills while solving engineering or engineering-like problems, they will be able to grasp these concepts and learn these skills more easily and retain them better, because the engineering design approach can provide real-world context to what are otherwise very abstract concepts.

Preliminary evidence supports this theory. For example, students who took courses developed by "Project Lead the Way" (PLTW) scored significantly higher on science and mathematics in the NAEP than students in a random, stratified comparison group (Bottoms and Anthony, 2005; Bottoms and Uhn, 2007). Research using a state achievement test as the basis of comparison has found more mixed results. PLTW students from schools serving a high proportion of low-income families showed less improvement in mathematics scores from grade 8 to 10 and no statistical difference in science achievement scores over that period, compared with a control group (Tran and Nathan, In press). And PLTW students attending schools serving predominantly affluent families exhibited small gains in mathematics achievement but no improvement in science achievement, compared with a control sample (Tran and Nathan, In press).

Students who had taken the "Engineering Our Future New Jersey" course, which is offered in 32 elementary, middle, and high schools in the state, demonstrated significant improvements in scores on both science and

BOX 3-2
The Push to Improve K–12 Science and Mathematics Education

In 1990, the Department of Education National Education Goals Panel released a report detailing necessary improvements in U.S. education. In that report, science and mathematics were the only subjects addressed specifically. Goal 5 was, "By the year 2000, United States students will be first in the world in mathematics and science achievement" (DOEd, 1989). Eleven years later, when the department published a definitive study of science and mathematics teaching in the United States, the conclusion was that little progress had been made toward reaching that goal (DOEd, 2000).

In the past few years, many studies, such as *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* have argued that improving science and mathematics education will require substantial reform (NAS et al., 2007). Many of these reports include data from the National Assessment of Educational Progress (NAEP) and two ongoing international comparative assessments, the Trends in International Mathematics and Science Study (TIMSS) and the Programme for International Student Assessment (PISA), to support the contention that U.S. K–12 students, particularly secondary students, simply do not measure up. Although TIMSS and PISA data are often used as indicators, some have argued that most interpretations of these data overstate the U.S. achievement problem, in part because they do not account for differences in the educational systems of the participating countries (Lowell and Salzman, 2007).

In 2007, the Department of Education published a review of all federally funded programs with a math or science education focus, looking at their effectiveness and at ways to integrate and coordinate them. The report focused on 115 programs that it considered to have the best evaluations and concluded that there was very little hard evidence as to which programs were effective and which were not (DOEd, 2007).

mathematics achievement tests[1] (Hotaling et al., 2007). Statistically significant gains in science and mathematics scores have also been reported by the

[1]In this study, the results were not disaggregated, and no measure of variance was provided. Thus we cannot know if the gains were uniform or if some subgroups were more or less impacted.

Center for Innovation in Engineering and Science Education at Stevens Institute of Technology, which has created a variety of online, problem-based K–12 engineering curricula (McKay and McGrath, 2007). Students who had participated in "Engineering is Elementary," a program developed by the Boston Museum of Science that integrates engineering with science content for elementary students, showed improvement in a post-test measuring science and engineering knowledge (Lachapelle and Cunningham, 2007). Unfortunately, there was no control group for comparison in this study.

Engineering design has been shown to encourage mathematical thinking. Akins and Burghardt (2006) studied teams of middle and high school students who applied mathematical reasoning to solve problems in a design challenge. Pre-test results were used to disaggregate students into quartiles, and all quartiles showed improvement on math and science tests. (No tests of significance were conducted, but post-test scores were 21 percent to 125 percent higher than pre-test scores.) The authors noted that the lowest scoring teams had the highest score gains, which suggests that engineering design has the potential to narrow achievement gaps; this possibility was not noted by the researchers, however.

In some cases, standardized test scores were not impacted by student participation in engineering activities, but other measures, such as the ability to explain, analyze, predict, or reason about science, mathematics, or technology, demonstrate that the students had learned a great deal. For example, a program at one inner-city school involved designing remote-control vehicles. Although the scores of students who participated in the program did not show improvements on district-wide physics achievement tests, pre-post measures showed that the students had a better understanding of the physics related to their vehicles (Barnett, 2005).

In the "Integrated Mathematics, Science, and Technology" (IMaST) curriculum project, participating students and non-IMaST students had similar gains on state mathematics and science achievement tests, but IMaST students scored higher on TIMSS math items than students in a control group (Satchwell and Loepp, 2002). Notably, IMaST students scored higher on measures related to "process" (i.e., mathematical problem solving and science inquiry) whereas the control students scored higher on measures related to "knowing" (i.e., understanding routine mathematics operations and scientific information).

A few studies have been done on the potential of K–12 engineering to differentially affect math and science achievement among girls and underrepresented minorities. In a middle-school study of modules in which engineering design and science were integrated, pre-post data showed that the achievement gap for African American and Latino/a students was narrowed, but the achievement gap for girls was increased (Cantrel et al., 2006). It is not clear in this case whether the students engaged in a truly iterative design process, which has been shown to encourage science learning for girls and students from families of low socio-economic status (SES) (Kolodner et al., 2003). Barnett (2005) reported on a study of inner-city, low SES, predominantly ethnic-minority high school students that included a significant population of English language learners and many students with disabilities. All of these students had participated in a project that involved designing remotely operated vehicles. Pre-post data revealed that, overall, the students' understanding of physics had improved. However, the improvement did not translate to higher scores on a district-wide final exam in physics.

So-called challenge-based environments can mimic design or motivate students to solve problems in order to learn engineering, science, and mathematics content. In a three-year study of this approach, "legacy cycles," Klein and Sherwood (2005) found that students in the experimental group had statistically larger gains in measures of relevant science knowledge and concepts. Although most of the modules did not involve design, they did require problem solving in the context of engineering and had many design elements. The researchers argue that design challenges embedded in science activities increase the likelihood that students will explore variables rather than stopping their inquiries as soon as the design criteria have been satisfied. The "Math out of the Box" program uses a modified legacy cycle in which engineering provides a context for learning applied mathematics (Diaz and King, 2007). This program has been implemented in several schools; the ones that have continued to use it have found that achievement scores in mathematics have risen, particularly for low-SES and African American students. The schools that discontinued the program found that mathematics scores fell.

Qualitative research in the learning sciences provides some insights into how and why science and mathematics learning may be impacted by participation in engineering activities, particularly design activities. Fortus et al. (2004) recorded significant increases in science knowledge among ninth graders engaged in the "Designed-Based Science" curriculum. The researchers suggest that this effect can be explained in part by students' personal ownership of science content as compared with consensus-driven ownership in other forms of inquiry. Students using this curriculum were also able to transfer their understanding of a concept from the original context to a different context (Fortus et al., 2005), which the researchers attribute to the way the design activity is structured to support learning for understanding in the context of solving a problem. Roth (2001) suggests that design activities, which present distributed representations of ideas, can stimulate discussions about science concepts. Ideas represented through design can then be inspected and tested.

Penner et al. (1998) explored how the design by elementary students of a physical model of an elbow can support science and mathematics learning related to the mechanics of motion. The success of the project depended on students having multiple opportunities to engage in and discuss their design experiences, teachers' use of analogies, and sense-making based on data collection and interpretation. Redesign gives students a chance to explore connections between science and design, to test their ideas, and to decide how to correct their designs and then adjust the corresponding understanding of the relevant scientific principle or concept (Sadler et al., 2000).

In summary, the available evidence suggests that under certain circumstances, engineering education can boost learning and achievement in science and mathematics. These effects may be more significant for certain populations, particularly underrepresented minority students. However, the positive effects are not universal and research has not clearly established the causal mechanism(s) to explain such benefits when they occur.

Increased Awareness of Engineering and the Work of Engineers

This goal, improving students' awareness of engineering and the work of engineers, can be of great benefit to a society, because engineering is central to technology development, and technology influences the well-being of everyone. Conversely, a lack of awareness of engineering and misconceptions or ignorance about what engineers do can be detrimental to a society. On a practical level, young people who believe engineers drive trains or repair car engines or who have negative stereotypes of the profession are unlikely ever to consider studying engineering or pursuing it as a career. If enough youngsters feel this way, it may become increasingly difficult to attract and retain a technically proficient workforce. Generally, individuals who do not have a basic idea of what engineers do are unlikely to appreciate how engineering and science contribute to economic development, quality of life, national security, and health care; such awareness is one aspect of technological literacy (NAE and NRC, 2006).

The engineering community, including engineering professional societies, schools of engineering, and firms that depend heavily on engineering talent, have spent hundreds of millions of dollars annually on initiatives to raise the level of the public understanding of engineering (NAE, 2002), for the most part unsuccessfully. For example, researchers have found that K–12 teachers and students generally have a poor understanding of what engineers do (Cunningham and Knight, 2004; Cunningham et al., 2005; Oware et al., 2007). Survey data suggest that many adults in the United States believe that engineers, as compared with scientists, are not as responsive to societal and community concerns and are not as important in saving lives (Harris Interactive, 2004).

This widespread misconception reveals a lack of awareness of the many ways engineering has dramatically improved the human condition (e.g., *www.greatachievements.org*). Teens and adults strongly associate engineering with skills in mathematics and science, according to recent online polling, but much more rarely with creativity, rewarding work, or a positive effect on the world (NAE, 2008).

Findings like these have prompted advocates of K–12 engineering education to argue for the importance of young people having opportunities to learn about engineers, engineering, and technology. Research has shown that participation in engineering education activities can provide those opportunities. For example, assessments showed that students who participated in the "Engineering Our Future New Jersey" program were able to name significantly more types of engineers and to describe types of engineering activities (Hirsch et al., 2005). These students were also able to recognize technology and the work of engineers (Hotaling et al., 2007).

Teachers, too, may be more aware of engineering career options after leading engineering design activities with students (McGrath et al., 2008). Pre-post tests found that young children who took part in the "Engineering is Elementary" program had a significantly broader conception of what technology is and were able to identify activities undertaken by engineers (Lachapelle and Cunningham, 2007). According to a study by graduate teaching fellows in K–12 education funded by the National Science Foundation, such changes in students' awareness of engineers and engineering can be sustained over time (Lyons and Thompson, 2006).

Understanding of and the Ability to Engage in Engineering Design

The iterative, open-ended, problem-solving method known as engineering design is the central activity of engineers. For this reason, a good deal of K–12, as well as post-secondary, engineering education is spent on developing students' understanding and capabilities in this area. In addition, as was mentioned above, design activities provide a real-world focus for abstract concepts, which may have a positive impact on learning not only in engineering, but also in other subjects, such as mathematics and science. In this section, we consider the evidence related to how well students learn to understand and engage in engineering design.

Data from a number of studies suggest that engineering design as practiced by engineers is neither quickly learned by students nor easily taught by teachers. Issues common to novice design, such as using trial-and-error methods (rather than a systematic approach) and spending too much time on defining the problem, have been well documented (e.g., Hill and Smith, 1998; Ressler and Ressler, 2004). Unless the teacher explicitly encourages a systematic approach, the design process can be overwhelmed by student excitement about hands-on activities (Seiler et al., 2001).

Specific concepts integral to engineering design also pose challenges to students. For example, in a project in which undergraduate engineering and education students developed design activities for students in the seventh through twelfth grades, Bergin et al. (2007) found that the K–12 students had difficulty understanding the idea of constraints. Penner et al. (1997) found that elementary students struggled to use modeling in a way that reflects engineering practice. In this study, student pairs were asked to design a functional model of an elbow. At first, the children tended to see models as small versions of the thing itself, and their first design iterations copied the form of an elbow but could not perform the functions of an elbow. After some discussion, it was clear that students had not isolated the motion of the elbow but had inferred a great range of motion based on the pivot of the shoulder. After experimenting with real elbow movements, they began a second iteration of modeling. This time the models incorporated constraints but also included nonfunctional but physically similar details, such as a representation of veins.

Interest in Pursuing Engineering as a Career

As many reports and commentators have noted, the economic competitiveness of the United States depends in large part on our ability to attract, train, and retain a large corps of highly qualified, creative engineers in a variety of fields (e.g., NAS et al., 2007). Unfortunately, many students who are capable of becoming engineers never even enter the educational pipeline leading to an engineering career because they either do not understand what engineers do or they believe that they do not have the necessary aptitude or interests to become engineers. This is particularly common for females and students from certain minorities, who are greatly underrepresented in engineering schools and in engineering practice (see Table 2-1) (Chang, 2002).

Up to now, the primary strategy for ensuring that the engineering pipeline is filled has been to insist that high school graduates have a good grounding in science and mathematics. Thus students are not exposed to engineering until they enter college, frequently not until their junior year. K–12 engineering programs offer a different strategy. By introducing students to engineering in K–12 programs—in theory, at least—more of them, from a wider variety of backgrounds, will be attracted to the field.

Although keeping the engineering pipeline flowing is an explicit goal of only a handful of the curricula we examined, the idea that exposure to engineering thinking, particularly design experiences, will attract more students to the pursuit of engineering or technology-related studies and careers seems intuitively sound. In this section, we examine the evidence for how K–12 engineering education affects student interest in engineering and related factors, such as school attendance, retention, and persistence.

Research has shown that students who choose to participate in engineering-related activities and coursework may become more interested in pursuing careers in engineering. For instance, both girls and boys who attended the "Discover Engineering" summer camp at Ryerson University in Canada reported an increased interest in engineering as a career (Anderson and Northwood, 2002). A follow-up study showed that approximately one-third of camp participants actually went on to pursue engineering degrees (Anderson et al., 2005). However, without a comparison group we cannot know if this group of students was representative of the general population.

Not all students respond the same way to educational interventions. Thus it is important to determine how specific groups tend to respond. For instance, in an engineering enrichment program for gifted students, participants completed small design projects as part of reaching a larger design goal (Bayles et al., 2007). Following the experience, 11 percent of students indicated that they felt less confident about their ability to become engineers, and 41 percent said they felt more confident. In a survey of students entering the "Discover Engineering" outreach program, Anderson and Gilbride (2003a) found that boys were significantly more interested than girls in pursuing engineering careers. Boys who claimed to have more knowledge of engineering were more interested than less-knowledgeable boys, but girls who claimed to be more knowledgeable were not more interested than their less knowledgeable peers. An assessment of student interest in engineering following participation in the program showed an increase in interest among both boys and girls, but girls' interest did not rise to parity (Anderson and Gilbride, 2003b). In a study of a different program, both boys and girls reported gains in confidence about engineering as a career after participating in engineering design activities, and girls and boys had equal scores (Zarske et al., 2007). An investigation of why the two studies produced different results could be potentially informative.

Some evidence suggests that engineering activities have coincided with higher school attendance, perhaps a reflection of increased interest. Barnett (2005) reported that attendance increased for a group of inner-city high school science students (largely from low-SES ethnic minorities) who were randomly assigned to classes in which the major focus was on engineering design projects, compared to their peers who were taught the standard science curriculum.

Studies have also been done on retention levels and persistence in engineering, primarily for students already interested in engineering. Most high school students who took an introductory engineering-design course based on a course for first-year college students, for example, went on to pursue engineering degrees in college (Bayles, 2005). Students who take courses from PLTW, a four-year college preparatory program, tend to take more advanced science and math courses and to consider them important to their future (Bottoms and Anthony, 2005; Bottoms and Uhn, 2007). Most PLTW students say they plan to attend college (Walcerz, 2007), although this cannot definitively be attributed to participation in PLTW because this is a self-selected group. The same students reported feeling confident about their career choices (mostly engineering and technology) because of the courses they took in high school. In addition, participation in PLTW has been shown to reduce attrition rates in college engineering programs and to increase the percentage of degrees attained (Taylor et al., 2006). These findings are positive, but the students who choose to take such courses cannot be considered a general population.

In a study of the long-term impact of a two-week engineering camp for middle schoolers, participating students were likelier than a control group to take STEM courses (Hubelbank et al., 2007). This finding is significant because both groups had applied to attend the camp, and the participants were selected by lottery. The camp experience did not affect students' interest in college-level engineering, however. Students in the control and experimental groups were equally likely to pursue engineering degrees.

Participation in K–12 engineering education programs may correlate with an increase in applications to engineering colleges. Zarske et al. (2007) found this to be true for a K–12 program in Colorado. However, although the number of applications increased, many applicants had not completed the coursework necessary for acceptance into the college program. One way of supporting these students is to provide a bridge program. Anderson-Rowland et al. (1999) demonstrated a significantly higher level of retention for students who attended the Summer Bridging Program (SBP) at Arizona State University, a program for entering minority freshmen. However, the effects of SBP were difficult to determine because participants were also required to enroll in an Academic Success Seminar during their freshman year.

Increased Technological Literacy

Many have argued that K–12 engineering classes improve students' technological literacy. Although this argument might not have been compelling 20 years ago, there is a growing appreciation today of the importance of technological literacy to individuals and to society as a whole. As defined in *Technically Speaking: Why All Americans Need to Know More About Technology*, "technological literacy combines basic knowledge about the various technologies in our world with the ability to think critically about technology and to make well-informed decisions about technological issues" (NAE and NRC, 2006).

A technologically literate person understands the essential characteristics of technology and how it influences society and the factors that shape technology, including engineering. Concepts central to engineering, such as systems, trade-offs, and intended and unintended consequences, provide a foundation for making informed decisions in a technologically dependent society like ours.

In *Technically Speaking*, the case for technological literacy is spelled out in detail. A technologically literate person can make informed decisions about his or her use of personal technologies, for example. Technologically literate citizens can be effective participants in decision-making processes involving technology—for instance, whether a city should support the building of a coal-fired power plant. In a society with a growing number of jobs that require technological skills and savvy, employers are more likely to find technologically competent workers if the general population is technologically literate.

In K–12 schools, technological literacy is largely the purview of technology education teachers. In the United States, 25,000 to 35,000 such teachers work in K–12 schools, mostly middle schools and high schools (Dugger, 2007). In 2000, the International Technology Education Association (ITEA) published *Standards for Technological Literacy: Content for the Study of Technology*, which accelerated an ongoing shift in the field of technology education away from its beginnings in industrial arts toward an emphasis on a broad understanding of the concept of technology. The standards in the ITEA document, developed with input from the National Academy of Engineering and National Research Council, include benchmarks related to engineering design (Box 3-3). ITEA and others have also produced curricular materials (e.g., "Engineering by Design," "Engineering is Elementary") that attempt to meet the learning goals spelled out in the standards.

Research shows that many Americans—children and adults—have a narrow, sometimes incorrect, view of technology. In one study, students

BOX 3-3
Selected Engineering-Design-Related Benchmarks, by Grade Band

To comprehend engineering design, students should learn that:

The engineering design process includes identifying a problem, looking for ideas, developing solutions, and sharing solutions with others. (Grades K–2)

Models are used to communicate and test design ideas and processes. (Grades 3–5)

Design involves a series of steps, which can be performed in different sequences and repeated as necessary. (Grades 6–8)

Engineering design is influenced by personal characteristics, such as creativity, resourcefulness, and the ability to visualize and think abstractly. (Grades 9–12)

SOURCE: ITEA, 2000.

in lower elementary grades associated technology mostly with things that require electricity (they conflated technology with lightning) (Cunningham, et al., 2005). Only a few children recognized bridges and bandages, for example, as technologies. First graders identified parrots as a technology nearly as often as they did cups. Surveys of adults have shown that the vast majority associate technology primarily with computers (ITEA, 2004). Several studies have shown that students who have been exposed to engineering education have a broader conception of technology and have corrected some misconceptions (Hotaling et al., 2007; Lachapelle and Cunningham, 2007). Being able to recognize technology is a basic prerequisite for technological literacy.

The committee did not find any published research that explicitly ties K–12 engineering education to improvements in other aspects of technological literacy. One reason may be that technological literacy, unlike science literacy, is a relatively new idea in education. In addition, there are significant challenges associated with the development of assessments of technological literacy. In an extended discussion of the latter problem, *Tech Tally: Approaches to Assessing Technological Literacy* (NAE and NRC, 2006) pointed out that the "capabilities" dimension of technological literacy may be especially difficult to measure. In that report the study committee reviewed 28 existing assessment instruments for measuring some aspect of technological literacy, even if they were not designed for that purpose. The committee found that none of these instruments was completely adequate for measuring technological literacy and that only two explicitly targeted engineering learning; one was developed for students in "The Infinity Project," and the other was an achievement test for fifth, eighth, and tenth graders in Massachusetts.

Interest on the national level in the technological literacy of K–12 students and improvements in measuring instruments, such as assessments, may increase in coming years. For example, when a revised version of the science portion of NAEP is administered for the first time in 2009, 10 percent of test items will focus on technological design (NAGB, 2008a). In addition, the National Assessment Governing Board, which oversees NAEP, has recently funded a feasibility study for an assessment of technological literacy (NAGB, 2008b). If the study, which runs until 2012, finds that technological literacy can be validly and reliably measured, NAGB may add an assessment of technological literacy to its portfolio of tests.

LIMITATIONS OF THE DATA

Besides the relatively small number of studies on the impacts of teaching engineering concepts and skills to K–12 students, our review of the literature revealed a number of weaknesses in the methodologies used in some studies. Several of these are highlighted below in hopes that they will be addressed in future research on the impacts of this emerging area of education.

An overarching concern with the data is that assessments of whether these well-intentioned initiatives achieve their desired goals frequently appear to be an afterthought. Assessments require advanced planning and viable pre-tests. Although pre- and post-tests cannot replace longitudinal data, they do indicate changes over time. Follow-up surveys can be used to determine the persistence of these changes.

Another problem is that the data are not "generalizable." For example, students who participate in engineering camps, clubs, and courses have chosen to do so. Thus the findings about the effectiveness of these activities cannot be generalized to students who do not choose to participate in these programs. This issue involves not only methodology. Because the findings do not provide information about the specific impacts on women and underrepresented minorities or on students who are not initially interested in learning about engineering, these assessments tell us little or nothing about the effectiveness of engineering education on general student populations. This can be a serious problem, because a goal of many of these programs is to increase the number of women and underrepresented minorities in engineering classes and ultimately in engineering practice.

When data on K–12 engineering education initiatives are collected, they often indicate only if participants enjoyed the program and include self-reported changes. It is known that participants in studies sometimes report positive results simply because they are in a study, the so-called Hawthorne effect (Landsberger, 1958). This methodological weakness could be addressed by measuring learning on pre-and post-tests.

Most of the studies we reviewed did not assess the impact of engineering education on student subgroups. The problem arises because in presenting data, it is critical to provide measures of central tendency and distribution. For example, the same average may be found for tightly clustered data, indicating that most respondents have similar scores, or for widely distributed data, indicating that approximately equal numbers of people had scores above and below the mean. The critical factor is the meaning of the spread. For instance, did minority students or students who most need to learn fall below the mean? The simple solution is to disaggregate data. This is only viable, of course, if the number of subgroup members in the study is sufficient to permit statistically valid comparisons.

These problems are not limited to studies of engineering education. In fact, definitive data about the impacts of educational interventions in most subjects are hard to come by. Even for the best-studied areas, such as reading and mathematics, little convincing evidence is available about the effectiveness of teaching approaches. In 2007, for example, the U.S. Department of Education published a review of all federally funded programs with a math or science education focus with the intent of determining their effectiveness as a basis for integrating and coordinating them. The report focused on 115 programs, 24 of them K–12 programs for which the "best" evaluations were done (DOEd, 2007).

> [D]espite decades of significant federal investment in science and math education, there is a general dearth of evidence of effective practices and activities in STEM education. Even the 10 well-designed studies [that the review identified] would require replication and validation to be used as the basis for decisions about education policy or classroom practice.

In short, the lack of a strong evidence base for the benefits of K–12 engineering education is consistent with the situation for much educational research in the STEM arena. This is another reason, if any were needed, for those who promote K–12 engineering education to pursue empirical, methodologically sound impact studies.

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4

The Current State of K–12 Engineering Education

A major goal of this project was to determine the scope and nature of current efforts to teach engineering to K–12 students in the United States. How many programs are there, who developed them, and which students have they reached? What purposes do they serve? How do they present engineering and engineering design? How do they relate to science, mathematics, and technology? What pedagogical strategies do teachers use? Have outcomes data been collected, and how good are these data? We approached this task in two ways: (1) by reviewing curricula for teaching engineering concepts and skills in K–12 classrooms and (2) by reviewing relevant professional-development initiatives for teachers.

As it turns out, the curriculum landscape is extremely varied; in fact, no two curricula occupy the same "ecological" niche. This is not surprising, given the diverse origins of these materials and points of view of their creators. In addition, because there is no widespread agreement on what a K–12 engineering curriculum should include, the committee decided not to compare programs directly but to identify areas of relative emphasis and notable omissions. This approach revealed certain cross-cutting themes, which are discussed in detail later in this chapter.

Developing a curriculum does not guarantee that engineering education in K–12 will be successful. A critical factor is whether teachers—from elementary generalists to middle school and high school specialists—understand basic engineering concepts and are comfortable engaging in, and teaching, engineering design. For this, teachers must either have appropriate background in mathematics, science, and technology, or they must collaborate with teachers who have this background. We held two data-gathering workshops to explore the professional-development situation for K–12 engineering educators. Information from those workshops is also included in this chapter.

Although the emphasis in this report is on engineering education in this country, the charge to the committee included a directive to find examples of pre-college engineering education in other nations, on the grounds that efforts elsewhere to introduce pre-college students to engineering might influence decisions here. The few initiatives we found are described briefly in an annex to this chapter.

Finally, we recognize that numerous efforts have been made to introduce engineering to K–12 students outside of formal school settings, through websites, contests, after-school programs, and summer programs. The committee charge did not require us to examine these informal K–12 activities. We note, however, that some of these initiatives appear to have increased students' awareness of and stimulated their interest in engineering (e.g., Melchior et al., 2005; TexPREP, 2003).

REVIEW OF CURRICULA

To identify K–12 engineering curricula, the committee relied on the joint efforts of committee members, Prof. Kenneth Welty,[1] University of Wisconsin-Stout, and project staff. The methods included reviews of websites of professional organizations, government agencies, and corporations with an interest in engineering education; searches of online curriculum clearinghouses and libraries; and direct communication with engineering educators, technology teachers, supervisors of state departments of education, and principal investigators of known K–12 engineering education programs and projects. In May 2008, the committee solicited public comments on a project summary, which brought several additional curricula to our attention.

Overall, the committee collected more than 10,000 pages of material, including lengthy narratives downloaded off the Web, material stored on compact disks, material assembled in three-ring binders, and material bound into textbooks. The materials ranged from 425 pages on a single

[1]The committee chose Prof. Welty because of his expertise in curriculum analysis, as well as his capacity as a co-principal investigator at the National Center for Engineering and Technology Education (NCETE) funded by the National Science Foundation. NCETE's research agenda complements the overall goals of this project.

topic—gliders—to just 46 pages on the huge topic of biotechnology. To ensure that patterns would be identified and meaningful conclusions drawn, the committee reviewed roughly equal numbers of curricula for each major K–12 grade band (i.e., elementary, middle, and high school).

Because of limitations on time and funding, as well as practical difficulties in locating some more obscure products, this curriculum review cannot be considered comprehensive. Nevertheless, the committee believes nearly all major initiatives and many less-prominent ones are included, thus providing a reasonable overview of the current state of K–12 engineering education in the United States. We are aware that there are individual courses not part of larger curricula that address engineering concepts and skills to varying degrees. These courses, typically developed and taught by technology educators, are not treated in our analysis, however.

Selection Criteria

To bound the analysis, the committee developed criteria to guide the selection of curricula that reflect the committee's consensus that design is the distinguishing characteristic of engineering. To be included in the study, therefore, curricula had to meet the following specifications:

- The curriculum must engage students in the engineering-design process or require that students analyze past solutions to engineering-design problems.
- The curriculum must explore certain concepts (e.g., systems, constraints, analysis, modeling, optimization) that are central to engineering thinking.
- The curriculum must include meaningful instances of mathematics, science, and technology.
- The curriculum must present engineering as relevant to individuals, society at large, or both.
- The curriculum must be of sufficient scale, maturity, and rigor to justify the time and resources required to conduct an analysis.[2]

[2]Specifically, each initiative had to be designed to be used by people and organizations outside the group responsible for its initial development. It also had to include at least one salient piece that had undergone field testing and subsequent revision and was no longer identified as a "draft." Finally, during the development of the initiative, it had to include some form of review of the initial concept, pilot or field testing, iterations based on feedback, an external evaluation, or a combination of these.

Review Process

The review process was overseen by Prof. Welty with the help of graduate fellows at NCETE. The committee initially underestimated the challenges of conducting in-depth reviews, such as the unique content, point of view, and organization of each curriculum and, often, their large size, which required many more hours of analysis than had been originally budgeted. As a result, the plan for reviews had to be modified midway through the project. Ultimately, we conducted two types of reviews: in-depth content analyses and descriptive summaries.

In-depth reviews were conducted on curricula that (1) appeared to be widely used in schools, (2) appeared to have longevity, or (3) had other special characteristics that merited close examination. The in-depth reviews covered all three grade bands (Table 4-1).

TABLE 4-1 Curricula Included in the Study[a]

Title	Developer
Pre-K	
1. Young Scientist Series—Building Structures	Educational Development Center
Elementary School	
2. The Academy of Engineering (also for middle school and high school)	PCS Edventures!
3. Children Designing and Engineering	The College of New Jersey
4. City Technology/Stuff That Works	City College of New York
5. Engineering is Elementary	Boston Museum of Science
6. Full Option Science System	Lawrence Hall of Science
7. Insights (Structures Unit)	Education Development Center
8. Invention, Innovation, and Inquiry	International Technology Education Association
9. A World in Motion	Society for Automotive Engineers
Middle School	
10. Building Math	Boston Museum of Science
11. Design and Discovery	Intel Corporation
12. Gateway to Technology	Project Lead the Way
13. The Infinity Project (Middle School)	Southern Methodist University
14. Learning by Design	Georgia Institute of Technology
15 LEGO® Engineering	Tufts University
16. TECH-Know	Technology Student Association

continued

TABLE 4-1 Continued

Title	Developer
17. Technology Education: Learning by Design	Hofstra University
18. A World in Motion	Society for Automotive Engineers
High School	
19. Designing for Tomorrow	Ford Partnership for Advanced Studies
20. DTEACh	University of Texas at Austin
21. Engineering: An Introduction for High School	Arizona State University/CK12 Foundation
22. Engineering by Design	International Technology Education Association
23. Engineering the Future	Boston Museum of Science
24. Engineering Your Future	Gomez, Oakes, Leone/Great Lakes Press
25. Engineers of the Future	(Curriculum based on design and technology courses developed in the United Kingdom)
26. Exploring Design and Engineering	The College of New Jersey
27. The Infinity Project	Southern Methodist University
28. INSPIRES	University of Maryland Baltimore County
29. Introduction to Engineering Design	Project Lead the Way
30. Material World Modules	Northwestern University
31. Principles of Engineering	New York State Dept. of Education/Hofstra
32. What is Engineering?	Johns Hopkins University
33. A World in Motion	Society of Automotive Engineers
Other	
34. TeachEngineering.org	Five-university collaboration (part of the National Science Digital Library)

[a]Curricula shaded in gray received in-depth reviews.

Each in-depth review included a detailed inventory of the content of the curriculum that addressed concepts and skills related to engineering, technology, mathematics, and science. The research team also identified stated goals, pedagogical strategies, prominent activities, and treatment (if any) of content standards. If available, the team also documented how extensively the curriculum had been implemented and findings related to its impact. The authors of the curriculum were contacted, as needed, to provide background information, clarify details, or confirm researchers' findings. Detailed written reports for each in-depth review were read and discussed by the committee. Descriptive summaries were prepared for the other curricular documents.

The descriptive summaries can be found in Appendix B and the in-depth reviews in Appendix C, included on the CD in the back cover of the report.

CONCEPTUAL MODEL OF ENGINEERING CURRICULA

The search for K–12 engineering education curricula turned up a wide variety of products from many different sources. Each curriculum had its own personality, and no two were completely alike in mission, content, format, or pedagogy. To deal with this complexity, Prof. Welty developed a "beads-and-threads" model (Figure 4-1) that enabled us to analyze the curricula in a systematic way using a manageable set of key variables.

The beads represent the "packaging" in which the engineering content of the curriculum is delivered to students. Most of the curricular materials used interesting technologies to package content into manageable chunks. For example, "The Infinity Project" focused on technologies likely to be of interest to students, such as the Internet and cell phones, digital video and movie special effects, and electronic music. Other developers organized materials around hands-on learning activities familiar to and popular with many students and teachers. For example, the middle school program of "Project Lead the Way," *Gateway to Technology*, includes activities for making and testing CO_2-powered dragsters, magnetic-levitation vehicles, water-bottle rockets, model rockets, and Rube Goldberg devices.

The content of several curricula was organized around the design process. For example, the "Design and Discovery" curriculum, by Intel Corporation, features lessons and learning activities for identifying problems, gathering information, brainstorming solutions, drawing plans, making models, building prototypes, and making presentations. Prominent local or regional industries, such as Ocean Spray Cranberries, Inc., were used as examples in interdisciplinary thematic units in the "Children Designing and Engineering" materials, developed at The College of New Jersey. The material in one curriculum, "Engineering is Elementary," was organized around traditional fields of engineering (e.g., civil, environmental, electrical, agricultural, and mechanical engineering).

In the conceptual model, the threads, which run through the beads, represent the core concepts and basic skills a curriculum is designed to impart, independent of the particular packaging. Three threads, mathematics, science, and technology, represent domain knowledge in these subjects that is used in engineering design. A fourth thread represents the engineering design process. The design thread incorporates a number of spe-

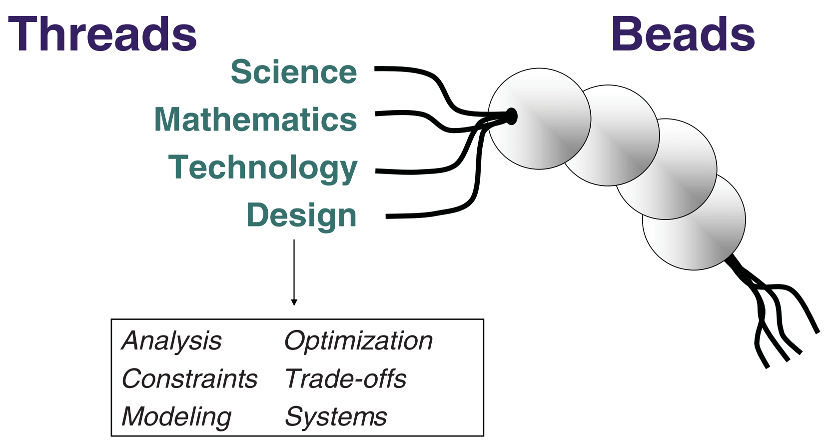

FIGURE 4-1 A beads-and-threads model of K–12 engineering curricula.

cific attributes of engineering design, such as analysis, constraints, modeling, optimization, and systems. The sections below describe of how these threads play out in the curricula.

The Mathematics Thread

We defined mathematics as patterns and relationships among quantities, numbers, and shapes. Specific branches of mathematics include arithmetic, geometry, algebra, trigonometry, and calculus. Our analysis suggests that mathematics is a thin thread running through the beads in most of the K–12 engineering curricula.[3] The thinness of the thread reflects the limited role of mathematics in the objectives, learning activities, and assessment tools of the curricula.

The mathematics used in the curricular materials reviewed by the committee involved mostly gathering, organizing, analyzing, interpreting, and presenting data. For example, in the "A World in Motion" curriculum, students build and test small vehicles (e.g., gliders, motorized cars, balloon-

[3]A separate analysis of curriculum, assessment, and professional development materials for three Project Lead the Way courses found explicit integration of mathematics "was apparent, but weakly so" (Prevost et al., 2009).

powered cars, wind-propelled skimmers). The testing involves measuring speed, distance, direction, and duration in conjunction with the systematic manipulation of key variables that affect vehicle performance (e.g., balloon inflation, sail size and shape, gear ratios, wing placement, nose weight). The data are organized into tables or graphs to see if they reveal patterns and relationships among the variables. The conclusions based on the data are then used to inform the design of subsequent vehicles.

Similar instances of gathering and using data for vehicle design were found in the *Models and Designs* unit in the "Full Option Science System" and the *Gateway to Technology* unit of "Project Lead the Way." Other materials engage students in counting and measuring, completing tables, drawing graphs, and making inferences, such as evaluating pump dispensers, conducting surveys, and testing materials.

Engineers often use mathematical equations and formulas to solve for unknowns. Young people can learn about the utility of this application of math in various ways, such as by calculating the amount of current in a circuit based on known values for voltage and resistance or determining the output force of a mechanism based on a given input force and a known gear ratio. Several instances of this kind were found in the "Engineering the Future" curriculum. In one activity, students calculate the weight of a proposed product (an organizer) based on three different materials prior to prototyping. Another requires that students calculate the mechanical advantage of a lever to determine how much force is required to test the strength of concrete.

However, most of the mathematics in the "Engineering the Future" curriculum is used to teach science concepts by illustrating relationships between variables, rather than to assist in solving design problems. For example, simple algebraic equations are used to represent the relationship between the cross-section of a pipe and its resistance to fluid flow, to calculate the output pressure of a hydraulic pump, and to determine the power produced by an electrical circuit. In these cases, mathematics is used to build domain knowledge in much the same way mathematics is used in science classes.

Several projects (e.g., "A World in Motion," "Building Math," *Gateway to Technology*, "Design and Discovery," "Designing for Tomorrow") introduce and require the application of basic geometry principles in conjunction with the development of technical drawings. For example, "Engineering the Future" includes lessons dealing with the concepts of scale and X, Y, and Z axes in the context of making orthographic, isometric, oblique, and perspective drawings. *Introduction to Engineering Design*, a unit in "Project

Lead the Way," addresses basic geometry in some detail in conjunction with the exploration of the modeling of solids using computer-aided design software. In this curriculum, students identify geometric shapes (e.g., ellipses, triangles, polygons), calculate surface area and volume, use Cartesian coordinates, and use addition and subtraction to create geometric shapes.

One strategy for increasing the mathematics content in some curricula was to include mathematical concepts in supplementary materials as enrichment activities. This approach might be characterized as a thread along the outside of the beads. The peripheral placement of the thread indicates that enrichment activities are optional, rather than integral to the unit but complement or extend instruction.

This approach was found in materials associated with projects in "Children Designing and Engineering," "Models and Designs," "Material World Modules," and "A World in Motion." For example, in an "extension activity" in "Models and Designs," students are asked to determine how long it took them to make an electrical device called a "hum dinger" (e.g., fastest time, slowest time, average time, total time). In an optional mathematics assignment in the *Gliders* unit of "A World in Motion," students determine the mathematical properties of different wing shapes (e.g., area, mean chord length, aspect ratio). At the high school level, the "Materials World Modules" invites teachers to engage students in using the formula for Young's modulus to determine the deflection of a fishing pole made out of drinking straws.

Mathematics is a dominant thread in "The Infinity Project" and "Building Math." The latter is designed to teach students how principles learned in middle school algebra can be used in the context of engineering challenges. For example, in the *Amazon Mission* unit, students design an insulated carrier for transporting malaria medicine, a filtration system for removing mercury from water, and an intervention plan for containing the spread of a flu virus. Like most of the other curricula reviewed, "Building Math" also requires that students collect data, make graphs, and interpret patterns, related to, for example, the insulating properties of materials; the flow of water through holes of different sizes; the deflection of materials based on their length, thickness, and shape; and the effect of angles on the speed of an object sliding down a string. A major goal of the "Building Math" curriculum is to teach students that engineers use mathematics to minimize guesswork in designing solutions to problems.

"The Infinity Project" is one of the few initiatives in which advanced algebra and trigonometry are introduced in engineering contexts. This curriculum encourages students to uncover, examine, and apply basic mathematical principles that underlie common digital communication and information technologies. Binary numbers, matrix operations, polynomials, and other forms of mathematics are presented as essential content for synthesizing music, compressing video, and encrypting data, and mathematical concepts and equations are presented as tools used by engineers to create or improve a given digital technology or system. In addition, the laboratory activities require that students use mathematics and mathematical reasoning to design, simulate, and explore digital communication and information technologies.

Engineers often develop mathematical models featuring the key variables in a process, system, or device. The variables include forces that act on a structure, the length of time required for a process, or the distance an object moves. The relationships between variables are represented by equations that can be used to test ideas, predict performance, and inform design decisions. However, our review of curricula did not find any projects or units in which students were instructed to develop and use mathematical models to assist them in designing solutions to problems.

The Science Thread

We defined "science" as the study of the natural world, including the laws of nature associated with physics, chemistry, and biology and the treatment or application of facts, principles, concepts, or conventions associated with these disciplines. Our analysis suggests that science is a moderately thick thread composed of two strands, (1) science concepts related to engineering topics and problems and (2) scientific modes of inquiry that build knowledge and inform design decisions.

The First Strand

The most common science topics in the first strand found in K–12 engineering curricula relate to materials, mechanisms, electricity, energy, and structures and typically involve concepts such as force, work, motion, torque, friction, voltage, current, and resistance. In the curricula, most of these concepts are presented in the form of encyclopedia-like explanations that are subsequently reinforced in laboratory activities.

"Engineering is Elementary" includes concepts related to water, sound, plants, and organisms. At the high school level, "Material World Modules" address natural degradation processes, bioluminescence and chemiluminescence, thermal and electrical conductivity, compressive and tensile forces on atoms, the relationship between molecular weight and viscosity, and the absorption and release of energy by molecular bonds.

The Second Strand

The second strand, scientific inquiry, is a major theme in several curricula, mostly to explore the interface between science and technology. For example, in the unit on *Composites* in "Material World Modules," students make and test foam beams laminated with varying amounts of paper to determine the strength and stiffness of composite materials. Similar experiments related to materials, structures, electrical circuits, and mechanisms are included in "A World in Motion," *Building Structures with Young Children*, a unit in the "Young Scientist Series," "Children Designing and Engineering," "City Technology," "Design and Discovery," "Engineering is Elementary," and "Engineering the Future." The results of these investigations are often applied in subsequent design activities.

Another way scientific inquiry is used in the curricula is related to the collection of data to inform engineering design decisions. For example, the second challenge in "A World in Motion" requires that students conduct investigations to determine the effect of different gear ratios on the speed and torque of a motorized toy vehicle. In some cases, scientific inquiry is used to discover, illuminate, or validate a law of nature, as might be done in a science classroom. For example, in *Gateway to Technology*, students experience Newton's Third Law by sitting on a scooter pointed in one direction, throwing a medicine ball in the opposite direction, and noting the direction and velocity of the scooter in relation to the direction and force used to throw the ball.

Many curricula engage students in scientific inquiry and inquiry-based learning in a symbiotic way. Several curricula introduce students to the basic principles of scientific investigation under the auspices of doing science. For example, "City Technology," "Material World Modules," and "A World in Motion" all stress the importance of manipulating one variable at a time while keeping the other variables constant. Learning activities in these programs include investigations that apply this principle in the contexts of packaging, structures, materials, and flight. In addition to teaching students about scientific investigations, they engage students in the generation, testing, revision, and validation of their ideas about protecting goods, making things stronger, and making models fly. In this sense, these curricula use scientific inquiry as a pedagogical strategy for building student knowledge of engineering design.

The Technology Thread

We defined "technology" as the study of the human-made world, specifically the knowledge, techniques, systems, and artifacts created by humans to satisfy their wants and needs. Our analysis suggests that technology in K–12 engineering curricula is a thick thread that often runs alongside the beads, rather than through them.

In most cases, the study of technology in K–12 curricula is used to build domain knowledge and develop a vocabulary for describing, discussing, and explaining a given technology. The emphasis on technical content is apparent in materials developed for "Project Lead the Way" and "The Infinity Project," both of which feature detailed treatments of specific technologies, such as digital electronics, digital communication and information technologies, automation, computer-aided design, and computer-aided manufacturing.

In some curricula, technologies are presented as concrete examples of scientific principles, especially in curricular materials that use engineering ideas or contexts to enrich science and mathematics learning. For example, a unit on composite materials in "Material World Modules" features discussions on technologies ranging from ancient bricks and clay pots to modern tennis rackets and automobile tires.

Some curricular materials are designed, at least in part, to improve technological literacy. For example, the central focus of the books written for "City Technology" is to "engage elementary children with the core ideas and processes of technology (or engineering, if you prefer)." The goal of "Engineering is Elementary" is to "tap into children's natural curiosity to promote [the] learning of engineering and technology concepts." "Exploring Design and Engineering" "help[s] youngsters discover the 'human-made world,' its design and development." "Engineering the Future" is intended to "help . . . high school students understand the ways in which they will engineer the world of the future—whether or not they pursue technical careers." "Invention, Innovation, and Inquiry" was created to "provide professional support for teachers interested in technological literacy in education."

The Design Thread

We defined "engineering design" as a purposeful, iterative process with an explicit goal governed by specifications and constraints. Our analysis suggests that design in K–12 engineering curricula is a strong, thick thread.

Virtually all of the curricula present a paradigm for designing solutions to problems that include a cyclical pattern of steps. Although the words and phrases used to describe the design process vary from one curriculum to another, the basic approaches are analogous. For example, on the elementary level in "A World in Motion," the design process is organized around themes, such as setting goals, building knowledge, designing, building, testing, and presenting. Similarly, in a project in the "Children Designing and Engineering"curriculum, student design teams are instructed to "know the problem, explore ideas, plan and develop, test, and present."

The patterns are similar in curricula on the middle school and high school levels. For example, in "The Infinity Project," the design process includes the following steps:

- Identify the problem or objective.
- Define goals and identify the constraints.
- Research and gather information.
- Create potential design solutions.
- Analyze the viability of solutions.
- Choose the most appropriate solution.
- Build and implement the design.
- Test and evaluate the design.
- Repeat all steps as necessary.

Analysis

We defined "analysis" as a systematic, detailed examination intended to (1) define or clarify problems, (2) inform design decisions, (3) predict or assess performance, (4) determine economic feasibility, (5) evaluate alternatives, or (6) investigate failures. Our analysis revealed isolated instances of the first three applications of analysis and even fewer instances of the next three. Overall, analysis was rarely an explicit, recurring theme in a design process. Thus in our model, analysis is characterized as a fragment of thread attached to the design thread.

In most of the curricula, the first step in a design activity is to pose a problem or define a task. For example, the first three challenges in "A World in Motion" are framed in the context of designing toy vehicles for a fictitious company. In all three, the challenge to elementary and middle school students is to analyze the contents of a letter or request for proposals to identify the problem and specifications of a successful solution. Similar problem scenarios appear in the *Building Structure with Young Children* unit in the "Young Scientists Series," "Building Math," "Children Designing and Engineering," "Engineering is Elementary," *Gateway to Technology*, and "Introduction to Engineering Design." All of these scenarios require basic reading comprehension but very little in the way of engineering analysis.

"City Technology" is one of the few curricula that engages students in a robust analysis to identify and define a problem. In one unit, *Designed Environments: Places, Practices, Plans*, elementary students monitor classroom procedures, identify problems, design and implement new procedures, evaluate the new procedures based on data, and use the findings of the evaluation to redesign the procedures as needed. A similar analysis is conducted to identify problems and develop design criteria to improve the configuration of the classroom.

Some of the materials engage students in a detailed analysis of everyday products using a process of reverse engineering. This is the predominant approach in materials in the "Design and Discovery," "City Technology," and "Designing for Tomorrow" curricula. For example, in a lesson in "Designing for Tomorrow," high school students analyze hand-powered can openers in terms of their primary and secondary functions, usability in different contexts, aesthetic qualities, and salient features. In the "Design and Discovery" curriculum, students dissect digital and mechanical alarm clocks to identify basic components and determine the relationships between form and function. The goals of these analyses are to understand how things work, to appreciate attention to detail, and to identify the strengths and shortcomings of given designs.

Engaging students in redesigning an existing product, rather than developing an original design, is also a major strategy in "City Technology," "Design and Discovery," and "Designing for Tomorrow." Students first analyze the performance of simple devices from a user's point of view. For example, in one "City Technology" unit, elementary students examine paper and plastic bags. In the "Design and Discovery" curriculum, middle school students study backpacks, toothpaste caps, and water bottles. In the "Designing for Tomorrow" curriculum, high school students investigate kitchen tools and training cups for toddlers. The analyses are then used to identify problems and/or opportunities for improving the design of the objects.

Most of the curricula include steps for assessing the performance of the final design, a type of analysis that includes both qualitative and quantitative techniques to determine how well the final design solves the original design problem. Examples of this kind of analysis can be found in "A World in Motion," "City Technology," "Design and Discovery," "Engineering is Elementary," and "Material World Modules."

Prior to implementing a design, engineers make decisions based on evidence that a given design will work; they rarely rely on trial and error. The evidence is often based on an analysis that predicts performance for a given configuration of variables. In several curricular projects, students are required to manipulate and test variables in various configurations to discover the patterns that can inform or optimize a design. This form of analysis is found in "A World in Motion," "City Technology," "Engineering is Elementary," and "Material World Modules." One of the richest treatments of this kind of analysis was in the *Glider* unit in "A World in Motion."

In contrast to engineering practice, the curricula provide few opportunities for analysis of the economic feasibility of a given design or of the relative feasibility of competing designs. However, economic factors that can influence design are addressed in "Building Math," "Design and Discovery," and "Engineering the Future." For example, in "Building Math," middle school students perform a variety of mathematical computations to design optimal interventions to contain the spread of a virus in a village in the Amazon rain forest on a budget of $10,000. In the "Design and Discovery" curriculum, students compare the costs and trade-offs associated with using different materials for beverage containers (e.g., aluminum, glass, plastic). In an exercise in "Engineering the Future" students perform simple calculations to estimate the cost of materials and production, project a retail price, and estimate the competitiveness of a product in the marketplace.

Many curricular materials encourage students to evaluate alternative design options. These analyses typically involve unstructured discussion among students working in a group about the perceived merits of each option to arrive at a consensus about which option should be further developed. For example, in "Building Math," middle school students design an insulated container of medicine that will maintain a temperature of 59°F to 86°F for a minimum of two hours. After gathering data about the insulating properties of various materials, each member of the design team sketches an idea for a container, describes it to the other members of his or her team, and then, "as a group," they "decide on one 'best' solution." None of the curricula include procedures or expectations for conducting a formal analysis of alternative solutions, such as a trade-off matrix for making quantitative comparisons of the strengths and weaknesses of competing designs (Garmire, 2002).

Investigating failure as a specific line of analysis appears in only a few curriculum projects. A good example, from the *Packaging and Other Structures* unit in the "City Technology" curriculum, requires elementary students to fill paper and plastic bags with containers of water until they fail. The broken bags are then studied in detail to determine the nature and location of the failures, and the results of the analyses are used to develop proposals for improving the performance of the bags.

Constraints

We defined "constraints" as the physical, economical, legal, political, social, ethical, aesthetic, and time limitations inherent to or imposed upon the design of a solution to a technical problem. Our analysis suggests that constraints are a frayed fragment of thread running through some of the beads. The frayed nature of the thread indicates the ambiguities of the concept of constraints and the many ways it is interpreted.

In engineering practice, constraints frame the problem to be addressed by defining the salient conditions under which it must be solved. These conditions can include budget limitations, government regulations, patent laws, and project deadlines, among others. In the curricular initiatives that address this concept at all, constraints were presented as "things"—usually time, money, and materials—that limit the design process. However, "City Technology" includes rules and regulations among constraints on the design process. *Gateway to Technology* includes aesthetic considerations and the limits of human capabilities in its definition. A module on *Reverse Engineering* in the "Designing for Tomorrow" curriculum introduces the idea of constraints as limitations in materials properties and manufacturing processes.

Other factors in addition to constraints that can help define a problem include design specifications (i.e., features of the final solution, without which the design will not solve the problem) and design criteria (i.e., the parameters that must be tested to evaluate the suitability of final product). In the curricula, the terms constraints, specifications, and criteria are usually used interchangeably.

The confusion is most apparent in the learning activities. For example, in a design unit, *Power and Energy: The Whispers of the Willing Wind* from the "Invention, Innovation, and Inquiry" curriculum, constraints for the design and construction of a working model of a windmill are outlined. The "constraints" stipulate that the tower must be no more than 12 inches high, that the side of the base must not exceed 6 inches, and that the turbine must be less than 5 inches in diameter. The reasons for these specifications are not disclosed, but they do not appear to have a relationship to the problem being addressed or to reflect engineering design practices. Their purpose seems to be to direct student behavior to ensure success, limit the amount of resources for the project, and make the teacher's management of the activity easier. This treatment of "constraints" is typical of many curricula we reviewed.

Modeling

We defined "modeling" as any graphical, physical, or mathematical representation of the essential features of a system or process that facilitates engineering design. Our analysis suggests that modeling is represented by a thin, varicolored thread running through most of the beads. The colors represent the different uses of modeling in engineering activities and in the teaching and learning process.

Engineers use models to help visualize potential solutions to design problems and/or as an interim step in the development of working prototypes. In many of the curricula, modeling is defined the same way. For example, in one unit in the "Engineering is Elementary" curriculum, a model is defined as "a small representation, usually built to scale, that serves as a plan." In the "Design and Discovery" materials, a model is defined as a "visual representation of a total design (or some aspect of the design) that is nonfunctional." In those same materials, a prototype is defined as a "working model used to demonstrate and test some aspect of the design or the design as a whole." In the *Gateway to Technology* unit of the "Project Lead the Way" curriculum, modeling is defined as "the process of creating three-dimensional representations of design solutions." Computer modeling is defined as "the use of computer software applications that allows the user to visualize an idea in a three-dimensional format."

As these characterizations suggest, most of the curricula engage students in making things, usually from everyday materials, to help them visualize their designs and present them to others. For example, in *Building Structures with Young Children*, students construct towers and enclosures using building blocks. In "Children Designing and Engineering," elementary students construct models of lighthouses and habitats for koalas. "Engineering is Elementary" projects engage students building models of windmills, water filters, paper bridges, alarm systems, and other objects. In "A World in Motion" projects, students construct and test toy vehicles (e.g., motorized cars, gliders). *Gateway to Technology* involves modeling cranes, magnetic-levitation trains, automated devices, airfoils, and rockets. "Material World Modules" involve the construction and testing of models of concrete roofing tiles, composite fishing poles, and humidity sensors. In "The Infinity Project" activities, students use simulation software to model sound-effect generators, video systems, and computer networks.

In engineering practice, physical and mathematical models are also used to obtain data as a basis for making informed decisions during the design process. An example of this can be found in *Challenge Number 3*, a unit of "A World in Motion," in which eighth graders collect and graph data relating the center of gravity of a model glider to where the wing is placed and to the amount of weight in the nose of the glider. Based on the graphs, students predict optimal flight performance by determining the nose weight that locates the center of gravity closest to the centerline of the wing. Thus this curriculum has students use a physical model, the toy glider, to generate data for a simple mathematical model that represents the relationship between key variables that affect flight. The model is then used to adjust the design of the glider to achieve desired flight behavior. In a "Gateway to Technology" project, students use simulations posted on the Internet to model the effects of changing variables on the performance of rockets. Although the students interact with a mathematical model through the graphical model, the instructional materials do not call attention to the mathematical modeling.

For the most part, models are not used to represent key variables in the early stages of the design process but are presented as steps in the later stage of the design process for refining a relatively mature design solution to a problem. Thus models are used to visualize a design, take it to a higher level of refinement, and communicate its features to others. In many ways, this use of modeling is representative of industrial design rather than engineering design. Industrial design is the professional service of creating and developing concepts and specifications that optimize the function, value, and appearance of products and systems for the mutual benefit of both user and manufacturer (IDSA, 2008).

However, the reader should keep in mind that the pedagogical role of modeling is independent of its role in engineering design. Strategies to engage students in cooperative learning, such as Socratic dialogue, inquiry and design, and reflection and debriefing, typically involve making, testing, and presenting models. Modeling requires that students generate ideas, translate them into concrete form, and assess their validity. In the process, they must re-examine their assumptions, identify misconceptions and failures, refine their thinking, and develop and implement new ideas. Ultimately, models are embodiments of thought processes, insights, and discoveries in a form that communicates them to others.

Optimization

We defined "optimization" as the pursuit of the best possible solution to a technical problem in which trade-offs are necessary to balance competing or conflicting constraints. Our analysis suggests that optimization is a thin, translucent thread that is often obscured by other threads.

Most of the curricula do not explicitly address the concept of optimization. More often than not, optimization is embedded in lessons rather than called out as a key concept in objectives, laboratory activities, or assessment instruments. Optimization is most often embedded in the concepts of iteration (i.e., making incremental refinements during the development of a design) and redesign (i.e., analyzing an existing design to identify deficiencies or opportunities for improvement). In both cases, the goal is to improve a design. However, improving a design is not always synonymous with making trade-offs.

In most of the curricular materials, optimization is equated with "think harder" and "make it even better" as part of iteration and redesign. Improvements are often based on brainstorming rather than analysis, and little, if any, attention is paid to trade-offs. None of the curricula address the potential of using mathematics, especially for optimizing designs that are subject to economic constraints.

Trade-Offs

We defined "trade-offs" as decisions made to relinquish or reduce one attribute of a design in order to maximize another attribute. Our analysis suggests trade-offs are, like optimization, a thin, translucent thread.

The *Skimmer Design Challenge*, a unit in "A World in Motion," challenges students to make informed decisions about the size, shape, and position of a sail on a paper sled that skims across a tabletop pushed by a fan. In this exercise, students must make trade-offs among the size of the sail and the speed, distance, and stability of the sled. They must also determine the proper relationship between the weight of the sled and speed, distance, and stability. Finally, they must determine the orientation of the sail on the mast and the location of the mast on the hull.

In the *JetToy Design Challenge* in the same curriculum, students must determine the optimal relationship between inflation of a balloon, the diameter of the nozzle, and the duration and amount of propulsive force. They must also find the optimal weight of the vehicle in relation to its speed and the distance it can travel. This "tuning process" is informed by data describing how each variable (nozzle size, balloon inflation, vehicle weight, and friction) affects vehicle performance (speed and distance).

Another example of trade-offs is embedded in the *Models and Designs* unit in the "Full Option Science System" curriculum. In the course of making and modifying a rubber-band-powered cart, the students are likely to engage in optimization because each challenge inevitably introduces unanticipated cause-and-effect relationships. For example, the size of the wheels affects how far the go-cart travels. If the wheels are bigger, the amount of force required to propel the go-cart may have to be increased. If more tension is applied to the rubber bands to propel the cart a greater distance, traction is likely to become an issue. The increase in tension is also likely to exacerbate the problem of friction. Each of these adjustments introduces the need for trade-offs. However, neither the concept of trade-offs nor the concept of making trade-offs in the interest of optimization is addressed directly in the curricular materials.

The unit on *Inquiry: The Ultimate School Bag* in the "Invention, Innovation, and Inquiry" curriculum includes the redesign and improvement of a backpack for carrying schoolbooks and personal items. Redesign intrinsically involves optimization, although the concept is not addressed directly here, either.

Some references are made to the concept of trade-offs in the *Building Structure with Young Children* unit in the "Young Scientist Series." Teachers are encouraged to prepare and ask questions about the advantages and disadvantages of different design options. For example, in the context of building a model house, teachers are encouraged to entertain ideas such as making the roof out of a lightweight material that requires less support but is not likely to be strong. If children chose to make a strong roof, they might also have to build in more support.

In the "Gateway to Technology" curriculum, trade-off is defined as "an exchange of one thing in return for another, especially relinquishment of one benefit or advantage for another regarded as more desirable." Although several assignments involve identifying the positive and negative impacts of various technologies, students do not directly address the balance between competing factors. For example, from a student's point of view, the main goal of an activity involving the building a compressed-air dragster is to design the fastest vehicle possible. In this exercise, speed is a function of the vehicle's mass, assuming that the propulsive force remains constant. Even though mass also affects the stability of the vehicle, the instructional materials do not require that students directly confront the trade-offs between mass, stability, and speed.

Systems

We defined a "system" as any organized collection of discrete elements (e.g., parts, processes, people) designed to work together in interdependent ways to fulfill one or more functions. Our analysis suggests that systems and systems thinking are fragments of thread interwoven with other, more continuous threads. By this, we meant that systems and systems thinking do not permeate any single curriculum. Both concepts are used selectively, often to help students analyze or explain how a technology works.

The committee's definition of systems is consistent with the definitions in the curricular materials that addressed systems in some manner. For example, "City Technology" explained systems as "a collection of interconnected parts functioning together in a way that make the whole greater than the sum of its parts." In "Engineering is Elementary," a system is defined as "a group of parts that interact to create a product"; in one unit it is defined as "a group of steps that interact to create a process." In the *Models and Designs* unit of the "Full Option Science Systems" curriculum, system is defined as "two or more objects that work together in a meaningful way."

The concept of systems is treated most directly in curriculum initiatives focused on domain knowledge. In these cases, systems thinking is often an undercurrent in the storyline of how a specific technology works. The same is true in "The Infinity Project for Middle School," which stresses that most technological systems follow a pattern of inputs, processes, and outputs. The materials provide illustrations of sophisticated systems in the form of simple flow charts that accompany explanations in the text of how the systems work; the illustrations are also organizers for laboratory activities related to such things as digital music, digital images, and data encryption.

The "Engineering is Elementary" and "Design and Discovery" curricula introduce the idea that systems can be divided into subsystems and that subsystems can be further divided into components. In the "Design and Discovery" curriculum, a laboratory activity is focused on analyzing bicycles in terms of systems, subsystems, components, and parts.

Several curricula featured units or lessons in which reverse engineering is used to engage students in studying simple devices from a systems perspective. These activities involve identifying parts, determining their function, uncovering relationships, discovering how they work together as a system, and identifying ways to improve their performance. This kind of systems thinking was the part of lessons in the "City Technology," "Design and Discovery," and "Designing for Tomorrow" curricula that ultimately engaged students in exploring opportunities for redesigning products.

In rare cases, systems and systems thinking are used to analyze the reasons a technology fails. One example is a module on *Reverse Engineering* in "Designing for Tomorrow." This module begins with a case study of failures associated with the space shuttle *Challenger* disaster. Through a simplified form of reverse engineering, the students, in theory, discover that the accident was caused by systems breakdowns in the NASA organization, as well as a failure in the space shuttle technology.

Reasons for Teaching Engineering

We were not surprised that the reasons for including engineering content in these curricula are as diverse as the materials themselves. It is surprising, however, that teaching engineering is not always a first-order objective. In most cases, the primary reason for including engineering is to enhance the study of science, mathematics, or both subjects. For example, the "Building Math" program uses examples from engineering to demonstrate "how math is used as a discipline of study and a career path." The materials in "A World in Motion" facilitate an "exploration of physical science while addressing essential mathematic and scientific concepts and skills." The "Insights (Structures Unit)" provides "students with exciting science experiences that extend their natural fascination with the world and help them learn the science skills and concepts they will need in later schooling and in life." Engineering materials in "The Infinity Project" provide "an innovative approach to applying fundamental science and mathematics concepts to solving contemporary engineering problems."

The materials designed to intensify learning in math and science and other core-curriculum subjects capitalize on the hands-on, interdisciplinary nature of engineering. For example, the goal of "Children Designing and Engineering" is to "develop innovative and unique contextual learning units that challenge students to think, act and share." Similarly, "Designing for Tomorrow" provides high school students with "high-quality interdisciplinary learning experiences that challenge them academically and develop their problem-solving, critical-thinking, and communication skills."

Sometimes the goal of enhancing the study of science and mathematics is more explicit. For example, *Building Structures with Young Children* makes "science the work and play of exploring materials and phenomena, while providing opportunities for children to learn from that experience." The "Building Math" program uses the study of engineering to demonstrate "how math is used as a discipline of study and a career path . . . [through]

. . . standards-based activities that integrate algebra and engineering using a hands-on, problem-solving, and cooperative-learning approach." The materials in "A World in Motion" are designed to facilitate an "exploration of physical science while addressing essential mathematic and scientific concepts and skills." The "Insights," "Material World Modules," and "The Infinity Project are all designed to improve science education and show how fundamental science and mathematics concepts can be applied to solve engineering problems.

Other curricula include engineering content to address the technological literacy needs of students. In the "City Technology" curriculum, the central purpose is to "engage elementary children with the core ideas and processes of technology (or engineering, if you prefer)." The goal of the "Engineering is Elementary" curriculum is "to harness children's natural curiosity to promote [the] learning of engineering and technology concepts." Similarly, the primary objective of the "Exploring Design and Engineering" initiative is to "help youngsters discover the 'human-made world,' its design and development." The "Invention, Innovation, and Inquiry" curriculum was created to "provide professional support for teachers interested in technological literacy in education."

Another more general goal of engineering curricula is to improve students' critical thinking. For instance, the goal of one "Gateway to Technology" unit is "to show . . . students how technology is used in engineering to solve everyday problems." "Engineering is Elementary" develops "interesting problems and contexts and then invite[s] 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."

Only a few curricula define their objective as teaching engineering concepts and skills to prepare young people for further education and, ultimately, engineering careers. The Ford Partnership for Advanced Studies curriculum, "Designing for Tomorrow," 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" is 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." And PLTW materials "provide students with the rigorous, relevant, reality-based knowledge necessary to pursue engineering or engineering technology programs in college."

In interviews, many curriculum developers stated that teaching engineering knowledge and skills was not their primary objective. Their reasons for including engineering content included reversing poor test scores in mathematics and science, engaging students in more scientific inquiry, and showing students that mathematics has practical applications.

Several developers deliberately passed up opportunities to address engineering concepts and skills to focus on other problems or opportunities. Some explained that their projects were required to include enough science content to be considered part of science education, and that too much emphasis on engineering design, constraints, modeling, optimization, and technological systems could tip the scale toward engineering. They had to maintain a delicate balance, they said, with a modest bias toward science, to improve the chances that their materials would be accepted and implemented. Other developers said their materials were required to have enough mathematics content to be approved for elective credit in mathematics. Finally, some noted that in the current No Child Left Behind climate of accountability for student achievement in core subjects, there isn't much room for engineering content in the school curriculum.

Another factor that had to be taken into consideration was the comfort level (sometimes the discomfort level) of elementary, science, and mathematics teachers. Elementary teachers, for example, must have a deep understanding of child development coupled with skills in teaching reading, writing, and mathematics, but teaching about engineering is largely uncharted territory. Consequently, in several curricula, materials were configured to capitalize on teachers' strengths and teaching responsibilities by introducing engineering in conjunction with language arts, social science, and natural science instruction.

At the secondary level, many teachers are specialists with teaching assignments based on their training in a given discipline. Because engineering is often outside their areas of expertise, teaching engineering concepts and skills would require learning new content to implement new lessons, learning activities, and assessment methods.

Diffusion of Materials

The curriculum materials reviewed for this study range in maturity from more than 20 years old to just off the press, and they range in sophistication from units of instruction that can be downloaded from the Internet at no cost to programs featuring courses of study that span multiple grade levels and involve formal commitments, professional development, and investments of large amounts of time, resources, and human capital. Much of the data on diffusion of these materials is limited to reports from curriculum pilot- and field-test sites, records of sales or dissemination of materials, and the number of teachers participating in professional development activities. However, none of these is a valid indicator of how widely a curriculum is used or whether it has been adopted by schools or school districts. Several developers of curriculum initiatives have entered into formal partnerships with participating schools and thus have mechanisms for structuring, supporting, monitoring, and assessing implementation. Table 4-2 summarizes what we have learned about the dissemination of these curricula.

Implementation and Costs

The costs for curricular materials range from $1,100 for a series of eight three-ring binders to no charge at all for a half-dozen large boxes of curricular and laboratory materials. The contents range from major curricular initiatives with no single objective to modest projects with more than 60. Some curricula can be implemented with everyday items at very little cost; others require large capital investments for specific, elaborate pieces of laboratory equipment.

Project Lead the Way (PLTW) has the most formal and systematic implementation process. For a school district to obtain and implement the curriculum, it must make a significant commitment to the program. This involves first submitting an application to become a PLTW site, then signing an agreement or memorandum of understanding that outlines the terms for participating in the program. The school district agrees to initiate a minimum of four courses within four years at the high school level, purchase required software through PLTW Inc., serve as a model program for other school districts, adhere to PLTW's implementation guidelines, ensure that teachers and guidance counselors complete PLTW's three-phase training program, establish an advisory committee or "Partnership Team," purchase equipment and supplies approved by PLTW, and participate in PLTW's systematic evaluation process.

Under this agreement, participating high schools must be certified by their second year in the program and recertified every five years thereafter. Certification, which is a requirement for participating in the PLTW testing process for earning college credit, includes a self-assessment, a site visit, and a classroom and portfolio review. Schools must demonstrate that they meet PLTW's quality standards for the professional development of teachers and

TABLE 4-2 Diffusion of Curriculum Materials (for selected programs)[a]

Curriculum	**Diffusion**	**Comments**
Project Lead the Way	The PLTW curriculum is used in all 50 states and the District of Columbia in 2,700 schools (2,000 high schools and 700 middle schools). About 600 high schools have completed PLTW's program certification process, and 34 middle schools have been recognized by PLTW's "School of Excellence Recognition Program." PLTW estimates that 225,000 students are currently enrolled in PLTW classes and that more than half a million students have taken at least one PLTW course.	
Materials World Modules	This curriculum has been used in about 500 schools in 48 states by some 35,000 middle shool and high school students. The U.S. Department of Defense uses MWM modules in 13 schools associated with military bases overseas. MWM materials are also used in 35 schools by 120 teachers and 1,200 students in seven cities and towns in Chihuahua, Mexico.	
Infinity Project	The high school course has been used in 350 schools in 37 states and some schools in several other countries. The materials are being used as an introductory engineering course at Southern Methodist University and DeVry University. A new set of middle school modules is being used in 20 schools in Texas.	The modules on robotics, sound engineering, rocketry, the engineering design process, and environmental engineering have been incorporated into mathematics, science, and technology classes.

Designing for Tomorrow	This curriculum, developed by Ford Partnership for Advanced Studies, is used in more than 300 schools in 26 states.	This program has been implemented in comprehensive high schools in urban and suburban settings, career and technical-education programs, freshman engineering courses at the college level, and historically black colleges and universities.
A World in Motion	This curriculum is used in all 50 states and in 10 Canadian provinces/territories. More than 65,000 AWIM kits have been shipped to more than 16,000 schools since 1990. The developer (Society of Automotive Engineers) estimates that more than 4 million students in North America have participated in AWIM activities (based on the assumption that the curriculum kits are reused an average of 2.6 times in classes averaging 24 students).	More than 17,000 engineers have volunteered in AWIM programs.
Engineering is Elementary	This curriculum is used in about 850 schools in 46 states and the District of Columbia. Based on sales figures and teacher participation in professional development workshops, the developer (Boston Museum of Sciences) estimates that about 15,000 elementary school teachers are using their materials. Approximately 1 million students have been exposed to the EiE curriculum since its inception.	Many fewer than 15,000 teachers—about 5,500—have received formal professional development to teach the EiE curriculum. The difference reflects estimates of teachers using the curriculum without having participated in an EiE PD program.

[a]These data are presented as reported by the curriculum developers.

counselors; the implementation of curriculum using required equipment and software; the formation and use of a Partnership Team, and more. The financial demands associated with implementing the program add up to tens of thousands of dollars over the course of several years, depending on course selection and existing laboratory resources. ("The Infinity Project" and "Designing for Tomorrow" have similar, but less formal requirements on a smaller scale.)

Several curriculum projects at the elementary and middle school levels offer resources to support implementation. The most comprehensive support is provided by "A World in Motion," "Children Designing and Engineering," "Engineering is Elementary," "Full Option Science System," and "Material World Modules." Implementation for these programs begins with the purchase of the instructional materials for the units of interest. These materials typically include teacher guides and, sometimes, videos or DVDs to support implementation. Student materials are presented as separate publications or reproducible master copies embedded in the teacher materials. "A World in Motion" requires participating teachers to involve a practicing engineer (a volunteer) in the delivery of the curriculum. The Society of Automotive Engineers (2009), which developed the curriculum, estimates that 17,000 engineer volunteers have participated since the program's inception.

Teacher materials typically cost $40 to $130, and classroom sets of student materials cost approximately $200. In addition, these programs offer kits of tools, supplies, and materials to facilitate the learning activities. The kits, which usually come in 4- or 5-cubic-foot containers that fit on a shelf or in a storage cabinet, cost $200 to $750, depending on the topic. "A World in Motion" provides the curriculum materials and kits free upon request, after a simple partnership agreement has been signed. Several projects also offer "refill packs" to replenish the consumables in the kits; these cost $20 to $250, depending on the nature of the materials.

Most of these curriculum projects maintain websites that can be used to purchase materials and kits, exchange ideas with other teachers, and tap into additional resources, such as lesson plans, links to relevant websites, a list of books and references, duplicate master copies, curriculum updates, safety data sheets, preparatory videos, discussion boards, additional learning activities, and professional develop materials.

Implementation of "City Technology," "Designing for Tomorrow," and "Invention, Innovation, and Inquiry" programs require purchasing one or more books and obtaining project-related tools and materials, which are available from popular suppliers, such as home stores, office supply stores, discount stores, and vendors for science and technology education. Several recommend that tools and simple mechanical devices for analysis activities be obtained from garage sales or flea markets. Although these programs do not require large capital investments, they do require significant amounts of a teacher's time and energy. The tools, materials, and supplies necessary to implement these curricula must be located, purchased, counted, labeled, organized, and stored. Despite their low cost and simplicity, assembling these materials for laboratory activities is a time-consuming process that requires thoughtful preparation to minimize problems during instruction.

Pedagogy

To get some sense of how the curricula envision the teaching of K–12 engineering, our analysis included an effort to tease out the materials' pedagogical approaches. Of course, neither we nor our consultant, Prof. Welty, was able to spend time observing teachers teach or attending teacher professional development sessions. Thus what we present below reflects pedagogy inferred from the written materials rather than a firsthand account of what actually is occurring in classrooms.

Most of the curricular materials the committee reviewed rely on time-honored teaching strategies for facilitating learning. These strategies include beginning lessons with an anticipator set, activating prior knowledge, presenting new concepts, using questions to promote thinking, providing first-hand experiences, posing authentic problems for students to solve, debriefing students about their experiences, and engaging students in reflection.

All of the curricula emphasize hands-on learning activities that involve the application of concepts and skills being investigated. Most learning activities also focus on solving real-world problems (i.e., problems in contexts beyond the school walls). For example, the "Young Scientist Series" includes a unit titled *Building Structures with Young Children,* in which students use building blocks to erect enclosures to provide shelter for a toy animal. In the "Engineering is Elementary" curriculum, students build and test models that address problems related to harnessing wind power, filtering water, moving materials in a factory, building a footbridge that spans a stream, and more. In the "Building Math" curriculum, middle school students address problems related to keeping medicine cool in a tropical environment, collecting rainwater in the absence of fresh water, and designing insulated clothing that allows for easy movement. In "The Infinity Project," high school students use simulation software to develop and test a system that counts the animals entering and leaving a given area in a refuge. Some curricula, however, do focus on problems that arise in schools. For example, the "City Technology" curriculum engages students in studying and addressing problems related to classroom interruptions, procedures, and layout.

In most of the curricula, teachers use a Socratic approach in conjunction with hands-on learning to actively engage students in learning. Questions are often used to reintroduce prior knowledge and experiences, solicit preconceptions that can be reassessed, launch and guide investigations, build and check for understanding, debrief students about their experiences, and facilitate reflection.

Some of the instructional materials are designed to follow a specific instructional model. For example, all of the units in "Engineering is Elementary" follow a sequence of lessons built on one another. The first lesson provides introductory activities that prepare students for the unit. The second lesson uses a fictional engineering story as an advanced organizer for the rest of the unit. The lesson that follows the reading is designed to orient students to a specific field of engineering (e.g., mechanical engineering, civil engineering, and agricultural engineering). The fourth lesson engages students in hands-on activities that address relationships between science, math, and engineering. All of the units end with engineering design problems consistent with the ones presented in the fictional account.

"Material World Modules" at the middle school and high school levels follow a similar pattern. Each module has three basic elements. Instruction begins with an introductory activity designed to stimulate interest in the topic at hand; this activity requires that students formulate a hypothesis about a cause-and-effect relationship. Second, students engage in four or five hands-on learning activities that introduce key principles, ideas, and methods related to the topic; these activities are framed in the context of one or more design problems. Third, students participate in a design project to develop a prototype product, applying the previously introduced science concepts and skills.

A prominent feature in several curricula is an emphasis on people and storytelling. For example, the "Design and Discovery" curriculum features stories about the history of the paper clip, the development of Kevlar™ by Stephanie Kwolek, the design of a bicycle for women by Georgina Terry, and so on. The textbook for "Engineering the Future" reads like transcripts of talks by a series of guest speakers who tell personal stories about their interest in engineering and their work. "Designing for Tomorrow," includes case studies of the development of the S.C. Johnson Administration Build designed by Frank Lloyd Wright, the space shuttle *Challenger* disaster, and so on. “Models and Design” includes stories about Henry Ford’s Model T, the cartoonist Rube Goldberg, and NASA’s use of simulation technology.

Evidence of Diversity

Gender and ethnicity play an important role in the development of a person’s self-efficacy, identity, approach to learning, and career aspirations (see, for example, Bandura et al., 1999; Maple and Stage, 1991). As noted in Chapter 2, engineers in the United States have historically been predominantly white males; and women, African Americans, and Hispanics are still significantly underrepresented in the profession. Exposing students to images of engineers who look like them and to engineering-related activities that resonate with their personal and cultural experiences may not only improve their understanding of engineering but may also make engineering more appealing as a possible career (EWEP, 2005; NAE, 2008).

Efforts have been made in several curricula to portray engineering as an interesting and accessible career for individuals from diverse backgrounds. For example, the textbook for “Engineering the Future” features 31 stories (or chapters) written by engineers, designers, architects, technologists, and technicians, almost half of them women and a third members of minority groups. Similarly, “Design and Discovery” includes vignettes that enable students to “meet engineers,” half of whom are women. Every unit in the “Engineering is Elementary” curriculum features a story about a child who uses basic engineering principles to solve a problem. The main characters in four of the nine units are female, and all of the characters come from different ethnic backgrounds. In addition, several stories include adult females as mentors and advisors.

In contrast, stories in the “Models and Designs” unit of the Full Option Science System curriculum are dominated by male inventors, scientists, engineers, and industrialists (e.g., Stephen Hawkings, Dick Covey, Rube Goldberg, Henry Ford, Eli Whitney). In addition, almost all of the photographs of people engaged in scientific and engineering pursuits are male.

Several curricula focus on topics and projects that research suggests are more likely to appeal to boys than to girls.[4] For example, “A World in Motion,” “Gateway to Technology,” and “Models and Designs” include

[4]There is an extensive literature on gender preferences related to technology and engineering (e.g., Weber and Custer, 2005) that suggests, among other things, that girls are more interested in socially relevant technologies, while boys are more interested in how technologies work, and that girls prefer collaborative work, while boys are more motivated by competition.

major learning activities that involve designing, making, and testing model structures or vehicles (e.g., towers, bridges, cars, rockets, airplanes, boats). Other curricula feature lessons and learning activities that capitalize on the knowledge and experience of both male and female students. For instance, in the "Design and Discovery" curriculum, engineering concepts and skills are applied to designing paper clips, improving the caps on tubes of toothpaste, and analyzing bicycle systems. "City Technology" introduces engineering principles in conjunction with testing the design and strength of shopping bags, designing packages, making maps, establishing classroom procedures, analyzing pump dispensers, and building shelves. In the interest of inclusiveness, the "Infinity Project" deliberately focuses on technologies likely to be found in a high school student's backpack (e.g., digital music players, digital camera, cell phone, etc.). Activities in "Designing for Tomorrow" involve the reverse engineering of simple kitchen devices and training cups for small children.

We were interested not just in the implicit or explicit messages conveyed through these curricula, but also in the diversity, or lack of diversity, in the student populations that used these materials. The committee was particularly interested in how many girls and underrepresented minorities had an opportunity to participate. Unfortunately, only one of the curriculum projects we reviewed in depth collects demographic data on student participation.

A program evaluation of PLTW for the 2006–2007 school year showed that the number of African American and Hispanic students in schools that used this curriculum was proportional to the populations in the states in which the schools were located (Walcerz, 2007). However, African American students were slightly underrepresented in PLTW classrooms compared with their numbers in most PLTW schools. Girls were dramatically underrepresented throughout the program; they comprised just 17 percent of all PLTW students that school year.

The number for girls cited above is similar to the percentage of entry-level female college engineering students (NSF, 2005) but is well below the proportion of females in the overall U.S. population, which is slightly more than 50 percent (U.S. Census Bureau, 2005). PTLW is taking steps to increase the program's appeal to women and underrepresented minorities, such as participating in an NSF-funded Engineering Equity Extension Service project[5] and partnering with the National Action Council for Minorities in

[5]For information about the project, see *http://www.nae.edu/nae/caseecomnew.nsf/weblinks/NFOY-75WLB5?OpenDocument.*

Engineering to start 100 academies of engineering under the auspices of the National Academy Foundation.

PROFESSIONAL DEVELOPMENT

As yet, there is no clear description of the knowledge and skills needed to teach engineering to children. Nor do states license or certify teachers of engineering the way they do teachers of science, mathematics, technology, and other subjects. Most instructors who teach engineering in middle and high schools have a background in technology education;[6] a smaller number have backgrounds in science education; and an even smaller number have backgrounds in engineering. Because engineering is a developing area of content for K–12 schools, professional training for teachers in this field is still in its infancy.

Teacher "content knowledge" can be thought of as having three dimensions. First, teachers must know the subject they are teaching, in this case engineering, and its organizing principles. Second, they must have curricular knowledge, that is, an understanding of the materials and programs available to deliver the content. Third, they must have pedagogical content knowledge, which has been defined as "that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding" (Shulman, 1987).

Building on Shulman's work, Ball et al. (2008) have identified subcategories of subject-matter knowledge and pedagogical-content knowledge that reflect the specialized understanding unique to teaching. First, teachers must have "knowledge of content and students," which means they must be able to predict what students will find interesting, motivating, and difficult and to interpret students' incomplete thinking. Second, teachers need "knowledge of content and teaching," which implies they must be able to sequence particular content for instruction, for example, or evaluate the advantages and disadvantages of various representations of specific ideas.

To get a better understanding of how teachers acquire knowledge and skills to teach engineering to K–12 students, the committee looked into a number of programs that provide pre-service and in-service professional-development programs. Two committee workshops, in October 2007 and February 2008, were substantially devoted to this topic and are summarized in what follows.

[6]For example, 67 percent of teachers delivering the Project Lead the Way curriculum have a teaching certificate in technology education (R. Grimsely, PLTW, personal communication, June 16, 2009).

In-Service Programs

Most of the professional-development activities we identified are in-service rather than pre-service programs that provide supplemental education based on specific curricula for teachers already working in the classroom (Table 4-3). One advantage of well-designed, curriculum-focused professional development is that teachers come away with in-depth understanding of the purpose of the materials and first-hand experience with some of the difficulties and successes students might encounter. A disadvantage is that potentially useful and important content or pedagogical knowledge that is not included in the curriculum will be omitted.

Education researchers have identified common characteristics of effective in-service professional development programs for teachers. In a discussion of in-service programs for K–12 science educators, Mundry (2007) identified the following requirements:

- clear and challenging goals for student learning,
- adequate time, follow-up, and continuity,
- coherence with local policy, teachers' goals, and state standards,
- active, research-based learning,
- critical reflection on practice to support a collaborative professional culture, and
- evaluation of teacher and student gains resulting from the professional development.

Mundry notes that professional development sustained over time is more likely to be coherent, have a clear focus, and support active learning than "one-shot" workshops and other limited interventions. Opinions differ on the necessary number of hours, but most experts agree that single experiences are not likely to support teacher competence or confidence (e.g., NCES, 2001).

Research at the NSF-funded National Center for Engineering and Technology Education (NCETE) has focused on identifying the requirements for preparing technology educators to teach engineering. One small, qualitative study identified about a dozen interrelated factors that are important to preparing teachers to introduce engineering design concepts into the K–12 classroom (Asunda and Hill, 2007). A member of the NCETE leadership team told us that professional development planned jointly by engineering and technology education faculty resulted in better outcomes for teachers than professional development planned by either one alone (Hailey et al., 2008).

NCETE also conducted an observational analysis of five professional-development programs, including three (Engineering the Future, Project Lead the Way, The Infinity Project) whose curricula we reviewed (Daugherty and Custer, unpublished). Among the study's findings were that (1) most of the programs were run by the curriculum developers, who rarely had a background in teacher professional development; (2) science, technology, and mathematics teachers have different professional development needs; and (3) hands-on activities were a very common element in the programs, but little instructional time was devoted to metacognitive reflection about either the teacher or student learning involved.

Although not all in-service programs for K–12 engineering teachers have all of the required features listed above, professional-development programs can have a dramatic impact on how widely the curriculum is used. A good example is "A World in Motion," developed by SAE International, which was launched in 1990; the first professional-development component was not added until 2005. Matthew M. Miller, manager of SAE's K–12 education programs, told us at the February 2008 workshop that the use of the curriculum doubled and the number of new classroom volunteers increased almost tenfold once the professional-development program was implemented.

Project Lead the Way (PLTW) has a very organized professional-development effort, which may, in part, explain its rapid growth. PTLW conducts two-week summer institutes, during which prospective PLTW teachers are immersed in the course they plan to teach, including completing all of the hands-on projects. PLTW has agreements with 36 universities to supply engineering faculty who team teach with PLTW master teachers to run the program. According to PLTW, about 7,200 teachers have taken part in the summer training sessions. Teachers who complete the course receive a certificate allowing them to teach the course. Ongoing assistance is available from PLTW through an online Virtual Academy (*www.pltw.org/moodle*).

Other in-service programs run the gamut from one-week summer institutes (e.g., "The Infinity Project") to self-paced coaching provided on a DVD included in the curricular materials for "Building Math"(Table 4-2).

Pre-Service Initiatives

Pre-service training of teachers has some distinct advantages over in-service training. The biggest difference is that teachers have longer exposure

TABLE 4-3 In-Service Professional Development Programs for Teachers of K–12 Engineering

Program/ Curriculum	Scope of Training	Target Audience	Training Force	Number of Teachers Reached	Notes
Project Lead the Way	All teachers are required to complete a two-week summer institute	Middle school and high school teachers, mostly technology educators	160 master teachers; 120 affiliate professors	7,200 teachers and 5,000 guidance counselors have been trained in all 50 states	Online Virtual Academy provides ongoing support
Engineering is Elementary	Optional training that varies from two-hour workshops to two-week sessions and semester-long programs	Elementary generalists	Professional development staff at the Boston Museum of Science	5,100 teachers in 28 states and the District of Columbia (as of June 2009)	A memorandum of understanding between the Boston Museum of Science and Valley City State University allows Engineering the Future to be used in VCSU online pre-service technology teacher education

City Technology	Optional training—a one-hour introductory workshop followed by 30-minute workshops on particular units	Elementary generalists, special education teachers, elementary science specialists, secondary math and science teachers, museum educators, after-school program staff, and parents	Authors of the curriculum (City College of New York)	Several thousand teachers and informal educators in about 20 states
Children Designing and Engineering	Required: 30-hour graduate course	Elementary teachers	In Virginia, the training is conducted through George Mason University	1,300 teachers since 1999 in six states, the bulk of whom (800) are participants in Virginia's Children Engineering Program

continued

TABLE 4-3 Continued

Program/ Curriculum	Scope of Training	Target Audience	Training Force	Number of Teachers Reached	Notes
Engineering Our Future New Jersey (based on the following curricula: Engineering is Elementary, World in Motion, Engineering the Future)	One- or two-day workshops	Elementary, middle, and high school teachers	Staff at the Stevens Institute of Technology	35 teachers in New Jersey	Planned expansion will reach 2,000 teachers
The Infinity Project	Required one-week summer institute	High school teachers		500 teachers in grades 9–12	Training includes an online discussion board for teachers
Material World Modules	Optional workshops that vary in length	High school teachers			
Engineers of the Future (training based on several different curricula)	Summer institute	High school and middle school technology educators, and elementary teachers		Nearly 700 trained, the majority using the Engineering is Elementary curriculum	Supported by $1.7 million grant from the New York State Education Department

Engineering the Future	Half-day, full-day, and multiple-day sessions in the Boston area and 20 to 40 hour moderated online professional development course	High school teachers			A memorandum of understanding between the Boston Museum of Science and Valley City State University allows Engineering the Future to be used in VCSU online pre-service technology teacher education
Building Math	Training DVD supplied with curriculum materials				
INSPIRES	Two-day workshops	Technology teachers in Maryland			
A World in Motion	One-day workshop	Elementary, middle, and high school teachers		65,000 kits shipped since 1990 (not clear how many teachers trained)	Teachers must agree to work with an engineer who volunteers in the classroom

times to concepts and skills, including math and science skills, necessary to teach engineering. The committee was able to identify just three programs that offer pre-service education to prepare individuals to teach engineering in K–12 classrooms.

Leveraging its model of in-service professional development, PLTW is working toward "infusing" its K–12 curriculum into teacher-preparation programs at nine university partners that already serve as sites for PLTW in-service summer institutes. The infusion of PLTW coursework into existing teacher-preparation curricula must be carefully planned to ensure that it aligns with state licensing requirements (Rogers, 2008). As of early 2009, fewer than 10 teachers had graduated from the new PLTW-infused programs (Richard Grimsley, Project Lead the Way, personal communication, January 5, 2009).

In contrast to PLTW's curriculum-focused approach, in 2002 the College of New Jersey (TCNJ) initiated the Math/Science/Technology (M/S/T) interdisciplinary degree program for aspiring elementary school teachers that requires coursework in all four STEM subjects. The program is a collaborative effort by the schools of engineering, education, and science administered by the Department of Technological Studies in the School of Engineering. The 32-credit program (Box 4-1) now has more than 150 graduates and current majors and is one of the fastest growing majors at TCNJ (Karsniz et al., 2007).

Students who matriculate from the M/S/T program appear to have an appropriate background for teaching engineering. Unfortunately, TCNJ does not track the employment histories of its M/S/T graduates who, according to school officials, are in great demand as science and math teachers (John Karsnitz, TCNJ, personal communication, September 20, 2007). So, at least for now, the TCNJ program does not appear to be contributing to the national supply of engineering teachers.

In 2006, Colorado State University in Fort Collins established a joint major in engineering and education. To the committee's knowledge, this is the only program of its kind in the United States. Students in the program must complete general-education requirements, core engineering requirements, engineering-school electives, and professional education requirements. In the first year, 11 students (70 percent of them female) were enrolled in the program. Graduates will receive an engineering degree and a teaching license (DeMiranda, 2008).

Other models of pre-service engineering education for teachers exist. For example, at Boise State University, students majoring in elementary

BOX 4-1
The M/S/T Major at TCNJ

The M/S/T program provides 10 units of "liberal learning" courses, such as creative design, calculus A, and a natural science. The 12-unit M/S/T academic major has an eight-unit core, which includes courses in multimedia design, structures and mechanics, two additional science courses, and one additional math course (either calculus B or engineering math). Areas of specialization must include four additional units in technology/pre-engineering, mathematics, biology, chemistry, or physics. Specialization is the equivalent of a minor in one of the disciplines and may require that specific courses be included in the core requirements. M/S/T students who major in education must also complete 10 units of professional education courses. Such students meet New Jersey's certification requirements for highly qualified teachers. In addition to primary K–5 certification, M/S/T majors can apply for an endorsement for teaching middle school mathematics or science, if they have completed 15 credits of coursework in the discipline and have passed the appropriate PRAXIS test. They may also receive technology-education certification, if they have completed at least 30 specified credits and passed the appropriate PRAXIS test.

SOURCE: Karsnitz, 2007.

education may enroll in an introductory engineering course offered by the College of Engineering. The course is supplemented by a seminar led by education faculty that considers how engineering projects can be used in the K–12 classroom to meet state teaching standards for math and science as well as reading, writing, and other non-technical subjects (Miller and Smith, 2006).

Through a collaboration with TERC (*www.terc.edu*), Lesley University and Walden University offer an online course, Engineering: From Science to Design, for education master's degree candidates. The course includes independent, hands-on work and group feedback and discussion in facilitated online forums (Sara Lacy, TERC, May 15, 2008).

At least two states have started programs to provide new K–12 teachers with STEM credentials. In California, the University of California, California State University, and state and industry leaders initiated Cal Teach (*http://*

calteach.berkeley.edu/), which recruits students majoring in math, science, and engineering to become K–12 teachers. The goal of Cal Teach is to have 1,000 teachers in place by 2010. A similar effort, UTeach (*http://uteach.utexas.edu/*), was launched in 1997 at the University of Texas at Austin. As of 2007, the program had graduated a total of 480 STEM students, 41 of whom had degrees in engineering in addition to teaching certificates (376 had degrees in the natural sciences) (University of Texas at Austin, 2007). Under the auspices of the National Math and Science Initiative, UTeach has been expanded to 13 additional colleges and universities across the United States.

OBSTACLES FACING PROFESSIONAL DEVELOPMENT PROGRAMS

Based on information provided during the two preliminary workshops and in the research literature, several barriers to professional development programs must be overcome in preparing educators to teach engineering in K–12 classrooms. For instance, teachers who are not familiar with engineering may feel anxious and apprehensive, which can inhibit the effectiveness of professional development programs. Christine Cunningham, the director of professional development for "Engineering is Elementary," described the problem (Cunningham, 2007):

> If most elementary teachers are afraid of teaching science, the notion of teaching engineering is often accompanied by terror. Much of the point of our professional development is to defuse their feelings of ineptitude through engagement.

Similarly, teachers who do not have adequate knowledge of science and, especially, mathematics sometimes have difficulty understanding the material. In addition, some have little, if any, desire to take part in training activities (Diefes-Dux and Duncan, 2007). Reportedly, some teachers also are uncomfortable with the open-endedness of engineering design. "A major challenge in PD for K–12 engineering is to undo the mindset that sees answers as right or wrong, and as complete or incomplete," note Benenson and Neujahr (2007). In a survey of 44 technology teacher-education programs, only 17 percent had completed the mathematics and science courses that would qualify them to teach PLTW courses (McAlister, 2005). McAlister also found that, when a group of 43 technology teachers was presented with two fairly simple problems involving structural load, half of them indicated that they would require additional training before they could teach those problems to students. Only one was able to identify the correct formula for solving one of the problems.

INSPIRES (INcreasing Student Participation, Interest and Recruitment in Engineering & Science), a small-scale professional-development program at the University of Maryland, Baltimore County, relies on engineering faculty to lead some activities. The program leaders note, however, that large numbers of engineering faculty might not be able to participate in such ventures because of their workloads and because of typical university reward structures (Ross and Bayles, 2007). More systemic problems, such as a lack of understanding of program content and learning progressions, may also interfere with the effectiveness of professional-development programs for K–12 teachers of engineering (Hailey et al., 2008).

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Annex

PRE-UNIVERSITY ENGINEERING EDUCATION IN OTHER COUNTRIES[1]

Given the universality of science and technology, the committee felt it appropriate to look into how other nations encourage engineering thinking in pre-college students. However, because of budget and time constraints,

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[1]This appendix is adapted from a paper written for the committee by Dr. Marc J. DeVries, Eindhoven University, The Netherlands, based on research conducted by Carolyn Williams, a 2007 Christine Mirzayan Science and Technology Policy Graduate Fellow at the National Academy of Engineering.

BOX 4A-1
Selected Countries with Pre-College Engineering Programs

England/Wales: General Certificate of Education, 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: Baccalauréat General, Série Scientifique Sciences de l'Ingénieur; Baccalauréat Technologique, Série Sciences et Technologies Industrielles
Netherlands: Technasium, Research and Design
Colombia: Pequeños Cientificos (Little Scientists)

the committee did not pursue this research and analysis with the same intensity as it had for U.S. efforts. In addition, because of differences in the organization and operation of educational systems in other countries, it was difficult to draw direct comparisons with the situation in the United States. Materials in languages other than English further complicated the analysis, and curricular documents were not always available. In many cases, the curriculum content had to be inferred from a review of sample assessment items. Despite these limitations, the committee was able to identify several important principles.

The committee used a variety of information-gathering techniques, including online searching; telephone interviews; and e-mail requests to professional, corporate, academic, government, and education groups and individuals. Eight programs or projects in eight countries were identified (Box 4A-1), all but one of which (Pequenos Cientificos) were for senior secondary-level students (i.e., grades 10–12). In all probability, these eight initiatives represent only a fraction of these kinds of activities around the world.

The Goals of Pre-College Engineering Education

Two primary purposes were identified for exposing pre-college students to the study of engineering—"mainline" goals (i.e., general education) and "pipeline" goals (i.e., preparation for engineering careers). The majority of programs were in the "pipeline" category. In France, for example, preparation for the academic study of engineering is preceded by a competitive selection process at the pre-college level with the goal of identifying the very best students for continued engineering education. Based on sample exam questions for prospective engineers in Israel, the committee inferred that the emphasis of the ORT engineering sciences program is on preparing students for post-secondary engineering education, rather than on expanding their general education.

Programs in some countries seem to serve both purposes. For example, in England and Wales, the General Certificate of Education, Engineering, has some features in common with the U.K.'s Design and Technology Curriculum, which is designed primarily for general education purposes. At the same time, to receive a General Certificate, students must master a good deal of specific knowledge in engineering domains, thus preparing them for further engineering studies.

Treatment of Engineering Concepts and Domains

The focus on core engineering concepts in international programs varies greatly. The U.K. materials, for example, treat the concepts of systems and control in some detail, while other concepts, such as optimization, are largely absent. The design process is evident, consistent with the influence of the design and technology paradigm. In the Israeli programs, the curriculum and sample exam questions focus on the concept of systems; related ideas, such as control, feedback, and parameters, are also treated in some detail. By contrast, the South African assessment materials have few explicit references to general engineering concepts; instead, they focus on ideas specific to electrical engineering, most of which are scientific rather than engineering concepts (e.g., voltage, current). Exam questions in the French Série de Sciences de l'Ingénieur explicitly refer to engineering concepts, including system analysis, requirements, and optimization.

Overall, the international pre-college engineering programs include a wide range of engineering domains. The U.K. General Certificate of Education, Engineering, reflects the compulsory pre-college design and technology curriculum; thus it explores the traditional disciplines of electrical and mechanical engineering, as well as less traditional areas, such as food technology and biotechnology. The exam questions for Australia's Higher School Certificate in Engineering (HSCE) Studies address issues in telecommunications, transportation, civil engineering, aeronautics, and electronics; the exam also includes a biotechnology module.

In addition to two engineering sciences courses, students pursuing the Israeli ORT curriculum pick a specialization course from one of the following areas: motion systems, biomedical engineering, robotic systems, artificial intelligence, or aerospace engineering. The content of the sample exam for the ORT curriculum, however, appears to focus on computer programming. The French baccalauréat programs cover a variety of engineering domains spread over different 'séries' in the 'bac'. In the engineering series, the focus is on electrical engineering, mechanical engineering, and information science.

Treatment of Science, Technology, and Mathematics

International pre-college engineering initiatives appear to face same challenges as U.S. initiatives, such as teaching students to use math and science to solve or optimize authentic design challenges. In the French curriculum, math and science are integrated, but at a high level of difficulty. Exam questions for the 'Séries de Sciences de l'Ingénieur' describe a technical device that has to meet a given set of requirements, and students are asked to calculate certain variables based on their knowledge of science.

In most instances, however, math and science concepts are treated as separate from technological content. For example, sample assessment items for the Australian HSCE require the application of scientific knowledge and mathematical skills to problems specific to technical devices. Either the technical device is used as a context for asking a question that requires knowledge of science and/or math, or the question is about technology and does not require science or math.

The same separation was evident in exam questions and practical assessment tasks in the South African curriculum. The exam includes questions about abstract situations (e.g., diagrams representing electrical and logical circuits) in which students must make calculations and apply their knowledge of the laws of electricity. The practical assignments are design challenges, but they do not encourage the application of science or math to develop or optimize the design solution.

5

Teaching and Learning Core Engineering Concepts and Skills in Grades K–12

Curriculum initiatives in the K–12 setting that include engineering content and courses (primarily in the context of science) have raised questions about teaching engineering to pre-college students, and especially pre-high school students. In response to these concerns, studies have been undertaken on a number of issues, including determining whether K–12 students, who have limited knowledge of basic mathematical concepts, can learn engineering concepts and skills and whether "positioning engineering design primarily as a tool for science learning runs the risk of misrepresenting . . . engineering as *applied science*" (Leonard, 2004).

Although engineering is rarely taught explicitly in K–12 classrooms in the United States, a growing body of evidence on the teaching and learning of core engineering concepts and skills suggests that elementary students are capable of engaging with this material. The committee commissioned two reviews (Silk and Schunn [2008] and Petrosino, Svihla, and Brophy [2008]) of this growing body of evidence. The relative paucity of research on K–12 students' understanding of engineering concepts and skills places significant limitations on what can be currently claimed. The following review presents our current best understanding of learning trends in this domain, including the challenges inherent in designing engineering instruction for K–12 students.

Deciding on the scope and sequence of teaching engineering-related concepts and skills can be difficult, sometimes even controversial. Like scientists, engineers in different areas of engineering require different sets of specific skills and concepts. The reviewers focused on core concepts and skills that are usually considered essential, defining features of "engineering." Although it is impossible to separate concepts from skills in engineering practice, the research literature tends to treat them separately. Thus, for the sake of simplicity, this chapter follows that dual structure.

The discussion of each skill or concept addresses (1) difficulties encountered by K–12 students in learning that particular concept or skill; (2) the development of students' understanding and cognitive capabilities during their K–12 years; and (3) the experiences and teaching interventions that facilitate an increasingly sophisticated understanding of each concept or skill. Based on the these three issues, the committee identified common principles: (1) the allocation of sufficient classroom time; (2) student engagement in iterative design activities; (3) sequencing of instruction that moves from easier-to-learn concepts to more difficult-to-learn concepts; and (4) the integration of tools (e.g., computer software or computational devices). These principles are discussed in more detail at the end of the chapter.

ENGINEERING CONCEPTS

Engineers generally agree that the prototypical engineering process is design and redesign. However, engineering design is not the same as trial-and-error "gadgeteering." Engineering design involves the following essential components: identifying the problem; specifying requirements of the solution; decomposing the system; generating a solution; testing the solution; sketching and visualizing the solution; modeling and analyzing the solution; evaluating alternative solutions, as necessary; and optimizing the final design. These essential components can be categorized into three type-specific groups of engineering concepts: basic science and math concepts, domain-specific concepts, and concepts common to most areas of engineering. Though this review does not focus on the social aspects of engineering design, engineering design is an inherently social enterprise, since those involved typically are working in teams and must communicate with clients or other stakeholders.

Research on the development of science and math concepts is not discussed in this chapter but has been extensively reviewed in recent studies by the National Research Council (e.g., *Taking Science to School: Learning and Teaching Science in Grades K–8* [Duschl et al., 2007] and *Adding It Up: Helping Children Learn Math* [NRC, 2001]). Very little research has been

TABLE 5-1 Engineering Concepts in the Categories 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

*Related empirical research on K–12 students is available on these concepts.

published about the development of domain-specific concepts, some of them closely connected to particular engineering disciplines (e.g., statics), in K–12 students. In fact, with the exception of students who enroll in higher level math and physics courses in high school, very few K–12 students are even exposed to these concepts. Based on Silk and Schunn's (2008) review of relevant literature, which includes national and international content standards in technology education and engineering, the concepts that are common to most areas of engineering include structure-behavior-function (SBF); trade-offs, constraints; optimization; and system, subsystem, and control. The discussion of the concepts is divided into two categories: systems and optimization. As depicted in Table 5-1, the majority of empirical research on systems focuses on the concepts of SBF and emergent properties (i.e., behaviors that emerge from dynamic interactions among system components). Most of the research on optimization is on multiple variables and trade-offs.

Systems

The concept of a system relates to how individual components of an object or process work together to perform a function. The analysis and design of systems is central to engineering, the purpose of which is to modify surroundings to achieve particular purposes. Engineers may focus on the role and performance of individual parts, subsystems, or levels in a system, or they may highlight the boundaries and interactions between a system and its surrounding environment. Thus the concept of a system has many aspects and can serve different purposes in the engineering design process. Thinking in terms of systems involves understanding (1) how individual parts function, (2) how parts relate to each other, and (3) how parts, or combinations of parts, contribute to the function of the system as a whole.

Structure-Behavior-Function

SBF, a framework for representing a system, can be used to describe both natural and designed systems. SBF relates the components (structures) in a system to their purpose (function) in the system and the mechanisms that enable them to perform their functions (behavior). The SBF framework has been used to explain designed physical systems, such as electrical devices (Goel, 1991; Goel and Bhatta, 2004), as well as to represent the process of design as conducted by experienced designers (Gero and Kannengiesser, 2004). Empirical evidence (Gero and Kannengiesser, 2004) suggests that functional considerations actually drive the design process for more experienced designers, who often label the framework FBS to reflect the change in emphasis. For our purposes, we distinguish between the three aspects of design without formally choosing their order of importance.

Researchers have found that young children, and even preverbal infants, seem to have a strong sense of cause-and-effect principles (Bullock et al., 1982; Koslowski, 1996; Leslie, 1984). By the end of the preschool years, most children can use reasoning processes and problem-solving strategies, including evaluating simple if-then rules. Thus they already have developed many capacities when they enter the formal learning environment (Duschl et al., 2007).

Based on a review of the literature, however, the commissioned authors concluded that very young students (second graders) are unlikely to spontaneously consider what causes an effect, the basis for an SBF understanding of a system. Older students (fifth graders) are more likely to consider the cause, but, in general, younger students are much more likely to consider surface features, even when prompted to think about what affected the system under investigation (Silk and Schunn, 2008). Younger students often use a device for its functional purpose without inspecting the elements or components of which the device is made (Rozenblit and Keil, 2002).

For example, Lehrer and Schauble (1998) interviewed second- and fifth-grade students to assess their reasoning about the mechanics of gears. The students were shown increasingly complex combinations of gears on a gearboard that performed no function and gears in familiar machines with a known purpose (e.g., a handheld eggbeater and a 10-speed bicycle). They found that, even though all aspects of the devices could be directly inspected and had no hidden parts, the students' ideas about the structures in the devices and the mechanisms that made them work varied by grade level.

Fifth graders were more likely than second graders to form causal chains of relationships among three or more components in the functional devices. In the function-free context, they were more likely to identify the gear teeth as the important feature that drives the motion of the gears. Interestingly, in the functional context (i.e., the eggbeater), both groups were likely to mention the gear teeth. In this case, the improved performance of the second graders may indicate the importance of context in helping young students to reason about causal mechanisms.

When fifth and sixth graders were compared, students at both grade levels were equally likely to mention that the relative gear size determined the speed of the gears, but sixth graders were more likely to take that idea a step further and actually count and calculate the ratio of gear teeth to velocity. Fifth graders also used this mathematical reasoning when analyzing more complicated combinations of gears, which may have been their way of minimizing the complexity of the task.

The authors of the study caution that, even when the structures of a design are visible, young students may recognize the function of an object without considering how the underlying structures contribute to the performance of that function. In addition, early elementary students appear to lack sophisticated strategies for explicitly articulating causal mechanisms and for using mathematical representations as tools to represent complex causal behaviors. However, when children are provided explicit support for developing mathematical descriptions of natural systems, they can often use them to support their understanding of causal mechanisms (Lehrer et al., 2001).

Studies by Hemlo-Silver and colleagues on differences between adults and students focused on how the understanding of systems in terms of SBF changes over time and with experience (Hmelo-Silver and Pfeffer, 2004; Hmelo-Silver et al., 2004). They found minimal differences between the way pre-service teachers and sixth graders think about structures. However, they found large differences in how they understood functions, and even larger differences in how they understood causal behaviors, which require an appreciation of "connectedness" among elements in a system. The authors suggest that causal behaviors are the most difficult to understand, because they are often dynamic and invisible, whereas functions lead to specific outcomes that are visible.

Silk and Schunn (2008) found that research on elementary and middle-school students (Kolodner et al., 2003; Penner et al., 1997, 1998) suggests that a primary method of advancing students' ideas about SBF was to engage them in designing models, especially successively complex models. Students' first models tend to focus on superficial features and structural features. However, as models are revised and refined, many constructive ideas come into play. In addition, teacher support appears to have a large impact on whether, and how much, model building furthers an understanding of the SBF concept. Teachers' questions that focus attention on design help students set step-wise, pragmatic goals for each revision, which deepens their understanding of SBF.

With considerable teacher support, both early elementary students and middle school students can move toward a conceptual understanding that emphasizes function, just as experienced designers do (Penner et al., 1998). Effective teacher strategies include (1) pointing out limitations of the class models as a whole (e.g., if none of the initial models includes a mechanism for motion, the teacher may suggest that students consider the specific idea of motion in their revisions); (2) providing information when there is no way for students to discover the information on their own (e.g., providing the mathematical concept of median as a way of representing a range of data); and (3) encouraging individual teams of students to pursue specific design challenges that extend their models in general ways (e.g., considering how the function of the object under investigation is similar to and different from a familiar related object). Students whose teachers used these strategies were able to design increasingly complex functional models, including models of the mechanism of motion, and then to develop data representations to support their claims about the performance of their designs.

The importance of teacher input cannot be overemphasized. Unfortunately, teachers who have had little or no experience with formal modeling may not have a deep understanding of the process and thus may not be able to formulate questions to guide students engaged in exploring functional relationships among constituent parts of models. Teachers who have not participated in differentiated, sustained staff development, may also lack underlying training in science and, therefore, may not be able to explain basic natural phenomena.

Another factor that can negatively affect students' conceptual understanding of SFB is the amount of time allocated for design/redesign cycles. In an already crowded curriculum, it may be difficult to set aside enough time for modeling activities that are not merely superficial exercises. So, although the findings about younger students' abilities to develop modeling concepts are encouraging, effective teacher development and making room in a crowded curriculum are paramount concerns.

Emergent Properties

Not all systems can be analyzed in terms of causal behaviors or a direct, linear sequence of events. Another framework for understanding systems is focusing on behaviors that emerge from dynamic interactions among system components. These emergent properties can be global, aggregate, or macro-level behaviors that emerge from local, simple, or micro-level interactions between (or among) individual elements or components of a system. Aggregate behavior is qualitatively distinct from the sum of behaviors of individual components and indicates a complex engineered system, such as highways, the Internet, the power grid, and many others, which are all around us.

Based on their review of the literature, Silk and Schunn (2008) concluded that a major impediment to understanding the concept of emergent properties is the strong, perhaps innate, tendency of individuals to ascribe a central plan or single cause to system behavior (Resnick, 1996). Thus, analyzing emergent properties, which requires thinking on multiple levels of a system, may be particularly difficult for elementary-age students. However, there is not enough research to support that claim, because most of the empirical studies on emergent properties have been with students in middle-school or above. It is possible, however, that the concept of emergent properties is not understood through everyday experiences, even by adults (Resnick, 1996), and may require special support or learning experiences.

In Resnick's study, 12 high school students used StarLogo, a complex systems-modeling program created by Resnick based on the Logo program, in which users specify the behaviors of individuals, then observe how interactions among them give rise to group-level behaviors. Working mostly in pairs, and with considerable help from Resnick, the students developed individualized projects using StarLogo.

For example, one project was a model of traffic flow on a one-lane highway. The behavior of each car was governed by three basic rules: (1) if a car was close ahead, the trailing car slowed down; (2) if no cars were close ahead, the car speeded up until it was going the speed limit; and (3) if a radar trap was detected, the car slowed down.

When traffic jams developed, the students first reasoned that the slowdowns must have been caused by a specific, localizable event or circumstance, which they decided was a speed trap. When they removed the speed trap, effectively eliminating rule 3, they were surprised that traffic jams continued to develop—even if all of the cars started at the same speed. Only when they specified that the cars move at a uniform speed and start from equally spaced positions, did each car accelerate to the speed limit and continue moving at that speed, thus ensuring the smooth flow of traffic.

Thus the randomness of the initial spacing of cars led to the emergent behavior—traffic jams. This result was directly counter to the students' ideas, which Resnick characterized as a *centralized mindset*. Their initial reaction was to assume that a "leader" (e.g., a bird at the head of a flock) or a specific restriction (e.g., a speed trap) was the reason for the emergent behavior.

As Resnick's concept of a centralized mindset suggests, most of the students, in fact most adults, prefer explanations based on a central control, single cause, and predictability. However, as the students tested their simulations with different starting parameters and refined their rules, and as Resnick continued to challenge their assumptions, they began to appreciate decentralized thinking and the concept of emergent properties. Levy and Wilensky (2008) found that in coping with emergent properties, middle school students often negotiated the relation between individual and aggregate levels by inventing an intermediate level involving a collection of individuals. The intermediate level facilitated understanding, because students could still identify individuals while simultaneously viewing how individual interactions produced aggregate behaviors that were not identical to those of the participating individuals. Taken together, these data suggest that once a person understands emergent properties, he or she can begin to reason about decentralized control and multiple causes and, eventually, understand stochastic and equilibration processes.

Resnick's conclusion that, with proper guidance, students can recognize emergent properties is supported by evidence from two studies by Penner (2000, 2001). The goal of these studies was not simply to characterize students' (sixth graders) understanding of emergent properties, but also to investigate ways of supporting the development of their understanding. Penner showed that through simulation, sixth graders were able to consider the idea that macro-level order in a group did not require an explicit, central plan. They learned that order may emerge when individuals follow simple rules in their interactions with each other.

An important precondition for the success of the simulations was proper motivation. The students understood how the simulation was related to the real-world question they were studying in their classroom, and they clearly predicted the results of the simulation.

Besides a centralized mindset, students may also naturally try to understand emergent behavior in terms of what they already know, such as direct causes or material substances. In a series of studies, Chi and her colleagues proposed that some misconceptions about scientific phenomena are difficult to change because they are classified conceptually in an inappropriate ontological category (Chi, 2005; Chi and Roscoe, 2002; Reiner et al., 2000; Slotta and Chi, 2006; Slotta et al., 1995). For example, as children become aware that plants are alive, they tend to overgeneralize the characteristics they associate with living things. Most children believe that plants "eat" or absorb nutrients through their roots, rather than synthesizing sugars in their leaves (Roth, 1984).

In short, these studies suggest that students must first be helped to form a category of emergent properties and then encouraged to restructure their existing understanding to align with their new understanding of emergent properties.

After reviewing the literature on cognitive reasoning, Silk and Schunn concluded that simulations in the classroom context can clarify connections between different levels of a system and help students transition from a strong tendency to attribute behaviors to central plans and/or single causes to a perspective more consistent with the concept of emergent properties. Investigations of how simulations influence the teaching of emergent properties include studies of the effects of life-sized, participatory simulations (e.g., Colella, 2000; Penner, 2001; Resnick and Wilensky, 1998) as well as software environments that help students manipulate complex systems (Resnick, 1996; Wilensky and Reisman, 2006; Wilensky and Resnick, 1999).

Although research indicates that both types of simulations were helpful, software environments tended to be more effective because students could more easily explore, manipulate, and finally understand concepts that spanned levels of a system (Resnick, 1996). Evidence also indicates that making connections between levels of a system explicitly facilitates students' understanding of emergent properties and that dynamic simulations make connections between the levels of a system apparent and thus easier to identify and understand (Frederiksen et al., 1999).

Optimization

The concept of optimization in engineering relates to the stage of the design process in which the functionality or effectiveness of the design is maximized (ITEA, 2000). Real-world designs must always meet multiple, conflicting requirements and are always subject to constraints. Thus optimization necessarily involves trade-offs among different aspects of a design to improve one quality at the expense of another (e.g., range of motion versus mechanical advantage or additional strength versus added material cost). The requirements and constraints may include (1) available resources, (2) cultural and social norms that influence how the qualities of a design are valued, and (3) physical laws that determine how things work. Thus, optimization is a core concept that brings together many related engineering concepts, including trade-offs, requirements, resources, physical laws, social constraints, cultural norms, and side effects.

None of the literature on cognitive development or the learning of science directly addresses the difficulties for K–12 students in understanding the concept of optimization in the context of engineering. Therefore, this discussion is focused on concepts that are relevant to the idea of optimization, although they may be discussed in slightly different terms. For instance, optimization can be thought of as the manipulation of the internal variables of a system or product to maximize the external performance measures of that system or product.

Understanding conceptually how to simultaneously consider the effect of multiple variables on an outcome is essential to optimization. In addition, when variables interact, trade-offs must be considered. Thus making trade-offs is an essential concept in student's understanding of optimization in engineering.

Multiple Variables

The goal of engineering is to design products or processes that result in predictable outcomes within a given set of resource and other constraints. Almost all real-world products or processes are designed based on trade-offs among a large number and wide range of input variables that have been "manipulated" to reach an optimal solution. That manipulation must be based on knowing which variables have a causal effect on the outcome.

People with an interest in introducing engineering concepts to young children may be concerned that children are simply not cognitively ready to work on complex engineering problems that require taking into account many variables and requirements. Overall, cognitive processes gradually improve throughout childhood. These include processing speed, working memory, and executive functioning (Kail, 2004). These general, age-dependent aspects of cognitive functioning can have a significant influence on task performance. However, domain-specific aspects (e.g., task strategies and prior knowledge) are as important, if not more so, in children's learning. Furthermore, considerable evidence supports cognitive load theory (CLT), which argues that the seemingly infinite intellectual capacity of humans is primarily attributable to modifications in long-term memory; short-term memory, at all ages, is tightly constrained to consideration of a maximum of five to seven elements at a time (Sweller and Chandler, 1994). Even well-practiced adults can only process three or four variables simultaneously without compensating for their constraints by some sort of "chunking" or bundling strategy or linear processing (Halford et al., 2005). So, although students' capabilities almost certainly do improve over the course of their years in K–12, many aspects of real-world engineering design are beyond the cognitive processing limitations even of adults.

Based on their review of the literature, Silk and Schunn came to the same conclusion—that the large number of variables involved in most engineering contexts can easily overwhelm the limited cognitive resources of most individuals, adults or students (Halford et al., 2005; Kuhn, 2007; Kuhn et al., 2000; Schauble et al., 1991). They also found that meta-level knowledge about the nature of causality and the goal of testing can organize their thinking about design. In addition, simplifying tasks by focusing on subproblems and using external representations (physical and mathematical) are effective strategies that can be taught to students in the K–12 setting. In fact, they found that a number of strategies can help young students overcome memory constraints and lead to mature learning, as well as authentic engineering practice. Research shows that these strategies can be learned in classroom settings.

For example, one strategy is to help students build schemas for analyzing multivariable systems, such as the strategy of assuming additive and consistent effects while controlling independent variables**.** Although these concepts can be explained at the meta-level, evidence suggests that they can be taught to young children by explicit instruction or experimentation (Keselman, 2003).

"Chunking" is another strategy for overcoming memory constraints. Similar to context-specific schemas, chunking involves creating a mental representation of a situation as a discrete element in memory with many aspects hidden underneath it (Chase and Simon, 1973; Miller, 1956). Another strategy—functional decomposition—is a design-specific strategy that can also be used to simplify a system and focus on one part of it. For example, the Wright Brothers used functional decomposition to isolate the effects of different aspects of the plane for testing before they built the entire system (Bradshaw, 1992). A third strategy is to produce physical representations of ideas to help students understand complicated situations. For example, a representation might be in the form of a prototype of the design that makes most aspects of it concrete and visible (Bradshaw, 1992).

Other strategies include "mathematizing," taking notes, and sketching. In mathematizing, conceptual ideas are represented as mathematical relationships. In contrast to prototyping, mathematizing purposely makes only some variables concrete and hides others. Studies by Lehrer and colleagues (2000) have shown a relationship between conceptual change and mathematizing. Note taking (Garcia-Mila and Andersen, 2007) and sketching (Anning, 1997; MacDonald and Gustafson, 2004; MacDonald et al., 2007) can also facilitate learning when working with multivariable systems. Sketching is more abstract than prototyping, more concrete than mathematical or graphic representations, and allows for hiding or deemphasizing irrelevant variables.

In short, Silk and Schunn found that strategies for simplifying tasks by focusing on sub-problems and using external representations (physical and mathematical) are effective learning strategies in the K–12 setting that enable students to construct and evaluate complicated designs in systematic ways.

Trade-offs

Trade-offs are one aspect of all real-world engineering design (Otto and Antonsson, 1991). They are always necessary in optimizing a system, both when considering input variables, which can be manipulated in the design process, and outcome variables, which indicate the quality of the design. A trade-off of an input variable occurs when a modification of the level of that variable impacts the effect of another variable on the outcome of the design. Thus trade-offs are not simply combinations of variables that influence an outcome in an additive way. There can also be cases when variables have opposing impact on an outcome. For example, the goals of controlling costs and producing the most effective product possible are often at odds.

Based on their review of the literature, Silk and Schunn (2008) concluded that, because K–12 students are unlikely to have a normative understanding of interactions among variables in a general sense, they may not easily come to a conceptual understanding of trade-offs. Nevertheless, some research studies (Acredelo et al., 1984; Zohar, 1995) have shown that youngsters may have some kinds of understanding that can be a basis for a more complete grasp of the trade-off concept.

For example, even in well understood physical settings, younger students understand direct relationships before they understand indirect relationships. Thus when considering the relationships between distance, time, and speed, fifth graders are likely to understand that speed is directly related to distance and that time is directly related to distance, but they are not likely to understand that speed and time are indirectly related to each other (Acredelo et al., 1984). Although it is not clear how students transition toward understanding indirect relationships, which are more cognitively demanding, an understanding of direct relationships in a system may be a necessary precondition.

Despite the difficulties of understanding trade-offs, Silk and Schunn concluded that certain classroom strategies can help students to consider trade-offs. One strategy is (1) to use mathematical representations to make connections between variables explicit and then (2) to engage in successive iterations in which variables are considered in isolation and in then in combinations (Schwartz et al., 2005). Mathematical formulas may be one way of conceptually representing trade-offs and thus helping students to consider variables that are indirectly related.

Schwartz and colleagues (2005) have demonstrated the effectiveness of simply encouraging students to represent situations mathematically. In a series of three studies, the first two with fifth graders and the third with fourth graders, they presented students with a balance-scale task (Siegler, 1976) in which they were asked to consider forces over a distance by predicting the outcome of balances that varied in two dimensions—the number of weights on each side and their distance from the fulcrum.

In the first study, they represented the weights as discrete pegs and as beakers of water filled up to different levels. The students in the beaker scenario were more likely to reason only about weight and not to consider the effect of distance. The researchers concluded that these students were less likely to quantify the beakers into discrete values, which made it more difficult to consider both dimensions simultaneously.

In the second study they tested this hypothesis. Students were given only peg problems and then asked to justify their predictions. Some students, however, were asked with a general prompt ("explain you answer"); others were asked to use math ("show your math"). Only 19 percent of the first group ("explain") considered both dimensions in at least one problem; in the second group ("math"), 68 percent considered both dimensions in at least one problem. Students in the first group switched between distance and weight as a justification, especially after receiving feedback on a problem they had predicted incorrectly, but they did not often represent the dimensions simultaneously.

Students in the second group also did better on more complex problems with weights at multiple locations on each side of the scale. Among all students who did consider both dimensions, the students in the second group were also more likely to consider both dimensions on these more challenging transfer problems.

The third study was similar to the second, but no sample justifications or examples of how to count were provided. The students, fourth graders, were less likely to use the multiplicative rule when predicting outcomes. However, the students in the math group did better on more complex problems with weights at multiple locations on each side of the scale; that is, they were more likely to use both dimensions in predicting outcomes.

Schwartz et al. considered these results in the context of extensive developmental research on the balance-scale task (Siegler, 1981), which showed that the reasoning of fifth graders was similar to that of kindergartners when they were presented with a problem that included hard-to-measure, continuous quantities in the form of a beaker. However, these same students performed as well as their peers when the problem included discrete, easy-to-quantify pegs. When they were given explicit instructions, feedback on their predictions, and encouragement to justify their answers mathematically, their reasoning was on a level similar to that of adults. Thus these studies provide compelling evidence that students, when encouraged to use mathematics, can represent physical situations and reason about them, even if they involve variables that are related indirectly.

The results of the studies described above have been supported by subsequent research with younger children. For example, in a study by Lehrer et al. (2000), second graders who were asked to reason about speed and distance were influenced by attempts to create mathematical models of the slope of the ramps they were using to study the movement of cars. In this case, the mathematical models were provided to one group of students, while another group had to invent the mathematical models themselves. The exercise only had positive effects for the second group.

Working on complex mathematical problems requires that students consider multiple paths and options in attempting to design optimal solutions. In another study, high-achieving sixth graders and college undergraduates were asked to develop individual business plans for a dunking booth at a school fair (Vye et al., 1997) using mathematical problem solving. To find possible solutions, college undergraduates were much more likely to consider more than one plan and select among them. But neither group was likely to test their solution against all of the initial constraints.

In a follow-up study, pairs of fifth graders were just as likely as the undergraduates to consider multiple solutions and to consider one or both of the constraints on their expenses. Success in this study was predicated not on the number of goals generated by each pair of students, but by appropriate reasoning and sound execution of the goals. Students who engaged in explanatory reasoning and counterarguments searched more of the "solution space" by monitoring each other, thus increasing their successful problem solving. This study provides some evidence that young students are capable of considering very complex mathematical problems that involve searching for optimal solutions. And, in this case at least, students seemed to benefit from having a partner who challenged them to justify their ideas and to monitor their subsequent actions.

ENGINEERING SKILLS

To understand the engineering process, K–12 students must learn not only engineering concepts, but also necessary skills. In their integrative review of research results on the development of core engineering skills in K–12, the commissioned authors focused on skills related to design and redesign, which are the prototypical engineering processes (Petrosino et al., 2008). The necessary skills include defining the problem, specifying requirements, decomposing systems, generating solutions, drawing and creating representations, and experimenting and testing. Because empirical evidence about how students develop most of these skills is limited, the commissioned authors could only glean evidence on the latter two topics, the development of drawing and representational skills and experimentation and testing skills.

Drawing and Representing

In professional design practice, drawing and representing have several purposes. Doodling commonly facilitates nascent ideas. "Exploded views" not only reveal the assembly of complex devices and their components, but also suggest the functionality of the system and components. Side and top schematics and computer-aided design (CAD) renderings show the aesthetics and scale of a device. Finally, drawings can communicate ideas and constraints (Anning, 1997; King and Fries, 2003; Stacey and Lauche, 2004).

Other forms of representation, such as modeling and "making" are also used in design. Various aspects of making representations are considered part of the design process, as it moves from concept to embodied design. Designers also use gestures and objects in their representations (e.g, they use their bodies to understand and convey their designs, especially inchoate designs). In the discussion that follows, the word "making" is used in relation to incipient design ideas.

From their review of the literature, Petrosino and colleagues (2008) concluded that, for children, drawing tends to be a way of recording significant personal events (Anning, 1997). Unless there is deliberate intervention, children's drawings are unlikely be used for design.

For example, drawing as part of a design activity has been described in an ethnographic study of design implementation for early elementary students in Australia in which students designed, made, and appraised vehicles (Rogers, 2000). After lectures on wheels, young students were shown examples of vehicles and instructed to make, out of simple objects, a vehicle with at least one wheel and then to draw it. The students were then divided into pairs, and each pair was asked to draw a picture of a vehicle to make and then to make it; they received no guidance on either of these steps. The student pairs did not directly compare their vehicles, although the teacher provided some comments.

This example highlights a number of missed opportunities and pitfalls. First, the teacher did not explain the differences between a design drawing and other types of drawings, and the students obviously did not understand the difference. This was apparent from the drawings themselves, which included details such as people and roads that were not related to the task at hand, and in the absence of details regarding the materials the vehicle would be made from. Also, conversations among students while drawing their vehicles did not focus on details such as what the car should be built from.

Second, because of the lack of connection between the design (drawing) phase and the making-and-appraising phase, students understood design as a linear, rather than iterative process, in which drawing served little or no purpose. In fact, the drawings had little correlation to the vehicles the students made (Rogers, 2000).

Third, although not noted by Rogers, Petrosino et al. suggested that the teacher could have drawn students' attention to the connection between design and the constructed vehicles by showing examples of vehicles before asking them to make drawings. Similar results in studies of elementary students also showed a lack of innate connection between a drawing and design (Anning, 1994; Samuel, 1991; Williams, 2000). In addition, young students have difficulty creating design drawings, which involve "graphical conventions of representing scale, spatial orientation and overlap" that are unfamiliar to them (Anning, 1994).

Other kinds of representation, such as models, without intervention, may preserve only structural and superficial features. Penner et al. (1997) conducted a study in which lower level elementary school students were asked to design functional models of elbows. Prior to the modeling activity, when students discussed the purpose of a model, the recurring criteria was physical resemblance. However, after a discussion of how models differ from real things, the students began to understand the functional differences between a simple, representational drawing and a model. The children, who worked in pairs, had access to a variety of everyday materials to make their models.

At first, the children tended to see models as small, superficial copies of the thing itself. Initially, the models were copies of the form of an elbow, but they did not perform the functions of an elbow. Although some of the models could flex, the flexure was unrestrained in direction. Discussion with the children revealed that they did not isolate the motion of the elbow and that they inferred a greater range of motion based on the pivot of the shoulder. After experimenting with real elbow movements, the students made new models. This time, the models incorporated constraints but also included more nonfunctional, but physically similar, details, such as representations of veins.

Johnsey (1995) conducted a study of pre-K through fifth-grade students in the United Kingdom to investigate the role of making in design. Eight case studies of students who tried to create designs with little or no teacher intervention revealed how children think about representations. Johnsey found that making representations played a role early in the design process; that it supported other design process skills, such as clarifying, specifying, and researching; and that it occurred in tandem with planning, generating, and modeling. The activity could generally be considered a make-evaluate-make cycle.

Making also encourages the development of a common design language among children. When students begin building well before they finalize their design (a divergence from professional design), they gain experience in moving between the actual and the possible. They develop norms and vocabulary appropriate to their designs as they need them, rather than imposing them from the beginning of the activity (Roth, 2001). Representations are particularly effective in collaborative situations (Arias et al., 2000). One of the benefits of design activities is that thinking and acting become inextricably connected. In fact, with continued iterations, designs become "tools to think with" (Roth, 1996).

The reviews of the literature by the commissioned authors show that, although schoolchildren do not naturally use drawings and representations effectively in the design process, some classroom practices can have a positive impact on the way they use them. Allowing young children to play with the construction materials they will use can lead to better design drawings, particularly when children also participate in a discussion of how their drawings will be used. Comparing drawings done before and after design can help determine the usefulness of the initial drawing (Claire, 1991; Pace and Larson, 1992).

Drawing and representing are useful methods of eliciting nascent ideas, but design representations tend to be highly specific and do not easily lead to abstraction or transference to other situations (Gick and Holyoak, 1980). Nevertheless, repeated experiences related to a single complex concept can encourage abstraction, and students' representations do evolve and improve over the course of the dynamic design process (Spiro et al., 1991). Iterations of a full design cycle can improve learning and challenge students to "translate experiential knowledge into abstract rational form" (Hill and Smith, 1998).

For young children, a preliminary to drawing may be investigation and exploration of materials. In one study, lower elementary students were allowed to play with a limited selection of materials and explore their possibilities before being asked to draw and then make a figure from those materials (Samuel, 1991). To support their drawings, they were supplied with notes about the materials and instructions, such as drawing top and side views rather than perspective views.

Another study (Fleer, 1999) in which children who were asked to draw designs of forts they had constructed led to an interesting observation about plan-view versus side-view drawings. The point of view tended to correlate with the drawing position of the child. If the fort was on the desk, the drawing tended to be a side view; it the model was on the floor, the drawing tended to be a plan view.

For young students who may not know what engineering is, contextualizing their design activity by using simple, familiar objects can be productive.

Solomon and Hall (1996) explain that drawing ability may be accelerated when students learn the various roles a drawing may play. Craft skills improve with familiarization via direct experience with the tools and materials to be used. Improvement in craft skills leads to improvement in spatial ability, including visual and haptic shape recognition, as well as manipulation and translation between two and three dimensions (Solomon and Hall, 1996).

In their review, Lehrer and Schauble (2006) pointed out various methods of instruction that evidence shows support modeling. First, informed decisions about the sequencing and timing of introducing new and more difficult forms of modeling are critical to support student learning. Second, involving students in group activities is essential to helping students understand and appropriate the inquiry processes, emphasize the development and use of different forms of representation, and capitalize on the cyclical nature of modeling. Third, modeling approaches only develop when inquiry is a priority in the classroom. Fourth, nuanced forms of modeling require a long-term effort and are more likely to develop in students who build on successively complex experiences with modeling. Finally, although this is not usually done in traditional classrooms, critiquing and discussing their own models and those of other students can support students' understanding of engineering design.

Experimenting and Testing

In professional practice, engineering designers use experimentation and testing to determine the level of optimization of a design and whether all of the requirements have been met. This step may be done with full or partial prototypes or with virtual models using finite elements analysis. Unlike scientific experimentation, the purpose of which is to identify causal relationships through a process that does not involve optimization and trade-offs, engineering experimentation and testing are iterative processes with multiple steps, including modeling and analysis (Schauble et al., 1991). The differences can be attributed to the similar but different purposes of engineering and science.

As described in Chapter 2, scientists ask questions about the world around us, whereas engineers modify the world to adapt it to our needs. Scientific inquiry is concerned with what is, while engineering design is focused on what can be. Models may be used by both, but the nature and purpose of models in science and engineering are different due to differences between scientific inquiry and engineering design. Understanding these differences is critical to understanding potential learning outcomes when engineering is used to teach science, especially because children's engagement in engineering experimentation is done, necessarily, without modeling, analysis, or mathematical optimization, which engineers use with experimentation.

In their review of the literature, the commissioned authors explained that inquiry commonly involves experimentation with multiple variables (Petrosino et al., 2008). However, when middle school students are presented with an activity in which they manipulate variables that contribute to flooding, for example, they tend to focus on outcomes and do not immediately experiment in an analytical way (Kuhn et al., 2000). Rather than isolating variables, they tend to change many at once and attribute the good or bad outcome to *all* variables, even those that had been determined to be good in prior experiments. Although many students progress toward altering one variable at a time, many others consistently alter multiple variables. Kuhn et al. suggest that students with "additive mental models of causality" are able to transition to a multivariate model, while those with "co-occurrence models of causality" are resistant this transition.

To address this issue, students in Kuhn's experimental group were presented with a scenario in which they argued about the effect of one variable. All of the students had participated in the flood activity described above, but more students in the experimenting group made valid inferences. An analysis of a meta-level test demonstrated that the experimenting students developed both implicit and explicit understanding, whereas the larger, control group developed only an implicit understanding and could not justify their responses (Kuhn et al., 2000). This study highlights the importance of attending to a student's experimental strategies.

Experimentation has been posited as a critical prerequisite to learning in design, including posing and solving problems (Childress and Rhodes, 2008; ITEA, 2000). In a study on the effects of experimentation on problem solving, fifth and sixth graders completed two experimentation tasks (Schauble et al., 1991). The first task was to design a canal with optimal water depth for boats traveling at a given speed. This task can be accomplished with no understanding of the causes of buoyancy and still be a complicated problem to solve. Thus although solving this problem requires some characteristic engineering processes, it is more akin to gadgeteering than engineering. The second task was to explore why boats float. This buoyancy task required that students engage in scientific experimentation, including manipulating variables (volume, mass, and position) as they measured the buoyancy using a spring. Although these tasks had some common principles, they required different problem-solving strategies.

Prior to the activities, the students were read a framing statement either about what scientists do or what engineers do to provide a context for their problem solving. After completing the activities, the students were asked to reconstruct what they had learned. Their answers revealed that they approached the two tasks differently, depending on how the task had been framed. When the tasks had been framed as exploring why boats float, students undertook a broader exploration of variables and a more thorough investigation of each variable, even of variables that seemed to be irrelevant to the goal.

The group that completed the water-depth task first showed greater improvement in making valid inferences than the group that completed the buoyancy task first. Despite the framing procedure, the water-depth task led to more inferences based on less evidence, and these inferences were more commonly related to causal variables. The buoyancy task tended to lead to inferences related to both causal and exclusive variables, which are critical to the formation of disconfirming evidence.

This example reveals some of the challenges in using design to teach science. However, the design in the study just described is unlike professional design, in that the design goals are created by the designers themselves, as opposed to being developed by a client or external source (Petrosino et al., 2008). Working within the constrains of the goals provided by a client or external source can have a significant impact on the design process.

Testing is necessary to determine if design requirements have been met. In elementary school classrooms, testing or evaluations are usually done by the teacher, but in professional settings, testing is done by the designer. Teacher evaluations of students' designs can be taken as personal criticism, even when couched as a question, such as "How can this design be improved?" It is recommended, therefore, that teachers evaluate student designs via comparisons to the design drawing, which facilitates metacognition, or via comparison to the original design goals, which is a common practice in professional design and can lead to further optimization. Evaluation also helps to promote the utility of the design drawings (Solomon and Hall, 1996).

Solomon and Hall (1996) suggest that design activities in K–12 classrooms should include a careful description of the customer who commissioned the design. In most studies, the teacher is the customer, which, because of the teacher's power position, can render the evaluation stage challenging and less than fruitful. Children may perform better when designing for themselves, their families, their community, or a historical or fictional character. The last two may also provide opportunities to contextualize design problems in interdisciplinary ways by tapping into other subjects taught in the classroom. Over-specification, which can cause students to feel less involved in the activity, can also interfere with K–12 design experimentation. Students perform best when the focus is not on any one student's work and when they have an opportunity to negotiate ideas in a group (Solomon and Hall, 1996).

Kolodner's learning-by-design (1997), which builds on case-based reasoning (Schank, 1999; Williams, 1992) and problem-based learning (Barrows, 1986), involves iterations of increasing complexity. In a study of Kolodner's program, Vattam and Kolodner (2006) addressed two challenges in teaching science via design. The first challenge, facilitating students' scientific understanding during design, was addressed by incorporating an explanation tool. In this scaffolding technique, students were prompted to explain the science behind their designs. A focus on the relationships between structures, behaviors, and functions, discussed above, also helped students connect science to design.

The second challenge, coping with time, material, and environmental constraints in the classroom, can be addressed through simulation-based design. The virtual design world enables students to isolate and test their designs before building a prototype in the real world. The ability to test and model at a smaller focal length encourages experimentation that leads to an understanding of the science behind the design (Vattam and Kolodner, 2006).

LESSONS LEARNED

Cognitive development research distinguishes between general developmental constraints (i.e., limitations related to the development of the mind) and knowledge constraints (i.e., limitations based on an individual's experiences and how he/she processes them). Researchers and others disagree about the extent to which these constraints exist, and, if they exist at all, which limitations have a greater impact in different domains of learning (Kuhn, 1997; Metz, 1995, 1997). Regardless of the reasons for cognitive development (architecture or experience), the demonstrated success of a number of the interventions reviewed here, even with students in early elementary grades, clearly shows that certain experiences can support relatively sophisticated understanding of engineering concepts and development of engineering skills.

As this chapter makes clear, there are significant gaps in our understanding of how K–12 students learn and might best be taught engineering concepts and skills. At the same time, the research that has been conducted provides some important clues about effective approaches to curriculum development and classroom practice. Based on the reviews of the literature in this chapter, we suggest the following guidelines for the incorporation of core engineering concepts (systems and optimization) and skills (representation and experimentation) in K–12 education:

1. allocating sufficient classroom time for students to develop core concepts through immersion in extended design activities;
2. encouraging iterative, purposeful revisions of student designs; and
3. sequencing instruction to build from the easiest-to-learn aspects of core concepts to the more difficult-to-learn aspects.

Sufficient Classroom Time for Extended Design Activities

In every successful intervention we reviewed, significant learning resulted only after an extended time for design activities in a meaningful context. Core engineering ideas and skills cannot be developed in a single class period. These ideas and skills must be developed and elaborated through extended investigations that give students time to engage in the full engineering process of design and redesign. Studies show that design activities are an appropriate context for introducing these core ideas and skills because they retain students' interest and invite increasingly sophisticated ways of understanding.

Iterative, Purposeful Revisions of Designs, Ideas, and Models

The second important idea is that iterative, purposeful modeling appears to be central to helping students to a more sophisticated understanding of the salient idea or skill. Modeling can take the form of a physical design or a conceptual, graphical, mathematical, or diagrammatic design. The models help students answer particular questions based on their analysis of previous designs, and as iterations continue, the questions become increasingly specific and operationally defined, and thus increasingly purposeful. As models are developed, revised, and refined over time, students begin to understand ideas in deeper ways. Ethnographic studies of engineers engaged in design work reveals that modeling is the most prevalent and challenging form of activity (Gainsburg, 2006; Neressian et al., 2003; Nersessian and Patton, in press).

Unfortunately, design in K–12 settings usually allows for only a single iteration of a design, which barely begins to reveal conceptual difficulties and design challenges that require further investigation. For modeling to be used productively in the classroom, mathematics education must allow for the development of spatial visualization and related design skills, and algebraic reasoning.

The teacher's role is crucial in shaping students' questions and directing their revisions. Although it may be tempting to allow students to direct their modeling themselves, the successful interventions reviewed here highlight the importance of the teacher providing explicit guidance and developing activities for investigating and negotiating contested claims. These strategies support students' progress toward increasingly sophisticated understanding and representations. In addition, the iteration of cycles based on the teacher's questioning of students' ideas and suggesting of resources for students to consider is essential to focusing attention on the core idea.

Sequencing Instruction from Easier to More Difficult Ideas

The third important idea is that knowledge builds on itself. Thus a simple understanding of an idea is likely to precede a more complex understanding in predictable ways. This applies to learning both engineering concepts and engineering skills. Although this may seem obvious, the purpose of drawing attention to this principle is to encourage the reader to focus on specifying cognitive developmental trajectories for particular concepts.

Common trajectories in the development of expertise can be identified in any domain of knowledge. Once these are specified, a logical sequence of experiences can be developed to build that knowledge over time. For instance, the commissioned authors found that structure was often easier for students to understand than behaviors or functions. Therefore, beginning an activity at the structural level may provide a basis for moving toward an understanding of the more difficult concepts of behavior and function.

Of course, the learning progressions, types of ideas, and depth of exploration of those ideas must be adapted for different grade levels (Duschl et al., 2007). Unfortunately, the literature on teaching core engineering concepts is not sufficient for us to make specific recommendations at this time. In general, however, our findings indicate that with a well thought out instructional sequence and sufficient time and support students can make the transition from a novice level of conceptual understanding and ability to a more sophisticated level. This is true even for students in the elementary grades.

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6

Findings and Recommendations

In comparison to K–12 education in science, mathematics, and technology, K–12 engineering education is still in its infancy in the United States. Nevertheless, we have enough examples of practice to begin to take the measure of this developing academic area. Although more and better impact studies will be necessary in the future, the available evidence shows that engaging elementary and secondary students in learning engineering ideas and practices is not only possible, but can lead to positive learning outcomes.

It is equally clear, however, that the potential effectiveness of K–12 engineering education has been limited by a number of factors, such as challenges associated with curriculum and professional development, difficulties in reconciling this new content with existing curricula in other subjects, the influences of standards-based education reform and accountability,[1] and the absence of teacher certification requirements and pre-service teacher preparation programs. Despite these challenges, it is the committee's judgment, supported by data gathered during the two years of this project, that much can be gained by working to improve the quality and increase the availability of K–12 engineering education.

[1]An ongoing study at the National Academy of Engineering is examining the potential value and feasibility of developing content standards for K–12 engineering education. Information about the project can be viewed at *http://www8.nationalacademies.org/cp/projectview.aspx?key=48942.*

Although improving teaching and learning in this nascent area is important, the committee is even more interested in seeing engineering education become a catalyst for improved learning in the other STEM subjects. Despite all of the concerns by policy makers, educators, and people in industry about the quality of U.S. K–12 STEM education, the role of technology education and engineering education have hardly been mentioned. In fact, the STEM acronym has become shorthand for science and mathematics education only, and even these subjects typically are treated as separate entities.

Finding 1. As STEM education is currently structured and implemented, it does not reflect the natural interconnectedness of the four STEM components in the real world of research and technology development.[2]

The committee believes that the disconnects between STEM subjects has not only impeded efforts to stimulate student interest and improve performance in science and mathematics, but has also inhibited the development of technological and scientific literacy, which are essential to informed citizens in the twenty-first century.

Finding 2. There is considerable potential value, related to student motivation and achievement, in increasing the presence of technology and, especially, engineering in STEM education in the United States in ways that address the current lack of integration in STEM teaching and learning.

In the rest of this chapter, we present the committee's recommendations and remaining findings. Because of the numerous unanswered questions about K–12 engineering education, the findings outnumber the recommendations, which are largely focused on research. We turn our attention first to "defining" engineering in the context of K–12 education. Next we address the scope, nature, and impacts of current efforts to teach engineering to pre-college students in the United States. The following section deals with policy and program issues associated with K–12 engineering education. The chapter concludes with a discussion of fully integrated STEM education.

[2]See, for example, Almeida et al., 2008; Gogate and Kabadi, 2009; and Hood et al., 2008.

GENERAL PRINCIPLES FOR K–12 ENGINEERING EDUCATION

One goal of this project was to clarify the place and "look" of engineering in K–12 classrooms in the United States. Chapter 4 goes a long way toward meeting that goal, but, based on our review of curricular materials, some of what now passes for engineering education is not aligned with generally accepted ideas of the discipline of engineering. We do not mean to suggest that K–12 students should be treated like little engineers or that engineering education in K–12 classrooms should resemble in scope or rigor the post-secondary engineering curriculum. However, we do mean to suggest that in any K–12 school subject for which there is a professional counterpart there must be a conceptual connection to post-secondary studies and to the practice of that profession in the real world.

The absence of standards or an agreed-upon framework for organizing and sequencing the essential knowledge and skills to be developed through engineering education at the elementary and secondary school levels limits our ability to develop a comprehensive definition of K–12 engineering education. Nevertheless, over the course of the committee's deliberations, general principles emerged based on our knowledge of engineering and technology, our review of K–12 engineering curricula, and key documents, such as the *Standards for Technological Literacy: Content for the Study of Technology* (ITEA, 2000).

Principle 1. K–12 engineering education should emphasize engineering design.

The design process, the engineering approach to identifying and solving problems, is (1) highly iterative; (2) open to the idea that a problem may have many possible solutions; (3) a meaningful context for learning scientific, mathematical; and technological concepts; and (4) a stimulus to systems thinking, modeling, and analysis. In all of these ways, engineering design is a potentially useful pedagogical strategy.

Principle 2. K–12 engineering education should incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills.

Certain science concepts as well as the use of scientific inquiry methods can support engineering design activities. Similarly, certain mathematical concepts and computational methods can support engineering design, especially in service of analysis and modeling. Technology and technology concepts can illustrate the outcomes of engineering design, provide opportunities for "reverse engineering" activities, and encourage the consideration of social, environmental, and other impacts of engineering design decisions. Testing and measurement technologies, such as thermometers and oscilloscopes; software for data acquisition and management; computational and visualization tools, such as graphing calculators and CAD/CAM (i.e., computer design) programs; and the Internet should be used, as appropriate, to support engineering design, particularly at the high school level.

Principle 3. K–12 engineering education should promote engineering habits of mind.

Engineering "habits of mind"[3] align with what many believe are essential skills for citizens in the twenty-first century.[4] These include (1) systems thinking, (2) creativity, (3) optimism, (4) collaboration, (5) communication, and (6) attention to ethical considerations. Systems thinking equips students to recognize essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behavior of individual subsystems. Creativity is inherent in the engineering design process. Optimism reflects a world view in which possibilities and opportunities can be found in every challenge and an understanding that every technology can be improved. Engineering is a "team sport"; collaboration leverages the perspectives, knowledge, and capabilities of team members to address a design challenge. Communication is essential to effective collaboration, to understanding the particular wants and needs of a "customer," and to explaining and justifying the final design solution. Ethical considerations draw attention to the impacts of engineering on people and the environment; ethical considerations include possible unintended consequences of a technology, the potential disproportionate advantages or disadvantages of a technology for certain groups or individuals, and other issues.

These principles, particularly Principle 3, should be considered aspirational rather than a reflection of what is present in current K–12 engineering education efforts or, indeed, in post-secondary engineering education.

THE SCOPE OF K–12 ENGINEERING EDUCATION

Because of the lack of reliable data, it is impossible to gauge how many U.S. K–12 students have been exposed to engineering-related coursework.

[3]The committee has adopted the term "habits of mind," as used by the American Association for the Advancement of Science in *Science for All Americans* (1990), to refer to the values, attitudes, and thinking skills associated with engineering.

[4]See, for example, The Partnership for 21st Century Skills, *www.21stcenturyskills.org.*

However, because a number of curriculum projects track the use of their materials, we can derive an indirect measure. With a few notable exceptions (e.g., ECCP, 1971), the first formal K–12 engineering programs in the United States emerged in the early 1990s. Since that time, the committee estimates that no more than 6 million K–12 students have had any kind of formal engineering education. By contrast, the estimated enrollment in 2008 for grades pre-K–12 for U.S. public and private schools was nearly 56 million (DOEd, 2008).

Another measure of the scale of K–12 engineering education is the number of teachers involved. Once again, no reliable data are available on this measure. However, most curricular projects include teacher professional development programs or activities and collect information about the individuals who participate in the training. Based on these and related data, the committee estimates that some 18,000 teachers have received pre- or in-service training to teach engineering-related coursework. This estimate does not take into account the nature, duration, or quality of the training, factors that markedly influence whether a participating teacher continues to teach engineering. By comparison, U.S. public and private middle and high schools employ roughly 276,000 mathematics teachers, 247,000 science teachers,[5] and 25,000 to 35,000 technology education teachers[6] (Dugger, 2007; NCES, 2007).

Finding 3. K–12 engineering education in the United States is supported by a relatively small number of curricular and teacher professional development initiatives.

K–12 curricular initiatives have been developed independently, often have different goals, and have been created by individuals with very different backgrounds and perspectives. In addition, the treatment of engineering concepts, engineering design, and relationships among engineering and other STEM subjects varies greatly. For these reasons, it is difficult to compare directly their strengths and weaknesses.

Finding 4. Even though engineering education is a small slice of the K–12 educational pie, activity in this arena has increased significantly, from almost no curricula or programs 15 years ago to several dozen today.

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[5]The figures for science and mathematics teachers do not include the over 1 million public and private school elementary school generalists, who are frequently responsible for teaching both subjects.

[6]Variations in research methodologies over the years have resulted in some uncertainty about the exact number of technology education teachers working in the United States.

At this point, it is impossible to predict whether this upward trend will continue, flatten out, or reverse itself. The committee believes that the future of K–12 engineering education will depend at least in part on whether engineering becomes a catalyst for integrated STEM education. (This idea is discussed more fully at the end of this chapter.)

Through the course of the project, the committee has come to appreciate the important role that technology education has played in the development of K–12 engineering education. Indeed, evidence suggests that technology educators form the bulk of the teaching force for engineering in K–12 classrooms, and many curricula intended to convey engineering concepts and skills have been developed in part or whole by those in the field. Given its historical hands-on, project-based emphasis and the more recent focus on technological literacy, it is not surprising technology education has gravitated toward engineering.

IMPACTS OF K–12 ENGINEERING EDUCATION

Finding 5. While having considerable inherent value, the most intriguing possible benefit of K–12 engineering education relates to improved student learning and achievement in mathematics and science and enhanced interest in these subjects because of their relevance to real-world problem solving. However, the limited amount of reliable data does not provide a basis for unqualified claims of impact.

Even fewer quality data are available on the impacts of K–12 engineering education on student engagement, technological literacy, understanding of engineering, and interest in engineering as a possible career. The paucity of data reflects a modest, unsystematic effort to measure, or even define, learning and other outcomes. Before engineering education can become a mainstream component of K–12 education, this information gap must be filled. Without better data, policy makers, teachers, parents, and others with a stake in the education of children will have no basis for making sound decisions.

RECOMMENDATION 1. Foundations and federal agencies with an interest in K–12 engineering education should support long-term research to confirm and refine the findings of smaller studies on the impacts of engineering education on student learning in STEM subjects, student engagement and retention, understanding of engineering, career aspirations, and technological literacy. In addition to looking at impact, researchers should attempt to ascertain, from a learning sciences perspective, how curricular materials are being used by teachers in the classroom.

RECOMMENDATION 2. Funders of new efforts to develop and implement curricula for K–12 engineering education should include a research component that will provide a basis for analyzing how design ideas and practices develop in students over time and determining the classroom conditions necessary to support this development. After a solid analytic foundation has been established, a rigorous evaluation should be undertaken to determine what works and why.

THE NATURE OF K–12 ENGINEERING EDUCATION

Finding 6. Based on reviews of the research literature and curricular materials, the committee finds no widely accepted vision of the nature of K–12 engineering education.[7]

A lack of consensus does not reflect disagreements among the visions of K–12 engineering education. Rather, it represents ad hoc development and that no major effort has been made to define the content of K–12 engineering education in a rigorous way.

Curriculum Content

Our curriculum review revealed that the central activity of engineering—engineering design—is a dominant feature of most of the curricular and professional-development activities we examined. Both curriculum developers and providers of professional development programs seem to understand engineering design as an iterative, problem-solving process in which multiple solutions are possible. However, the treatment of key ideas in engineering, many closely related to engineering design, is much more uneven and, in some cases, shows a lack of understanding on the part of curriculum developers. Some concepts, such as systems, are generally well explained and appropriately used to support student learning, but others, such as optimization, modeling, and analysis, are incompletely developed or presented in ways that do not reflect their role in engineering practice.

[7]This finding appears to apply also to the non-U.S. pre-college engineering education initiatives considered in this project (see Chapter 4).

One reason for these shortcomings is the absence of a clear articulation of the engineering knowledge, skills, and habits of mind that are most important, how they relate to and build on each other, and how and when (i.e., at what age) they should be introduced to students. As far as the committee knows, no one has attempted to develop a rigorous, systematic specification of age-appropriate learning progressions. A handful of states, most notably Massachusetts (Massachusetts Department of Education, 2006), has developed K–12 curriculum "frameworks" that include a modest degree of engineering content. The majority of state-developed learning goals, however, do not consider engineering at all.

Finding 7. The variability and unevenness in the curricula we reviewed can be attributed largely to the lack of specificity and the lack of a consensus on learning outcomes and progressions.

One approach to addressing this problem might be to develop content standards for K–12 engineering education. After discussing this idea several times, most committee members concluded that, although a thoughtful, authoritative parsing of engineering content appropriate for K–12 would lead to more coherence in teaching and learning, another layer of academic requirements in the current standards-laden U.S. education system would surely meet with strong resistance. A study by the National Academy of Engineering is already under way on the value and feasibility of developing standards for K–12 engineering education, and the results of that study could provide valuable guidance on this important issue.

Curriculum Connections

Finding 8. Existing curricula do not fully exploit the natural connections between engineering and the other three STEM subjects.

The three most important types of interconnection—(1) scientific investigation and engineering design, (2) mathematical analysis and modeling, and (3) technological literacy and K–12 engineering education—are described below.

Scientific Investigation and Engineering Design

Scientific investigation and engineering design are closely related activities that can be mutually reinforcing. Both are methods of solving problems, both must be conducted within constraints, and both require creative thinking, communication, and collaboration. In the curricula we reviewed, we found instances in which scientific inquiry was used to explore the interface between science and technology and, less often, to generate data that could then be used to inform engineering design decisions. We also found numerous instances in which engineering design was used to provide contextualized opportunities for science learning.

A more systematic linkage between engineering design and scientific inquiry to improve learning in both domains has intriguing possibilities. One option, which was evident in several of the curricula we reviewed, is to use engineering as a pedagogical strategy for laboratory activities.

Mathematical Analysis and Modeling

Although mathematical analysis and modeling are essential to engineering design, very few of the curricula or professional development initiatives reviewed by the committee used mathematics in ways that support modeling and analysis. There may be many reasons for this. Curriculum developers may be unfamiliar with how mathematics is used in engineering design or may not understand mathematics learning progressions. Curriculum developers may have concerns about students' mathematical understanding and skills and may be afraid that poor performance would be a barrier to exposing students to engineering material.

Despite the paucity of mathematics in most curricula, the committee believes that K–12 engineering education could contribute to improvements in students' understanding and performance on certain areas of mathematics. For example, numerical manipulations required for measurements and analyses associated with engineering design may, through exposure and repetition, increase students' confidence in their mathematical abilities. In addition, specific concepts, such as ratio and proportion, fractions, and decimals, are useful for a variety of engineering design projects. Understanding these concepts is closely linked to success in algebra, which is a gatekeeper course for advancement in STEM education (NMAP, 2008).

RECOMMENDATION 3. The National Science Foundation and/or U.S. Department of Education should fund research to determine how science inquiry and mathematical reasoning can be connected to engineering design in K–12 curricula and teacher professional development. The research should be attentive to grade-level differences in classroom environment and student cognitive development and cover the following specific areas:

- the most important concepts, skills, and habits of mind in science and mathematics that can be taught effectively using an engineering design approach;
- the circumstances under which students learn important science and mathematics concepts, skills, and habits of mind through an engineering-design approach as well or better than through science or mathematics instruction;
- how engineering design can be used as a pedagogical strategy in science and mathematics instruction; and
- the implications for professional development of using engineering design as a pedagogical tool for supporting science and mathematics learning.

Technological Literacy and K–12 Engineering Education

Technology in K–12 engineering education has primarily been used to illustrate the products of engineering and provide a context for thinking about engineering design. However, using engineering to explore ideas consistent with other elements of technological literacy, such as the nature and history of technology and the cultural, social, economic, and political dimensions of technology development are less prevalent.

A number of concepts important to understanding the nature of technology, such as systems, optimization, and trade-offs, are salient to engineering design. The way technology has influenced the course of human affairs provides a natural bridge to other K–12 subjects, such as social studies and history. For students to have an appreciation of the value and limits of engineering, they should have an understanding of the nontechnical dimensions of technology, such as an awareness that all technologies can have unintended consequences and that the decisions to develop and use a technology necessarily involve ethical considerations.

The committee believes that the value of K–12 engineering curricula and of professional development for teachers of K–12 engineering would be increased by stronger connections to technological literacy, as described in such documents as the *Standards for Technological Literacy: Content for the Study of Technology* (ITEA, 2000).

Professional Development Programs

Finding 9. As reflected in the near absence of pre-service education as well as the small number of teachers who have experienced in-service professional development, teacher preparation for K–12 engineering is far less developed than for other STEM subjects.

Nearly all teacher in-service initiatives for K–12 engineering education are associated with a few curriculum projects. Many of these professional development initiatives lack one or more of the characteristics known to lead to teacher learning, such as professional development that lasts for a week or longer, ongoing in-classroom or online support following formal training, and opportunities for continuing education. No active pre-service initiatives seem likely to contribute significantly to the supply of qualified engineering teachers in the near future. Indeed, the qualifications for an engineering educator at the K–12 level have not even been defined. Thus, although graduates of a handful of teacher-preparation programs have strong backgrounds in STEM subjects, including engineering, few if any of them appear to end up teaching K–12 engineering classes.

The reader should keep in mind the important differences between elementary and secondary schools and between teachers in these two branches of the K–12 education system. At the elementary level, separate courses for individual subjects and teachers with special credentials, for example, a licensed "engineering teacher," are very rare. At the secondary level, teacher specialization is more common. Thus approaches to professional development vary depending on grade level.

According to input from the workshops and public comments on the committee's project summary report, many K–12 teachers are unfamiliar with engineering, do not have content knowledge in science, and have relatively little preparation for teaching mathematics. All of these factors are certain to make in-service professional development for engineering education less effective. Furthermore, no accepted model for professional development for K–12 engineering has yet been developed. However, based on research in other domains, such as mathematics and science, we can get a good idea of successful approaches to preparing teachers in engineering.

Current K–12 engineering teachers come predominantly from the ranks of technology educators. Only a few science and math teachers teach engineering; even fewer engineers have become K–12 teachers. The lack of certification or licensing for "engineering" teachers, which is an issue at the secondary school level, reflects the relative newness of the field and uncertainties about the knowledge and pedagogical skills engineering teachers need to be competent. Over the long term, it is not clear where future engineering teachers for K–12 will come from, which could delay the acceptance of K–12 engineering education as a mainstream component of the school curriculum.

RECOMMENDATION 4. The American Society of Engineering Education (ASEE), through its Division of K–12 and Pre-College Education, should begin a national dialogue on preparing K–12 engineering teachers to address the very different needs and circumstances of elementary and secondary teachers and the pros and cons of establishing a formal credentialing process. Participants in the dialogue should include leaders in K–12 teacher education in mathematics, science, and technology; schools of education and engineering; state departments of education; teacher licensing and certification groups; and STEM program accreditors. ASEE should consult with the National Center for Engineering and Technology Education, which has conducted research on this topic.

Diversity

Finding 10. Based on evaluations, anecdotal reports, and our own observations, lack of diversity is a serious issue for K–12 engineering education.

As was noted in Chapter 2, the lack of diversity in post-secondary engineering education and the engineering workforce in the United States has been well documented The diversity problem in K–12 engineering is manifested in two ways. First, the number of girls and underrepresented minorities who participate in K–12 engineering education initiatives does not correspond to their proportion of the general population. Second, with a handful of exceptions, curricular materials do not portray engineering in ways likely to be meaningful to students from a broad range of ethnic and cultural backgrounds. Such students often have life experiences and technological interests different from those of the curriculum developers or of the majority culture.

For K–12 engineering education to yield the benefits its supporters claim for it, access and participation will have to be broadened considerably, if only because, according to predictions, the U.S. population will shift to "majority minority" by midcentury (U.S. Census Bureau, 2008). Thus ensuring that a wide range of K–12 students have an opportunity to experience engineering education will require reaching out to diverse groups and may lead, in the long run, to a more diverse technical workforce, which some have argued will be more capable of anticipating and addressing the technological needs of a diverse society and a global marketplace (Page, 2007).

Attracting girls and minority students to K–12 engineering education will require pro-active efforts by curriculum developers, teachers, providers of professional development, and supporters of these efforts. These efforts could include more effective communication about the work of engineers and how it contributes to human welfare. As part of a recent project at the National Academy of Engineering, messages for improving public understanding of engineering were developed and tested for their effectiveness and appeal to young people of all backgrounds (NAE, 2008). Tests on teens and adults, including large samples of African Americans and Hispanics, showed that the most effective messages stress the beneficial impacts of engineering on people and the environment.

RECOMMENDATION 5. Given the demographic trends in the United States and the challenges of attracting girls, African Americans, Hispanics, and some Asian subpopulations to engineering studies, K–12 engineering curricula should be developed with special attention to features which appeal to students from these underrepresented groups, and programs that promote K–12 engineering education should be strategic in their outreach to these populations. Both curriculum developers and outreach organizations should take advantage of recent market research that suggests effective ways of communicating about engineering to the public.

POLICY AND PROGRAM ISSUES

Many questions remain to be answered about the best way to deliver engineering education in the K–12 classroom and its potential on a variety of parameters of interest, such as science and mathematics learning, technological literacy, and student interest in engineering as a career. Despite these uncertainties, engineering is already being taught in K–12 schools scattered around the country, and, the trend appears to be upward. Given this situation, it is important that we consider the best way to provide guidance and support to encourage this trend.

An underlying question for policy makers is how engineering concepts, skills, and habits of mind should be introduced into the curriculum. There are at least three options along a continuum in terms of ease of implementation—ad hoc infusion, stand-alone courses, and interconnected STEM education.

- Ad hoc infusion, the introduction, or infusion, of engineering ideas and activities (i.e., design projects) into existing science, mathematics, and technology curricula is the most direct and least complicated option, because implementation requires no significant changes in school structure. The main requirements would be (1) willingness on the part of teachers and (2) access to instructional materials. Ideally, teachers would also have a modicum of engineering pedagogical content knowledge to deliver the new material effectively. The ad hoc option is probably most useful for providing an introductory exposure to engineering ideas rather than a deep understanding of engineering principles and skills.
- Stand-alone courses for engineering, an option required for implementing many of the curricula reviewed for this project, presents considerably more challenges for teachers and schools. In high schools, the new material could be offered as an elective. If that is not possible, it would either have to replace existing classes or content, perhaps a science or technology course, or the school day would have to be reconfigured—perhaps lengthened—to accommodate a new course(s) without eliminating existing curriculum. Stand-alone courses would also require teacher professional development and approval at various levels (e.g., state department of education, school board). This option has the potential advantage of providing a more in-depth exposure to engineering.
- Fully interconnected STEM education, that is, using engineering concepts and skills to leverage the natural connections between STEM subjects, would almost certainly require changes in the structure and practices of schools. Research would be necessary to develop and test curricula, assessments, and approaches to teacher professional development. New interconnected STEM programs or "pilot schools" might be established to test changes before they are widely adopted.

The three options just described, as well as others that are not described here, are not mutually exclusive. Indeed, the committee believes that implementation of K–12 engineering education must be flexible because no single approach is likely to be acceptable or feasible in every district or school. To illustrate the need for flexibility, three case studies of schools that have made engineering a significant part of their curricula can be found in the annex to this chapter.

Broader inclusion of engineering studies in the K–12 classroom also will be influenced by state education standards, which often determine the content of state assessments and, to a lesser extent, curriculum used in the classroom. Forty states have adopted the technological literacy standards developed by the International Technology Education Association, which contain a number of learning goals related to engineering design (Dugger, 2007). However, only 12 states require students to take coursework in technology education as a requirement of graduation.

It is worth noting that the No Child Left Behind Act of 2001 (P.L 107-110) puts considerable pressure on schools and teachers to prepare K–12 students to take annual assessments in mathematics, reading/language arts, and science,[8] and these assessments are based on state learning standards. Thus NCLB currently provides little impetus for teaching engineering.

Plans for implementing changes to include engineering in a school curriculum at any level must take into account places and populations (e.g., small rural schools, urban schools with high proportions of students of low socio-economic status, etc.) with a limited capacity to access engineering-education resources.

Another important element of implementation is the "technical core" of education, that is, what actually happens in the classroom between the teacher, the student, and the content (Elmore, 2000). In many respects, this is where real change and improvements in teacher practice and student learning occur. However, it is also very difficult for reformers to gain access, because schools have structures and traditions to isolate this core from the effects of change. One way to gain access might be to work toward "coherence," that is, to create educational systems in which standards, curricula, professional development, and student assessments are aligned and school leadership supports the need for change. A recent report from the National Science Board (NSB, 2007) calls for more coordination among stakeholders

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[8]Unlike in mathematics and reading, scores from the science assessments are not used to judge states' progress toward so-called Adequate Yearly Progress, a measure of the proportion of children who are meeting or exceeding specified achievement levels.

in STEM education and urges the development of national STEM content guidelines and student assessments as part of an effort to encourage "horizontal coordination and coherence." Although the current situation for K–12 engineering shows little evidence of coherence, working toward greater coherence is an important, long-term objective.

The committee believes that, ideally, all K–12 students in the United States should have the option of experiencing some form of formal engineering studies. We are a long way from that situation now.

RECOMMENDATION 6. Philanthropic foundations or federal agencies with an interest in STEM education and school reform should fund research to identify models of implementation for K–12 engineering education that embody the principles of coherence and can guide decision making that will work for widely variable American school systems. The research should explicitly address school populations that do not currently have access to engineering studies and take into account the different needs and circumstances of elementary and secondary school populations.

K–12 engineering also has policy and program implications for the articulation between high school and college. If K–12 engineering education emphasizes design activities, then two- and four-year post-secondary institutions may have to place early emphasis on design projects to avoid "turning off" students who expect that experience in their first year. Schools of engineering and other post-secondary institutions may also have to improve interactions among science, mathematics, and technology departments to accommodate the expectations of students who have experienced interconnected STEM education in high school.

Finally, the need for qualified teachers to teach engineering in K–12 classrooms raises a number of policy and program issues. Putting aside the uncertain definition of "qualified" in this context, it is not clear that solutions are available that can be funded, accommodated in the current structure of schools, and sustained. A variety of traditional and alternative mechanisms should be evaluated as part of the initiative suggested in Recommendation 4.

INTEGRATED STEM EDUCATION

Perhaps the most compelling argument for K–12 engineering education can be made if it is not thought of as a topic unto itself, but rather as part of integrated STEM education (Box 6-1). After all, in the real world engineering is not performed in isolation—it inevitably involves science, technology, and mathematics. The question is why these subjects should be isolated in schools. This same issue was raised by Project 2061 of the American Association for the Advancement of Science more than 15 years ago, long before the STEM acronym appeared on the scene (AAAS, 1993, pp. 321–322).

> By "science," Project 2061 means basic and applied natural and social science, basic and applied mathematics, and engineering and technology, and their interconnections—which is to say the scientific enterprise as a whole. The basic point is that the ideas and practice of science, mathematics, and technology are so closely intertwined that we do not see how education in any one of them can be undertaken well in isolation from the others.

BOX 6-1
"Integrated" STEM Education

The committee chose to use the word "integrated" to describe its vision for STEM education, in part because this term is in wide use already within the education community. The modest literature that examines efforts at integration in STEM education mostly concerns science and mathematics (e.g., Berlin and Lee, 2005; Pang and Good, 2000) and, occasionally, science and technology (e.g., Geraedts et al., 2006). Integration suggests connections on at least one and perhaps many levels, including curriculum, professional development, instruction, and standards, in concert with supporting policies at the school, district, or state level. A major barrier to discerning which integration approaches may be effective and why is that researchers and practitioners appear to have no common definition of what integration means (Hurley, 2001). In addition, some types of integration may have higher barriers to implementation than others (e.g., Czerniak et al., 1999). For example, integration may require a high level of teacher content and pedagogical content knowledge in multiple STEM fields. Other models of integration, with lower barriers to implementation, might rely on content specialists in individual STEM disciplines to introduce students to key concepts in those areas. Some concepts would be reinforced or elaborated through connections to other subjects. For example, the design process could be taught by a biology teacher in the context of biomimicry or by a physics teacher exploring assistive technologies. Schools could facilitate this kind of integration by co-locating STEM teaching areas, identifying STEM "teams," providing time for STEM teachers to coordinate lesson plans, and encouraging STEM teams to redesign existing activities to emphasize connections.

Finding 11. Although the term "STEM education" is used in national education policy, it is not implemented in a way that reflects the interdependence of the four STEM subjects.

Although the committee did not target K–12 STEM education initiatives specifically, based on the personal experience and judgment of committee members, the great majority of efforts to promote STEM education in the United States to date focus on either science or mathematics (generally not both) and rarely include engineering or technology (beyond the use of computers). By contrast, the committee's vision of STEM education in U.S. K–12 schools includes all students graduating from high school with a level of "STEM literacy" sufficient to (1) ensure their success in employment, post-secondary education, or both, and (2) prepare them to be competent, capable citizens in a technology-dependent, democratic society. (The three school case studies described in the annex to this chapter represent varying degrees of STEM integration.) Engineering education, because of its natural connections to science, mathematics, and technology, might serve as a catalyst for achieving this vision. The committee was not asked to determine the qualities that would characterize a STEM-literate person, but making such a determination would be a worthwhile exercise.

RECOMMENDATION 7. The National Science Foundation should support research to characterize, or define, "STEM literacy," including how such literacy might develop over the course of a student's K–12 school experience. Researchers should consider not only core knowledge and skills in science, technology, engineering, and mathematics, but also the "big ideas" that link the four subject areas.

Pursuing a goal of STEM literacy in K–12 will require a paradigm shift by teachers, administrators, textbook publishers, and policy makers, as well as by scientists, technologists, engineers, and mathematicians involved in K–12 education. Standards of learning, instructional materials, teacher professional development, and student assessments will have to be re-examined and, possibly, updated, revised, and coordinated. Professional societies will have to rethink their outreach activities to K–12 schools in light of STEM literacy. Colleges and universities will have to cope with student expectations that may run counter to traditional departmental stovepipe conceptions of courses, disciplines, and degrees.

Why do we suggest such a comprehensive change? First, the committee believes that STEM-literate students would be better prepared for life in the twenty-first century and better able to make career decisions or pursue post-secondary education. Second, interconnected STEM education could improve teaching and learning in all four subjects by reducing excessive expectations for K–12 STEM teaching and learning. This does not mean that teaching should be "dumbed down," but rather that teaching and learning in fewer key STEM areas should be deepened and that more time should be spent on the development of a set of STEM skills that includes engineering design and scientific inquiry.

A FINAL WORD

In the course our efforts to understand and assess the potential of engineering education for K–12 students, the committee underwent an epiphany of sorts. To put it simply, for engineering education to become more than an afterthought in elementary and secondary schools in this country, STEM education as a whole must be reconsidered. The teaching of STEM subjects must move away from its current siloed structure, which may limit student interest and performance, toward a more interconnected whole. The committee did not plan to come to this conclusion but reached this point after much thought and deliberation.

We feel confident that our instincts are correct, but other organizations and individuals will have to translate our findings and recommendations into action. Meaningful improvements in the learning and teaching of engineering and movement toward integrated STEM education will not come easily or quickly. Progress will be measured in decades, rather than months or years. The changes will require a sustained commitment of financial resources, the support of policy makers and other leaders, and the efforts of many individuals both in and outside of K–12 schools. Despite these challenges, the committee is hopeful that the changes will be made. The potential for enriching and improving K–12 STEM education is real, and engineering education can be the catalyst.

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Annex

THREE CASE STUDIES

High Tech High

At High Tech High in San Diego, engineering instruction is integrated not only with the other STEM subjects (science, technology, and mathematics), but also with many other subjects, including art, writing, and literature. High Tech High is a compelling example of how engineering can be woven into the fabric of a high-school curriculum.

High Tech High was founded in 2000 by a group of San Diego educators and business leaders as a charter high school. Since then, it has grown to include five high schools, two middle schools, and one affiliated elementary school. The goal of High Tech High is to provide students with personalized, project-based instruction (High Tech High, 2008a). Teachers work closely with students, adapting class content to individual learners. Students take only four subjects per semester, instead of the usual six or seven, to ensure that the curriculum remains focused. The school has no sports teams, no marching band—just academics.

Class sizes are small—generally 20 to 25 students—as is the student body. In 2008, the eight schools that make up High Tech High had a total of 2,500 students; even the oldest and largest of the eight, Gary and Jerri-Ann Jacobs High Tech High, had only 490 students in grades 9 through 12 (High Tech High, 2008b).

The success of High Tech High in teaching students from diverse backgrounds has been widely reported (e.g., Murphy, 2004). Students are selected by lottery from a pool of applicants from all over San Diego County; no aptitude tests or assessments are required for admission. Yet every high school student graduates, and every one of the graduates has been accepted to a college, 80 percent to four-year colleges and universities (High Tech High, 2008a). About 35 percent of High Tech High graduates so far have been the first in their families to attend college, some the first to finish high school. Colleges attended include Stanford, University of California at Berkeley, Massachusetts Institute of Technology, Yale, Dartmouth, Georgetown, Northwestern, and Rensselaer Polytechnic Institute. More than 30 percent of High Tech High alumni enter a science, engineering, or mathematics field, compared with a national average of 17 percent (High Tech High, 2008c).

Engineering has been taught at High Tech High almost since its inception. Near the end of the inaugural 2000–2001 school year, David Berggren was hired to be an engineering instructor starting in the fall of 2001. Like a number of other teachers at the school, Berggren did not have a traditional teaching background. He studied engineering at the California Maritime Academy, where he earned a B.S. in marine engineering technology with a minor in computer science; he then worked for several years on factory fishing trawlers in the Bering Sea. In 2000 and 2001, he worked with his father to build, from scratch, a 58-foot steel salmon-fishing boat, which was delivered to its owners in Alaska in May 2001. By that time, looking for something different to do, Berggren had applied for the teaching position at High Tech High and had been accepted.

With no formal training on how to teach engineering to high school students—indeed, with no background in education at all—Berggren turned to the Project Lead the Way (PLTW) program, which, he says, was a "lifesaver." PLTW provides a variety of well developed modules and courses that can be taught as is to engineering students. Berggren found that by using PLTW, he was able to focus his attention on aspects of teaching other than course development. For his first course, on the principles of engineering, he used PLTW's course materials. As he became more comfortable and familiar with the materials and with teaching, he began modifying PLTW material to suit his students' needs and his own ideas of the best way to teach the subject.

Berggren found himself teaching different areas of engineering, depending on the students' interests and on the other teachers with whom he was collaborating at the time. To do this, he had to ask himself exactly what his students should be learning about engineering. "Over the years, it's something I really struggled with—what is common across the different fields of engineering." Ultimately, he says, he decided that the most important thing was for the students to learn and be able to use the design process. "I feel like this design process is not only common to all areas of engineering, but it's something that can be applied to all areas of life," he says.

In the past few years, Berggren has been teaching engineering design principles to seniors at High Tech High who must all complete a senior project (a large, complex project, sometimes combined with a few small projects to help them get started). Berggren is one of six teachers teaching these seniors; the others are an art teacher, a multimedia teacher, a physics teacher, and two English teachers. The students rotate through four of them, two each semester, so that one group of students may take, for example, art and physics in the fall and English and engineering in the spring. Each semester course is actually a double course that takes up half the day; by the end of the year students have taken a full-year equivalent of art, physics, English, and engineering. “In the past we let the seniors choose their disciplines,” Berggren says, “but we decided we wanted to expose them to as much as possible.” Now the school decides which of the four classes each senior will take. “We’re constantly changing,” Berggren says, “trying new things.”

Whenever possible, the senior-project teachers collaborate so no matter which courses a particular student takes in a given semester, he or she will be taught with an emphasis on various connections and common subjects. This is easier to do for some pairings than others, Berggren notes. When he was paired with the art teacher, for instance, they worked on creating pots. In the spring 2008, he was paired with an English literature teacher, and they did mostly separate things.

Over the years, Berggren says, he has found that the most difficult thing for students working on a senior project with an engineering component has been to identify the problem that had to be solved. So, before the 2007–2008 school year, he traveled to Purdue University to be trained in their Engineering Projects in Community Service (EPICS) program. EPICS students work in design teams to solve problems for nonprofit organizations in the local community (Coyle et al., 2005). Originally developed for students in college engineering classes, EPICS is now being tested in 15 to 20 high schools around the country, including High Tech High.

Today, instead of students trying to come up with a design problem on their own, Berggren has them begin by researching nonprofit organizations in the community. Once a group of students decides on a nonprofit they would like to work with, they set up a meeting with members of that organization to discuss what they can design to help the organization run better or to do things it can’t do. “The students identify a problem, research it, see what’s been done, come up with solutions, settle on a design, build it, test it, and deliver it to the organization,” Berggren says. “They have a real customer—it’s not me telling them what to do. And it gives them more ‘buy in’ because they are selecting the organization.”

In one case, Berggren describes how his students worked with the local chapter of United Cerebral Palsy to design a specialized paper holder for a woman with visual problems. To keep her place on a line of words as she was typing, she had an assistant move a bar along the paper for her. The students created a motor-driven system "that allows her to move the bar up and down herself," Berggren says. "She was just beaming with excitement and joy, and the students were really excited. They felt they had really done something to change this person's life."

In addition to PLTW and EPICS, Berggren also works with US FIRST, an organization started by the inventor Dean Kamen to inspire young people's interest in science and engineering (FIRST is an acronym for For Inspiration and Recognition of Science and Technology). US FIRST sponsors and organizes robotics competitions in which teams of students have six weeks to solve a particular problem using a standard parts kit and a common set of rules (US FIRST, 2008).

Berggren sponsors a team for his students as an extracurricular activity. About 30 students participate, including students from other schools in the High Tech High system. Besides designing and building their robot, the students also make presentations at schools, conferences, and local fairs. US FIRST expects the team to run itself as a corporation, Berggren says, with the goal of learning how engineering is done in the real world. Many late nights and weekends are spent working, he says. "I do it because you see what the kids get out of it."

The kids also get much out of the High Tech High engineering classes, he says, especially "an understanding of and an interest in engineering." Of the 80 students in his engineering classes over the course of a year, he estimates that about 15 to 20 percent pursue engineering in college. And, he says, at least a few of them tell him something along the lines of, "I had no idea what this was, it never crossed my radar screen, but now I want to go on to college and study engineering."

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Texarkana ISD K–16 Engineering Collaborative

Texarkana Independent School District (TISD) and Texas A&M University-Texarkana have forged a powerful partnership. Working together, they are building a pipeline for students well versed in science, technology, engineering, and math (STEM) education from kindergarten through college. This model, the first of its kind in the country, may turn out to be one that can be replicated in other school districts.

The planning for the program, officially called the Texas A&M University-Texarkana—Texarkana ISD K–16 Engineering Collaborative—began in January 2005, when a blue-ribbon committee of TISD had its first meeting. Members of the committee included parents, community and business leaders, and school district representatives. The purpose of the meeting was to review the school district's facilities and programs and determine how to improve its STEM program. This committee had a strong incentive—a need for more engineers at the local level to support businesses, such as International Paper, Domtar Paper Mill, and Alcoa.

As plans for the K–16 vertically aligned program evolved, the planning committee received good news. The family of Josh Morriss, Jr., donated land near the Texas A&M-Texarkana campus for the new K–5 elementary school. The first piece of the K–16 pipeline, this school, called the Martha and Josh Morriss Mathematics and Engineering Elementary School, focuses on math, science, and engineering.

The new school opened its doors in the fall of 2007, with Principal Rick Sandlin at the helm. Students apply to attend the school and are selected on a first-come-first-served basis. The school's first cohort of 396 students has about 23 percent African American, Hispanic, Asian, and American Indian students and 15 percent from low-income households. No matter where the students live or what their backgrounds are, they are all expected to live up to the school's high standards.

The planning team of TISD decided to develop its own engineering curriculum working with faculty from Texas A&M to design K–5 learning units that would be age-appropriate, hands-on, and conceptually based. The units are also aligned with the Texas Essential Knowledge and Skills (TEKS) curriculum, so students will be prepared for the state exams given each year.

The school day begins with engineering. Students work on units covering many topics, such as problem solving, architecture, weather and space, bioengineering, forces of motion, robotics, and engineering structures. "Our goal is to teach as much engineering as we can," explains Sandlin. "We teach the engineering process of 'imagine, plan, design, improve, and share' in the engineering program, as well as throughout the curriculum." At the end of many of the six-week units, students participate in an Engineering Encounter, a presentation for parents and community members to showcase what they have learned. The event also serves as an embedded assessment.

Just as students are held to high standards, so too are teachers. Every teacher in the school must have a master's degree and either Texas Master Mathematics Teacher Certification or Texas Master Technology Teacher Certification, both of which can be obtained through programs at Texas A&M. For teachers who do not yet have a master's degree, the district pays for coursework if the teacher makes a commitment to stay at the school for four years.

In addition to educational requirements, teachers also must take two courses in curriculum design and curriculum delivery designed by Texas A&M faculty specifically for this program. Throughout the school year, the school curriculum coach works with teachers by conducting weekly planning sessions. "We're working on raising the bar in the way we teach engineering," says Principal Sandlin.

By all accounts, these efforts have paid off. In the first year of the program, 98 percent of the students in grades 3 through 5 scored high enough on the state exam to meet the standards in math. Fifth-grade students also take a science assessment test, and 98 percent of them also met those standards. Perhaps even more important, the students clearly enjoy the program. Even though the academics are difficult, most students opt to stay at the school. Of the 396 kids admitted in the first year, only 25 left. The school is already at capacity for the upcoming school year.

In the fall of 2008, the district expanded the engineering program to include the sixth grade. Creating a "school within a school" at Texas Middle School, the district is adding two STEM-related components. The first is a modular program called Synergistic Technologies, a series of science and technology units with an emphasis on problem solving. Working in pairs, students use a combination of hands-on activities and technology to explore a range of topics, including biotechnology, heat and energy, and light and lasers. The modules encourage students to work independently, with the teacher acting as a guide and facilitator.

To prepare for the new academy structure at the middle-school level, all sixth grade teachers participated in a training program in the summer of 2008. The program included an accelerated version of the curriculum design and curriculum delivery courses designed for Morriss Elementary School teachers and is meant to prepare the sixth grade teachers to use inquiry-based, hands-on instructional methods. "If the modules work well in sixth grade, we may consider using them in the seventh and eighth grades, which will be added over the next couple of years," explains Ronnie Thompson, assistant superintendent for school improvement.

The second addition to the middle school program is an accelerated math course for sixth graders, which introduces the main concepts of algebra. This course gives students the background they need to take Algebra I in seventh grade.

By taking the elementary engineering program and the new STEM offerings in middle school, students will be prepared to take the engineering courses already in place at the district high school. As part of the partnership with Texas A&M, a faculty member teaches two electrical engineering courses on the high school campus. Students who take these courses receive both high school and college credit. Other engineering courses at the high school level include AutoCAD and upper level math courses, including statistics and calculus.

"We want to see the program all the way through," says Thompson. "Over the next several years, we will be collecting longitudinal data to determine how many of the 66 kids per grade from the new elementary school program stay with engineering through high school and beyond. While building a strong engineering pipeline, we also want to build a model program that gives all students a strong foundation in math and science."

Denver School of Science and Technology

When the Denver School of Science and Technology (DSST) opened its doors in 2004, it had two goals: (1) to serve an economically and socially diverse population and (2) to ensure that this population succeeded in the school's rigorous science, technology, and engineering curriculum. Since then, DSST has come a long way toward realizing those goals. A college preparatory charter school in the Denver Public School (DPS) system, DSST selects students by lottery. Adding one grade a year, the school now serves all four high school grades; the sixth grade (in middle school) was added in fall 2008. Of the 425 high school students, about 34 percent are African American; 24 percent are Hispanic; and 34 percent are white. About 45 percent are girls, and 46 percent come from low-income households.

"We are a diverse school for a reason," explains Bill Kurtz, who heads the school. "You are going to be living and working with people who are different from you. Part of our goal in this school is to say, 'We have people from all backgrounds, and we are about demonstrating that a community of people can use that difference as a strength.'" Indeed, a close-knit community is integral to the school's culture, which emphasizes hard work and success. But DSST does not expect students to meet these high standards alone. Many mechanisms are in place to ensure that none of them slips through the cracks.

The school day begins with a school-wide meeting to give students and faculty an opportunity to share problems, successes, and issues of concern. Each student is also part of a small bi-weekly advisory class that offers help and support on a smaller scale and closely connects each student with an adult in the school. If students come to school with homework uncompleted, they must stay after school that day to finish it. Tutoring also is available after school. These strategies exemplify how all members of the school live by its core values of respect, responsibility, integrity, courage, curiosity, and doing your best.

Students also exemplify the school's values by working hard to master the rigorous curriculum. The engineering curriculum was designed by University of Colorado, Boulder, professors and DSST teachers. The goal is to interest students in the possibility of studying engineering in college. Although the emphasis in ninth and tenth grade is on building a strong foundation in the liberal arts, students performing at grade level in mathematics and reading can begin taking engineering electives in ninth grade. These design-based courses range from fashion engineering to biomimicry.

In their senior year, students can choose to focus on a physics/engineering program or a biochemistry/biotechnology program. Among the seniors who graduated in 2008, two-thirds opted to specialize in engineering. Those students took both an engineering course and an advanced physics course, which included how physics can be applied to engineering design.

Academic expectations at the school are high. To graduate, all students must pass pre-calculus and complete five core lab-based science courses (physics, chemistry, biology, earth science, and physics/engineering or biochemistry/biotechnology), four years of college preparatory language arts, three years of Spanish, and two electives. "The culture of our school stresses engineering and applied math and science degree paths and careers more than any other school I have seen," says Mark Heffron, head of the math department, who has two engineering degrees. "Engineering is often stressed as a reason for learning something in a math or science class."

Another way DSST strives to make the curriculum relevant to students' lives is through an internship program. All high school juniors must complete a 10-week internship, which involves "going to work" for about eight hours a week. Ideally, the students work with a mentor who evaluates their progress and is in regular contact with the school. Throughout the internship, students keep a journal and complete other projects as assigned.

Students can choose either an engineering- or science-based internship; 10 to 15 percent opt for an engineering internship. HDR, Inc, is an engineering and architecture firm that often works with students from DSST. According to Terry Heffron, project manager at the company, "We have students analyzing bridge plans, calculating quantities of concrete needed, and figuring out the linear feet of pipe. By the end of the internship, some students have even progressed to the point where they are doing reinforced-concrete design and preliminary wall layouts. They learn very fast."

During senior year, each student is expected to complete a senior project, which includes an extensive research paper and a work product, such as building a solar car, running a conference, creating a presentation, or producing a film. Again, about 10 to 15 percent choose to complete an engineering-related project.

Through DSST's partnership with the University of Colorado at Boulder, one DSST engineering teacher has been trained directly by university professors; in addition, university engineering faculty teach some engineering courses. Mark Heffron, who teaches math and engineering electives and was a structural engineer before becoming a teacher, brings real-world experience directly to the classroom.

Although the school is still quite new, its scores on standardized math tests are the best in DPS. DSST's first class of ninth graders received the highest scores on the Colorado Student Assessment Program (CSAP) math exams, with 55 percent scoring at the proficient or advanced levels, compared to 17 percent in DPS and 38 percent statewide. Sixty-four percent of DSST tenth graders scored at the proficient or advanced level, compared to 18 percent in DPS and 31 percent statewide. For two consecutive years, the ninth grade classes have been one of the top two math classes in DPS.

Perhaps even more gratifying than the specific results on test scores has been DSST's rating on a statewide measure that evaluates not only what students know now but how much they have progressed since entering high school. On this key measurement, DSST showed the top growth rate in DPS.

The school's own statistics help explain why. Of the 132 students in DSST's first freshman class, 100 did not pass a proficiency exam and had to attend a three-week summer academy; not all of the kids from this first group stayed with their class. Some left the program altogether, and 15 were held back a year. The 79 students who stayed with their class and persevered are now among the top achievers in DPS, and all 79 have been accepted to four-year colleges or universities. Of these 79 students, 50 percent are the first in their families to reach this milestone. One-quarter of 2008 DSST graduates went on to study engineering in college, and all seniors in the class of 2009 have been accepted into four-year colleges.

Although this is good news for many students, DSST still faces a serious problem. The level of readiness of students coming to DSST hasn't changed significantly in the past three years. About 75 percent of students who take the post-admission proficiency exam continue to need intensive remediation, and some just cannot catch up in four years. This problem is what motivated DSST to open a middle school in the fall of 2008. "We realized that we have to start working with the students sooner," says DSST founder David Greenberg. "By the time they enter high school, they've had eight years of poor education, and for many, it's almost impossible to catch up. We want to help even more kids succeed, and we think that adding grades 6 through 8 to our program will be the most effective approach."

DSST has accomplished much in its first four years, mostly by plain hard work. But the school also had many advantages. An initial challenge grant from the Bill and Melinda Gates Foundation, contributions from corporate, foundation, and philanthropic donors, and a DPS construction bond enabled DSST to build a state-of-the art building that is inviting to students and conducive to learning. "We held focus groups to find out what the kids wanted," says Greenberg. "Girls wanted nooks where they could peel off into small groups. They wanted bright colors and soft furniture. We did all we could to build a 'cool school.'"

In addition, the exposed ductwork and heating and ventilating systems offer a ready-made engineering lesson. The school also is wireless, making it possible to provide each student with a laptop that works in any part of the building. The new $8 million Morgridge Middle School is the first school in the district built according to guidelines for "green" buildings.

Although other urban schools may not have all of these advantages, they can still learn much from DSST's example. One state has already initiated a project inspired by DSST. The Texas High School Project, a consortium of the Texas Education Agency, the Bill & Melinda Gates Foundation, and the Michael and Susan Dell Foundation, has chosen DSST as one of its best-practices models. The project is creating 35 public STEM (science, technology, engineering and math) secondary schools.

"People ask about how expensive our model is," says Greenberg. "It probably costs about 10 percent more per year than a conventional urban public school. But think about it. We had more minority kids [from DSST] going to the University of Colorado than any other school in the state. We also scored fifth highest in Colorado on the ACT exam. DPS, on the other hand, has a 50 percent drop-out rate. So which model is really more expensive?"

Appendix A

Committee Biographies

Linda P.B. Katehi (*chair*) is chancellor of the University of California, Davis. Previously, she served as provost and vice chancellor for academic affairs at the University of Illinois at Urbana-Champaign; the John Edwardson Dean of Engineering and professor of electrical and computer engineering at Purdue University; and associate dean for academic affairs and graduate education in the College of Engineering and professor of electrical engineering and computer science at the University of Michigan. Professor Katehi led the effort to establish the Purdue School of Engineering Education, the first department at a U.S. university focused explicitly on engineering education, particularly on K–12 engineering curricula, standards, and teacher education. The author or coauthor of 10 book chapters, she has published more than 600 articles in refereed journals and symposia proceedings and owns 16 patents. She is a member of the National Academy of Engineering (NAE), a fellow and board member of the American Association for the Advancement of Science, chair of the Nominations Committees for the National Medal of Science and National Medal of Technology and Innovation, and a member of the Kauffman National Panel for Entrepreneurship. She is currently a member of a number of NAE/National Academy of Sciences committees and the Advisory Committee for Harvard Radcliffe College and a member of the Engineering Advisory Committees for Caltech, the University of Washington, and the University of California, Los Angeles.

Lynn Basham received her B.S. in 1977 and M.S. in 1985 from the University of Southern Mississippi and completed her doctoral work in 2006 at Louisiana State University. As a state specialist for technology education at the Virginia Department of Education, she is responsible for curriculum projects and the development of new initiatives. Ms. Basham has received many professional honors and has been active in professional organizations throughout her career. From 2000 to 2002, she was Region 2 representative for the International Technology Education Association (ITEA) Board of Directors and was recently president of the ITEA Council for Supervisors (CS). She was awarded the ITEA-CS Distinguished Service Award in 2004 and the ITEA-CS Outstanding State Supervisor Award in 1992 and 2001. Ms. Basham is also a member of the Mississippi Valley Technology Teacher Education Conference, a member and past president of the Southeastern Technology Education Conference, and a member of the Association for Career and Technical Education, American Association for Training and Development, and American Society for Curriculum Development. She is currently working on the U.S. Department of Energy Real World Design Challenge.

M. David Burghardt is a professor of engineering, a licensed professional engineer in New York, and a Chartered Engineer in the United Kingdom. He is also co-director of the Hofstra University Center for Technological Literacy (CTL), which he established in 1989, and the author of 11 books on engineering and secondary-school technology education. Since 1993, through CTL, he has won seven major National Science Foundation grants for work on improving technological literacy. Dr. Burghardt's particular interest is in how engineering design can promote student learning in mathematics and science, especially for lower performing students. In addition to developing engineering courses at the university level, he was co-creator of a master's degree program for in-service teachers, which now has more than 300 graduates.

Kathleen Conn, assistant professor at Neumann College in the Division of Human Services, is a scientist, educator, and former school administrator. She earned her Ph.D. in physics/biology at Bryn Mawr College, completed postdoctoral work at Lankenau Medical Research Center in Philadelphia, and took her legal training at Widener University School of Law. She was a participant and leader in the Thayer School of Engineering (Dartmouth College) "Engineering Concepts in the High School Classroom" Program, which trains mathematics and science teachers to use problem-solving approaches. Dr. Conn has been a delegate to international conferences on physics education and a member of the Advisory Council for the Mechanical Universe High School Adaptation (MUHSA) and the Comprehensive Conceptual Curriculum for Physics (C3P), two pre-college physics curriculum projects sponsored by the National Science Foundation. She is also an adjunct professor at Widener University School of Law, Wilmington, Delaware.

Alan G. Gomez, an instructor at the University of Wisconsin College of Engineering, and an engineering instructor and career and technical education coordinator for the Sun Prairie Area School District. He received his B.S. in Technology Education from the University of Wisconsin-Stout in 1995, his M.S. in Industrial/Technology Education from Stout in 2004, and a Ph.D. in Industrial and Systems Engineering from the University of Wisconsin-Madison in 2008. He has written a National Foundations of Technology curriculum and a National Introduction to Engineering curriculum for the International Technology Education Association Center to Advance the Teaching of Technology and Science. A member of the team writing technology education standards for the state of Wisconsin, he has published materials in professional journals and in the *Proceedings of the American Society for Engineering Education*. Dr. Gomez is principal author of *Engineering Your Future: A Project-Based Introduction to Engineering* and *Survey of Engineering*.

Craig Kesselheim is currently senior associate for the Great Schools Partnership in Maine, where he not only assists and consults with secondary schools on reform initiatives, but also directs a three-year math science partnership of three public schools, a career and technical school, and a community college. Previous positions include director of curriculum and staff development for Maine School Union 98; principal of Tremont Consolidated School (K–8) in Bass Harbor, Maine; assistant professor of biology at the University of Central Arkansas; and science facilitator for the Maine Mathematics and Science Alliance. Dr. Kesselheim earned his B.A. from College of the Atlantic and an M.A.T. from Bridgewater State College. He earned his Ph.D. in science education from the University of Maine in 1997.

Michael C. Lach, officer of high school teaching and learning, oversees curriculum and instruction in 120 high schools in the Chicago School System. Mr. Lach began teaching high school biology and general science at Alceé

Fortier Senior High School in New Orleans in 1990 as a charter member of Teach for America. After three years, he became director of program design for Teach for America, where he developed a portfolio-based alternative-certification system that was adopted by several states. He subsequently returned to teaching science, first in New York and then in Chicago. In 1995, Radio Shack named him one of the Top 100 Technology Teachers; the same year he was named Illinois Physics Teacher of the Year. As an Albert Einstein Distinguished Educator Fellow, he was advisor to Congressman Vernon Ehlers (R-MI) on science, technology, and education. He was also lead curriculum developer of "Investigations in Environmental Science" (It's About Time, Inc.), and has written extensively about science teaching and learning for *The Science Teacher*, *The American Biology Teacher*, *Scientific American*, and other publications. He earned a bachelor's degree in physics from Carleton College and master's degrees from Columbia University and Northeastern Illinois University.

Richard Lehrer is professor of science education in the Peabody College of Teaching and Learning at Vanderbilt University. Previously, at the University of Wisconsin, Madison, he was associate director of the National Center for Improving Student Learning and Achievement in Mathematics and Science. He collaborates with teachers to develop, implement, and assess modeling of mathematics and sciences in the elementary grades and works with engineers and science educators at City College of New York to conduct studies of engineering design in the elementary grades. A former high school science teacher, he has pioneered classroom research on using cognitive technologies as tools for teaching mathematics, science, and literacy. He was a member of the National Research Council Committee on the Foundations of Assessment and Systems for State Science Assessment.

Deborah McGriff has worked for almost four decades to transform the lives of underserved urban school students. Currently, she is president of the Education Industry Association, an association of providers of education services; a member of the Advisory Board of the National Council on Teacher Quality; a founder and national board member of the Black Alliance for Educational Options; and a member of the Advisory Board of the Program on Education Policy and Governance at the Harvard University John F. Kennedy School of Government. She is also a partner at NewSchools Venture Fund, where she works on investment strategy and quality teaching. In 1993, after years of working as an administrator for public school systems in Detroit, Cambridge, Massachusetts, Milwaukee, and New York, she became the first public school superintendent to join EdisonLearning (formerly Edison Schools), where she held numerous positions, including president of Edison Teachers College and executive vice president of charter schools. She has a bachelor's degree in education with a minor in history from Norfolk State University, a master's degree in education, with a specialization in ready pedagogy from Queens College of the City University of New York, and a doctorate in administration, policy, and urban education from Fordham University.

Roland (Rollie) J. Otto is Director of Education Outreach and the Global Teacher Academy for the Berkeley Center for Cosmological Physics at the University of California, Berkeley. From 1988 to 2006, he was head of the Center for Science and Engineering Education at the Lawrence Berkeley National Laboratory, and from 1995 to 1998, he was executive director of the California Science Project, a statewide teacher professional-development network. From 1986 to 1988, he was assistant director of the Lawrence Hall of Science at the University of California, Berkeley. In 2001–2002, Dr. Otto was a member of the Science Subject Matter Committee, California Commission for Teacher Credentialing, which establishes subject-matter content standards for science teachers. He was also principle writer and advisor for the California Science Framework Committee (2000-2001) and chair of the Content Review Panel for the science instructional-materials adoption process (1999). He has a Ph.D. in nuclear/physical chemistry from Purdue and a B.S. in chemistry from Valparaiso University. He did his postgraduate work with Nobelist Glenn T. Seaborg.

Richard J. Schaar, an executive advisor at Texas Instruments (TI), recently retired from his post as a senior vice president of TI, where he was math and science education policy advisor for the corporation. Under his guidance, TI developed educator-support services, including technology training, to increase teachers' confidence and ability to integrate technology education into their classrooms. Dr. Schaar served on the National Science Foundation (NSF) Advisory Committee of the Directorate for Education and Human Resources and chaired the Subcommittee on the Instructional Workforce. He extended TI's commitment to education by partnering with NSF on educational initiatives, including serving as the leading corporate sponsor of the Urban Systemic Programs, Model Institutions for Excellence, and the Superintendents' Coalition. Under his leadership, TI supports an executive director for the Benjamin Banneker Association and helped establish the Dorothy Strong Scholarship for Professional Development. He holds a B.S. from Purdue University, an M.B.A. from the University of Illinois, and a Ph.D. in applied mathematics from the University of Chicago. Dr. Schaar has also received a Woodrow Wilson Fellowship and an NSF Graduate Research Fellowship.

Mark Schroll joined the Kern Family Foundation in August, 2007, where he is program coordinator for engineering and innovation programs, including Project Lead the Way (PLTW). As a member of the original staff of the Science Academy of South Texas, he co-authored and implemented PLTW, a unique four-year pre-engineering curriculum, and later worked to implement a PLTW program at his school. From 2001 to 2007 he was a PLTW teacher trainer for two courses, Digital Electronics and Engineering Design and Development. Drawing on his experience with pre-engineering curricula and instruction, he collaborates with grant-management staff on the application-review and grant-monitoring processes. He also works closely with grantees to develop networks of strong partnerships and sustainability plans.

Christian D. Schunn is an associate professor of psychology and a research scientist in the Learning Research and Development Center at the University of Pittsburgh. His basic research involves studying experts and novices in complex domains, such as science, engineering, submarining, and weather forecasting, to develop theoretical and computational models of cognition underlying expert performance and the difficulties of developing expert-like performance. His applied research involves developing and evaluating tools and curricula to help novices achieve expert performance. Dr. Schunn has developed design-based learning curricula for middle and high school science classrooms that have been found to be more successful than existing hands-on and textbook science curricula at teaching basic science concepts and scientific reasoning skills and stimulating interest in engineering, science, and technology careers. He received his Ph.D. from Carnegie Mellon University in 1995.

Jacquelyn F. Sullivan, associate dean for student cultivation, College of Engineering and Applied Science, University of Colorado (UC) at Boulder, heads the college diversity, recruitment, and retention programs. A founding co-director of the Integrated Teaching and Learning Program and Laboratory, Dr. Sullivan was a driving force behind this hands-on K–16 learning initiative, which now serves more than 4,000 undergraduate engineering students annually. For this work, she was a co-recipient of the 2008 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education from the National Academy of Engineering, and in 2005, she received the inaugural Lifetime Achievement Award from the K–12 Division of the American Society of Engineering Education. She also directs the TEAMS Program (Tomorrow's Engineering—creAte. iMagine. Succeed), funded by the National Science Foundation, and was a co-developer of a retention-building First-Year Engineering Projects course at UC Boulder. Dr. Sullivan is a founding board member of the Denver School of Science and Technology, a public, urban high school that incorporates science, engineering, and technology into a humanities-rich setting focused on student achievement. Her articles have appeared in *Science*, *The Bridge*, and many other publications. She received her Ph.D. in environmental health physics and toxicology from Purdue University and has 14 years of engineering experience in the energy and software industries and nine years of experience as director of a water resources and environmental engineering research center.

Robin Willner is vice president, Global Community Initiatives, for IBM, which she joined in 1994 to design and implement Reinventing Education, a $90 million philanthropic initiative that promotes K–12 school reform through grant partnerships with school districts and states to develop new applications of technology to overcome common barriers to school improvement and raise the level of student achievement. She also oversees a range of philanthropic and volunteer programs and was project manager for the 2001, 1999, and 1996 National Education Summits, which were co-hosted by IBM. She was instrumental in the initial planning and start-up of Achieve Inc., a national education organization for standards-based reform. Prior to joining IBM, Ms. Willner was executive director for strategic planning/research and development for the New York City Public Schools. She is a member of the boards of directors of the National Center for Educational Accountability, Grantmakers for Education, and Center for Education Policy in Washington, D.C. She was a member of the U.S. Department of Education Expert Panel on Educational Technology from 1999 to 2000. She graduated from Columbia University with a degree in urban affairs.

Appendix B

Curriculum Projects—Descriptive Summaries

The Academy of Engineering

The Academy of Engineering (AOE) is a mobile engineering laboratory that combines hands-on activities with either Fischertechnik® or LEGO® manipulatives to teach students science, technology, engineering, math, architecture, communications, and robotics. According to the company, AOE includes hundreds of hours of course work and activities. Versions appropriate to elementary, middle, and high school are available. The program also includes online teacher training, student assessment and support, and a virtual online community that includes quarterly engineering challenges, and at-home extension activities. The curriculum is comprised of four volumes of real-world mechanical engineering projects that naturally embed mathematics, design, technology literacy, communications, and science. The volumes address simple machines, power transfer, gear trains, and principles of robotics and each book provides enough materials to cover an entire semester.

Developer: PCS Edventures Inc.
Website: http://edventures.com/imssc/nsimssc/
To Obtain Materials: Contact Sales and Product Information at 800/429-3110 or sales@pcsedu.com

Children Designing & Engineering

Children Designing & Engineering was a collaboration between the College of New Jersey's Department of Technological Studies, the New Jersey Chamber of Commerce, and the Institute of Electrical and Electronics Engineers. With funding from the National Science Foundation, the project developed contextual learning units for children in grades K–2 and 3–5. Each unit is framed in the context of a prominent New Jersey business (i.e., Six Flags Wild Safari, Lucent Technologies, Marcal Paper, Public Service Electric and Water, Elizabethtown Water, Johnson & Johnson, Ocean Spray). They are designed to run from four to six weeks (or 15 to 22 hours), and they begin with a design challenge that must be addressed in the final week. The subsequent instruction enables students to develop a solution to the challenge by engaging them in researching topics, generating ideas, planning courses of action, making things, and testing and presenting their designs. Addressing these challenges requires students to apply concepts and skills from mathematics, science, technology, and other academic subjects.

Developer: The College of New Jersey
Contact: Alison Goeke
E-mail: goeke2@tcnj.edu
To obtain materials: Materials out of print.

DTEACh

DTEACh (Design Technology and Engineering for America's Children) is a product of the Cockrell School of Engineering at The University of Texas at Austin. It began in 1992 as a grassroots science, technology, engineering, and mathematics teacher education project for elementary school teachers. In 2000, DTEACh began partnering with National Instruments to offer robotics and automation workshops using LEGO MINDSTORMS. Over the past eight years, the program has helped hundreds of Central Texas educators integrate cutting-edge technology into the classroom through the DTEACh Robotics and Automation Summer Institutes. Participants learn to use the engineering design process to more effectively teach state-mandated science and math standards. Mentors from the engineering community held these teachers use LEGO MINDSTORMS to engage their students in learning that integrates core STEM subjects while incorporating 21st century skills. DTeach has one published curriculum, for grades 3–4, on automation and control.

Developer: Cockrell School of Engineering, The University of Texas at Austin
Website: www.engr.utexas.edu/dteach
Contact: Cheryl Farmer
E-mail: cheryl.farmer@mail.utexas.edu
To obtain materials: The curriculum on automation and control can be downloaded at http://www.engr.utexas.edu/dteach/resources/DTEACh_Robotics_3-5.pdf

Engineering: An Introduction for High School

Engineering: An Introduction for High School is an open-source high school "flexbook" created using software developed by the CK–12 Foundation by engineering and education faculty at Arizona State University. The flexbook format allows the book to be customized for multiple audiences. The text can be updated, expanded, and repurposed as necessary to support specific standards and classroom needs. The current draft has four content chapters that cover the nature of engineering, engineering and society, engineering design, and the connection between engineering, science, and mathematics.

Developer: Faculty at Arizona State University
Contact: Darryl Morrell
E-mail: DARRYL.MORRELL@asu.edu
To obtain materials: http://flexbooks.ck12.org

Engineering by Design™

Engineering byDesign™ (EbD) is a national model program developed by the ITEA-CATTS (International Technology Education Association-Center to Advance the Teaching of Technology and Science) Consortium in consultation with the ITEA Technology Education Advisory Council, ITEA institutional members, and the mathematics, science, and engineering communities. At the K–5 grades, the program provides content that can be integrated with other school subjects. In grades 6–12, the program offers nine discrete courses, ranging in length from 18 weeks to 36 weeks. Engineering by Design™ is built on the constructivist model, and students in the program learn concepts and principles in an authentic, problem-based environment. A network of technology teachers (EbD™ Network) has been selected to collaborate and conduct action research (through eTIDEonline™ and the EbD Online Assessment & Design Challenge) in order to better understand the complexities of student learning and to help all students succeed and be prepared for the global society in which they will grow up.

Developer: International Technology Education Association
Website: http://www.iteaconnect.org/EbD/ebd.htm
Contact: Barry Burke
E-mail: bburke@iteaconnect.org
Materials available to members of the ITEA-CATTS Consortium.

Engineering Your Future: A Project-Based Introduction to Engineering

Engineering Your Future: A Project-Based Introduction to Engineering is a high-school level, project-based introduction to engineering. The 19-chapter text includes information related to the history of technology and engineering; engineers and the engineering profession; the big ideas in engineering, including systems, optimization, problem solving, design, and modeling; technology, society, and ethics; and fundamental mathematical and physics concepts used in mechanical and electrical engineering. There are 43 case studies that engage students in various types of learning activities. An instructor's guide can also be purchased.

Developers: Alan Gomez, William Oakes, Les Leone
Contact: Al Gomez
E-mail: aggomez@spasd.k12.wi.us
To obtain materials: Great Lakes Press, Paul Bruner (paul@glpbooks.com) or 800-837-0201

Engineers of the Future

Engineers of the Future is a set of eight middle and high school courses modeled on the design and technology curriculum of the United Kingdom and intended for use by technology education teachers in the United States. The course are (1) Introduction to Design, Engineering and Technology for Middle School; (2) Foundations of Design, Innovation, Engineering and Technology for High School; (3) Engineering Design and Product Development for MS and HS; (4) Exploring our Designed World; (5) Pro/Desktop Designing and Modeling for MS or HS; (6) Pro Engineering and Prototyping for HS; (7) Introduction to Biotechnology and Bioengineering; and (8) Introduction to Digital Electronics and Control Systems. According to the developers, the courses and accompanying professional development experiences are meant to complement and enhance the delivery of integrated STEM education. The courses were piloted in New York in 2007. Partners in the effort include Buffalo State College, Technology Department; the New York State Education Department; PTC Corporation; and the MIT Consortium.

Developer: Buffalo State College, Technology Department
Website: http://www.buffalostate.edu/technology/eof.xml
Contact: Steve Macho
E-mail: machos@buffalostate.edu

Exploring Designing and Engineering

Exploring Designing and Engineering (ED&E)™, initially funded by the New Jersey Commission on Higher Education, offers teacher professional development and instructional materials that are contextual, problem-based, and authentic. Six-week units for grades 6-8 focus on science and technology integration in "Pack It Up, Ship It Out"; "Community by Design"; "Materials & Processes," and "The Big Thrill—Dream It, Plan It, Build It." High School units include "Digital DJ," "Ready, Set, Sail," "Xtreme Automata" and the "Capstone Course" for advanced students. *Design and Engineering with ProDESKTOP*, ED&E's classroom text, guides students through the skills of computer-aided design and visualization used in the ED&E units. Over 500 New Jersey teachers have taken ED&E workshops since 2000, with nearly 15,000 students now participating in design and engineering activities statewide.

Developer: The College of New Jersey, Center for Mathematics, Science, Technology and Pre-Engineering
Website: http://njtqe-r.grant.tcnj.edu/index.htm
Contact: John Karsnitz
E-mail: karsnitz@tcnj.edu

The Infinity Project (Middle School)

The Infinity Project introduced its middle school (grades 6–8) engineering curriculum in fall 2008. It consists of six three-week modules developed in partnership with engineering professors at Southern Methodist University and middle school educators. Modules can be grouped together and offered as a standalone course or individually incorporated into existing math, science, or technology classes. Additional modules spanning the disciplines of electrical, mechanical, civil, environmental, and biomedical engineering will be introduced in fall 2009.

The initial six modules are:

- Introduction to Engineering Design
- Rocketry—Achieving Liftoff I
- Rocketry—Achieving Liftoff II
- Robots from Concept to Completion
- Sound Engineering—Making Great Sounds
- Engineering in the Natural World

Schools must apply to become an Infinity Project school and offer the middle school engineering curriculum. Once accepted into the program, teachers attend week-long training during the summer. Professional development materials include instructor notes, homework solutions, sample test questions, a daily lesson plan guide, PowerPoint chapter lectures, and online support.

Developer: The Infinity Project, Southern Methodist University
Contact: Dianna McAtee
E-mail: dmcatee@infinity-project.org

Insights: An Inquiry-Based Elementary School Science Curriculum (Structures Module)

Insights: An Inquiry-Based Elementary School Science Curriculum was developed by a coalition of science curriculum specialists at Education Development Center, Inc. and teams of elementary school teachers from Baltimore, Boston, Cleveland, Los Angeles, New York, Montgomery County (Maryland), and San Francisco school districts. Each module was pilot tested by team teachers, revised, field tested on a larger scale, and revised a second time before publication. The Center for the Study of Testing, Evaluation, and Educational Policy (CSTEEP) at Boston College provided evaluation and assessment specialists for the project. In the Structures Module, sixth grade students begin to develop an understanding of some of the basic principles that answer the question, Why do structures stand up? They look at structures in the school neighborhood, observing the variety in size, shape, material, and function. They build their own structures, using straws, index cards, and other materials. As they build, students explore some of the basic concepts of standing structures, such as live load, dead load, tension and compression, the role of shapes, and trusses. By comparing their structures with those in their community, students learn how structure and design are influenced by function, materials, and aesthetics. The last activity in the module challenges students to design and construct a unique piece of playground equipment.

Developer: Center for Science Education, Education Development Center, Inc.
Website: http://cse.edc.org/curriculum/insightsElem/
Contact: Karen Worth
E-mail: kworth@edc.org
To obtain materials: Kendall/Hunt Publishing Company, 800-542-6657, ext. 1042, or orders@kendallhunt.com

INSPIRES: INcreasing Student Participation, Interest and Recruitment in Engineering and Science

INSPIRES is a collaborative project between the University of Maryland Baltimore County and University of Maryland School of Medicine. It is funded through a grant from the National Science Foundation. The curriculum has five units:

- Engineering in Health Care
- Engineering and Flight
- Engineering and the Environment
- Engineering in Communications and Information Technology
- Engineering Energy Solutions

INSPIRES aims to provide students with hands-on experiences and inquiry-based learning with "real world" engineering design exercises. The materials target the ITEA Standards for Technological Literacy as well as national standards in science and mathematics. In addition, the project includes in-service training with curriculum and professional development opportunities for technology education teachers prior to classroom use. A specific objective is to increase the involvement of women and other underrepresented groups in engineering and technology by providing role modes in the classroom and developing case studies that encourage interest and participation by all groups.

Developers: UMBC and UMSM
Contact: Julia Ross
E-mail: jross@umbc.edu

Learning by Design

Learning by Design is a project-based inquiry approach to science for middle school students (grades six through eight). This initiative is housed at the Georgia Institute of Technology and funded by the National Science Foundation, the BellSouth Foundation, the James S. McDonnell Foundation, and the Robert W. Woodruff Foundation. The thrust of the project is to help students "learn science content deeply" in conjunction with developing the "skills and understanding needed to undertake solution of complex, ill-structured problems." Students study science in the context of addressing design challenges that help them make connections between their experiences, science concepts and skills, and the world around them. During the design process, they practice designing and running experiments, analyzing data and drawing conclusions, making informed decisions and justifying them with evidence, working collaboratively in a team, and communicating ideas and experiences to others. Each unit requires students to "publicly describe to their peers what they've done and how they've been reasoning, allowing the teacher and their peers to hear their reasoning and help them around hurdles." The units of instruction center on designing parachutes, erosion management systems, model vehicles, lifting devices, and subway tunnels.

Developer: Georgia Institute of Technology
Website: http://www.cc.gatech.edu/projects/lbd/home.html
Contact: Janet Kolodner
E-mail: jlk@cc.gatech.edu

LEGO® Engineering

LEGO Engineering, a collaboration between the Tufts Center for Engineering Education Outreach and LEGO Education, offers five fully developed curriculum modules based on LEGO design projects. Each module consists of a set of class sessions, with each session building upon previous learning. Modules include lesson plans, teacher resource documents, student handouts, and assessment materials. Four of the modules are designed for grades 3–5: Design a Musical Instrument: The Science of Sound, Design a Model House: The Properties of Materials, Design an Animal Model: Animal Studies, and Design a People Mover: Simple Machines. The fifth module, Robotics: Assistive Devices for the Future, is intended for grades 6–8. All five modules were developed with funding from the National Science Foundation. The LEGO Engineering website also contains a number of discrete Lego design activities, sequences of these activities, and video tutorials (podcasts).

Developers: Center for Engineering Educational Outreach, Tufts University, and LEGO Education
Website: www.legoengineering.com
Contact: Merredith Portsmore
E-mail: merredith@legoengineering.com
To obtain materials: Curriculum resources are downloadable for free from the LEGO Engineering website.

Principles of Engineering

Principles of Engineering (PoE) was a major curriculum project developed under the auspices of the New York State Education Department in 1989, field tested in 65 school districts across New York State from 1989 to 1992, and revised in 1995. PoE was a one-year high school course targeted to students in grades 11 and 12 who had completed two years of Regents level mathematics and two years of Regents level science, preferably including physics. The course included a set of hands-on, laboratory-based case studies and was taught in a laboratory setting, providing students access to tools and materials for individual, small-group, and large-group projects. The case studies addressed auto safety, ergonomics of communication technology, machine automation, structural design, and designing for people with disabilities. Engineering concepts addressed in the course included design, modeling, systems, optimization, technology-society interactions, and engineering ethics. After field testing, a National Science Foundation grant provided funding to disseminate the course nationally through a series of professional development workshops. Teachers from 20 states participated in these workshops.

Developer: New York State Department of Education
Contact: Michael Hacker
E-mail: Michael.Hacker@hofstra.edu
To obtain materials: This curriculum is out of print.

TeachEngineering.org

TeachEngineering.org is a collaborative project between faculty, students and teachers associated with five universities and the American Society for Engineering Education, with funding from the NSF National Science Digital Library. TeachEngineering.org is a searchable, web-based digital library collection populated with standards-based engineering curricula for use by K–12 teachers and engineering faculty to make applied science and math (engineering) come alive in K–12 settings. The collection provides access to a growing curricular resource of multi-week units, lessons, activities and living labs. Materials on the site are organized according to 43 subject areas, each containing related curricular units, lessons, and activities. The site allows users to determine the extent to which a given unit, lesson, or activity is consistent with individual state or national-level educational standards. Initiated by the merging of K–12 engineering curricula created by four universities, the collection continues to grow and evolve over time with new additions from other universities, and input from teachers who use the curricula in their classrooms.

Developer: Multi-university collaboration, ASEE
Website: http://www.teachengineering.org/
Contact: Jackie Sullivan
Email: jacquelyn.sullivan@colorado.edu
To obtain materials: Materials downloadable free from the website.

TECH-Know

The TECH-Know curriculum was developed by North Carolina State University and is a standards-based curriculum adapted from 20 technology-based problems issued by the Technology Student Association (TSA). There are 10 units each for middle and high school classrooms. The following topics are covered in the middle school units:

- Agricultural/Biotechnology
- Cyberspace Pursuit
- Dragster Design Challenge
- Environmental Challenge
- Flight Challenge
- Mechanical Challenge
- Structural Challenge
- Transportation Challenge
- Medical Technology Challenge
- Digital Photography

The following topics are covered in the middle school units:

- Desktop Publishing
- Film/Video Technology
- Manufacturing Prototype
- Radio Controlled Vehicle Transportation
- SciVis
- Structural Engineering
- System Control Technology
- Technology Challenge
- Medical Technologies
- Agricultural and Biotechnologies

Developer: North Carolina State University
Website: http://www.ncsu.edu/techknow/aboutproject.html
Contact: Jerianne Taylor or Rosanne White
Contact e-mail: taylorjs@appstate.edu; rwhite@tsaweb.org
To obtain materials: Materials out of print.

Technology Education: Learning by Design

Technology Education: Learning by Design is a middle school textbook developed by the Center for Technological Literacy at Hofstra University. The text uses the "informed design" approach, which encourages research, inquiry, and analysis; fosters student and teacher discourse; and cultivates language proficiency. The book contains seven units:

- The Nature of Technology
- Design for a Technological World
- Materials, Manufacturing, and Construction
- Communication and Information Technology
- Energy, Power, and Transportation
- Biological and Chemical Technology
- The Future of Technology in Society

Also available are a student activity guide, annotated teacher's edition, teacher's resource binder, test bank with ExamView CD-ROM, and a technology timeline poster.

Developer: Center for Technological Literacy, Hofstra University
Contact: David Burghardt
E-mail: M.D.Burghardt@hofstra.edu
To obtain materials: Pearson Prentice Hall, k12cs@custhelp.com or 800/848-9500

What is Engineering?

What is Engineering? originated as an introduction to engineering class offered to first semester freshmen at Johns Hopkins University (JHU). JHU adapted the course so it could be taught as a summer program aimed at rising high school juniors and seniors as well as incoming college freshmen. The class is an intensive four-week experience where students actively participate in hands-on team activities including laboratory experiments and virtual Internet-based simulations while attending college-level lectures related to these activities. Field trips to local companies that employ engineers and informational sessions on college and career choices are integrated into the course schedule. The curriculum links math, science, and engineering concepts to practical problems as a means of teaching students the essential problem-solving skills required to be a successful engineer. Students may earn college credit from JHU for participating in the class. Course locations include Maryland, California, New Mexico, and Pennsylvania. In California, several of Engineering Innovations' sites are offered in partnership with MESA (Mathematics Engineering Science Achievement) program.

Developer: Johns Hopkins University, Whiting School of Engineering
Contact: Lindsay Carroll (Program Manager) or Michael Karweit (Academic Director)
E-mail: lindsay.carroll@jhu.edu or mjk@jhu.edu
To obtain materials: http://engineering-innovation.jhu.edu

A World in Motion® (High School)

A World In Motion® (High School), developed by SAE International, is an activities-based curriculum focused on electricity and electronics. Student teams conduct in-depth experiments involving transistors and semiconductors, analog integrated circuits, and digital integrated circuits. As with other World in Motion® curricula, the high school program requires teachers to work with a volunteer classroom mentor from a science, engineering or technical profession. World in Motion® has the goal of increasing student interest in math and science. SAE International provides the AWIM curriculum and materials at no cost to classroom teachers who complete a Statement of Partnership.

Developer: SAE International
Website: http://www.sae.org/exdomains/awim/
Contact: Matt Miller
E-Mail: matt.miller@sae.org
To obtain materials: AWIM hotline, 1-800-457-2946

Appendix C

Curriculum Projects— Detailed Analyses

Building Math

Institution

Museum of Science
Science Park
Boston, MA 02114
Tel: (617) 589-0230
Fax: (617) 589-4448
E-mail: eie@mos.org
Web site: http://www.mos.org/eie/index.php

Leaders

Peter Y. Wong, National Center for Technological Literacy
Barbara M. Brizuela, Tufts University

Funding

GE Foundation

Grade Level

6-8

Espoused Mission

"…to involve math students in collecting and analyzing their own data in hands-on investigations integrated with engineering design activities."

Organizing Topics

The curriculum features the following three units of instruction:

- *Everest Trek* is a sixth-grade unit presented in the context of scaling the world's tallest peak. It engages students in designing a well-insulated coat, a ladder bridge to span a crevasse, and an emergency zip-line transportation system.
- *Stranded!* is a seventh-grade unit presented in the context of being marooned on a deserted South Pacific island. It engages students in designing a shelter, a water collection device, and a strategy for loading and unloading a canoe.
- *Amazon Mission* is an eighth-grade unit that is presented in the context of helping indigenous people in Brazil. It engages students in designing an insulated carrier that will keep medicine cool, a water filtration system, and a strategy for tempering the spread of an influenza virus.

Format

The Building Math program comprises three spiral-bound books. Each book represents a unit of instruction for a given grade level that features three distinct design challenges. Every design challenge features a series of lessons that follow an eight-step engineering design process that is outlined at the beginning of each unit. The books have reproducible handouts, rubrics, and self-assessment checklists for students.

Pedagogical Elements

The following pedagogical elements can be found in each unit.

- All the units and their design problems are framed in authentic sounding contexts that middle school students should find interesting and challenging.
- Every unit begins with a series of exercises that can be used to assess or address prerequisite knowledge and skills.
- Each unit also begins with a team-building activity that asks small groups of students to complete a task that cannot be achieved without benefit of cooperation.
- Each design challenge includes a series of lessons (or tasks) that use an engineering design process to construct knowledge in small and sequential increments.
- The lessons (or tasks) feature objectives, implementation procedures, guiding questions, possible answers, and support materials for students.
- The instruction is very Socratic in nature (i.e., posing questions, addressing questions).
- Most of the learning activities involve inquiry. More specifically, developing solutions to the problems posed involves making observations, taking measurements, gathering data, interpreting data, generalizing patterns, applying patterns to the solution, building and testing models, and reflecting on the quality of the solutions as well as the learning process.
- Each unit includes a very detailed and comprehensive rubric for facilitating student assessment.

Maturity

The GE Foundation funded the project for three years. The materials underwent two years of pilot testing and refinement during that period of time. The final units are currently available through Walch Publishing. *Stranded* and *Everest Trek* bear a 2006 copyright and *Amazon Mission* shows a 2007 copyright.

Diffusion & Impact

The series was pilot tested with hundreds of students in ten Massachusetts schools over the course of two years. This process produced positive testimony from pilot-site teachers. For example, Joseph McMullin at the Mystic Valley Regional Charter School in Malden, Mass., was quoted as stating: "In addition to relating math concepts to the physical world, my students improved their communication, graphing, critical thinking, and problem solving skills. Students especially enjoyed designing their own test."

An analysis of teacher testimony, samples of student work, direct observations, and videotape data supported the underlying premise of the curriculum. More specifically, the study of mathematics can be enriched with contextual units of instruction that employ hands-on learning activities that require students to apply a variety of math concepts and skills while following an engineering design process to solve problems. The collection and analysis of their data during engineering design activities helped math students develop and demonstrate algebraic thinking skills.

Initiative **Building Math**

Title

Amazon Mission

Broad Goals

During *Design Challenge 1: Malaria Meltdown*, students will:
- Calculate and interpret the slope of a line.
- Graph a compound inequality.
- Conduct two controlled experiments.
- Collect experimental data in a table.
- Produce and analyze a line graph that relates two variables.
- Distinguish between independent and dependent variables.
- Determine when it's appropriate to use a line graph to represent data.
- List combinations of up to five layers of two different kinds of materials.
- Draw a three-dimensional object and its net.
- Find the surface area of a three-dimensional object.
- Apply the engineering design process to solve a problem.

During *Design Challenge 2: Mercury Rising*, students will:
- Calculate the surface area of a sphere using a formula.
- Solve a multistep problem.
- Convert measurement units (within the same system).
- Use proportional reasoning.
- Write a compound inequity statement.
- Graph and analyze the relationship between two variables.
- Design and conduct a controlled experiment.
- Apply the engineering design process to solve problems.

During *Design Challenge 3: Outbreak*, students will:
- Identify and extend exponential patterns.
- Generalize and represent a pattern using symbols.
- Graph simulation data and describe trends.
- Calculate compound probabilities.
- Use a computer model.
- Apply the engineering design process to solve a problem.

Salient Concepts & Skills

<u>Math</u>
- making line graphs
- heuristics (rules of thumb)
- independent variables

<u>Science</u>
- climate zones
- tropical
- subtropical
- temperature
- cold

<u>Technology</u>
- shabono
- model
- prototype

- dependent variables
- X-axis
- Y-axis
- scale
- scaling axes
- proportional reasoning
- exponential patterns
- linear patterns
- rounding up
- rounding down
- interpreting line graphs
- ratios
- converting units
- equivalent fractions
- cross-multiply
- recursive equations
- Cartesian plane
- calculate the slope of a line
- graph a compound inequality
- sphere
- polar
- rate of heat transfer is based on differences in temperature
- controlled experiment
- extinct
- endangered
- indigenous
- virus
- mercury
- malaria
- rain forest

Engineering

The materials introduced the following ideas about the nature of engineering.

- Engineers play a part in the design and construction of things like houses, roads, cars, televisions, and phones.
- Engineering is “the application of math and science to practical ends, such as design or manufacturing.”
- All engineers use the engineering design process to help them solve problems in an organized way.
- The engineering design process includes defining the problem, conducting research, brainstorming ideas, choosing the best solution, building a model, testing and evaluating a prototype, communicate the design to others, and redesigning the solution.
- The engineering design process “is meant to be a set of guidelines” for solving technical problems.
- Engineers may not always follow all the steps in the design process in the same order every time.
- Engineers communicate their designs to others to solicit

feedback and ways to improve the design.
- Engineers often go back to an earlier step in the design process during the "redesign" process.
- The solution to a problem might go through several cycles of the design process before it is ready for "real-world use."
- A full-scale working prototype may be constructed once the design has gone through several cycles of the design process.
- Constraints are "limiting factors" that engineers need to consider during the design process.
- Criteria are the specifications that need to be met for the solution to be successful.

Prominent Activities

The unit starts with a team-building activity and a review of prerequisite math skills.
1. Read and analyze a poem (The Law of the Wolves) and discuss how it relates to working in teams.
2. Review basic mathematics skills that will be utilized during the unit (e.g., make a line graph, find the slope of two points, calculate surface area).
3. Review basic math skills related to converting units of measure.
4. Compose and use heuristics or rules of thumb.

Introducing the Engineering Design Process engages students in the following activities to develop a basic understanding of the nature of engineering.
1. Read background information about the Yanomami people (i.e., their way of life, the threats to their existence).
2. Discuss the questions: What is an engineer? What does an engineer do?
3. Put cards describing the basic steps of the engineering design process into a logical sequence.
4. Match a series of events related to making and testing sails for a boat race with the basic steps in the design process.

Design Challenge 1: Malaria Meltdown engages students in the following activities to design a container for transporting medicine that has to be kept cool in a tropical climate.
1. Read a scenario that contains the problem to be solved, the criteria that needs to be met, and the material constraints.
2. Analyze a graph containing data (temperature over time) that depicts the performance of the current container for transporting the medicine.
3. Gather, graph, and interpret data regarding the rate of heat conduction for specific materials (corrugated cardboard, foam board, bubble wrap, aluminum foil).

4. Gather, graph, interpret, and present data regarding the rate of heat conduction for combinations of multiple materials.
5. Utilize research findings and material costs to develop a dimensioned sketch for a potential medicine-carrier design.
6. Select the best design from those developed by the members of the team through discussion and consensus.
7. Sketch a three-dimension representation of the selected design that includes dimensions and labels the materials used.
8. Sketch a “net” (a.k.a., development) of the selected design (a drawing that illustrates what a three-dimensions object would look like if it were spread out in the form of a two-dimensional layout).
9. Calculate the area of the materials needed to construct the selected design and use the results to determine the cost of making the final product.
10. Build a prototype for the selected design.
11. Use pieces of scrap to test the heat transfer rate of the materials used to make the container.
12. Test the ability of the container to protect a fragile object (an egg) by dropping the container to the floor from a height of one meter.
13. Determine the cost of making the actual container (a scaled-up version).
14. Present the final design to the class (e.g., how it performed in relation to the design constraints and criteria, the advantages of the design, the disadvantages of the design, the cost and profit potential of the design).
15. Reflect on the design and describe how it might be improved through redesign.
16. Conduct a self-assessment of the contributions made by each member of the team.
17. Reflect on how well the team worked together on the project (e.g., what went well, what did not work well, what can be improved).

Design Challenge 2: Mercury Rising engages students in the following activities to design a water filtration device that removes mercury from river water.

1. Read a scenario that contains the problem to be solved, the criteria that needs to be met, and the material constraints.
2. Calculate the surface area of spheres with different diameters.
3. Determine the most cost-effective package of spheres to achieve a desire amount of total surface area.
4. Convert the units of measurement for minimum flow rate from 540 liters per day to the number of seconds need to filter 250 milliliters.

5. Convert the units of measurement for maximum flow rate from one liter per minute into the number of seconds need to filter 250 milliliters.
6. Gather, graph, and interpret data for the amount of time required for 250 milliliters of water to pass through different diameter holes.
7. Conduct a controlled experiment to gather, graph, and interpret data regarding another factor that could affect the amount of time required for 250 milliliters of water to pass through a filter.
8. Sketch a potential design for a water filter that shows where water will enter, be filtered, and subsequently exit. Use the research results to define how large the exit opening needs to be.
9. Select the best design from those developed by the members of the team through discussion and consensus.
10. Develop a drawing for the selected design that shows dimensions, identifies the materials used, and describes the role that each material plays in the filtering process.
11. Build a model filter based on the selected design.
12. Test the amount of time it takes for 250 milliliters of water to pass through the filter.
13. Present the final design to the class (e.g., how it performed in relation to the design constraints and criteria, the advantages of the design, the disadvantages of the design, what materials would be used to make a real filter).
14. Reflect on the design and describe how it might be improved through redesign.
15. Conduct a self-assessment of the contributions made by each member of the team.
16. Reflect on how well the team worked together on the project (e.g., what went well, what did not work well, what can be improved).

Design Challenge 3: Outbreak engages students in the following activities to design a virus intervention plan to contain the spread of the flu.

1. Read a scenario that contains the problem to be solved, the criteria that need to be met, and the material constraints.
2. Conduct a simulation to illustrate exponential rate at which a virus can spread and infect a population.
3. Calculate the rate at which a virus would spread if a doctor were able to treat one member of the population per day.
4. Determine the rate at which a virus would spread if every member of the population wore a filtration mask that reduced the risk of infection by 50 percent.

5. Use the results to graph the rate at which people become infected if there is no treatment, if there is one doctor, and if everyone wears a mask.
6. Calculate the chance of infection based on different combinations of interventions (e.g., the use of air filtration masks and antiviral hand gel, the use of antiviral hand gel and vaccinations).
7. Develop intervention plans that will reduce the rate of infection to less than 25 percent during a 30-day window of time.
8. Discuss the advantages and disadvantages associated with each team member's intervention plan.
9. Identify the best intervention plan by determining what the individual plans have in common, identifying the best parts of the individual plans, and combining the best parts into one design.
10. Test the final intervention plan using a computer simulation model (an applet).
11. Use the results of the computer simulations to redesign the intervention plan and make it as cost effective as possible.
12. Present the refined intervention plan to the class (e.g., how it performed in relation to the design constraints and criteria, the advantages of the plan, the disadvantages of the plan, how would it be different if more money were available, how would it work with a larger population).
13. Reflect on the design and describe how it might be improved through redesign.
14. Conduct a self-assessment of the contributions made by each member of the team.
15. Reflect on how well the team worked together on the project (e.g., what went well, what did not work well, what can be improved).

Initiative **Building Math**

Title

Everest Trek

Broad Goals

During *Design Challenge 1, Geared Up*, students will:
- Interpret a line graph.
- Locate and represent the range of acceptable values on a graph to meet a design criterion.
- Extrapolate data based on trends.
- Conduct two controlled experiments.
- Collect experimental data in a table.
- Produce and analyze graphs that relate two variables.
- Determine when it's appropriate to use a line graph or a scatter plot to represent data.
- Apply the engineering design process to solve a problem.

During *Design Challenge 2, Crevasse Crisis*, students will:
- Use proportional reasoning to determine dimensions for a scale model.
- Use physical and math models.
- Conduct two controlled experiments.
- Collect experimental data in a table.
- Produce and analyze graphs that relate two variables.
- Compare rates of change (linear versus non-linear relationships).
- Distinguish between independent and dependent variables.
- Apply the engineering design process to solve a problem.

During *Design Challenge 3, Sliding Down*, students will:
- Conduct a controlled experiment.
- Measure angles using a protractor.
- Compare and discuss appropriate measures of central tendency (mean, median, mode).
- Apply the distance-time-speed formula.
- Produce and analyze a graph that relates two variables.
- Locate and represent the range of acceptable values on a graph to meet a design criteria [criterion].
- Distinguish between independent and dependent variables.
- Apply the engineering design process to solve a problem.

Salient Concepts & Skills

Math	Science	Technology
• making line graphs • equal intervals	• icefall • controlled experiment	• insulator • thermometer

- cross-multiplying
- heuristics (rules of thumb)
- data extrapolation based on trends
- complete data tables
- application for line graphs versus scatter plots
- identifying variables
- independent variables
- dependent variables
- X-axis
- Y-axis
- proportional reasoning
- scale
- non-linear patterns
- linear patterns
- measuring angles with a protractor
- interpreting line graphs
- ratios
- measures of central tendency (mean, median, mode
- Cartesian plane
- calculate the slope of a line
- calculating speed
- centimeters
- temperature
- hypothermia
- compression
- tension
- strength
- modulus of elasticity
- tensile strength
- ultimate tensile strength
- altitude
- density of air
- altitude sickness
- gravity
- acclimatize
- altitude sickness
- insulator
- materials for clothing (wool, fleece, nylon)
- layering materials
- prototype
- model
- beams (e.g., T-beam, I-beam, square channel)
- bridge
- ladder bridge
- zip-line

Engineering

The materials introduced the following ideas about the nature of engineering.

- Engineers play a part in the design and construction of things like houses, roads, cars, televisions, and phones.
- Engineering is "the application of math and science to practical ends, such as design or manufacturing."
- All engineers use the engineering design process to help them solve problems in an organized way.

- The engineering design process includes defining the problem, conducting research, brainstorming ideas, choosing the best solution, building a model, testing and evaluating a prototype, communicate the design to others, and redesigning the solution.
- The engineering design process "is meant to be a set of guidelines" for solving technical problems.
- Engineers may not always follow all the steps in the design process in the same order every time.
- Engineers communicate their designs to others to solicit feedback and ways to improve the design.
- Engineers often go back to an earlier step in the design process during the "redesign" process.
- The solution to a problem might go through several cycles of the design process before it is ready for "real-world use."
- A full-scale working prototype may be constructed once the design has gone through several cycles of the design process.
- "Engineers use a lot of math in their work."
- "Using statistics and probability, engineers can test their hypotheses by analyzing data" from samples.
- "Engineers use data analysis, such as filtering and coding information, to describe, summarize, and compare the data with their initial hypotheses."
- "Engineers use modeling and simulations to predict the behavior and performance of their designs before they are actually built."
- Constraints are "limiting factors" that engineers need to consider during the design process.
- Criteria are the specifications that need to be met for the solution to be successful.

Prominent Activities

The unit starts with a team-building activity and a review of prerequisite math skills.

1. Use a simple device made out of a rubber band and segments string to stack cups in a limited amount of time without touching them directly and discuss how it relates to working in teams.
2. Review basic mathematics skills that will be utilized during the unit (e.g., interpreting a line graph, making a line graph, measuring length in centimeters, adding and multiplying decimals).
3. Compose and use heuristics or rules of thumb.

Introducing the Engineering Design Process engages students in the following activities to develop a basic understanding of the nature of engineering.

1. Read background information about climbing Mount Everest

(i.e., the challenges associated with climbing, the gear that is used, the importance of teamwork).
2. Study a simple map of the southern route up Mount Everest and relate the height and distances to more familiar things.
3. Discuss the questions: What is an engineer? What does an engineer do?
4. Put cards describing the basic steps of the engineering design process into a logical sequence.
5. Match a series of events related to making and testing sails for a boat race with the steps in the design process.

Design Challenge 1: Gearing Up engages students in the following activities to design a coat that protect team members from the harsh weather conditions on Mount Everest.

1. Read a scenario that contains the problem to be solved, the criteria that need to be met, and the material constraints.
2. Interpret a line graph illustrating heat loss under simple cotton clothing and relate the pattern to the design problem.
3. Determine a range of values for meeting the design criteria, explain the relationship between time and temperature, and describe the rate of change in the data.
4. Conduct a controlled experiment to determine the insulation qualities of different clothing materials (e.g., denim, fleece, nylon, wool).
5. Develop a line graph illustrating the relationship between the independent variable (time) and the dependent variables (temperature) for the four materials.
6. Conduct a controlled experiment to determine the potential benefit of layering a given materials.
7. Develop a bar graph illustrating the relationship between the independent variable (number of layers) and the dependent variables (temperature after 30 seconds).
8. Review the criteria and constraints associated with the design problem (i.e., minimum insulation performance, maximum material thickness, keeping the cost as low as possible).
9. Brainstorm potential coat designs (e.g., materials, number of layers, cost).
10. Select the best design from those developed by the members of the team through discussion and consensus.
11. Draw sketches of each team's coat designs.
12. Assemble swatches of material to represent the design of their coats (prototypes).
13. Test the insulation quality of their designs (layers of different materials) using ice packs.
14. Reflect on the design and describe how it might be improved through redesign.

15. Conduct a self-assessment of the contributions made by each member of the team.
16. Reflect on how well the team worked together on the project (e.g., what went well, what did not work well, what can be improved).

Design Challenge 2: Crevasse Crisis engages students in designing a bridge that can be used to cross a crevasse in the ice.

1. Read a scenario that contains the problem to be solved, the criteria that need to be met, and the material constraints.
2. Determine the basic dimensions for building scale models.
3. Brainstorm factors that affect the strength of a bridge and how a craft stick will react to a force applied to its thickness versus it width.
4. Test their ideas about the strength of a craft stick relative to it orientation to a force (applied to its thickness versus its width).
5. Conduct controlled experiments to determine how the width of foam strips affect their strength when spanning the distance between two books while supporting the weight of a penny.
6. Develop a line graph illustrating the relationship between the independent variable (width of the foam strips) and the dependent variables (the amount of deflection under the load).
7. Conduct controlled experiments to determine how the thickness of foam strips affect their strength when spanning the distance between two books while supporting the weight of three pennies.
8. Develop a line graph illustrating the relationship between the independent variable (thickness of the foam strips) and the dependent variables (the amount of deflection under the load).
9. Build and test the strength of different shapes of beams (e.g., I-beam).
10. Individually brainstorm and sketch potential designs for bridges.
11. Select the best design from those developed by the members of the team through discussion and consensus.
12. Draw sketches of each team's bridge designs.
13. Build models for each team's bridge design (prototype).
14. Test the strength their bridge designs by spanning the distance between two books, suspending a cup from the middle, and adding pennies until it fails.
15. Reflect on the design and describe how it might be improved through redesign.
16. Conduct a self-assessment of the contributions made by each member of the team.
17. Reflect on how well the team worked together on the project (e.g., what went well, what did not work well, what can be

improved).

Design Challenge 3: Sliding Down engages students in designing a zip-line transportation system to bring a sick teammate down the mountain.

1. Read a scenario that contains the problem to be solved, the criteria.
2. Conduct controlled experiments to determine how the speed of something (a drinking straw) traveling down a zip-line (fishing line) is affected by the angle of descent.
3. Review measures of central tendency (i.e., mean, median, mode) and select the best representation to decrease the effects of human error (using the median).
4. Calculate the average speed for the straws traveling down the line by dividing the amount of time required to travel the length of the line by the length of the line.
5. Develop a line graph illustrating the relationship between the independent variable (angle of the line) and the dependent variables (speed of the straw).
6. Brainstorm factors that can affect the stability and safety of the zip-line transportation system.
7. Review the design criteria and constraints (speed, safety, return) and draw designs for the zip-line transportation systems.
8. Select the best design from those developed by the members of the team through discussion and consensus.
9. Draw sketches of each team's zip-line transportation systems.
10. Build models for each team's zip-line transportation system (prototypes).
11. Test the zip-line transportation systems using toy figures.
12. Reflect on the design and describe how it might be improved through redesign.
13. Conduct a self-assessment of the contributions made by each member of the team.
14. Reflect on how well the team worked together on the project (e.g., what went well, what did not work well, what can be improved).

Initiative **Building Math**

Title

Stranded

Broad Goals

During *Where Are We*, students will:

- Interpret a scale on a map.
- Use proportional reasoning to calculate actual distance and drawn distance on a map according to a scale.
- Use the relationship speed = distance/time to find one quantity given the other two quantities.
- Solve a multistep problem.
- Use a ruler.

During *Design Challenge 1, A Storm Is Approaching!*, students will:

- Identify similar three-dimensional objects.
- Identify corresponding dimensions of similar objects.
- Use a ruler to measure three-dimensional objects.
- Calculate surface area and volume of rectangular prisms.
- Analyze a table of values for patterns.
- Generalize patterns using symbols.
- Use a scale to calculate the amount of materials available for building a scale model.
- Apply the engineering design process to solve a problem.

During *Design Challenge 2, We Need Water!*, students will:

- Find the area of an irregular two-dimensional shape using strategies for finding the areas of triangles, rectangles, and parallelograms.
- Use a ruler to measure three-dimensional objects (cylinders and rectangular prisms).
- Calculate the surface area and volume of three-dimensional objects.
- Analyze a table of values for patterns.
- Make and test conjectures about the relationship between surface area and volume, and dimensions and volume.
- Produce and analyze line graphs that represent the relationship between two variables.
- Apply the engineering design process to solve a problem.

During *Design Challenge 3, Balancing Act!*, students will:

- Investigate how the weight and distance of objects on a horizontal platform with a center fulcrum relate physically and mathematically to keep the platform balanced.

- Generalize and represent a pattern using symbols.
- Apply the engineering design process to solve a problem.

Salient Concepts & Skills

Math	Science	Technology
• scale • heuristics (rules of thumb) • scale (on a map) • proportional reasoning • use a formula to calculate an unknown quantity based on two known quantities • linear measurement (centimeters) • three-dimensions • detect patterns in data • ratio • nets (or developments) • calculate surface area (square, rectangles, trapezoids, triangles parallelograms) • square centimeters • calculate area for an irregular shape • calculate volume for cylinders and square boxes • radius • circumference • relationship between surface area and volume • relationship between dimensions and volume	• balance • fulcrum	• shelter • model • prototype • rainwater collector • canoe

- plotting a double-line graph
- interpreting a double-line graph
- cubic centimeters
- milliliters
- relationship of weight and distance in the context of balance
- physical and mathematical representations of balance.

Engineering

The materials introduced the following ideas about the nature of engineering.

- Engineers play a part in the design and construction of things like houses, roads, cars, televisions, and phones.
- Engineering is "the application of math and science to practical ends, such as design or manufacturing."
- All engineers use the engineering design process to help them solve problems in an organized way.
- The engineering design process includes defining the problem, conducting research, brainstorming ideas, choosing the best solution, building a model, testing and evaluating a prototype, communicate the design to others, and redesigning the solution.
- The engineering design process "is meant to be a set of guidelines" for solving technical problems.
- Engineers may not always follow all the steps in the design process in the same order every time.
- Engineers communicate their designs to others to solicit feedback and ways to improve the design.
- Engineers often go back to an earlier step in the design process during the "redesign" process.
- The solution to a problem might go through several cycles of the design process before it is ready for "real-world use."
- A full-scale working prototype may be constructed once the design has gone through several cycles of the design process.
- Constraints are "limiting factors" that engineers need to consider during the design process.
- Criteria are the specifications that need to be met for the solution to be successful.

Prominent

The unit starts with a team-building activity and a review of

Activities prerequisite math skills.

1. Address a problem related to retrieving a limited number of survival items from a stranded shipwreck yacht before it sinks.
2. Discuss how solving the problem relates to working in teams.
3. Review basic mathematics skills that will be utilized during the unit (e.g., interpret a scale on a map; solve for speed, distance or time given two know quantities, measure in centimeters, calculate surface area).
4. Compose and use heuristics or rules of thumb.

Where Are We engages students in using given pieces of information along with a map featuring a scale to determine the location of a deserted island.

Introducing the Engineering Design Process engages students in the following activities to develop a basic understanding of the nature of engineering.

1. Read background information about being stranded on a deserted island.
2. Discuss the questions: What is an engineer? What does an engineer do?
3. Put cards describing the basic steps of the engineering design process into a logical sequence.
4. Match a series of events related to making and testing sails for a boat race with the steps in the design process.

Design Challenge 1: A Storm is Approaching engages students in the following activities to design a shelter for protection from the wind and rain.

1. Read a scenario that contains the problem to be solved, the criteria that need to be met, and the material constraints.
2. Investigate the concept of scale relative to one-dimensional, two-dimensional, and three-dimensional objects (e.g., width, depth, height, area, volume).
3. Identify the scale that will be used to make a model shelter and determine the dimensions of the materials that will be used to make the model.
4. Explore potential configurations for a simple shelter and discuss their advantages and disadvantages based on the available materials.
5. Individually brainstorm and sketch potential designs for a simple shelter.
6. Select the best shelter design from those developed by the members of the team through discussion and consensus.
7. Draw sketches of each team's bridge designs.
8. Build models for each team's shelter design (prototypes).

9. Test the sturdiness, spaciousness, and water-resistance of their model shelters.
10. Reflect on the design and describe how it might be improved through redesign.
11. Conduct a self-assessment of the contributions made by each member of the team.
12. Reflect on how well the team worked together on the project (e.g., what went well, what did not work well, what can be improved).

Design Challenge 2: We Need Water engages students in the following activities to design a rainwater collector.

1. Read a scenario that contains the problem to be solved, the criteria that need to be met, and the material constraints.
2. Calculate the area of an irregular shape using multiple strategies.
3. Explore the relationship between area and volume in the context of making and testing two cylinders with the same surface area.
4. Make a line graph illustrating the relationships between cylinder radius versus volume and cylinder height versus volume.
5. Determine the optimal height and diameter for a cylinder with a given amount of surface area to achieve the greatest volume.
6. Measure square boxes and calculate their surface area and volume.
7. Determine the relationship between the height and width of boxes with the same surface area relative to their volume.
8. Individually brainstorm and sketch potential designs for a water collection system.
9. Select the best design for a water collection system from those developed by the members of the team through discussion and consensus.
10. Draw sketches of each team's designs for a water collection system.
11. Determine if they have enough material for their designs by calculating its surface area.
12. Build models for each team's water collection system (prototypes).
13. Test the strength, integrity, stability, and capacity of their water collection systems.
14. Reflect on the design and describe how it might be improved through redesign.
15. Conduct a self-assessment of the contributions made by each member of the team.
16. Reflect on how well the team worked together on the project

(e.g., what went well, what did not work well, what can be improved).

Design Challenge 3: Balancing Act engages students in the following activities to design a strategy for loading, balancing, and unloading objects in an unstable canoe.

1. Read a scenario that contains the problem to be solved, the criteria that need to be met, and the material constraints.
2. Investigate, both mathematically and physically, how the weight and distance of objects on either side of a central fulcrum affect balance.
3. Individually brainstorm a strategy for loading and balancing people and goods in a 10-meter canoe.
4. Select the best loading strategy from those developed by the members of the team through discussion and consensus.
5. Organize weights that will be placed on a scale to represent a strategy for loading and balancing people and goods in a 10-meter canoe.
6. Test strategies for loading and balancing people and goods in a 10-meter canoe by placing weights on a scale in a step-by-step manner.
7. Reflect on the design and describe how it might be improved through redesign.
8. Conduct a self-assessment of the contributions made by each member of the team.
9. Reflect on how well the team worked together on the project (e.g., what went well, what did not work well, what can be improved).

Salient Observations

Building Math was developed through a collaborative effort between the Museum of Science, Boston, and Tufts University with funding from the GE Foundation's "Math Excellence" initiative. The project was launch in response to the "national concern that high schools are not graduating enough students with the necessary math skills to study mathematics, engineering, science, or technology in college." The authors sought to put a dent in this problem by increasing both mathematics and engineering content at the middle school level in the interest of establishing a stronger foundation for the study of mathematics at the secondary and post-secondary levels. This initiated a three-year effort to provide professional development for middle school teachers in the area of mathematics and engineering and to develop an innovative approach to teaching mathematics by integrating it with engineering.

The basic design of the curriculum uses contextual learning to engage students in applying a variety of math concepts and skills while following an engineering design process to solve problems. The curriculum comprises three units of instruction, one for each grade in most middle school settings (i.e., sixth, seventh, eighth). Each unit is framed in a fictional context that uses a remote setting featuring a unique culture to pose three design challenges. To meet the challenges students must work in teams to employ algebraic reasoning, investigate linear and non-linear relationships, identify and generalize patterns, and work with variables. The problem-solving process requires students to collect and analyze data. They also use physical and mathematical models to uncover quantitative patterns and explore natural phenomena. During the course of the program, students also use both kinds of models to represent, test, and convey their design ideas.

Engineering

The materials define engineering as "the application of math and science to practical ends, such as design or manufacturing." This definition is consistent with the nature of the activities that students are asked to perform. For the most part, engineering is portrayed as a process that is used to solve problems. Little if any attention is given to the different fields of engineering that can be associated with the problems that students are asked to solve. The most deliberate treatment of engineering can be found in the introduction of each unit. For the most part, engineering is equated with a process for solving problems.

Design

All three units use an engineering design process that features eight basic steps. The model utilizes the following themes to orchestrate the design process.

1. Define the problem
2. Conduct research
3. Brainstorm ideas
4. Chose the best solution
5. Build a model or prototype
6. Test the prototype
7. Communicate the design
8. Redesign the prototype

Although the materials clearly stress engineering design is not a linear process, the learning experiences that are based on the engineering design process are structured in a very linear way. Furthermore, the design process is very repetitive across the units and their challenges. However, it is important to note that the units are designed to be implemented across three years of instruction.

The richest portions of the design process are the steps that involve conducting research and testing the final design. The other steps follow a simple formula and even use the same wording. One of the final steps in the design process asks students to reflect on their solutions and consider ways to make them better under the auspices of redesign.

Analysis

The lessons and learning activities engage students in doing a variety of analyses. The richest and most prominent forms of analysis in the materials involve interpreting data and uncovering quantitative patterns and relationships. The materials also ask students to conduct analyses in the contexts of solving engineering problems. More specifically, students perform analyses in conjunction with testing, evaluating, and reflecting upon their designs.

Constraints

The materials define constraints as “limiting factors” that engineers need to consider during the design process. Most of the constraints are presented in the form of limitations regarding the materials that can be used to solve the problem. Another factor that tempers the designs is financial considerations. In most cases, students are simply asked to solve the problem at the lowest cost possible while still achieving performance expectations. In other cases, students are given a finite amount of funds to work with.

Modeling

The materials define a model as “an object that has been built to represent another, usually larger, object.” Most of the design challenges require students to use simple materials to construct physical models that can be used to represent and/or test their design ideas.

The materials also engage students in using models that go beyond this definition. Several design challenges involve mathematical models that range from simple formulas to relatively complex paradigms. For example, students are presented a simple formula for balancing loads on either side of a fulcrum in *Balancing Act*. This model is used to make decisions about the location of items in a fictitious canoe that are subsequently tested on a simple balance. Students also use mathematical modeling in *Outbreak* to work with compound probabilities that inform the development of a strategy for containing the spread of a flu virus. The intervention plan is then tested using a computer model (the applet).

Both models and modeling play integral roles in the learning activities. However, the concepts of models and modeling are given little formal attention in the instruction beyond the definition that is presented in the glossary of terms.

Optimization

The concept of optimization is not targeted directly in the goals, objectives, or glossary of important terms. However, the concept is embedded in all the design challenges by virtue of the fact that the challenges require balancing the performance of a design with its cost. More specifically, the problems are posed in such a way that the pursuit of performance is mitigated by the need to minimize the cost of materials. Conversely, the quest for economy is tempered by the need to achieve performance goals.

The concept of optimization is also addressed through mathematics. This is especially prominent in *Outbreak,* the third challenge in the *Amazon Mission*. It asks students to design an intervention plan to contain the spread of a flu virus. More specifically, given limited resources, their task is to reduce the rate of infection to less than 25 percent within a 30 days. This is accomplished by configuring the most advantageous combination of doctor’s care, vaccinations, air filtration masks, and antiviral hand gel.

Systems

The word systems appears in several design challenges that require configuring parts that must work together in a purposeful way. For example, in *Stranded* students must design, model, and test a rainwater collection system using materials that represent pieces of wreckage from their crashed airplane. Similarly, *Everest Trek* challenges student to configure a zip-line transportation system. *Amazon Mission* asks students to design a filtration system that will remove mercury from the water supply at a given rate.

It can be argued all the solutions to the design challenges are essentially systems. Most problems that have to be solved involve bringing together parts that need work together in interdependent ways to perform a task that the individual parts alone cannot perform. Furthermore, most of the systems can be designed, analyzed, and discussed in terms of their inputs, processes, and outputs. However, the concept of systems and systems thinking is not addressed in a direct and overt manner.

Science

Most of the emphasis in all units is on mathematics. However, consistent with the nature of engineering, the units also involve the application of science. For example, several units require students to conduct "controlled experiments" with independent and dependent variables. For example, in *Everest Trek* students have to determine how the thickness of foam strips affects their strength (a.k.a., deflection) while spanning the distance between two books under the load of three pennies. Another challenge in the same unit requires students to determine the effect that the angle of a fishing line has on the speed of a straw traveling down the line in the context of developing a zip-line transportation system.

The challenges also address science concepts. For example, both *Amazon Mission* and *Everest Trek* involve thinking about climate and temperature. The *Crevasse Crisis* problem in *Everest Trek* has students exploring the concepts of compression, tension, modulus of elasticity, tensile strength, and more. *Stranded* targets the concept of balance relative to weight and distance on either side of a fulcrum.

There are instances were the treatment of key science concepts is flawed or incomplete. For example, *Amazon Mission* challenges students to design an insulated container/carrier that will protect medicine from the imposing topical heat. The problem statement and subsequent investigations include numerous references to "keeping heat out." The frequency and use of this phrase suggests a linear interpretation of heat transfer that is akin to popular misconceptions in contrast to a more dynamic representation of heat transfer. Furthermore, very little attention is given to the actual science of heat transfer (i.e., conduction, convection, radiation).

The investigations that inform the selection and configuration of materials to "keep the heat out" emphasize minimizing conduction. The lack of attention given to convection and radiation is problematic given the nature of the materials students were asked to test and subsequently use in their designs. For example, the inclusion of aluminum foil introduces some complexity to activities that are designed to be simple. Although aluminum foil is not a good insulator from a conduction point of view, it can be a very effective material in reflecting radiant heat. Thus, in combination with other materials, it can play an important role in an insulation system, especially one that is configured to keep something cool in a tropical context.

The investigations do not account for this valid application of the material. However, observations made during pilot testing indicate that there was a lot of confusion surrounding the use of the material. Anecdotes from classrooms suggest students had an intuitive sense that foil could contribute something to the solution to the problem. Furthermore, it was an attractive material because it was portrayed as inexpensive. More importantly, pilot testing indicated that the students' experience of conflicting test results was associated with the use of foil that could not be accounted for in the absence of a richer treatment of the science involved.

The curriculum authors attributed some of the students' inclinations to use aluminum foil in their designs to its use in other applications (e.g., food packaging). In reality, the fact that reflective materials are often used when keeping something hot or cold is an issue. For example, it is likely students have seen it used in construction projects. Modern homes are often enclosed with rigid foam insulation with a foil facing to reflect radiant heat away from the house during the summer months. Thus the desire to transfer this kind of observation to the making of an insulated container is understandable. A more in depth treatment of the science associated with heat transfer was needed to legitimize the inclusion of aluminum foil and to inform it use.

Mathematics

Math concepts and skills dominate the objectives and learning activities. The study of mathematics is clearly the primary focus of all three units. Each unit requires students to use a variety of math concepts and skills in conjunction with designing viable solutions to problems. The emphasis on using algebraic reasoning, investigating linear and non-linear relationships, identifying patterns, and working with variables is very consistent with how mathematics is used in engineering. More importantly, it is not simply introduced to ensure the inclusion of math. The mathematics that students are asked to perform has a direct bearing on the solution to the problem. In some cases, doing the math clearly makes solving the problem easier. The subtle need to optimize solutions in light of economic constraint gives additional credence to the mathematics. The problems are designed in such a way that attempts to circumvent the mathematics with trial and effort are not likely to render the desired results.

Despite all the attention given to mathematics, the only unit that calls attention to the fact that engineering uses mathematics as an essential tool in the engineering design process is *Everest Trek*. It points out engineers use mathematics to test hypotheses and to predict the behavior and performance of their designs prior to making them.

Technology

Very little attention is given to the nature of technology in the three units. For example, students are asked to design a shelter in the unit titled *Stranded*. The brainstorming process is informed by a series of simple drawing of basic structures constructed out of natural materials (e.g., teepee, hut, lean-to). No attention is given to what makes a simple shelter stable and structurally sound. Similarly, little attention is given to technology used to construct clothing, insulated containers, and simple bridges.

Treatment of Standards

The materials are correlated with selected standards from the National Council of Teachers of Mathematics. More specifically, they outline standards related to number and operations, algebra, measurement, geometry, and data analysis. Attention is also given to problem solving, communication, representation, and connections. One can connect the standards cited with the objectives and learning activities with relative ease. However, it is important to note that most of the unit objectives and the learning activities address the application of mathematics concepts and skills in contrast to their initial construction.

The materials also claim alignment with the national Standards for Technological Literacy (ITEA 2000); the Massachusetts Mathematics Curriculum Framework; and Massachusetts Science and Technology/Engineering Curriculum Framework (MA DOE 2006). These alignments tend to be more vicarious than those articulated for the math content. It is easy to envision how students would encounter many of the idea expressed in the technology standards by virtue of the learning activities. However, most of the objectives for each unit are dedicated to the study of math content. For the most part, the study of technology and engineering is used as a vehicle for achieving the math objectives. The fact that students have multiple experiences going through the design cycle in different contexts is likely to result in some insights about the nature of technology that are consistent with those outlined in the cited standards.

Pedagogy

The units are very deliberate in their use of contextual learning to make the study of mathematics more interesting, practical, and engaging. Students do not manipulate numbers for the sake of math alone. The numbers, patterns, and relationship that students encounter during the course of their learning experiences are grounded in the context of the unit and have a direct bearing on the solution to the problem. The mathematics is genuinely needed to solve the problems posed.

The use of contextual learning strategies in the units make them very compatible with the popular practice of implementing interdisciplinary units at the middle school level. By virtue of their design, the units include content related to geography, anthropology, environmental science, physical science, and biological science. The potential of these units to provide a basis for interdisciplinary instruction in a middle school setting is not addressed in a direct manner. However, the materials are rich enough in their treatment of mathematics, social science, and natural science to inspire implementation in ways that involve teachers and content from different subjects.

The materials are also very consistent in their use of the engineering design process to orchestrate the learning experiences. The use of the engineering design process is consistent with the notion that students construct their own understanding of concepts by using prior knowledge, posing questions, seeking answers, testing ideas, revising ideas based on experience, and reflecting on the nature of knowledge and the learning process.

Implementation

According to the authors, the *Building Math* units are designed to be used in place of analogous units in an existing algebra program. They can also be used as supplementary or enrichment lessons in the core math curriculum. Lastly, they are written in such a manner that they can be used for summer programs. Each challenge requires approximately one week, or five to seven 50-minute class periods, to complete.

Each book in the series includes reproducible student handouts and teacher support materials (for each grade level). A set of materials includes a poster outlining the design process and DVD. The DVD features video vignettes that can be used for professional development activities and a Java applet that provides a computer model for one of the learning activities.

The three books that comprise the program are available through

Walch Publishing for about $114. They can also be purchased individually for approximately $40 each. The consumable materials needed to implement the investigations and design activities are commonly available and relatively inexpensive if they had to be purchased. Most of the non-consumables are also relatively inexpensive and easy to obtain.

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Gary Benenson
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Funding

National Science Foundation

Grade Level

Elementary (K-6)

Espoused Mission

"…to engage elementary children with the core ideas and processes of technology (or engineering, if you prefer)."

Organizing Topics

- Designed Environments: Places, Practices, Plans
- Mapping
- Mechanisms & Other Systems
- Packaging & Other Structures
- Signs, Symbols & Codes

Format

The curriculum materials are presented in the form of five soft cover books that are between 150 and 190 pages in length. Each book includes the following elements:

- Information about the curriculum (e.g., purpose, history, goals, organization)
- Simple and concrete things that the teacher can do to become familiar with the technology in question.
- An encyclopedia-like section that uses simple language and everyday examples to explain the technical concepts that will be addressed in the curriculum.
- Lesson plans and handouts that guide and support the implementation of the curriculum and instruction.
- Case studies that describe what the curriculum looks like in

action (e.g., sample of student work, teacher observations, student comments, project leader commentaries).
- A list of resources that can complement and support the curriculum implementation process.
- Lists that show how the curriculum aligns with national standards for technology, science, mathematics, and English language arts instruction.

Pedagogical Elements

- Lessons plans feature elements like prerequisite knowledge, vocabulary, key concepts, strategies for pre-assessment and set inductions, and group work.
- The instruction is very Socratic in nature (i.e., posing questions, addressing questions).
- Most of the learning activities involve inquiry (e.g., analyzing common objects, making observations, taking measurements, gathering and analyzing data, drawing conclusions).

Maturity

Started in 1979

Diffusion & Impact

- Field-tested in 19 states throughout the country
- Forty-nine teachers have been trained to provide professional development in 16 states across the country

Initiative **City Technology**

Title

Designed Environments: Places, Practices, Plans

Broad Goals

The content and activities… will help meet the following educational goals:

- Introduce the fundamental theme of environments as complex systems that are designed and evaluated.
- Develop a broad view of technology and its role in everyday life;
- Develop an understanding of technology design.
- Develop process skills in observation, data collection, categorization, problem identification, data organization, and presentation, design and evaluation.
- Develop skills in communication and group work.
- Develop awareness of problems in the immediate environment, and responsibility for solving them.
- Foster a sense of control in relation to everyday problems.

Salient Concepts & Skills

Math	Science	Technology
• counting • measuring • collecting data • organizing data (e.g., graphing, tables) • analyzing data for patterns • scale • area • perimeter	• observation	• designed environments • maps • mapping to scale • floor plans • control • systems and subsystems • parts and functions • habitat (human-made)

Engineering

The unit takes advantage of the fact that many of the things in school are the products of "casual design" that did not involve any thoughtful analysis or evaluation. Using everyday problems in their classroom, students engage in activities that involve "technological design." These activities include the following:

- Defining the problems clearly.
- Gathering and analyzing information about the problems.
- Describing the characteristic of good solutions.
- Identifying the limitations (constraints).
- Generating ideas for solutions.

- Presenting possible solutions to others.
- Selecting and trying the best solutions.
- Determining how well they work.
- Redesigning the solutions as needed.

Prominent Activities

1. Analyzing and reducing classroom interruptions.
2. Solving problems related to classroom procedures (e.g., distributing materials, putting coats away, lining up).
3. Addressing rules that are broken in school.
4. Redesigning how to play the "Connect Four" game.
5. Redesigning their classroom.
6. Designing a habitat for a classroom pet based on its likes and dislikes.

Initiative **City Technology**

Title

Mapping

Broad Goals

The content and activities… will help meet the following educational goals:

- Develop fundamental themes of two-dimensional representation of three-dimensional space.
- Illustrate and explore concepts of orienting, symbol use, point of view, scale, and one-to-one correspondences.
- Demystify common artifacts, and by extension, technology in general.
- Promote literacy as students interpret and develop graphic communications.
- Develop process skills in observation, classification, ordering, inferring, collecting and organizing data, representing data, design, and evaluation.
- Provide rich opportunities for group work.

Salient Concepts & Skills

Math
- scale
- coordinates
- spatial relationships
- one-to-one correspondence
- sequencing
- measurement
- using grids

Science
- observation
- comparing observations
- recording observations
- cardinal directions
- magnetic north

Technology
- maps
- graphic communication
- orientation
- symbols
- showing relationships between things
- schematic diagrams
- using a compass

Engineering

Most of the emphasis is on making and using maps as documentation and communication tools. Direct linkages to engineering were not found.

Prominent Activities

1. Studying a box relative to top and side views.
2. Drawing a “bird’s eye view” of a collection of objects.
3. Tracing one’s hand to note one-to-one correspondence
4. Identifying things, describing locations of things, and following directions to things in large and small groups.
5. Brainstorming what is a map.
6. Analyzing a variety of existing maps.
7. Reading maps to identify where things are located.
8. Drawing maps of their desktop and classroom.

9. Making a map that defines a route to a location.
10. Developing a map of the classroom to scale.
11. Mapping the diffusion of food coloring in a Petri dish of water.
12. Mapping a gas (odor from perfume) in a classroom.

Initiative **City Technology**

Title

Mechanisms & Other Systems

Broad Goals

The content and activities… will help meet the following educational goals:

- Introduce and explore fundamental themes of systems, inputs and outputs, cause-and-effect, models.
- Illustrate and explore concepts of force, distance, motion, lever, simple machine, friction, electric current, electric circuit, information, control, feedback and energy.
- Demystify common artifacts, and by extension, technology in general.
- Promote literacy as students formulate problems and find effective ways to communicate with others in order to achieve and document solutions.
- Develop process skills in observation, classification, generalization, use of materials, modeling, and design.
- Provide rich opportunities for group work.

Salient Concepts & Skills

Math

- distance
- ratio
- measuring
- estimating
- collecting, recording, and analyzing data

Science

- simple machines
- Law of the Lever
- lever & fulcrum
- 1st, 2nd, & 3rd class levers
- wheel and axle
- wedge
- pulley
- inclined plane
- screw
- motion (translation, rotation, reciprocating oscillating)
- effort and load
- mechanical advantage
- current
- observing
- conductors and insulators

Technology

- mechanisms
- systems (inputs, processes, outputs)
- links and joints (pin and slide)
- compound levers (a.k.a. linkages)
- fixed pivot
- floating pivot
- circuit
- switch
- control
- modeling

Engineering	The key engineering concept that is embedded in this unit is modeling. The students make and manipulate a variety of mechanical and electrical models and use their experiences with these models to make inferences about how things work.
Prominent Activities	1. Identifying the simple machines in everyday objects. 2. Describing the subsystems within larger systems. 3. Dissecting a ballpoint pen for cause and effect relationships. 4. Making models of mechanisms. 5. Identifying conductors and insulators. 6. Making and testing different circuits (i.e., with and without switches, two switches one bulb). 7. Designing, making, and using electric board games. 8. Designing a water-level alarm.

Initiative **City Technology**

Title

Packaging & Other Structures

Broad Goals

The content and activities… will help meet the following educational goals:

- Develop fundamental themes of systems, material properties, spatial relationship, and trade-offs.
- Motivate and illustrate concepts of forces, structure, load and failure; compression, tension, and shear; repair, redesign, and re-use.
- Demystify common artifacts, and by extension, technology in general.
- Develop process skills in observation, classification, generalization, prediction, control variables, design, and evaluation.
- Provide rich opportunities for group work.
- Develop environmental awareness.

Salient Concepts & Skills

Math	Science	Technology
• counting	• equilibrium	• packaging
• measuring	• tension	• structures
• collecting data	• compression	• struts
• organizing data	• shear	• ties
• graphing data	• viscosity	• failure
• making inferences from data	• fair testing	• fasteners
• spatial reasoning	• center of mass	• beams
	• force	• lamination
	• load	• column

Engineering

Conducting tests that involve controlling variables, taking measures, and analyzing data to…

- analyze existing designs (e.g., bags, pump dispensers, corrugated cardboard).
- determine how shape, configuration, materials, and fastening techniques effect the strength and performance of a structure (a shelving unit that is made of corrugated cardboard).

Prominent Activities

1. Categorizing packages.
2. Classifying different kinds of bags.
3. Testing the strength of bags.
4. Protecting fragile objects.
5. Evaluating pump dispensers.
6. Determining how strength is affected by the

a. shape of a column
b. shape of a beam (shelf)
c. type of materials used (cardboard)
d. direction of corrugations
e. type of glue used
f. type of support provided

Initiative **City Technology**

Title

Signs, Symbols & Codes

Broad Goals

The content and activities… will help meet the following educational goals:

- Develop fundamental themes of information, representation, sign, symbol, and communication.
- Promote literacy by developing a variety of techniques for sending and receiving information.;
- Promote numeracy by developing awareness of symbols as media for representing quantitative information.
- Demystify common artifacts, and by extension, technology in general.
- Develop process skills in observation, classification, generalization, communication, and design.
- Develop awareness of immediate environment.
- Provide rich opportunities for group work.

Salient Concepts & Skills

Math
- counting
- collecting data
- organizing data
- analyzing data

Science
- observing
- classifying
- sorting

Technology
- symbols
- signs
- system
- system of notion
- key
- pictograms
- ideograms
- phonograms
- channels
- encoding
- decoding
- expressive symbols
- arbitrary symbols
- icons

Engineering

Communication is the main idea in this unit. However, several activities require students to go through a design process that involves identifying problems, designing solutions, testing solutions, gathering and analyzing data regarding solutions, evaluating the effectiveness of solutions, and redesigning solutions if needed.

Prominent Activities

1. Identifying and decoding common signs and symbols.
2. Designing and making signs that address a need in the classroom.
3. Designing and testing a signal that gets everyone's attention.
4. Interpreting symbols on a map or floor plan.
5. Creating and using a graphic symbol to express secret messages to others.
6. Devising and using hand signals for communication between the teacher and the students.
7. Designing a symbol that communicates a message on an ad or package.

Salient Observations

The primary audience for this curriculum is elementary school teachers. A tremendous amount of attention is given to supporting and enhancing teachers' content knowledge and pedagogical content knowledge (how to teach specific pieces of content). This attention is evident in the intellectual "appetizers" that help teachers become familiar with the technical content using concrete examples from everyday life; the encyclopedia-like explanations of the key concepts and technologies that are being addressed in the curriculum; and the implementation stories that feature photographs, samples of student work, children's dialog, teacher comments, and the authors' commentaries.

The City Technology materials use interesting and illuminating topics to organize the curricula into manageable chunks. They appear to be based the authors' efforts to make the curriculum practical for teachers and developmentally appropriate for students in contrast to being based on a formal conceptualization of engineering endeavors. The materials are not comprehensive or inclusive in any way. Rather, they utilize a diverse set of topics to address the nature of design and technological systems in multiple contexts.

Engineering

These materials do not espouse to be an engineering curriculum. Instead, they focus on building an understanding technology through everyday things. However, the emphasis on uncovering how technology works includes engineering ideas and ways of thinking that are appropriate for elementary school children. They can be found in the analysis, design, or redesign of everyday things (e.g., mechanisms, electrical circuits, plastic bags, maps, classrooms, packages).

Design

The curriculum addresses design from two perspectives with almost equal attention. First, it engages students in design projects that begin with a problem and culminate with a solution. These activities represent developmentally appropriate versions of engineering design. Second, it engages students in analyses of existing designs (e.g., bags, pump dispensers, maps, scissors). This form of inquiry is analogous to reverse engineering.

Analysis

One of the most prominent themes running through all five books is the use of quantitative analysis to inform and/or evaluate designs. Over half of the learning activities involve collecting, organizing, and analyzing data. More importantly, the data is used to define the problem, make a design decision, evaluate a design, or refine a design.

Constraints

The concept of constraints is addressed in *Designing Environments: Places, Practices, Plans*. It is described as things that limit design possibilities. In even simpler terms it is defined as, “What limits what we can do.” Students are taught it can be time, money, space, knowledge, materials, rules, and regulations. It also introduces the notion that constraints can include a lack of authority to implement a design or the need to secure permission to carry out a design.

Lots of attention is given to establishing and meeting design criteria. In this context, design criteria are the things that the design must do to be considered successful or acceptable. Students are asked to identify design criteria (in conjunction with design constraints), address the criteria during the course of the design, and evaluate the final design in relation to the design criteria.

Modeling

Another prominent theme is the use of physical models to illuminate the subtle technologies that are embedded in everyday things like toys, tools, packaging, signs, and maps. The models include simple objects and working mock-ups that are constructed by the students. During the course of instruction the models often serve as hands-on manipulatives as well as tangible representations of student thinking. In some cases, the models serve as sources of data in ways that are analogous to how physical models are used in engineering endeavors.

Optimization

The materials do not address the concept of optimization directly. However, they do deal with the concept of trade-offs and redesign. In the case of trade-offs, students are taught they involve two or more things that compete with one another and require some form of compromise. Redesign is equated with the notion that one “…can always make it [the design] better.” However, it is important to note that redesign is more than simply making improvements. The curriculum and instruction also emphasizes the need to inform a redesign based on evaluation data relative to the design criteria. While these concepts sound too advanced for elementary students, it is important to note that they are being addressed in the context of things like improving classroom procedures, refining rules that are broken, and reconfiguring their classroom.

Systems

The concept of systems is taught directly and indirectly throughout the materials. It is most clearly addressed in *Mechanisms & Other*

Systems. It defines systems as “A collection of interconnected parts functioning together in a way that make the whole greater than the sum of its parts.” It uses a Socratic and developmental approach to build the students’ understandings of simple systems. More specifically, children are asked to address questions like the following.

- “What is the purpose of the system?”
- “What does it do?”
- “What are its parts?”
- “How are the parts connected to one another?”
- “What do you have to do to make them work?”

Mechanisms & Other Systems also addresses systems from the perspective of inputs, processes, outputs, and feedback. Toward that end, students are asked to analyze, draw, and label the “ins and outs” of simple mechanisms like can openers, ice cream scoops, and staple removers. Students are also asked to address questions about the part of the system that they use to make it work (the input) and the part of the system that actually does the work (the output).

Systems and systems thinking can also be found in *Packaging & Other Structures*. This book defines systems as, “The arrangement or interrelation of all of the parts of the whole.” Although the instruction does not address the concept of systems directly, it does engage students in analyzing and making simple systems and paying attention to the roles parts play in the context of the whole.

Science

The materials are clearly dedicated to the study of technology. Science concepts like mechanical advantage, equilibrium, tension, compression, viscosity, and center of mass are introduced, explained, and used to understand how common technologies work.

Science skills such as observation, classification, measurement, data collection, and documentation are introduced, applied, and reinforced throughout the materials. Furthermore, the concept of conducting a “fair test” by controlling variables is addressed in a robust manner in *Packaging & Other Structures*. Inquiry can be found all through the curriculum. In some cases the intent of the inquiry is to uncover a basic law of nature. However, most of the inquiry is directed toward understanding a design or informing a design (or redesign).

Mathematics

The curriculum does not attempt to teach mathematics directly. It does however, consistently engage students in counting phenomena, taking measurements, recording and organizing data in meaningful ways (tables, charts, graphs), analyzing data to make comparisons or uncover patterns, and using data to make inferences about problems or design performance.

Technology

Technology is the central focus of the curriculum. Students are introduced to different forms of technology that range from simple mechanisms to symbol systems and from everyday structures to maps. The treatment of technology includes technology as human-made objects, the knowledge used to make objects, the techniques used to make objects, as well as the need or desire to make objects.

Treatment of Standards

Each book in the series features a chapter on national standards that includes the *Standards for Technological Literacy* (ITEA, 2000), *Benchmarks for Science Literacy* (AAAS, 1993), the *National Science Standards* (NRC, 1996), the Principles and Standards for School Mathematics (NCTM, 2000), the Standards for the English Language Arts (NCTE, 1996), and the Curriculum Standards for Social Studies. They provide a brief, yet rich, discussion of the standards that includes their history and recommendations for reform. Much of the curriculum design appears to be based on theory underpinning the standards.

A lot of work was invested in aligning the curriculum's content and learning activities with national standards. The basis on which these alignments were made is not clear. However, an analysis of these alignments on an individual basis suggests the depth, breadth, and sophistication of ideas that are embedded in most of the standards goes far beyond those addressed in the curriculum. However, it is important to note that most standards were written to be addressed over a significant span of time (e.g., kindergarten through grade 2, grades 3 through 5). Therefore, *City Technology* just one of the tools that could be used in conjunction with others over time to build the understanding and skills recommended in national standards.

Pedagogy

The composition and contents of all five books show attention was also given to curriculum continuity and lesson scaffolding. It is very easy to align the mission with the goals, the goals with the key concepts, and the key concepts with the learning activities. The sequence of concepts and learning activities clearly progresses from topics and tasks that are simple, concrete and familiar to topics and tasks that are more complex, abstract, and novel.

Posing and addressing questions is very pervasive throughout the curriculum and instruction of *City Technology*. The questions can be found in the content narrative, lesson plans, learning activities, assessment strategies, and case studies. Furthermore, the questions are simple in composition, narrow in scope, and well within the students' experiences or abilities.

Implementation

The focus on using and studying simple and abundant technologies from everyday life makes the curriculum accessible to most teachers from both an economic and intellectual point of view. Most of the examples and objects of study are available for free or at a low cost. Their simplicity and familiarity in everyday life make them non-threatening to teachers who are easily intimidated by technical things. Furthermore, their use intrinsically capitalizes on prior knowledge given their pervasiveness in urban as well as rural culture.

Design and Discovery

Institution
Design and Discovery
Intel Corporation
2200 Mission College Blvd.
Santa Clara, CA 95052
Web site: http://www.intel.com/education/Design/index.htm

Leaders
Jon Price
Stefanie Hausman

Funding
Intel Corporation

Grade Level
Middle School (grades 5 through 9)

Espoused Mission
"Design and Discovery is an academic enrichment opportunity that 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."

Organizing Topics
The curriculum is divided into six units. The first one provides overview of design. The second focuses on the basic nature of materials, electricity, and machines. The remaining units take students through the process of developing a new product. The titles of the units are as follows:

- Understanding the Design Process
- Engineering Fundamentals
- Thinking Creatively
- Making, Modeling, and Materializing
- Prototyping
- Final Presentation

Format
The curriculum materials are available for download in a PDF format from http://www.intel.com/education/Design/index.htm. The materials include a facilitator guide, a student guide, implementation strategies, and a supply list.

Pedagogical Elements
The following pedagogical features can be found in the materials.

- Short narratives that provide an overview of the key concepts that can be addressed in each lesson.

- List of resources for gathering additional information about the topics in question.
- Lesson plans that feature a goal statement, an outcome statement, a lesson description, a list of required supplies, safety guidelines, recommendations for lesson preparation, a list of procedures for implementing the lesson, a scenario for bring the lesson to a close, and an announcement of the next lesson.
- Handouts that guide students through the learning activities.
- Readings that explain key concepts, tell short stories about selected inventions, or describe the work of engineers, technologists, and designers.
- The instruction and learning activities use questions to solicit participation and to guide inquiry.

Maturity

The materials bear a 2004 copyright.

Diffusion & Impact

According to program leaders, there is no formal mechanism in place to monitor the number of schools implementing *Design and Discovery* curriculum. The Intel Corporation simply disseminates the curriculum through their web site as a free download with no strings attached. They did report that the Girl Scouts of America endorsed the curriculum and have been using it since 2001.

The only evaluation of the curriculum was conducted in two schools in the greater Dublin area of Ireland in 2004. It included school visits, interviews, and two surveys, and revealed the following:

- Implementing the curriculum was characterized as being very demanding on the teachers.
- Students and teachers identified with the short and practical tasks that comprise the curriculum.
- The curriculum captured the interests of a majority of the students in both schools.
- Students demonstrated a richer awareness of nature of engineering, its processes, and its role in society as a result of the program.
- Students tended to equate their design experiences with studying physics.
- The lack of attention given to the quantitative aspects of design and engineering were perceived to be a deficiency, especially in the context of encouraging students to take physics courses.
- Using the Design and Discovery curriculum to encourage

students to study physics was thought to be problematic because of the striking difference in the two programs.

- While considered to be a highly enjoyable curriculum, it had virtually no influence on students' thoughts about pursuing course work in physics or entertaining a career in engineering.
- The curriculum was perceived to be more suited for informal education (e.g., after school programs).

Initiative **Design and Discovery**

Title

Understanding the Design Process

Broad Goals

During this unit, students will

- Learn how to look at the world from a design perspective by examining and redesigning everyday objects.
- Develop skills by thinking creatively about designed things they use.
- Learn to identify problems that lead to opportunities for new design solutions.

The following goal statements are presented in the unit's lesson plans regarding the nature of design.

- Experience the design process by reengineering an everyday object.
- Become familiar with the design process.
- Thoroughly review the design process.

The following goal statements are presented in the unit's lesson plans about the designed world.

- Learn to identify problems, needs, and opportunities for design improvements.
- Introduce and practice Activity Mapping, a creative technique for identifying design opportunities.
- Introduce and practice SCAMPER, a creative technique for improving existing designs.
- Apply the SCAMPER technique to the components of a backpack.
- Know the difference between a superficial improvement and a functional improvement.

Salient Concepts & Skills

Math	Science	Technology
	• the scientific method • hypothesis • Hooke's law (objects stretch in proportion to the force applied) • observational analysis	• history of the paper clip • fasteners • shape's effect on function • wire diameter • use tools to bend wire

Engineering

The unit begins with a description of "The Design Process." It contains the following steps:

- Identify a design opportunity.
- Research the design opportunity.
- Brainstorm possible solutions to the problem.
- Draft a design brief.
- Research and refine your solution.
- Prepare design requirements and conceptual drawings.
- Build models and component parts.
- Build a solution prototype.
- Test, evaluate, and revise your solution.
- Communicate the solution.

Activity mapping is a technique for breaking processes down and identify problems or opportunities within processes. The mapping process is organized around the following elements.

- Pre-activity: Describing what is done before an activity.
- Activity: Explaining what is done during the activity.
- Post-activity: Outlining what is done after the activity.
- Assessment: Defining how one knows the activity was successful.

SCAMPER is a strategy for thinking about how to improve an existing design. This tool involves using a series of themes or prompts to inspire ideas about how to enhance a design. The word "SCAMPER" is an acronym and a mnemonic device for the following thought provoking ideas.

- Substitute
- Combine
- Adapt
- Minimize/Magnify
- Put to other uses
- Eliminate/Elaborate
- Reverse/Rearrange

Error analysis is another strategy for uncovering design problems and opportunities. It involves making a list of everything that can go wrong while using a product. The product's vulnerabilities represent potential problems or chances to make it better.

Prominent Activities

The first set of activities introduces students to doing reverse engineering, keeping a designer's notebook, and defining a design problem. This is accomplished through activities that center on designing a "better" paper clip and refining the design of a toothpaste cap. The redesigning processes engage students in the following activities.

1. Read about the history of the paper clip.

2. Examine the form and function of standard wire paper clips.
3. Draw sketches of new paper clip designs.
4. Test the bending characteristics and holding power of different kinds of wire.
5. Use tools to make new wire paper clips that address a given set of design specifications.
6. Record designs, observations, and test results in a design notebook.
7. Discuss the results and the nature of the design process.
8. Read about the relationship between form and function.
9. Identify the problems associated with caps for toothpaste tubes.
10. Research the contexts surrounding toothpaste caps (e.g., opening and closing, sanitation, dispensing the product).
11. Brainstorm potential solutions to the problems associated with toothpaste caps.
12. Develop a "design brief" that clearly defines the problems that need to be solved as well as the characteristics of an effective solution.
13. Research the nature of the toothpaste caps that are currently being used.
14. Prepare design specifications and drawings for a new and improved toothpaste cap.
15. Describe how to build a model of a new and improved toothpaste cap.
16. Explain the materials and features of a prototype toothpaste cap.
17. Outline how to present the solution to an appropriate audience and gather feedback about the design.

The second set of activities focuses on techniques for identifying problems and improve designs. This section of the unit engages students in the following activities.

18. Conduct a walking tour of a facility to uncover potential problems or opportunities in that environment.
19. Use the activity mapping techniques to identify potential problems or opportunities within a process.
20. Use the themes associated with the SCAMPER technique to identify problems and opportunities in existing designs.
21. Apply the SCAMPER technique to improving a backpack.

The final activity introduces students to the difference between superficial improvements and functional improvements. Students then examine common household items and discuss whether or not the improvements are superficial or functional

Initiative **Design and Discovery**

Title

Engineering Fundamentals

Broad Goals

During this unit, students will

- Learn about material classifications, properties, and cost considerations when selecting materials.
- Explore electrical circuits and learn how to wire simple, series, and parallel circuits.
- Study the principles of simple machines and apply them to the design of a mechanical toy.
- Examine the difference between form and function while comparing alarm clocks.

The following goal statements are presented in the unit's lesson plans for studying the nature of materials.

- Understand the classes of materials and be able to differentiate materials based on their properties.
- Evaluate properties of materials for specific applications.
- Understand factors other than material properties when choosing materials.
- Look at common objects and determine whether their materials make a difference in function and effectiveness.

The following goal statements are presented in the unit's lesson plans for studying the nature of electricity.

- Become familiar with electronics basics (a simple circuit) and what an electrical engineer does.
- Understand series and parallel circuits using a breadboard.
- Understand short circuits.
- Learn about how light-emitting diodes (LEDs) work.
- Identify electrical units in the home.

The following goal statements are presented in the unit's lesson plans for studying the nature of machines.

- Recall and gain experience with motion and energy transfer.
- Reinforce concept about simple machines.
- Study moving machine parts to learn how force can be transferred or change direction to accomplish work.
- Discover ways to use moving parts, and get ready to make a unique mechanical toy at home.

The following goal statements are presented in the unit's lesson plans for studying the nature of problems.

- To examine one object and see the different ways it can meet requirements.
- To understand what is meant by "form follows function."
- To understand how clocks use electricity and mechanical components to make them tick.

Salient Concepts & Skills

Math
- volume
- calculating density
- calculating volume
- organization of data
- measurement
- calculating cost per pound

Science
- metals
- ceramics
- polymers
- density
- mass
- ductility
- strength
- fatigue
- electrical conductivity
- thermal conductivity
- optical properties
- corrosion
- environmental impact of CO_2
- electricity
- Ohm's law
- definition of work
- potential energy
- kinetic energy
- friction
- energy transfer

Technology
- applications for materials
- recycling materials
- circuit
- series circuits
- parallel circuits
- conductor
- measuring electricity
- breadboards
- short circuit
- fuses
- switches
- diodes
- LED
- simple machines
- compound machines

Engineering

In addition to developing domain knowledge, this unit introduces the following ideas about the nature of engineering.

- Reverse engineering (an analysis of material selection in objects within the student's local environment).
- Materials testing (i.e., density, ductility, fatigue, tensile strength, electrical conductivity, thermal conductivity, optical properties).
- Analyzing the properties of materials as they apply to a specific problem (i.e., the design of a golf club).
- Environmental trade-offs related to materials selection.
- Economic trade-offs related to materials selection.
- Developing accurate design requirements.

Prominent Activities

The first set of activities addresses the properties of materials. During these activities, students do the following:

1. Calculate the density of three different materials (i.e., brick, wood, Styrofoam).
2. Explore the ductility of selected objects (e.g., a wooden craft stick, a plastic cable tie, a paper clip).
3. Conduct fatigue testing of selected objects (e.g., a wooden craft stick, a plastic cable tie, a paper clip).
4. Determine the tensile strength of strips of selected materials (i.e., heavy-duty aluminum foil, heavy plastic bags, paper).
5. Test the electrical conductivity of selected materials (i.e., aluminum foil, plastic bags, paper, ceramic tile).
6. Explore the thermal conductivity of selected materials (i.e., aluminum foil, plastic bags, paper, ceramic tile).
7. Analyze the selection of materials within objects located in the room.
8. Examine the optical properties of transparent, translucent, and opaque materials (e.g., clear plastic bag, foggy-looking plastic cup, solid colored plastic cup).
9. Read about the nature of metals, ceramics, plastics, and composites.
10. Propose the best materials for addressing a series of problems (i.e., a spoon for dispensing hot corn syrup; lightweight, ridged, and non-conducting golf clubs; modern clothespins; new public phone booth).
11. Read about a materials engineer (Stephanie Kwolek).
12. Conduct a cost analysis of using different kinds of materials for beverage containers (i.e., plastic, aluminum, glass).
13. Read about an environmental engineer.
14. Survey their homes for objects that are made of materials that have properties that are consistent with their applications.

The second set of activities deals with the nature of electricity. During these activities, students do the following:

15. Break a flashlight down into its basic parts and use the parts to make and diagram simple series circuits.
16. Read about the work of different kinds of engineers (i.e., chemical engineers, civil engineers, electrical engineers, computer engineers, mechanical engineers, aeronautical engineers, aerospace engineers, agricultural engineers, biomedical engineers, environmental engineers, industrial engineers, materials engineers, mining engineers, nuclear engineers, petroleum engineers, systems engineers).
17. Use simple electrical components to wire series and parallel circuits on a breadboard (e.g., switch, lamps, buzzer).
18. Read about a computer engineer.

19. Examine the consequences of a short circuit and test a fuse made of aluminum foil.
20. Survey their homes in search of circuit breakers, items that feature LEDs, and items that have switches.

The third set of activities focus on simple machines and simple mechanisms. They engage students in performing the following tasks:

21. Use common materials (e.g., rubber bands, film canister, washers, drinking straw) to building a toy that rolls three to five feet under its own power.
22. Read about the invention of the “Slinky” and its spin-off applications.
23. Design, build, and test a device that employs at least one simple machine to perform a task (put a washer in a cup that is located 48 inches away from a starting point and follows a path that includes a right angle)
24. Read about a mechanical engineer.
25. Build a simple toy that features a crankshaft.

The last set of activities looks at how a single problem might have multiple solutions. It engages students in the following tasks:

26. Study a clock radio and outline its design specifications.
27. Read about a project manager.
28. Analyze various clocks to determine how form follows function.
29. Determine how the electrical and mechanical components of a simple clock work.

Initiative **Design and Discovery**

Title

Thinking Creatively

Broad Goals

During this unit, students learn how to do the following:

- Gather information about a problem and begin to develop a solution using brainstorming techniques.
- Analyze their design ideas from the perspective of the user.
- Develop a design brief.
- Conduct a patent search.

The following goal statements are presented in the unit's lesson plans for problem identification.

- Add and prioritize the list of problems and improvements that students began in Session 2, *The Designed World*.
- Students gather data about design opportunities to help them select a design project.
- Students brainstorm possible solutions to their design project.

The following goal statements are presented in the unit's lesson plans for preparing a design brief.

- Learn how to define the user of the product.
- Learn the content of a design brief.
- Refine and describe a problem to solve and a proposed solution.
- To identify appropriate mentors for students.

The following goal statements are presented in the unit's lesson plans for researching the problem.

- To "think outside the box" for creative solutions to problems.
- Use research on similar design solutions to refine ideas.
- Begin planning the development of the design project.
- To carefully examine solutions ideas.

Salient Concepts & Skills

Math	Science	Technology
		• invention • patent • trademark • copyright

Engineering

This unit engages students in the following engineering processes.

- Identify a design problem or opportunity.
- Research the design opportunity.
- Use brainstorming techniques, such as SCAMPER, to begin

developing solutions to the problem.
- Develop a design brief (a written plan that identifies a problem to be solved, it criteria, and its constrains).
- Determine what are the components, parts, and materials involved in building the solution to the problem.
- Consider the cost, safety, and practicality of a solution.

Prominent Activities

The first set of activities focuses on helping students identify potential problems that they can address. During these activities, students do the following:

1. Generate and prioritize a list of potential design problems or opportunities for their design project.
2. Research design opportunities by observing, interviewing, and shadowing people using products related to their list of problems or opportunities.
3. Use the information gathered to define and describe the problem that they want to address in their design project.
4. Employ the SCAMPER technique to generate a list of potential solutions to the problem they have selected.
5. Read about a "design planner."

The second set of activities guides students in the development of a design brief. During this set of activities, students do the following:

6. Examine a variety of everyday objects from the perspective of a user (e.g., toys, tools, kitchen items).
7. Read about an industrial engineer.
8. Study an example design brief and discuss how its elements can be applied to their own problem.
9. Develop and present a design brief that describes the problem associated with a product, how the current product is used, the typical user of the product, a solution to the problem, and the design specification for a solution to the problem.
10. Identify a mentor that can advise their work.

The third set of activities engages students in researching their solution to their problem. During this set of activities, students do the following:

11. Research inventors and inventions on the Web to uncover ideas that can be applied to their design problem.
12. Review the U.S. Patent Office Web site to study ideas related to their design problem.
13. Read about the work of an engineering student.
14. Use the *HowStuffWorks* Web site to begin thinking about the nature of the systems, subsystems, parts, and components of their design problem and potential solution.

15. Consider the cost, safety, and practicality of their design.

Initiative **Design and Discovery**

Title

Making, Modeling, and Materializing

Broad Goals

During this unit, students will

- Think about the systems in a product.
- Identify the systems, components, and parts of their own project ideas.
- Develop design requirements for their projects and sketch a solution to their problem.
- Learn about model making.

The following goal statements are presented in the unit's lesson plans regarding the nature of systems.

- Learn about analyzing a complex product for its designed systems and components.
- Learn about mechanisms of four bicycle systems: Study the components, the parts, and connections for each.

The following goal statements are presented in the unit's lesson plans about design requirements and drawings.

- Understand the design project timeline.
- Fine-tune a project design by taking a closer look at the needs of the user.
- Learn how conceptual drawings help fine-tune a design.

The following goal statements are presented in the unit's lesson plans about planning for modeling and testing.

- Understand that the design process involves many cycles of revision as each step present new information and ideas for refinement of a design.
- Learn about available materials and plan model(s) to build.
- Consider structural decisions about the project before making a model.

The following goal statement is presented in the unit's lesson plan about building models and testing systems.

- Learning how models contribute to design.

Salient Concepts & Skills

Math	Science	Technology
• two-dimensional		• systems
• three-dimensional		• subsystems
• horizontal axes		• components
		• parts

- systems as things
- systems as processes
- how parts relate to one another
- how systems are connected to other systems
- synergy of systems
- drive system
- braking system
- steering system
- structural system
- drawings
- orthographic sketches
- isometric sketch
- oblique sketch
- model
- prototype
- collapsible principles (e.g., folding, hinging, sliding, nesting, fanning)

Engineering

This unit introduces students to the idea that design occurs in iterations and often involves the use physical models to refine and evaluate design ideas.

Prominent Activities

The first set of activities uses bicycles as concrete examples to help student think about things in terms of systems. During these activities, students do the following:

1. Read about the nature of systems in the context of bicycles.
2. Examine the systems, subsystems, components, and parts of bicycles.

The second set of activities focuses on defining design requirements with the aid of drawings. During these activities, students do the following:

3. Review the status of their design project by checking steps off a list and thinking about what is left to do.
4. Read about how Georgina Terry refined the design of a bicycle to fit the needs of women.
5. Write design requirements for their design projects.

6. Practice basic mechanical drawing techniques like sketching circles, straight lines, arcs, and composing multiview drawings
7. Use the drawing process to uncover issues with their designs, visualize their designs in greater detail, and refine their designs.
8. Read about a communication designer.

The third set of activities focuses on planning the making of models. During these activities, students do the following:

9. Reflect on how their designs have evolved during the design process and discuss how they will continue to evolve during the modeling, prototyping, and testing processes.
10. Make decisions about the features of appropriate physical models of their designs as well as the tools and materials needed to make their models.
11. Read about a model shop manager.
12. Examine and discuss the different ways objects can be reduced in size for storage (e.g., folding, hinging, rolling, sliding, nesting, fanning).

The last set of activities engages students in making models of their design ideas. During these activities, students do the following:

13. Work on their design projects with their mentors by making models and documenting changes in the design.
14. Read about two materials engineers.

Initiative **Design and Discovery**

Title **Prototyping**

Broad Goals

During this unit, students learn how to:

- Create project specifications, consider materials, and prepare a budget.
- Construct a prototype of their design.
- Conduct user testing to collect feedback from others and plan revisions to their prototype.

The following goal statements are presented in the unit's lesson plans regarding the nature of prototypes.

- Understand what a prototype is.
- Consider materials for developing a prototype.
- Consider the budget for developing a prototype.
- Help students to structure concentrated work time for developing their prototypes.

The following goal statement is presented in the unit's lesson plan about making prototypes.

- Learn how to develop a working prototype.

The following goal statements are presented in the unit's lesson plans about testing prototypes.

- To gather user feedback on function, appeal, and value of the product.
- Evaluate feedback from user testing to plan changes to the prototype.

Salient Concepts & Skills

Math	Science	Technology
• charting a timeline • establishing a budget		• using spreadsheet software • prototype development

Engineering

Students experience the following engineering tasks during this unit.

- materials selection
- prototype development
- prototype testing
- design iterations

Prominent

The first set of activities involves preparations for making

Activities prototypes. During these activities, students do the following:

1. Chart the users' needs, design requirements, and design specifications of their problem and its solution.
2. Read about the design of a soap dispenser.
3. Consider the properties of the materials that they will use for the prototype.
4. Develop a budget (bill of materials) using spreadsheet software.
5. Make a chart that outlines how they will structure their time (e.g., work sessions, class meetings, mentor meetings, science/engineering fair deadlines).

The next activity engages students in building prototypes with the assistance of their mentors.

The last set of activities deal with testing prototypes. During these activities, students do the following;

6. Conduct user tests of their prototypes (e.g., give the prototype to a typical user, observe him or her using the prototype, ask questions about the prototype).
7. Plan modifications to their prototype based on user feedback.
8. Read about a project manager.

Initiative **Design and Discovery**

Title

Final Presentation

Broad Goals

During this unit, students learn how to prepare a display board for a fair.

The following goal statements are presented in the unit's lesson plans about preparing a fair.

- Learn what is needed to participate in a science/engineering fair and begin to plan for participation.
- To create presentation boards for the fair.

The following goal statements are presented in the unit's lesson plans about conducting a fair.

- Develop presentation criteria and plan presentations.
- This activity gets students ready to share their ideas and project in a formal way.
- Students get last-minute details together for the fair.
- To reflect on the fair, students' *Design and Discovery* experience, and to plan for next steps.

Salient Concepts & Skills

Math	Science	Technology
		• logistics

Engineering

Most of the attention in this unit is on developing the skills and tools needed to communicate the evolution and merits of a design to others.

Prominent Activities

The first set of learning activities deals with planning and participating in a science and engineering fair. During this session, students do the following activities:

1. Hear from past participants of science and engineering fairs.
2. Plan a "Science and Engineering Fair" to showcase their design projects.
3. Read about the work of *Intel Science and Engineering Fair* finalists (i.e., recycling crayons, recycling plastic, test eggs for incubation).
4. Read about an engineer (Jenna Burrell).
5. Develop a display of their invention for a fair.

The last set of activities engages students in planning and practicing their presentations for a science and engineering fair.

They complete the following tasks.

6. Review a mock science and engineering fair presentation.
7. Establish guidelines for critiquing presentations and providing constructive feedback.
8. Practice presenting their design projects to their peers.
9. Make changes to their presentations based on the feedback provided.
10. Prepare a mini-engineering fair (e.g., room set-up, decorations, food, awards).

Salient Observations

The Intel Corporation developed the *Design and Discovery* curriculum for students between the ages of eleven and fifteen. The materials are designed to engage students in doing design and thinking like a designer. Most of the learning activities are organized in a way that helps students experience each steps in a design process. It also features activities that branch off these steps to help students understand specific design techniques and concepts (e.g., activity mapping, error analysis, SCAMPER, systems and subsystems, orthographic drawings, models, prototypes).

A special emphasis is placed on engaging female students in engineering activities. Most of the stories about the work of engineers, technologists, and designers center around women. All of the photographs of students engaged in hands-on activities are females. Many of the examples and learning activities appear to be attentive to the needs and interests of female students. For example, there is clearly an emphasis on looking at technology from a human versus as technical point of view. Technology and engineering are portrayed as vehicles for making life easier. Most of the design activities focus on improving everyday products in some to enhance how they work or to reduce their impact on the environment. Despite all the attention given to female students, it is important to note that the curriculum can be used in settings that include male students without any significant modifications.

Engineering

The strength of the *Design and Discovery* curriculum lies in its potential to provide students an introduction to the design process. For the most part, the curriculum is dedicated to engaging students in thinking like designers. It provides a step-by-step procedure for uncovering problems and opportunities associated with existing products and developing ways to improve their design. It places a strong emphasis on defining a problem, determining design criteria (from the user's perspective), and developing design specifications in the form of notes, drawing, models, and prototypes. The process culminates in the presentation of how a solution to a given problem was brought to fruition with the aid of narratives, charts, graphs, models, and prototypes. However, the process used to guide students in "Getting from 'think' to 'thing,'" appears to be more representative of industrial design than engineering design.

Design

The materials define the design process as "a systematic problem-solving strategy, with criteria and constraints, used to develop many possible solutions to solve a problem or satisfy human needs and wants and to winnow (narrow) down the possible solutions to one final choice" (p. 6). The instruction takes students through a design process that includes the following elements:

- identifying a design problem or opportunity
- researching the design problem or opportunity
- brainstorming possible solutions
- drafting a design brief
- researching and refining the solution
- preparing design requirements and conceptual drawings
- building models
- making, testing, and evaluating a prototype
- revising the design based on observations
- communicating the evolution and merits of the design to others

To the materials credit, they point out the problem-solving process is "not truly linear" and often, in practice, involves revisiting steps as more information is gathered and new problems are encountered. Some of the redundancy built into the instruction and the problem-solving process reinforce this depiction of design.

The materials also describe the steps as being iterative in nature. More specifically, they portray design as an evolutionary process that begins with lots of foggy ideas and options and culminates in a refined and more concrete solution to a problem.

Analysis

One of the main themes running through the curriculum is making everyday products better. Towards that end, the curriculum clearly engages students in a lot of analysis. They analyze existing products, problems associated with products, economic considerations, technological systems, alternative design ideas, information from a variety of sources, and proposed solutions. Some of this analysis is conducted as an integral part of the design process while other instances are embedded in peripheral activities. In most cases, the analysis process involves making observations, gathering simple forms of qualitative or quantitative data, and ultimately, formulating conclusions or making decisions. None of the analysis is predictive in nature.

Constraints

The curriculum makes several passing references to constraints without defining or discussing the concept in any detail. For example, in the activity titled, "Build a Better Paper Clip," the students are told their final product "can be no bigger than 2 inches by 2 inches (5 cm x 5 cm)" (p. 13). However, these conditions are not connected with the concept of constraints. In this example, the constraints are presented like rules for a game and do not seem to be ground in the context of a design problem (e.g., how much people are willing to pay for pape rclips, opportunities for a new kind of paper clip in the market place, a need to account for the motor skills of the projected users, a need to be able to read and turn over documents that are held together without removing the paper clip).

Modeling

The materials define a model as a "visual representation of a total design (or some aspect of the design) that is non-functional" (p. 288). It goes on to define a prototype as a "working model used to demonstrate and test some aspect of the design or the design as a whole" (p. 288). The notion that models can be physical or mathematical representations of the problem or opportunity that can be used to inform the design process during the early stages of design was not addressed. Instead, the concept of models and modeling is presented as one of the latter steps in the design process that is applied to a relatively refined and mature solution to a problem. It is portrayed as a means to visualize a design, take it to a high level of refinement, and communicate it features to others.

In general, the treatment of models and modeling is more representative of industrial design than engineering design. This perception is based on the attention given to product design and absence of other kinds of engineering design contexts. Most of the design activities deal with the form and function of existing products and the need to make them better from a user's point of view. Most of the students' attention is directed toward how products work, what they look like, how to make them better, and seeing if people like the changes. Very little attention is given to the manufacturability of products (e.g., reducing costs, combining parts, eliminating parts, reducing steps). Furthermore, the material does not present the concepts of models and modeling in a way that can be easily applied to other forms of engineering (e.g., civil, environmental, chemical). However, leaning the curriculum towards an industrial design perspective does make it more accessible to younger students and less dependent on domain knowledge.

Optimization

The emphasis placed on redesigning everyday products suggests a hint of optimization is embedded in the instruction. This is reinforced by the attention given to the idea that the designs for solutions to problems tend to evolve over time in an iterative manner. The curriculum also comes close to including optimization while introducing the idea of economic trade-offs related to the selection of materials for models and prototypes. However, despite these opportunities, the curriculum stops short of defining and addressing the concept in a decisive and overt manner.

Systems The fourth unit in the curriculum targets the concept of systems and systems thinking under a lesson titled “Bicycle Breakdown: Systems, Components, and Parts.” As the title suggests, this lesson capitalizes on the bicycle to help students examine the nature of technological systems. Bicycles constitute an excellent case study for uncovering the nature of technological systems because they are a familiar and accessible technology that is often taken for granted. They are relatively simple devices, yet they have lots parts that work together in interdependent and synergistic ways. They are composed of systems (e.g., steering, braking, structural) that can be divided into subsystems (e.g., brake controls, brake calipers). Each subsystem can be further divided into working components (or assemblies) and individual parts. Furthermore, most of the systems, subsystems, components, and parts are in plain view and can be easily manipulated to discover the relationships between things.

Science The curriculum is designed to help create a learning environment where science and engineering concepts and skills are applied in ways that students are likely to find meaningful. This is especially evident in its portrayal of science and engineering ways of thinking. More specifically, the curriculum does engage students in problem solving, making and using models, documenting work, describing things in detail, formulating questions, collecting and interpreting data, and presenting results to others. These are activities that can be applied to both science and engineering with some attention given to contextual differences.

Given the open-ended nature of the curriculum, it does not have the specificity needed to orchestrate specific applications of science to the resolution of predetermined problems. The section titled “Engineering Fundamentals” contains the most direct treatment of scientific and technological content knowledge. Although the level of detail provided in the section is relatively low, it contains an introductory look at the nature of materials and their physical properties, the basics of electricity and common electrical components, and the fundamental physics behind simple and compound machines. However, the treatment of key concepts like density, power, and mechanical advantage does not go beyond simple definitions and explanations. In fairness to the curriculum, each one of these topics could be a standalone unit of instruction. The modest treatment of these topics can be attributed, at least in part, to the emphasis on design as a way of thinking. A richer treatment of things like materials, electricity, and mechanism could detract from the design process.

It is important to note that design is intrinsically a synthesis endeavor that requires prerequisite knowledge that is often scientific or technological in nature. However, addressing specific science concepts in detail can be considered beyond the scope of an enrichment program. One could easily assume the authors tempered the treatment of specific science concepts because these have a home in the core curriculum while the study of engineering and design does not.

Mathematics

Very little attention is given to the important roles that mathematics plays in engineering. But, the materials do feature some modest applications as basic algebra appears in the unit on materials, electricity, and machines. It includes things like taking measurements, organizing data into a table, and calculating density, volume, and cost per pound. A modicum of mathematical reasoning is needed when students are asked to rank materials from most ductile to least ductile, from strongest to weakest, etc. The testing of designs does have some quantitative aspects (e.g., counting, adding, averaging). The bottom line is most of the mathematics presented in the curriculum is relatively rudimentary.

Technology

Most of the curriculum is dedicated to teaching engineering principles, the engineering design process, and engineering ways of thinking. Very little attention is given to domain knowledge because it is highly dependent on the kinds of problems that the students choose to address. The second unit in the curriculum does focus on what it calls “Engineering Fundamentals.” More specifically, it addresses basic concepts related to the nature of materials, electricity, and mechanisms (a.k.a., simple machines). The treatment of these topics, from both a scientific and technological point of view, is a little shallow. For example, concepts like voltage, current, resistance, Ohm’s law, series circuits, and parallel presented in one-paragraph explanations. These explanations are followed-up with the laboratory activities that involve making and testing simple circuits with an emphasis on the path that electricity follows.

Treatment of Standards

No attempt was made to cite national standards or to align the content with national standards. However, despite the lack of attention given to standards, it is easy to see how the materials could be used to address specific standards. For example, the lesson titled “Bicycles Breakdown: Systems, Components, and Parts” addresses some of the important ideas in the following standard published in *Benchmarks for Science Literacy* (1993) by

American Association for the Advancement of *Science* (AAAS).

> By the end of the 8th grade, students should know that
> - Thinking about things as systems means looking for how every part relates to others. The output from one part of a system (which can include material, energy, or information) can become the input to other parts. Such feedback can serve to control what goes on in the system as a whole.
> - Any system is usually connected to together systems, both internally and externally. Thus a system may be thought of as containing subsystems and as being a subsystem of a larger system. (p. 265)

A similar alignment can be made between the following standard and the attention given to testing the properties of common materials and selecting materials for a new design.

> By the end of the 8th grade, students should know that
> - The choice of materials for a job depends on their properties and on how they interact with other materials. Similarly, the usefulness of some manufactured parts of an object depends on how well they fit together. (p. 190)

Pedagogy

The instructional design found in the lesson plans is very simple and includes only a few basic elements of the teaching and learning process. A typical lesson features the following elements:

- Goal (a modest statement of the intent of the lesson).
- Outcome (a description of what the students have done by the end of the lesson).
- Description (an overview of what students will do during the course of the lesson).
- Supplies (a list of the tools, materials, or props needed to implement the lesson).
- Preparation (tasks that need to be performed prior to teaching the lesson).
- Procedures (a modest list of steps for implementing the lesson).
- Wrap Up (a simple task or a series of simple questions that can be used to debrief students, summary content, or formatively assess student understanding).
- Follow With (a statement defining the next learning activity).

The authors of the curriculum clearly addressed the need to engage students in hands-on activities that involve analysis, inquiry, decision making, visualizing, fabrication, collaborating, and communicating. Furthermore, the emphasis place on solving authentic problems, addressing the wants and needs of people, examining the human aspects of technology, presenting female role models, utilizing mentors, and communicating ideas to others is consistent with basic gender equity principles.

The emphasis on reengineering simple things (e.g., paper clips, toothpaste caps, water bottles, backpacks) has pedagogical merit. Such objects are familiar to students, they do not require domain knowledge that is beyond the grade-level being targeted, and they should not distract students from the concepts and skills being addressed. Furthermore, redesigning a product requires one to comprehend the existing design for synthesizing a new one. Starting with concrete objects provides a practical context for relatively abstract concepts (e.g., energy).

The outcomes and objectives are more thematic than substantive. Some identify what students should know or be able to do as a direct result of the lesson and its accompanying learning activities in very general terms. Others describe the tasks or artifacts that need to be done upon completion of the experience. Very little attention is given to formally assessing students' understanding or capabilities. The lack of formality and precision in these items is consistent with the nature of an enrichment program, especially when one accounts for the fact that engineering and design is not assessed on standardized tests.

Implementation

The curriculum can be easily downloaded from Intel's Web site in a PDF format. The PDF files are organized into four categories, facilitator guide, student guide, implementation strategies, and supply list.

The *Implementation Strategies Guide* contains three parts: planning a program, instructional practice, and participating in a fair. The planning a program section provides recommendations for staffing, budgets, mentors, and fieldtrips. The instructional practice section provides a thorough description of the details needed to implement the curriculum, including suggestions for storage space and project workspace. The *Supply List* outlines all the materials needed to implement the curriculum in a detailed matrix that identifies each item, lists all learning activities that use the item, and proposes vendors for purchasing the item.

All of the pages in the *Student Guide* are included in the

Facilitator Guide; however, the facilitator guide does not reference the corresponding student guide page. With the exception of a five page explanation of engineering disciplines that is oddly located in between an activity on a simple circuit and a lesson about breadboards, the facilitator guide is well organized and easily to follow.

According to Intel's Web site, the curriculum is intended to be an academic enrichment program that is conducted as a summer workshop or an after school program. The need for the curriculum to be implemented outside normal classroom hours is based on the need for relatively large blocks of time for conducting hands-on activities and accessing mentors. As an enrichment rogram and given its emphasis on female students, it has been embraced by the Girls Scouts of America as a way to expose young women to non-traditional careers while developing their knowledge and thinking skills.

Since engineering does not have a specific place in the core curriculum, it is not surprising that the Intel Corporation chose to design the curriculum as an after school or summer enrichment program. Nevertheless, a thoughtful technology teacher (a.k.a., industrial arts teacher) could implement the curriculum during the school day with minor modifications. The teacher's expertise and access to tools and materials could reduce the need for large blocks of time. Dedicating laboratory resources and adding additional structure to the curriculum would render additional efficiencies. However, the technology teacher would have to embrace design and design ways of thinking as the primary thrust of at least one class to make the program a formal part of the school's the curriculum. An appreciation for the pedagogical potential of redesigning simple products from everyday life and a genuine empathy for feminine ways of thinking about technology would ease the implementation process.

Engineering is Elementary

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Hewlett-Packard
Millipore

Grade Level Elementary K-5

Espoused Mission "At its core, EiE is designed to have students engineer. The program develops interesting problems and contexts and invites children to have fun as they use their knowledge of science and engineering to design, create, and improve solutions."

The curriculum project has two major goals. They are to increase:

- Children's technological literacy.
- Elementary educators' abilities to teach engineering and technology to their students.

Organizing Topics

- *Catching the Wind: Designing Windmills*
- *Water, Water Everywhere: Designing Water Filters*
- *A Sticky Situation: Designing Walls*
- *To Get to the Other Side: Designing Bridges*
- *Marvelous Machines: Making Work Easier*

- *Sounds Like Fun! Seeing Animal Sounds*
- *The Best of Bugs: Designing Hand Pollinators*
- *Just Passing Through: Designing Model Membranes*
- *An Alarming Idea: Designing Alarm Circuits*

Format

Each unit includes the following resources:

- A paperback storybook.
- Lesson plans.
- Duplication masters for student handouts.
- Detailed background information for the teacher.
- Assessment tools.
- English Language Learner (ELL) suggestions.
- Literacy Connection activities.

Pedagogical Elements

- Lessons plans feature elements like prerequisite knowledge, vocabulary, key concepts, strategies for pre-assessment and set inductions, and group work.
- Uses an illustrated storybook to set the stage for the unit. It serves as an advanced organizer for subsequent lessons and learning activities.
- Features literacy activities that address things like reading comprehension to aid in integrating the unit into the existing Language Arts curriculum.
- The instruction is very Socratic in nature (i.e., posing questions, addressing questions).
- Each unit engages students in exploring the topic in question (e.g., mechanical, structural, electrical) through examining, tinkering, and observing everyday things.
- Each unit features a lesson and learning activity that requires the students to collect and analyze data in the interest of informing their design and to make connections between mathematics, science, and engineering.
- Each unit culminates in an "engineering design challenge" that asks students to use what they have learned to design, create, and improve a solution to a problem.

Maturity

The project started in 2003 and field tested its first set of units in 2004. To date, 15 units have been developed, field tested, and published. Another three units are under development and are scheduled to be field tested during the 2009-10 school year. The project plans to publish a total of 20 units. Several of the earlier units have been revised and are in second edition.

Diffusion & Impact

The project estimates that their materials are being use by about 15,000 elementary school teachers and have impacted approximately one million students. These figures are based on the number of teacher guides that are given to national field sites (i.e., California, Colorado, Florida, Massachusetts, Minnesota) as well as the sales of teacher guides. It is also informed by follow-up inquiries that suggest 80 percent of teachers who obtain the materials use them for more than one year. Another assumption underpinning these estimate is one guide is being used by only one teacher with a class of 25 students. The project characterizes these estimates as being conservative.

The project conducted several formal studies and evaluations during the first four years that examined the impact of their materials on students and teachers. These investigations revealed the following.

- Pre- and post assessments suggest children that use the materials developed a rich understanding of the kinds of work that engineers do when compared to the ideas of children that did not experience the materials.
- Children that experienced the materials are more likely to be able to discriminate between activities that involve designing things versus constructing or repairing things.
- Children that experienced the materials were able to recognize more examples of technology than those that did not experience the materials.
- Pre- and post-assessments showed student gains in the areas of technical vocabulary, understanding the design process, comprehending related science concepts, and recognizing the properties of materials.
- Teachers reported that the materials worked well with diverse populations, that they are clear and easy to follow, that they are pedagogically sound, and that they increased students' awareness of engineering in their lives.
- Teachers reported that the materials were better than their conventional science curriculum in terms of encouraging student learning of science concepts, facilitating student engagement, fostering collaboration, encouraging creativity, and connecting science and engineering with things outside of school.
- After using the materials, teachers reported spending more time on complex and open-ended problems, using different kinds of problem-solving strategies, and having students explain their solutions.

Initiative **Engineering is Elementary**

Title

Catching the Wind: Designing Windmills

Broad Goals

Students will be able to:

- Define engineer.
- Identify different uses of windmills and wind turbines.
- Understand that wind energy can be harnessed to do useful work.
- Recognize the role of mechanical engineers.
- Identify moving parts of a machine.
- Identify common objects that are machines.
- Diagram how they move a machine and how the machine reacts.
- Predict which materials will make the best sail.
- Observe and describe how different materials and shapes catch the wind as sails.
- Notice that the material, shape, and size of a sail affect how well the wind can move the raft to which it is attached.
- Compare the performance of different sails and decide which properties have the greatest effect on sail performance.
- Use each step of the engineering design process.
- Brainstorm several ideas for designing blades for a windmill.
- Create detailed plans for making blades for a windmill that include materials lists and labeled drawings.
- Create prototypes of their blade designs and test them.
- Analyze their prototypes for strengths and weaknesses, and imagine ways that they could improve their designs.
- Implement some of their improvement ideas.

Salient Concepts & Skills

Math

Science

- energy
- motion
- weather
- vejr (*vair* - Danish word for weather)
- wind is moving air
- wind has energy
- wind pushes on objects
- predict

Technology

- technology
- prototype
- design
- anemometer
- beaufort scale
- blade
- rotor
- sail
- machine
- wind turbine
- windmill

Engineering

- An engineer is a person who uses his or her creativity and understanding of materials, tools, mathematics, and science to design things that solve problems for people.

- Mechanical engineering is a branch of engineering that deals with the design and performance of machines.
- Design is a "plan for how to build a solution to a problem."
- The design process follows the themes: "Ask," "Imagine," "Plan," "Create," and "Improve."

Prominent Activities

1. Reading and discussing a story that introduces a problem that needed to be solved (add oxygen to water for gold fish) within a multicultural context (Denmark) and describes how the characters solved the problem using ideas related to mechanical engineering (agitate the water with a windmill).
2. Analyzing simple mechanical devices like glue sticks, hand pumps, and eggbeaters to identify their moving parts, uncover how their parts interact with each other, and plot changes in motion.
3. Predicting, testing and observing how different materials and shapes interact with the air coming off an electric fan in the context of testing sail designs.
4. Designing, building, testing, and improving blades for a wind turbine that must harness moving air to turn an axle and raise a small cup that contains some modest weights.

Initiative **Engineering is Elementary**

Title

Water, Water Everywhere: Designing Water Filters

Broad Goals

Students will be able to:
- Define engineer.
- Discuss environmental quality problems and engineering solutions.
- Recognize environmental engineers' role.
- Use the vocabulary: contaminants, contamination, and pollution.
- Identify multiple human uses for water, soil, and air.
- Identify ways that water, soil, and air become contaminated.
- Make predictions about the efficacy of different filter materials.
- Observe and describe the performance of different filter materials.
- Analyze and compare the performance of different filters.
- Compare results in a controlled experiment.
- Identify the steps in the engineering design process.
- Brainstorm ideas for a design.
- Create a plan for a design.
- Create and test a design.
- Analyze their designs.
- Implement some of their improvement ideas.

Salient Concepts & Skills

Math
- counting
- data
- money
- multiplication
- addition
- time (seconds)
- scoring
-

Science
- bacteria
- chlorine
- contaminant
- environment
- evaporation
- glacier
- kachua (*ka-chew-ah* - a Hindi work for turtle)
- microbes
- monsoon
- natural vs. artificial
- particle
- pollution
- ultraviolet light
- water cycle

Technology
- test
- filter
- water purification

- water vapor
- freezing
- melting
- condensing

Engineering

- An engineer is a person who uses his or her creativity and understanding of materials, tools, mathematics, and science to design things that solve problems for people.
- Environmental engineering is a branch of engineering that is concerned with solving problems with the natural environment (e.g., air, water, soil).
- Design is a "plan for how to build a solution to a problem."
- The design process follows the themes: "Ask," "Imagine," "Plan," "Create," and "Improve."
- Constraint is a "restriction or limit on a designed solution or the design process itself" (e.g., time, money, materials).

Prominent Activities

1. Reading and discussing a story that introduces a problem that needed to be solved (a turtle is living in polluted water) within a multicultural context (India) and describes how the characters solved the problem using ideas related to environmental engineering (filter the contamination in the water).
2. Investigating how water, air, and soil can become contaminated, looking at sources of contamination, and learning how contamination can be prevented and cleaned up.
3. Testing how well and how fast different materials filter the particles from contaminated water.
4. Designing, building, testing, and improving a water filter that will clean contaminated water.

Initiative **Engineering is Elementary**

Title

A Sticky Situation: Designing Walls

Broad Goals

Students will be able to:

- Define engineer and materials engineer.
- Analyze the properties of materials in terms of choices for them.
- Identify the steps of the engineering design process.
- Identify materials comprising commonly engineered objects.
- Describe the different properties of different materials.
- Analyze the properties of materials in terms of uses for them.
- Compare actual wall designs.
- Observe and describe earth materials when dry and wet.
- Predict which earth materials will produce the strongest mortar.
- Predict which mixture of earth materials will produce the strongest mortar.
- Use each step of the engineering design process.
- Create a detailed plan for a design that includes materials and a labeled drawing.
- Create a mortar mixture design and test it.
- Analyze their designs for strengths and weaknesses.
- Improve a design.

Salient Concepts & Skills

Math
- "Scoops" as a unit of measurement for volume
- rating scale

Science
- clay
- durability
- experiment
- material
- mixture
- particle
- properties

Technology
- demolition
- mortar

Engineering

- An engineer is a person who uses his or her creativity and understanding of materials, tools, mathematics, and science to design things that solve problems for people.
- Materials engineering is a branch of engineering that is concerned with creating new materials with new properties.
- Design is a "plan for how to build a solution to a problem."
- The design process follows the themes: "Ask," "Imagine," "Plan," "Create," and "Improve."
- Redesign is a process for changing or improving the looks, cost, function, or operation of a technology.

Prominent Activities	1. Reading and discussing a story that introduces a problem that needed to be solved (protect a garden) within a multicultural context (China) and describes how the characters solved the problem using ideas related to materials engineering (create a brick using earthen materials). 2. Examining the properties of different materials and the properties of materials make them a good or poor choice for solving a problem. 3. Determining how well different materials like soil, sand, and clay serve as a motor that holds two ceramic tiles together. 4. Designing and testing a combination of soil, sand, and clay to make the best mortar.

Initiative **Engineering is Elementary**

Title

To Get to the Other Side: Designing Bridges

Broad Goals

Students will be able to:

- Identify the technologies discussed in the story.
- Discuss some of the problems, criteria, and solutions associated with designing bridges.
- Recognize the role of civil engineers.
- Identify the steps in the engineering design process.
- Identify some of the forces that act on structures.
- Understand that pushes and pulls must be balanced, or a structure will move or collapse.
- Observe and describe the performance of three types of bridges with different kinds of supports: beam bridges, arch bridges, and deep-beam bridges.
- Analyze and compare the abilities of the three different bridges to support weight.
- Decide which kinds of bridge designs are best for supporting a lot of weight.
- Compare results of a controlled experiment.
- Recognize that the shape of a bridge affects how well it can distribute forces and support weight.
- Recognize that different kinds of bridge designs are suitable given different requirements.
- Use the steps of the engineering design process to design a bridge.
- "Imagine" several ideas for making a bridge out of paper.
- Observe and describe what happens when they test their bridges.
- Analyze their bride designs for strengths and weaknesses and imagine what to "Improve" their designs.
- Discuss the strengths and weaknesses of the materials they are using for their bridges (paper), the forces acting on their bridges, and ways to make their bridges more stable.
- Implement some of their improvement ideas.

Salient Concepts & Skills

Math	Science	Technology
• span • weight as a quantity	• balance • force • stability	• arch • abutment • pier • beam bridge • structure • suspension bridge • prototype

- failure

Engineering

- An engineer is a person who uses his or her creativity and understanding of materials, tools, mathematics, and science to design things that solve problems for people.
- Civil engineering is a branch of engineering that is concerned with the design and construction of public structures such as buildings, bridges, roads, and water systems.
- Design is a "plan for how to build a solution to a problem."
- The design process follows the themes: "Ask," "Imagine," "Plan," "Create," and "Improve."
- Constraint is a "restriction or limit on a designed solution or the design process itself" (e.g., time, money, materials).
- Redesign is a process for changing or improving the looks, cost, function, or operation of a technology.

Prominent Activities

1. Reading and discussing a story that introduces a problem that needed to be solved (cross a stream to get to a fort) within a multicultural context (Texas) and describes how the characters solved the problem using ideas related to materials engineering (design a foot bridge).
2. Investigating the pushing and pulling forces that act on structures.
3. Testing different kinds of bridge configurations (e.g., beam, deep beam, arch) using index cards.
4. Designing, building, and testing a paper bridge that address a given problems with a limited amount of materials.

Initiative — **Engineering is Elementary**

Title — **Marvelous Machines: Making Work Easier**

Broad Goals

Students will be able to:

- Define engineer.
- Identify simple machines.
- Identify engineering problems solved by simple machines.
- Discuss simple machines as solutions for different problems.
- Discuss the role of industrial engineers in designing processes.
- Explain "engineering process."
- Identify a process as a kind of technology.
- Discuss assembly lines, how they work, and pros and cons of their use.
- Observe and describe the performance of simple machines.
- Analyze and compare the performance of simple machines in reducing and changing direction of force required to move a load.
- Analyze the ergonomics of simple machines.
- Compare results in a controlled experiment.
- Identify the steps in the Engineering Design Process.
- Brainstorm ideas for a design.
- Create a plan for a design including materials and labeled diagram.
- Create a prototype and test it.
- Analyze their prototype.
- Improve their designs.

Salient Concepts & Skills

Math
- distance
- newtons as a unit of measure

Science
- effort
- ergonomics
- load
- newton
- work

Technology
- prototype
- assembly line
- pulley
- double pulley
- lever
- inclined plane
- production
- simple machine
- subsystem
- system
- wedge
- wheel and axle

Engineering

- Engineer a person who uses his or her creativity and

understanding of materials, tools, mathematics, and science to design things that solve problems for people.
- Industrial engineering is a branch of engineering that is concerned with improving industrial systems and making work easier, faster, and safer.
- Design is a "plan for how to build a solution to a problem."
- The design process follows the themes: "Ask," "Imagine," "Plan," "Create," and "Improve."
- Redesign is a process for changing or improving the looks, cost, function, or operation of a technology.

Prominent Activities

1. Reading and discussing a story that introduces a problem that needed to be solved (move a load from the floor to a loading dock in a potato chip factory) within a multicultural context (Boston) and describes how the characters solved the problem using ideas related to materials engineering (design simple machines).
2. Experience advantages and disadvantages of custom and assembly line production techniques while making folders.
3. Using quantitative measure and qualitative observations to discover how simple machines reduce force or change direction of the force needed to move a load.
4. Designing, building, and testing a simple machine (subsystem) to lift a one-pound load from the floor to the top of a desk (a.k.a., a loading dock).

Initiative **Engineering is Elementary**

Title

Sounds Like Fun!: Seeing Animal Sounds

Broad Goals

Students will be able to:

- Recognize the role of acoustical engineers in designing technology having to do with sound.
- Discuss how vibrations traveling through matter make sounds.
- Identify possible ways to represent sound.
- Participate in a discussion of the engineering design process.
- Identify primary and competing sounds in their experience.
- Recognize that many acoustical engineers work to damp unwanted sounds, and discuss some ways they do so.
- Investigate and explain two ways to damp sound vibrations.
- Analyze and compare the performance of different materials used in different ways for damping sounds.
- Identify and distinguish between different properties of sounds, and discuss how they can change independently.
- Discuss and catalog different ways that scientists and others use visual representations of sounds.
- Discuss and compare multiple ways to visually represent the same sound.
- Discuss and develop a representation system for properties of sounds.
- Understand that a visual representation system is a type of technology.
- Understand why scientists need to visualize sound.
- Use the engineering design process to design, create, and improve a visual representation system.

Salient Concepts & Skills

Math	Science	Technology
• waveform	• sound	• spectrogram
• intensity over time	• vibrations	
• frequency	• biologist	
• duration	• dampen	
• representation	• absorb	
	• pitch	
	• rransmit	
	• visual	
	• volume	

Engineering

- An engineer is a person who uses his or her creativity and understanding of materials, tools, mathematics, and science to design things that solve problems for people.

- Acoustical engineering is a branch of engineering that is concerned with solving problems related to sound.
- Design is a "plan for how to build a solution to a problem."
- The design process follows the themes: "Ask," "Imagine," "Plan," "Create," and "Improve."
- Redesign is a process for changing or improving the looks, cost, function, or operation of a technology.

Prominent Activities

1. Reading and discussing a story that introduces a problem that needed to be solved (communicating a drum rhythm to a distance village) within a multicultural context (Ghana) and describes how the characters solved the problem using ideas related to materials engineering (create a visual representation of sound).
2. Investigating different ways to dampen sound by reducing vibrations at the source and by tempering the transmission of vibrations through matter.
3. Designing a way to visualize the pitch, volume, and duration of sound.
4. Designing, drawing, and testing a system for representing the songs of birds.

Initiative **Engineering is Elementary**

Title

The Best of Bugs: Designing Hand Pollinators

Broad Goals

Students will be able to:

- Define engineer.
- Identify the steps in the Engineering Design Process.
- Recognize that a system may fail if a part is not working.
- Identify the parts of systems.
- Discuss the role and work of agricultural engineers.
- Discuss how the natural work can provide both problems and solutions for people.
- Recognize how agricultural engineers need to understand science.
- Discuss the engineering use of IPM and its advantages and disadvantages.
- Conduct a controlled experiment.
- Make predictions about the properties of pollinator materials.
- Observe and describe the performance of different pollinator materials.
- Analyze and compare the performance of different pollinator materials.
- Analyze how different flower models require different designs.
- Brainstorm ideas for a design.
- Create a plan for a design.
- Create a model and test it.
- Analyze their models.
- Improve their designs.

Salient Concepts & Skills

Math

Science

- pollen
- insect
- metamorphosis
- nectar
- pollination
- hypothesis
- property
- experiment
- observation

Technology

- pesticide
- hand pollinator
- integrated pest management (IPM)
- prototype

Engineering

- An engineer is a person who uses his or her creativity and understanding of materials, tools, mathematics, and science to design things that solve problems for people.

- Agricultural engineering is a branch of engineering that is concerned with designing solutions to problems related to living systems or biology.
- Design is a "plan for how to build a solution to a problem."
- The design process follows the themes: "Ask," "Imagine," "Plan," "Create," and "Improve."
- Redesign is a process for changing or improving the looks, cost, function, or operation of a technology.

Prominent Activities

1. Reading and discussing a story that introduces a problem that needed to be solved (a plant does not have a pollinator) within a multicultural context (Dominican Republic) and describes how the characters solved the problem using ideas related to materials engineering (design a hand pollinator).
2. Performing a short play about the use of Integrated Pest Management (IPM) in the context of an apple orchard.
3. Conducting a controlled experiment that tests the efficacy of different materials for picking up and depositing pollen.
4. Designing, building, and testing a hand pollinator for one of four different model flowers.

Initiative **Engineering is Elementary**

Title

Just Passing Through: Designing Model Membranes

Broad Goals

Students will be able to:

- Recognize the role of bioengineers in designing technologies based on ideas from the natural world.
- Explain that a membrane separates or protects structures in an organism by allowing some thing to pass through it but not others.
- Identify the basic needs of organisms and how different organisms meet those needs.
- Discuss events in the story and how they represent steps of the engineering design process.
- Distinguish between objects and processes found in the natural work and those designed by humans (technologies).
- Match an object or process found in the natural world to a technology (human-made object or process) with a similar function.
- Recognize that bioengineers look to the natural world to inspire the technologies that they design.
- Observe and describe the properties and functions of a natural membrane (raisin skin).
- Understand and compare the flow rate of water through natural and model membranes.
- Observe and describe the performance of model membrane materials.
- Analyze and compare the performance of different model membrane materials.
- Identify the steps of the engineering design process.
- "Imagine" model membrane designs and select one to "Create" and test.
- "Plan" their model membrane designs with detailed diagrams and materials lists.
- "Create" and test their model membrane designs.
- Make observations about their designs, analyze their success, and "Improve" accordingly.

Salient Concepts & Skills

Math	Science	Technology
• rate	• adrenaline	• human-made
	• amphibian	• model
	• anti-microbial	
	• biological	

- habitat
- natural
- organism
- rain forest
- canopy
- basic needs
- membrane

Engineering

- An engineer is a person who uses his or her creativity and understanding of materials, tools, mathematics, and science to design things that solve problems for people.
- Bioengineering is a branch of engineering that is concerned with design technologies that solve problems in nature or use natural materials to solve man-made problems.
- Design is a "plan for how to build a solution to a problem."
- The design process follows the themes: "Ask," "Imagine," "Plan," "Create," and "Improve."
- Constraint is a restriction or limit.
- Redesign is a process for changing or improving the looks, cost, function, or operation of a technology.
- A model is a small representation, usually built to scale, that serves as a plan.

Prominent Activities

1. Reading and discussing a story that introduces a problem that needed to be solved (help a frog survive by keeping its skin moist) within a multicultural context (El Salvador) and describes how the characters solved the problem using ideas related to materials engineering (design a membrane).
2. Playing a game that involves matching the function or behavior of an organism with a technology with a similar function or behavior.
3. Exploring the properties of a biological membrane (raisin skin) and the properties of materials that can be used to make a model membrane.
4. Designing, building, and testing a model membrane that will dispense water in a controlled manner for an imaginary frog.

Initiative **Engineering is Elementary**

Title

An Alarming Idea: Designing Alarm Circuits

Broad Goals

Students will be able to:

- recognize the role of electrical engineers in designing and improving technology having to do with electricity.
- Identify how an understanding of conduction and of electrical engineering technology and processes can help inform a design.
- Discuss events in the story and how they represent steps in the engineering design process.
- Identify technologies that use electricity including those run by battery or alternative-generated sources like solar panels.
- Identify how electrical technologies transform electricity into other energy forms.
- Recognize that energy is the ability to do work, and identify some examples of work being done by energy.
- Identify and distinguish between complete and incomplete circuits.
- Discuss and explain why standard symbols systems like schematic diagramming are important.
- Create schematic diagrams for circuits that include batteries, bulbs, wires, open & closed switches, and buzzers.
- Build a simple series circuit from a schematic diagram.
- Identify the steps of the engineering design process.
- Brainstorm ideas for an alarm circuit and select one idea to build and test.
- Draw a detailed plan of their alarm circuit, including a schematic diagram and a labeled diagram of their switch connection.
- Construct the alarm circuit and switch connection designed by another group.
- Test and analyze the success of their alarm circuit designs.
- Brainstorm ways to improve their designs.
- Implement some of their improvement ideas.

Salient Concepts & Skills

Math	Science	Technology
• kilometer	• electricity	• generators
	• energy	• contractor
	• insulator	• symbol
	• transform	• switch
	• work	• schematic drawing
	• conductor	• battery
	• mechanical	• circuit

Engineering

- An engineer is a person who uses his or her creativity and understanding of materials, tools, mathematics, and science to design things that solve problems for people.
- Electrical engineering is a branch of engineering that is concerned with solving problems involving electricity.
- Design is a “plan for how to build a solution to a problem.”
- The design process follows the themes: “Ask,” “Imagine,” “Plan,” “Create,” and “Improve.”
- Redesign is a process for changing or improving the looks, cost, function, or operation of a technology.

Prominent Activities

1. Reading and discussing a story that introduces a problem that needed to be solved (not knowing when the water trough is low) within a multicultural context (Australia) and describes how the characters solved the problem using ideas related to materials engineering (design an alarm).
2. Conducting a scavenger hunt to uncover applications for electricity.
3. Using symbols to create and read schematic drawings for simple electrical circuits.
4. Designing, building, and testing an alarm circuit.

Salient Observations

The *Engineering is Elementary* series (*EiE*) is organized around different fields of engineering (e.g., mechanical, electrical, civil, acoustic). Together, the units of instruction illustrates how a wide range of problems can be overcome through a systematic engineering design process that involves the application of mathematics, science, and creativity.

At the core of each unit is a story that features different people (the characters), a problematic situation (the setting), a pursuit of a resolution to a technical problem (the plot), and ultimately, a viable solution (the conclusion). Embedded in these stories are issues that children can appreciate. For example, in "Javier Builds a Bridge," the bridge becomes a metaphor for overcoming challenges in mixed families (stepbrothers/sisters) while it addresses the challenge of crossing a stream. Some of the other childhood issues that surface in these stories include things like bullying in "Juan Daniel's Futbol Frog," friendship separation in "Leif Catches the Wind," and doing chores in "A Reminder for Emily."

A variety of family members, friends, and acquaintances are portrayed as being engineers in the stories. They include fathers, mothers, stepfathers, grandfathers, aunts, neighbors, brothers, and members of the community at large. Furthermore, the children in the stories are often depicted as aspiring and novice engineers themselves. Across the series these characters are both male and female as well as representatives of an array of cultural and ethnic backgrounds. The stories are also set in a variety of geographic settings that include eight different countries and several different regions of the United States. Consequently, a very deliberate attempt is made to convey all kinds of people are engineers and anyone can become an engineer.

Engineering

The *EiE* series presents students a wide variety of problems can be addressed through a systematic design process that draws on mathematics, science, and creativity. The idea that "Engineers are people who combine creativity with their knowledge of math and science to solve problems" is introduced and reinforced throughout the stories and learning activities in the series.

The curriculum is also very consistent in its treatment of the engineering design process that follows the themes "Ask," "Imagine," "Plan," "Create," and "Improve." However, the treatments of concepts like constraints, modeling, and systems are a little irregular and less decisive. In fairness to the curriculum, addressing these concepts in a more decisive way would have added to an already ambitious a list of goals and objectives.

Design The engineering design process that students are encouraged to follow can be found on the back cover of each storybook. It simply uses the themes "Ask," "Imagine," "Plan," "Create," and "Improve" to operationalize the design process and to sequence the learning activities. During the "Ask" phase students address questions like: "What is the problem?" "What have others done?" "What are the constraints?" The "Imagine" stage engages students in brainstorming potential solutions and choosing the best one. The "Plan" step involves making drawings and listing the materials needed to make a model or prototype. The "Create" part engages students in making and testing representations of their solution to the problem in question. Lastly, "Improvement" challenges students to make their designs even better and to test them again. Clearly an attempt has been made to present engineering design in a developmentally appropriate manner.

The materials target the misconception that solutions to engineering problems come from a trial and error approach. This is demonstrated in "Aisha Makes Work Easier." In this story, Aisha's friend Tanya asks, "Okay, now what?" in hopes of learning how to begin building a simple machine. Aisha responds to the question by saying, "Just dive in and start building stuff!" Examples such as this can be found in the storybooks and they are followed by a correction or clarification about the nature of engineering design process by an authority figure in the story.

Analysis Each unit engages students in some form of analysis. For example, in *Water, Water Everywhere: Designing Water Filters* the students conduct tests to uncover how well various materials (screen, coffee filters, sand) filter water contaminated with cornstarch, tea, and soil. They collect and analyze data about the materials being trapped, the color of the water, and how fast water can pass through the filter. The data is used to determine the advantages and disadvantages of each material and to formulate the optimal combination of materials to filter the water. These analyses are used to inform the design process as well as evaluate the products of design.

Constraints The materials define a constraint as a "restriction or limit on a designed solution or the design process itself" (e.g., time, money, materials). However, a rich discussion of the constraints associated with a given problems is not explored in any depth. Instead, they tend to be more implied than defined. If one reads between the lines, the constraints can be construed from the expectations for a solution to a problem and from the materials that are made available for addressing the problem.

Modeling

The concept of models or modeling is addressed in the unit titled, *Just Passing Through: Designing Model Membranes*. It defines a model as "a small representation, usually built to scale, that serves as a plan." In this case, students design a model membrane through which water can pass at a given rate.

Models play two roles in the curriculum and instruction. First, they are physical representations of the students' ideas about solutions to problems. Second, they are used as teaching tools that play an important role in conduct inquiries that will contribute

Optimization

The materials address optimization in the improvement stage of its engineering design process. During this step, in most cases, the students are challenged to make changes that they think will make their design even better. They are then asked to test their solution again to see if the changes actually enhance its performance. In other cases, they are simply asked to identify and draw ways to make their design better (e.g., *Water, Water Everywhere: Designing Water Filters*).

The cyclical and iterative nature engineering design is also reinforced during the improvement stage. In a few units, the materials introduce a new cycle by requiring students to "Ask Again," "Imagine Again," and "Plan Again." This kind of spiral treatment of the design process can be found in *Marvelous Machines: Making Work Easier* and *Catching the Wind: Designing Windmills*.

Systems

Two of the units touch on the concept of a system. It is defined as "A group of parts that interact to create a product." The notion that a system can also be "a group of steps that interact to create a process" is presented in one of the units. Lastly, one of the units describes a subsystem as a "system that is part of a larger system." Beyond these modest and isolated instances, the materials treatment of systems is more implied then overt. Ironically, virtually all the units contain rich opportunities for students to explore the nature of systems by examining the parts that make up a technology, determining their relationships with one another, and uncovering their interdependence. For example, in the unit titled, "*An Alarming Idea: Designing Alarm Circuits*," the students build and test electrical circuits. A simple series circuit is composed of parts that work together to power a device (e.g., bulbs). If the parts are not arranged and connected correctly, the device will not work. If one part fails to perform its function, the whole system will not work properly. These kinds of ideas about systems could be very easy to integrate into the materials if a teacher took the initiative to do so.

Science

The *EiE* curriculum does not aspire to teach science directly. It is designed to complement and enhance an existing science curriculum by integrating engineering concepts and learning activities with science topics and content. Towards that end, each unit is articulated with one or more popular pieces of science instruction. For example, the *EiE* unit titled *Just Passing Through: Designing Model Membranes* is correlated with lessons, investigations, or learning activities found in science units by GEMS (*Terrarium Habitats*), FOSS (i.e., *Animals Two by Two, Environments, New Plants*), STC (i.e., *Organisms, Animal Studies*), and INSIGHTS (i.e., *Growing Things, Habitats, Human Body Systems*). According to the *EiE* materials, the relevant science concepts can be taught either prior to or in conjunction with the engineering stories and learning activities.

The nature and the amount of science content addressed in each unit vary depending on the branch of engineering being depicted and the nature of the problem being addressed. The stories related to environmental engineering, agricultural engineering, and bioengineering seem to be richer in science content than the ones based on civil engineering and industrial engineering.

The science concepts in each unit are spelled out in a developmentally appropriate manner. For example, in *Catching the Wind: Designing Windmills* the nature of wind is presented in the following manner:

- Wind is moving air.
- Wind (moving air) has energy.
- Wind pushes on objects and interacts with them.
- Wind can be used to do work.

Similarly, in *Sounds Like Fun!: Seeing Animal Sounds*, the following statements are used to characterize the nature of sound:

- Sounds are vibrations traveling through matter.
- Sounds are produced by vibrating objects.
- Properties of sound include pitch, volume, and duration.
- Some kinds of matter absorb sound better than others.

In *Water, Water Everywhere: Designing Water Filters*, the unit presents the science content in the following way.

- During the water cycle, water moves through air and land.
- Water can exist in solid, liquid, and vapor forms.
- Water can freeze, melt, evaporate, and condense.
- Water can be found in many different places.

Again, it is important to note that the *EiE* materials do not attempt to teach the more specific concepts embedded in these statements (e.g., energy, vibrations, pitch, water cycle, water vapor, condense). They are to be addressed in the existing science or with the aid of other curricula (e.g., STC, FOSS, GEMS).

Mathematics

The relationship between mathematics and engineering is introduced in the definition of an engineer in each book (e.g., "Engineers are people who combine creativity with their knowledge of math and science to solve problems"). There are also references to the roles that mathematics plays in engineering endeavors in the stories presented throughout the series.

In addition to these modest citations, each unit includes learning activities that draw upon students' knowledge and skills in mathematics. For example, the mechanical engineering story, *Leif Catches the Wind*, mathematical reasoning is applied in the context of designing, building, and testing windmill blades. The students have to choose geometric shapes for their blades, orient their blades perpendicular to the force of simulated wind, adjust the angle of their blades relative to the flow of air, use approximation to space and align the blades, and more. This kind of attention to mathematics tends to be embedded in the context of the stories as well as the hands-on activities rather than in discrete and dedicated pencil and paper assignments. As such, the units tend to subliminally portray math as an underlying skill that is needed for engineering.

Students are also engaging in taking measurements; making quantifiable observations; gathering, organizing, and analyzing data; and completing tables and making charts.

Technology

Each story unfolds in a way that illustrates technical problems can be solved. Moreover, the pursuit of solutions to problems requires the use of technology and often results in new technologies that improve the quality of life.

The stories include definitions that range from incidental references to technology to explicit definitions. For example, in *A Reminder for Emily*, a story about electrical engineering, Emily says, "I realized I needed some thing or process – a technology –

to help me solve the problem." In *Aisha Makes Work Easier,* a story reflecting industrial engineering, one of the characters states, "Technology is more than just electronic gadgets," it is "…any thing or process that people design to solve a problem." Lastly, in *Javier Builds a Bridge,* a story about civil engineering, the main character learns the "…things that people design to solve problems, are technology." Other ideas about the nature of technology include things like technology can be made of lots of different materials, some materials (like plastics) are examples of technology, an engineer's job is to design technology, and anyone can design technology.

The materials make an overt effort to address misconceptions that both teachers and students are likely to possess (e.g., technology is only things that move, technology is only computers, technology is only things that use electricity). Clear distinctions are made between "what is" and "what isn't" technology in each teacher's guide. For example, science is equated with things in nature and technology is associated with things are human-made.

The assessment tools featured at the end of each unit target popular conceptions and misconceptions about the nature of technology. One instrument graphically depicts human-made things along with things found in nature. Students are asked to determine which images represent technology. Another shows simple images of people doing technical work as well as non-technical work. In this instance students are asked to identify the images that depict the work that engineers do. However, the validity of these instruments is questionable due to their visual clues, verbal cues, and lack of precision. The reasons why students make their selections are likely to be more informative than their actual answers. Therefore, they may be more valuable as a means of generating discussion and soliciting thought processes than assessing students' conceptions of technology and the work that engineers do.

Treatment of Standards

The teacher guides outline how each unit is aligned with select standards for the study of engineering and technology. More specifically, they cite the relevant standards from the Massachusetts Engineering and Technology Standards and the International Technology Education Association's Standards for Technological Literacy. The basis for these alignments is not explained in the materials. However, some of the standards identified can be easily correlated with the contents, key questions, and learning activities in each unit. For example, the key question "What is engineering design" can be easily correlated with "The engineering design process includes identifying a problem, looking for ideas, developing solutions, and sharing solutions with others" (ITEA, 2000). Furthermore, the design activities run parallel to steps outlined in the standard. However, the relationships between some of the contents of a unit and the standards cited are not as clear.

Pedagogy

All of the units follow a simple sequence of lessons that build on one another. The first lesson provides teachers introductory activities that prepare their students for the unit. It engages them in looking at everyday objects, discussing the problems that they address, and describing the materials used.

The next lesson uses a fictional story as an advanced organizer for the balance of the unit. The story also provides a means to integrate the unit into the existing Language Arts curriculum. Students are ask questions that help them prepare for the reading, uncover the main ideas during the reading, and reflect upon the engineering in the story. The reading is also accompanied by activities that help students practice their literacy skills (e.g., answering comprehension questions, making character webs, drawing a scene from the story, sequencing the events in the story).

The lesson that follows each reading is designed to orient students to the field of engineering being targeted (e.g., mechanical engineering, civil engineering, agricultural engineering). This is accomplished through hand-on activities that enable students to examine both the work and the technologies associated with the field in question.

The next lesson is designed to engage students in hands-on activities that address the relationships between science, math, and engineering. These activities typically involve engaging in inquiry along with the collection and analysis of data. The purpose of this lesson is to provide teachers an interface with their science and mathematics curricula while helping students build knowledge that will inform their designs.

All the units culminate in engineering design problems that are consistent with the one presented in the story they read. The students follow the recommended engineering design process to design, create, and improve a solution to the problem.

A variety of strategies are used to orchestrate the lessons. They provide instructions and tips for introducing the lesson, conducting the activities, and debriefing the students (reflection). All of these steps feature numerous questions in bold print. Overall, the instruction is very Socratic in addition to being hands-on. More specifically, questions are used to activate prior knowledge and experiences, to encourage and check for reading comprehension, to solicit preconceptions, and to build and check for understanding.

The materials are very attentive to issues of diversity. A deliberate effort is made to address the needs of underrepresented and under-served populations, especially females. Collectively, the units feature a variety of cultures, ethnicities, languages, exceptionalities, and geographic locations. In terms of targeting the needs of females, the stories are framed in a social context, feature role models and mentors, involve relationships between people, and focus on solving problems to improve the quality life (e.g., people, plants, animals).

Implementation

The *Engineering is Elementary* curriculum is designed to engage children of diverse backgrounds and abilities in highly contextualized, integrated, and experiential learning activities under the auspices of enhancing technological literacy. To fulfill this mission each unit includes a paperback storybook, a set of lesson plans and reproducible masters, content abstracts and references for background information, suggestions for addressing the needs of special populations and troubleshooting problems, and much more.

The materials account for a long list of teacher needs as well as potential obstacles to implementation. They are clearly written to enrich and complement existing instruction in contrast to adding something more to the already overburdened curriculum. The emphasis on literacy is especially noteworthy because of the large amounts of time and energy that are invested in language arts at the elementary level.

Engineering the Future

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Cisco Systems, Inc.
Highland Street Foundation

Grade Level
High School (9-12)

Espoused Mission
"… the course is intended 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."

Organizing Topics

Units
- Manufacturing and Design
- Sustainable Cities
- Going with the Flow
- Power to Communicate

Projects
- Design the Best Desk Organizer
- Design a Building of the Future
- Improve a Patented Boat Design
- Electricity and Communication Systems

Format
The curriculum is presented in the form of a textbook, a laboratory manual, and a teacher's guide.

Pedagogical Elements

- Stories about real engineers and the work that they do.
- Narrative explanations of scientific principles and engineering concepts.
- Lesson plans that feature vocabulary terms, key concepts, and strategies for implementing instruction and conducting assessments
- Student projects and labs that require cooperation and teamwork.
- Socratic instruction (i.e., posing questions, addressing questions).
- Learning activities that involve inquiry (e.g., making observations, taking measurements, gathering data, drawing conclusions).

Maturity

The Engineering the Future project began curriculum development work in 2003, conducted multiple rounds of field and pilot testing Massachusetts between 2004 and 2006, and published its materials through Key Curriculum Press in September 2007.

Diffusion & Impact

Evaluation data collected during field and pilot testing were used to inform the curriculum development process. The project did not conduct any formal assessments to determine the impact of the final curriculum on teachers, students, or programs.

Initiative **Engineering the Future**

Title

Manufacturing and Design

Broad Goals

Students will…

- Develop a deep and rich understanding of the term "technology."
- Develop their abilities to use the engineering design process.
- Understand the complementary relationships among science, technology and engineering.
- Understand how advances in technology affect human society, and how human society determines which technology will be developed.
- Be able to apply fundamental concepts about energy to a wide variety of problems.

Salient Concepts & Skills

Math	Science	Technology
• linear measurement • calculating area and volume • measuring mass • calculating density • orthographic projection • isometric, oblique, and perspective drawings		• casting • molding • separating • forming • assembling • finishing • inventory • systems design • computer-aided design • appropriate technologies

Engineering

This unit introduces students to the engineering design process. More specifically, students are asked to define the problem, research the problem, generate different solutions, select the best solution, build a prototype, evaluate the prototype, and communicate the solution to others, and engage in redesign. During the course of the engineering design process, they are also introduced to the also following engineering principles.

- Criteria and constraints
- Trade-offs
- The Importance of Teamwork
- Optimization
- Markets (niche markets, mass markets)
- Cost-benefit analysis
- Life cycle analysis

Prominent Activities

1. Watch a video featuring an industrial design team engaged in a project.
2. Complete readings featuring engineers, inventors, and technicians that describe aspects of the engineering design process and introduce a variety of engineering concepts.
3. Develop a design concept for a better cell phone holder.
4. Construct a mock-up using simple materials.
5. Calculate the cost of materials, the cost of production, the volume of packing space per unit, the number of products that will fit in a case, the wholesale cost of a case of products, and the retail cost of a cell phone holder.
6. Make a variety of engineering drawings for simple objects (e.g., orthographic, oblique, isometric, perspective).
7. Define the problem and constraints associated with a given scenario about a business that manufactures "organizers."
8. Conduct market survey to determine what people want and need in an organizer.
9. Engage in individual and team brainstorming sessions.
10. Evaluate potential designs by making a "Pugh Chart" that outlines design criteria and constraints, identifies potential solutions, and features ratings for each solution relative to the design criteria and constraints.
11. Work in teams to develop designs, drawings, and models for a new organizer.
12. Test and evaluate a prototype organizer (e.g., identify materials and calculate their weight, develop a manufacturing sequence, conduct a life cycle analysis, determine the cost of manufacturing, research the product's market value).
13. Present the merits of their design to others.
14. Redesign the desk organizer so that it can be manufactured efficiently.
15. Build and test prototype organizers.

Initiative **Engineering the Future**

Title

Sustainable Cities

Broad Goals

Students will…

- Develop a deep and rich understanding of the term "technology."
- Develop their abilities to use the engineering design process.
- Understand the complementary relationships among science, technology and engineering.
- Understand how advances in technology affect human society, and how human society determines which technology will be developed.
- Be able to apply fundamental concepts about energy to a wide variety of problems.

Salient Concepts & Skills

Math

- measurements of population density
- scale, ratio, and proportion
- algebraic reasoning
- creating, reading, and interpreting graphs
- calculation of heat transfer
- calculation of mechanical advantage

Science

- heat conductors and insulators
- first law of thermodynamics
- second law of thermodynamics
- thermal energy flow equals the temperature difference divided by the resistance
- R-values
- energy transfer and storage
- heat and temperature
- thermal resistance
- difference drive change

Technology

- green architecture
- urban sprawl
- foundations
- trusses
- designed systems

Engineering

The students engage in a variety of activities that require them to use mathematics to perform calculations (e.g., cost/benefit ratio, elongation of materials, stress and strain, mechanical advantage, heat loss). The skills are then applied to the design and presentation of a multi-use building that will address urban sprawl.

Prominent

1. Examine the problem of urban sprawl.

Activities

2. Study the “new urbanism” movement where city planners, architects, and engineers work together to design building that have multiple functions.
3. Complete readings featuring an urban planner, an architect, a construction manager, and various engineers that describe different issues that need be addressed in the design and construction of new buildings.
4. Work in teams to design a building that provides housing while serving at least one other function (e.g., office space, retail establishments, manufacturing facilities).
5. Design a structure (a deck) that will withstand heavy loads and dynamic forces.
6. Determine the optimum dimensions for a platform that will support the weight of a fish tank.
7. Analyze the members of a simple structure that is carrying a load to determine if they are under tension or compression.
8. Design, build, and test a model tower that will efficiently carry a load.
9. Test materials to determine their tensile and compression strength as well at their resistance to bending and shearing.
10. Describe the mechanical properties of various materials in terms of their elasticity, plasticity, hardness, and malleability.
11. Experiment with concrete to determine the relationship between its ingredients and its strength.
12. Calculate the heat transfer rate for a simple building.
13. Test a model building and estimate its heat transfer rate.
14. Analyze and draw scale drawings for simple living spaces (i.e., small house, apartment, classroom)
15. Design a building that is structurally sound, thermally efficient, and addresses the problem of urban sprawl.

Initiative **Engineering the Future**

Title

Going with the Flow

Broad Goals

Students will…

- Develop a deep and rich understanding of the term "technology."
- Develop their abilities to use the engineering design process.
- Understand the complementary relationships among science, technology and engineering.
- Understand how advances in technology affect human society, and how human society determines which technology will be developed.
- Be able to apply fundamental concepts about energy to a wide variety of problems.

Salient Concepts & Skills

Math

- algebraic reasoning
- calculating unknowns based on a given ratio
- calculating area and volume

Science

- properties of fluids
- compressibility of gases
- rigidity of liquids
- fluid resistance by virtue of frictional drag
- Charles' law
- Gay-Lussac's law
- Pascal's law
- convection
- conduction
- radiation
- thermal expansion
- work
- efficiency
- geothermal energy
- nuclear energy
- renewable and non-renewable energy resources

Technology

- open and closed systems
- open and closed pneumatic systems
- open and closed hydraulic systems
- pneumatic pump
- hydraulic press
- purpose and contents of patents
- processing a patent
- design and fabrication of dies and molds
- quality control
- prototype testing
- power plant design
- steam turbine design
- Stirling engine

Engineering

The students engage in a variety of activities that prepare them to redesign a toy boat that is propelled by a simple steam engine. This redesign may or may not include things like increasing the pressure produced by the engine, reducing the drag of the hull, or increasing the efficiency of the engine.

Prominent Activities

1. Review the original patent from 1891 for a toy boat that is propelled by a simple steam generator.
2. Complete readings featuring different kinds of engineers that describe projects and concepts related to vehicles, engines, energy resources, and sewage systems.
3. Brainstorm ways to improve the form and/or function of a steam powered toy boat.
4. Use easy to work materials to fabricate and test a simple steam powered boat from a given set of plans.
5. Experiment with simple fluidic systems using syringes (e.g., relationship between pressure and volume, compressibility of air versus water, calculating force and pressure).
6. Explore the relationship between temperature and pressure for a gas that is kept constant using syringes, acetone, hot water, and cold water.
7. Examine the resistance of a fluid flowing through a tube by blowing through straws of different diameters, lengths, and configurations (bends).
8. Redesign a steam powered toy boat (e.g., change the size, shape, or composition of the boiler; modify the length, area, or configuration of the tubes; alter the shape or appearance of the hull; refine the manufacturing process).
9. Prepare a patent application that describes, explains, and illustrates the changes made to the toy boat's design.

Initiative **Engineering the Future**

Title

Power to Communicate

Broad Goals

Students will…

- Develop a deep and rich understanding of the term "technology."
- Develop their abilities to use the engineering design process.
- Understand the complementary relationships among science, technology and engineering.
- Understand how advances in technology affect human society, and how human society determines which technology will be developed.
- Be able to apply fundamental concepts about energy to a wide variety of problems.

Salient Concepts & Skills

Math

- calculating energy and power in circuits
- binary code
- calculating unknowns values based on two known values

Science

- electrical conductors and insulators
- electrical resistance
- electrical power
- reflection and refraction
- electromagnetic radiation
- electromagnetic spectrum
- waves and frequencies
- alternating current
- direct current
- charge
- current
- current and voltage

Technology

- electrical components (e.g., batteries, bulbs, wires, resistors, LEDs)
- series and parallel circuits
- schematic drawings
- function and use of ammeters, voltmeters, and ohmmeters
- control systems
- photovoltaic circuits
- motors and generators
- amplifier
- numeric display
- digital and analog signals
- data storage and retrieval
- speakers and microphones
- fiber optics
- cathode ray tubes

- AM and FM signals
- electrical distribution grid
- wireless networks
- encoding and decoding signals
- cell phones
- satellites
- Internet

Engineering

Most of the unit is dedicated to building a basic understanding of electricity and electronics.

Prominent Activities

1. Complete readings featuring engineers, an electrician, an entrepreneur, a computer scientist, a computer programmer, and an educator that describe projects and concepts related to electricity and communication systems.
2. Become familiar with the components in a "Snap Circuit Kit" (basic electrical components that can be snapped together to make simple electrical circuits).
3. Examine the behavior and function of basic electronic components (e.g., switches, motor, bulb, photoresistor).
4. Configure and draw schematics for a variety of circuits using only a battery, a bulb, and a single piece of wire.
5. Build and use an open circuit to test a variety of materials to determine if they are electrical conductors or insulators.
6. Design, build, and test a simple circuit that contains batteries, a lamp, and a switch under the auspices of a "Rodent Detector."
7. Experiment with an ammeter in simple electrical circuits (e.g., in series within the circuit, attached peripherally to a series circuit, effect of polarity on the meter's movement).
8. Study concepts related to electrical current (e.g., conventional current flow, polar versus non-polar devices, alternating current versus direct current).
9. Study the concept of a capacitor and examine its behavior in a simple circuit.
10. Design a circuit that will charge and discharge a capacitor.
11. Study the concept of voltage, current, and resistance.
12. Examine the effect increasing the number of loads (bulbs) in a simple series circuit has on the amount of current flowing through the circuit as well as the brightness of each bulb in the circuit.
13. Examine the amount of current flowing through the branches of a parallel circuit that contain a single bulb.
14. Use Ohm's law to calculate unknown values in series and

parallel circuits featuring resistors.

15. Examine the brightness of multiple bulbs in series, parallel, and series-parallel circuits.
16. Design, build, and test an electrical circuit that features two speeds, an on/off switch, and a way to go forward and reverse.
17. Study the various scales and setting for voltage, current, and resistance on a simple multimeter.
18. Examine the effect that increasing the amount of voltage applied to a simple circuit has on the current flowing through the circuit.
19. Develop a "Consumer Information Sheet" that illustrates and defines the specifications for devices featuring different configurations of batteries and bulbs (e.g., flashlights, emergency lighting systems).
20. Study the concept of power.
21. Experiment with solar cells (e.g., voltage output relative to the amount of surface area exposed to a light source).
22. Experiment with motors and generators as power sources for simple series and parallel circuits featuring multiple loads.
23. Design an emergency light system that includes, notes, calculations, and schematic drawings.
24. Study and experiment with a simple communication system that features a microphone, amplifier, and speaker.
25. Study communication concepts (e.g., analog signals, digital signals, storage and retrieval, fiber optics, lasers, speakers and microphones).
26. Encode and decode the binary code sequence for short messages.
27. Use a simple integrated circuit to store and retrieve a short audio message.
28. Build and test a simple circuit that converts sound into light.
29. Build and test a circuit that illuminates blue, green, and red LEDs.
30. Experiment with a home-made speaker made out of a paper cup, magnets, and a coil of wire.
31. Design a communication system

Salient Observations

The curriculum comes in the form of a textbook, a laboratory manual, and a teacher's guide. The textbook is basically an anthology of short narratives that are authored by different kinds of engineers and technologists (e.g., technician, architect, construction manager, industrial designer, inventor). Each one includes biographical information about the author and at least one description of a real engineering project. The narratives provide authentic glimpses into the work that engineers do from an insider's perspective. In addition to profiling engineers and their work, each narrative presents encyclopedia-like explanations of relevant scientific principles, technological concepts, and engineering practices.

The contents of the laboratory manual are presented in a series of textboxes that feature simple illustrations and modest narratives. Together, they explain technical concepts, pose questions to be answered, and present the tasks to be performed. The format and content suggest a lot of attention was given to clarity and brevity. The reading demands placed on students by the laboratory manual are very modest.

The materials do not include objectives for each of the topics, concepts, or skills that are addressed. Instead, the curriculum declares five broad goals that run through the series of four projects. Thus, each project espouses to address the meaning of the word "technology"; the engineering design process; the relationships among science, technology and engineering; the effect technology has on society and the effect society has on technology; and the application of energy concepts to wide range of technical problems. It is relatively easy to correlate the themes embedded in the goals with the contents of the curriculum materials. However, the relationship between the curriculum's goals and its instruction is not explicit.

Engineering

This curriculum was developed to introduce the study of engineering at the high school level.

Design

The curriculum provides students numerous opportunities to engage in design. Some of the design challenges are clearly intended to be incremental and formative while others are intended to be culminating and summative. The extent to which they require students to engage in "engineering design" is somewhat tenuous. For example, students are asked to use simple materials to design a model for a backyard deck that will support an undisclosed load. The need for engineering is tempered by the fact that this problem is introduced without the benefit of instruction that illuminates how simple materials can be configured and arranged to add strength. In a later activity, students are asked to "…redesign any aspect..." of a toy boat. Similarly, another design problem requires students to "design a communication system" using parts from their electronic kits. The openness of these design problems does not intrinsically call for engineering and the need for engineering is highly dependent on how students operationalize the problem. Another design problem asks students to wire a motor under the auspices of controlling an electric fan that has two speeds and can run in two directions. A basic understanding of polarity, simple circuits, and common electrical components is enough to address the problem through trial and error without engaging in any genuine engineering.

In some cases, the lack of specificity in the design problems reduces the need to apply the scientific principles and engineering concepts that were addressed in the prerequisite lab activities. For example, in problem 3, students are given the option to redesign the appearance of a toy boat and/or improve its performance. Enhancing the aesthetics of a toy boat falls more under the domain of industrial design more than engineering design. Improving the boat's performance could include increasing the pressure produced by the propulsion system or reducing the drag associated with the hull. These could involve increasing heat, reducing friction, or reducing losses–all of which can be accomplished through tinkering or engineering. However, despite the loose wording of this design problem, the evaluation rubric does call for scientific reasoning (e.g., fluid flow, resistance in pipes, temperature differences, convection).

Analysis

The materials contain numerous instances where students engage in an analysis. For example, they are asked to estimate how different materials will affect the weight of a product based on their density; to uncover the affect that the ingredients in concrete have on its strength; to determine the relative resistance that a fluid will encounter in a pipe depending on its diameter, length, and configuration; and to calculate the current flowing through series and parallel circuits based on a given voltage and resistor value. However, there is very little evidence of engaging students in analysis to predict the performance of a design prior to its implementation. Most of the opportunities for predictive analysis are underdeveloped or dependent on student initiative.

Constraints

The concepts of design criteria, trade-offs, and constraints are addressed in the curriculum. More specifically, they are introduced in the first project that requires the students to design products (i.e., cell phone holder, organizer). However, some of the design problems that the students are asked to address are very open-ended and do not impose a lot of restrictions on their creativity nor do they focus the engineering process.

Modeling All of the projects use modeling in one form or another. Students are asked to fabricate mock-ups, make representations, test prototypes, and configure systems. These models are sometimes artifacts from the engineering design process and serve as physical representations of the students' ideas. Other times they serve as instruction tools or media that illustrate scientific concepts and support the teaching and learning process. The models are not used as vehicles for generating the data needed to engineer a design.

Optimization The concept of optimization is defined and discussed in the materials. They state it means, "to increase the efficiency or effectiveness of a process as much as possible." Furthermore, students address trade-off in the context of the appearance and features of a product relative to its cost and manufacturability.

A modest form of optimization is also addressed under the auspices of redesigning solutions to problems (e.g., a product, a toy boat). The lab that calls for the redesign of a new product simply challenges the students to find one more way to improve their organizer. The extent to which the redesign of a toy boat calls for optimization or simply improving a design is not clear. The treatment of this concept is a little vague

Systems The materials define a system as "a group of parts that work together to achieve a specific goal." The curriculum clearly provides students numerous opportunities to experience systems first hand in a variety of contexts. These experiences include things like combining materials to make a product that fulfills a need, putting electrical components together to convert energy and do work, configuring materials into structures that carry loads, and assembling simple devices to transmit force through the movement of a fluid. In some cases, the instruction calls attention to the fact that systems have components that serve as input devices, control devices, and output devices. However, the synergy and interdependence among the parts of a system is more implied than defined. Despite the numerous opportunities to call attention to the nature of systems and systems thinking, they are only addressed in a direct manner in a few isolated instances.

Science All three documents address a wide range of science principles. Furthermore, the laboratory activities engage students in a lot of inquiry. More importantly, many of the design problems require students to apply laws of nature to solve technical problems. For example, students have to apply concepts about pressure, force, area, and heat to the propulsion system of a steam power toy boat. Another example requires students to make informed decisions about the design of a building based on the forces applied to structure members and the thermal properties of materials.

Mathematics Mathematical content can be found throughout the materials. It is often presented in the form of formulas that are used in conjunction with narratives to describe patterns and relationships among things (e.g., fluid flow rate in relation to the area of a fluid conductor). In these instances, they are used to facilitate comprehension and the students are not asked to perform any computations.

There are also instances where formulas are used to calculate the value of unknown variables based on two or more known variables. This use of mathematics is very prominent in the sections that address material properties, heat transfer, and electricity/electronics.

None of the math found in the materials requires more than a functional understanding of basic algebra.

Technology One of the major goals of the curriculum is to help students "…develop a deep and rich understanding of the term 'technology.'" Developing a robust understanding would include ideas about technology as artifacts, knowledge, processes, and volition. Although these ideas are embedded in the readings and learning activities, they are not targeted directly in the readings, laboratory activities, or assessment tools.

The study of technological concepts and system can be found throughout the materials. However, the extent to which they are explained in the readings, experienced in the lab activities, and evaluated by the assessment tools is not as consistent as it is with the science content. For example, in project one, manufacturing concepts like separating, forming, assembling, molding, casting, conditioning, and finishing are explained in the readings. The laboratory activities calls for fabricating models that intrinsically involve modest forms of separating, forming, and assembling. However, these concepts are not addressed directly in the laboratory manual. The assessment tool evaluates the completion and quality of the prototypes or models, but it does not hold the students responsible for any conceptual understanding. The study of technology erodes as one progresses from the readings to the laboratory activities and then to the assessment tools.

There are several instances where the materials oversimplify complex systems. Some of these oversimplifications could lead to inaccuracies and misconceptions. For example, students are asked if they "…think that brake systems on cars are hydraulic or pneumatic?" The preferred answer is hydraulic. However, modern brake systems include brake boosters that make applying the brakes easier and less dependent on the strength of the driver. These brake boosters are essentially pneumatics devices. Therefore, the answer to the question is both. Similarly, students are also asked, "Which kind of system do you think robotic arms use? Again, the correct answer needs to be both. When speed is needed on a modest scale, robotic systems tend to be pneumatic. However, if the work in question requires heavy or precise work and speed is not a major consideration, hydraulic systems are often used.

Treatment of Standards

The teacher's guide states, "*Engineering the Future* maps directly to the *Standards for Technological Literacy* (ITEA, 2000), *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Standards* (NRC, 1996)." The broad themes embedded in the five goals are analogous to those used to organize and compose some of the national standards. However, the absence of specific objectives makes validating this claim extremely difficult.

Pedagogy

One of the most prominent features of the curriculum is the emphasis placed on people and story telling. The textbook reads like transcripts from a rich series of guest speakers. Each one tells a story about his or her interesting in engineering and the work he or she does from a personal perspective. Similarly, the last two sections of the laboratory materials name historical figures that uncovered the scientific principles that govern engineering endeavors (e.g., Robert Boyle, Blaise Pascal, Sadi Carnot, Michael Faraday, Alessandro Volta, Georg Ohm, Marie Ampere).

All of the laboratory activities are broken down into very small pieces that build upon one another in a very incremental manner. In the context of a high school curriculum some of the labs appear to be remedial in nature. This is especially prominent in the section dealing with electricity. It features laboratory activities that are similar to those found in elementary curricula (e.g., building simple series circuits; testing for conductors and insulators; making a circuit with a battery, a bulb, and a single pieces of wire; locating the terminals on a light bulb). Introductory experiences can also be found in a lab relating to tension and compression in simple structures, the transfer of heat, and the relative compressibility of gasses and liquids. Therefore, the curriculum does not make any assumptions prerequisite knowledge. The materials simply start with the basics and builds knowledge from there.

Most of the laboratory activities are loosely connected to the culminating design problems. The culminating design problems provide the students a lot of latitude to be creative and to operationalize the problem in a way that capitalizes on their interests. Given the openness of the final problems, students may or may not put all the knowledge that they gained in the prerequisite labs to work in their designs.

Implementation

A wide variety of tools and materials are required to implement the curriculum. Most of the consumables are inexpensive and they can be obtained from popular business supply and home stores. Some of the more specialized items need to be purchased from commercial vendors that market science and technology education supplies and kits. The only items that are likely to be perceived as expensive are the snap together modules that are used to build electrical circuits. It is important to note that these components represent, for the most part, a one-time expense because they can be reused from one year to the next. Teachers should expect to replace some of the components from time to time due to loss or damage. Organizing, storing, and managing all the tools, materials, and components are likely to be one of the challenges associated with implementing the curriculum.

Ford Partnership for Advanced Studies

Course 4: Designing for Tomorrow

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Funding	Ford Motor Company Fund
Grade Level	High School (9-12)
Espoused Mission	"The Ford Partnership for Advanced Studies (Ford PAS) provides high school students with high-quality interdisciplinary learning experiences that challenge them academically and develop their problem-solving, critical thinking, and communication skills. By building strong local partnerships with business and higher education, Ford PAS encourages and prepares students for success in college and professional careers in fields such as business, engineering, and technology."
Organizing Topics	The following three modules constitute the fourth course in a series of five classes. The other courses in the sequence address topics related to communications, change, management,

marketing, and the global economy. The fourth course, *Design for Tomorrow*, was selected for this review because of its emphasis on engineering and technology. The titles of the three modules, or units of instruction, that comprise the course in question are as follows:

- *Reverse Engineering*
- *Different by Design*
- *Energy for the Future*

Format

The review focused on the "Teacher Guide" for each module in the course. The guides are basically spiral bound versions of the student materials with additional information for the teacher. The student documentation across the three modules includes narratives that explaining key concepts, directions for learning activities, stories about design problems and projects (a.k.a., case studies), additional readings, lists of the references, and glossaries of terms.

The following elements were inserted between the pages of the student materials to inform, guide, and support the teacher.

- An overview of the module.
- A sample planning calendar.
- A table outlining the learning goals, national standards, core skills, and assessment tools for each learning activity.
- Lists of all the standards and core skills that correlate with the module.
- Suggestions for teaching the module (e.g., software, teamwork, preparing materials).
- Tables outlining the materials needed, the quantity required, and where they might be obtained.
- Instructions for orchestrating specific lessons and learning activities.
- Reproducible masters for handouts, laboratory sheets, and assessment tools.
- Answer keys for the test and quizzes.
- Recommendations for additional references

Pedagogical Elements

- Lessons plans feature elements like prerequisite knowledge, vocabulary, key concepts, strategies for pre-assessment and set inductions, and group work.
- The instruction is very Socratic in nature (i.e., posing questions, addressing questions).
- Most of the learning activities involve analysis (e.g., analyzing common objects, making observations).

Maturity

The Ford PAS imitative began in 2001. The development of modules 10, 11, and 12 began in the winter 2002/spring 2003 and were pilot tested in fall 2003. Modules 10 and 11 were copyrighted in 2004 and module 12 was copyrighted in 2005.

Diffusion & Impact

The Ford PAS program has developed over 50 partnerships between organizations that are committed to education (e.g., state department of education, post-secondary education institutions, community organizations, Business/Education Advisory Councils, local schools districts). Collectively these partnerships support the implementation of the program in over 160 schools in 25 states across the United States. The program has been implemented in comprehensive high schools in urban and suburban settings, career and technical education programs, freshman engineering courses at the college level, and Historically Black Colleges and Universities.

The program is currently undergoing an external evaluation that is examining the following variables.

- The impact of the program on participants.
- Aspects of the program that work well as well as those that do not.
- How the impact of the program may vary across student populations (e.g., gender, academic standing).

Initiative **Ford Partnership for Advanced Studies**

Title

Reverse Engineering

Broad Goals

- Identify primary and secondary functions of various products.
- Analyze a product's usability.
- Facilitate a team meeting by structuring and managing the flow of idea.
- Analyze how well a product's design meets the needs of the intended users.
- Describe how to design a product for ease of assembly and use.
- Analyze products to determine what manufacturing processes were used to create them.
- Justify why a particular manufacturing process is appropriate for a product or particular material and how changing the way a product is made may affect its usability, assembly, and or cost
- Use the Internet to research the raw materials, energy issues, manufacturing processes, and waste outputs related to a product.
- Create instruction and illustration to precisely communicate the process for assembling a product.
- Critique and improve process instructions to increase their ease of use.
- Explain the conditions under which a particular product must operate.
- Determine a plan to evaluate the suitability of a material for particular use, based on its physical and mechanical properties.
- Make complex decisions that take into account conflicting concerns and points of view with an organization.
- Explain and provide support for a particular position on an ethics issue that involves the safety of people.
- Document through accepted methods the process of reverse engineering.

Salient Concepts & Skills

Math
- measuring
- metric units of measurement
- collecting data
- organizing data
- analyzing data
- qualitative versus quantitative

Science
- mass
- brittle
- compression
- corrosion
- crack propagation
- creep
- ductile
- fatigue
- tension
- documentation

Technology
- function
- secondary function
- assemble
- assembly
- component
- disassemble
- blow molding
- casting
- extrusion
- forging

		• fair test (controlling one variable while holding others constant) • covalent bonds	• injection molding • machining • sintering • assembly drawing • perspective drawing • technical illustration • vanishing point • composite • biomimetics

Engineering

This unit introduces the following ideas about the nature of engineering.

- Documenting engineering projects with a "logbook."
- How to structure, manage, and conclude meetings (e.g., creating agenda, establishing recorders and timekeepers, paraphrasing input from participants, refocusing discussions, providing positive feedback, review and summarize).
- Introduction to concept of reverse engineering ("analyzing a product to understand how the product was originally produced").
- The use of reverse engineering to legally modify or improve existing products that are manufactured by competitors.
- The seven "Principles of Universal Design" (i.e., flexibility in use, simple and intuitive, perceptible information, safety and tolerance of error, low physical effort, size and space for use, equitable use).
- Design for ease of assembly (e.g., reduce the number of parts, incorporate multiple functions in one part, group parts into subassemblies, allow space for fastening tools, reduce the number of fasteners, standardize parts to reduce variety).
- Industrial designers "combine practical knowledge with artistic ability to turn abstract ideas into formal designs" for products.
- Relative cost of labor and materials in relationship to the number of products produced annually.
- The composition of a flow-process diagram (i.e., raw materials, energy requirement, production processes, products, waste).
- Analysis of a product to determine the inputs, processes, and outputs of the manufacturing system used to produce the product.
- Selecting materials based on their environmental impact (e.g., recycled content, recyclability, toxicity, cost of disposal).
- Using reverse engineering to determine why a product failed.
- The role of technical illustrations to record and convey a

product's design.
- Analysis of material composition and failure.
- Causes of engineering disasters (e.g., human factors, design flaws, material failures, extreme conditions).
- Introduction to the ethics of engineering (e.g., avoiding conflicts of interest, representing knowledge accurately, fulfilling the terms of a contract).

Prominent Activities

1. Analyze a variety of can openers to determine why they are designed and made the way they are.
2. Determine how can openers are designed to be used and analyze which one would be best for different users (e.g., people who are left-handed, people with arthritis).
3. Start maintaining a "design logbook" to record their students' investigations.
4. Analyze a product in the classroom (a desk chair) and determine if it meets the needs of its intended user (e.g., flexibility in use, simple and intuitive, safety and tolerance of error).
5. Disassemble and sketch children's "spill proof" sippy cups (a.k.a., training cups) to understand their design and assembly.
6. Identify the features of the design that enable sippy cups to be prevent leakage.
7. Conduct tests to determine which design features work the best.
8. Study the design of sippy cups to determine how well they address the needs of the users (care givers and small children).
9. Research common manufacturing processes that are used to transform raw materials into products.
10. Study common kitchen tools (a.k.a., "gadgets") to identify the processes used to manufacture them.
11. Explore the relations between a product's design and the limitations of the manufacturing processes used to make the product in question.
12. Participate in a field trip to see how products are manufactured.
13. Develop a set of instructions for making a structure with a given set of components.
14. Use instructions developed by others to make a structure from a given set of components and then produce a "technical illustration" of the final product.
15. Evaluate a set of instructions for a model kit during the course of assembling the kit.
16. Revise the instructions that were written by other students for making a structure from given components.
17. Examine data to uncover the cause of a product's failure.
18. Analyze the physical and mechanical properties of metals and

plastics.

19. Study the demands placed on parts made of different materials during a product's use.
20. Explore the ethics associated with a catastrophic engineering failure in a case study about the *Challenger* space shuttle disaster.
21. Use reverse engineering techniques to study accident reconstruction, to uncover what happened, and to determine the cause of a failure.

Initiative **Ford Partnership for Advanced Studies**

Title

Different By Design

Broad Goals

- Determine the aspects of a product's design that are important to consumers, producers, and other stakeholder groups.
- Analyze consumer feedback to determine product features.
- Apply appropriate techniques for idea generation in a theme.
- Given a set of product needs, generate several design concepts for a product.
- Survey competitive products to analyze their features.
- Analyze product concepts to identify which concepts to develop further.
- Assess the financial outlook for a new product design, including development, production, marketing costs.
- Use decision-making methods to choose among several desirable options.
- Identify and describe the successful use of industrial design techniques.
- Use industrial design techniques to create a unique identify for a product.
- Create technical drawings of a product to scale.
- Create visual representations of a product that are appropriate for specific audiences.
- Create a redesign proposal for a product.
- Design and deliver an effective presentation of a product redesign proposal, including visual representations.

Salient Concepts & Skills

Math
- qualitative versus quantitative
- collecting data
- organizing data (decision matrix, cost revenue schedule)
- analyzing data for best solution

Science

Technology
- base-case model
- differentiation
- ergonomic design
- functionality
- industrial design
- user interface
- design patent
- dimension lines
- orthographic drawings
- patent
- technical drawing
- utility patent

societal impacts

Engineering

This unit introduces the following ideas about the nature of engineering.

- Pursuing universal design (building in features that work for as many consumers as possible regardless of their limitations).
- Keeping a design log for recording ideas, sketches, and steps in the design process.
- Applying principles of industrial design to develop a product that has a pleasing look and feel for the target market.
- Communicating the merits of a design to multiple audiences using drawings.
- Solving problems in teams by assigning roles, establishing the topic, setting time limits, giving people time to think, recording every idea, etc.
- Analyzing the physical properties of competing products (a.k.a., benchmarking).
- Generating ideas for the redesign of a product (a.k.a., product concepts).
- Developing a base-case model that features projected development costs, ramp-up costs, marketing costs, production costs, and sale revenues over several quarters.
- Pursuing good industrial design (e.g., quality of the user interface, emotional appeal, ease of maintenance and repair, appropriate use of resources, product differentiation).
- Addressing functionality by addressing the question, “Does the product do what it is suppose to do?”
- Balancing form and function.
- Representing designs with technical drawings and illustrations.
- Patenting a design (e.g., utility patents, design patents).
- Determining specifications for materials based on the form and function of the product.

Prominent Activities

1. Study products to determine what features contribute to their success, address the target market, and feature changes in recent iterations of the design.
2. Form design teams and select a product that they believe can be improved through redesign.
3. Explore how the results of usability evaluations, warranty claims, and market research are used to develop product need statements that drive redesign.
4. Compare and contrast competing products that perform the same task and address the same consumer need.
5. Use function/feature mapping and benchmarking to develop ideas for redesigning products.
6. Develop a benchmarking chart to examine the product they would like to redesign with comparable products on the

market.

7. Employ a “decision matrix” to outline, screen, and score potential concepts for a set of headphones.
8. Determine the most promising concept for improving headphones.
9. Study the financial considerations associated with designing a product (e.g., cost of product development and production, projected sales revenue, estimated profit on a quarterly and yearly basis).
10. Examine two different financial plans for redesigning a product (one that is inexpensive and short term as well as one that is expensive and long term).
11. Analyze the aesthetic and ergonomic features of two products to determine which one has the best design.
12. Assess the industrial design of a portable music player and use the findings to inform a new design.
13. Apply ideas about industrial design to the redesign of a product.
14. Specify the physical characteristics of a product using words, technical drawings, technical illustrations, and advertisements.
15. Compare the features and information presented in technical drawings and illustrations.
16. Study the role patents play in design and conduct a search to determine if their redesign of a product has already been patented.
17. Develop technical drawings and illustrations to show their redesign of a product.
18. Present their redesign of products to the rest of the class for review and feedback.

Initiative **Ford Partnership for Advanced Studies**

Title

Energy for the Future

Broad Goals

- Identify the different forms and sources of energy.
- Determine the social, environmental, and economic concerns associated with different sources of energy.
- Describe and map the transformations of energy in a given system.
- Describe the fundamental principles of generators and motors.
- Analyze a system that uses energy in order to determine its efficiency.
- Calculate the inputs and outputs of energy in a system, given a set of measurements
- Determine the amount of energy needed to meet the needs of a given system.
- Analyze the environmental and social impact and safety of a renewable energy technology.
- Synthesize research to design and present information about a renewable energy technology.
- Debate the benefits and drawbacks of different renewable energy technologies, comparing their characteristics.
- Use questioning strategies to obtain more information from a presenter and, as a presenter, be prepared for questioning.
- Determine the most appropriate sources of energy to use in particular circumstance.
- Present and justify recommendations for a plan to meet a system's energy needs.

Salient Concepts & Skills

Math
- calculations
- conversions
- measurement
- diagram/ chart
- financial cost comparison
- kilowatt-hour
- megawatt-hour
- kilocalorie
- metric units of measurement (e.g., mega, kilo, centi, milli, micro)

Science
- energy
- fossil fuels
- ampere
- British thermal unit (BTU)
- calorie
- current
- joule
- ohms
- transformation
- voltage
- gravitational acceleration
- Newton

Technology
- biomass
- energy systems
- passive solar energy
- power grid
- turbine
- energy consumption/ conservation
- energy conversion (form)
- mapping

- power
- watts
- work
- load
- sources of energy
- forms of energy
- potential energy
- kinetic energy
- temperature
- force
- mass
- acceleration
- calories
- power
- Ohm's law

Engineering

This unit introduces the following ideas about the nature of engineering.

- Analyzing energy conversion systems.
- Weighing competing factors (e.g., cost, impacts, performance).
- Selecting the optimum choice among multiple options.
- Efficiencies of various energy systems.
- Conducting cost/benefit analysis.
- Composing and presenting a proposal for adopting a technology to an audience.

Prominent Activities

1. Identifying different forms and sources of energy.
2. Uncover the kinds of energy used during the course of a day.
3. Review case studies (e.g., *Frozen Food, Inc., Eagle Ranch Community Center*) to identify the pros and cons of different energy utilization options (e.g., coal, nuclear, biomass, geothermal, solar, fuel cell, wind).
4. Consider the environmental, social, and economic issues associated with various sources of energy.
5. Gather information about a technology that utilizes a renewable energy resource (i.e., photovoltaic cells, wind turbines, biogas generation, fuel cells).
6. Examine how chemical energy can be converted into heat.
7. Trace the energy conversions in an automobile (e.g., chemical to mechanical, chemical to thermal).
8. Calculate energy efficiency.
9. Experiment with simple energy conversion devices (i.e., making and testing a lemon battery, using a hobby motor as a generator).
10. Make and test a simple circuit that converts solar energy into

electricity and converts electricity into mechanical energy.

11. Study the concepts of work, power, kinetic energy, and potential energy.
12. Calculate the amount of work done to determine the amount of potential energy in a given system.
13. Investigate the environmental, social, and cost factors related to given renewable energy resources.
14. Make and present posters to the class that describe the advantages and disadvantages of renewable energy resources.
15. Prepare and present proposals for using a given renewable resource to meet the needs of a small town's library
16. Discuss the advantages and disadvantages of each renewable energy proposal and select the best one for a small town's library.
17. Compare their selection for a renewable energy resource for a library with that generated by a computer program (HOMER).
18. Analyze the school lighting system and determine the amount of electricity being used by the system.
19. Develop a practical, efficient, and cost-effective plan for using a renewable energy resource based on the school's location, the availability resources, and the financial constraints.
20. Present the energy plans to school representatives.

Salient Observations

The Ford PAS curriculum strives to apply academic skills and concepts from numerous sets of national standards in authentic contexts like design and product development, information systems, sustainable environments, global economics, business planning, and marketing. The program features a series of five semester-long courses that are subdivided into 15 six-week modules. The primary purpose of the program is to prepare students for further education and ultimately careers in a contemporary work environment.

The following observations are based on a review of course number four, *Designing for Tomorrow* that features modules on *Reverse Engineering*, *Different by Design*, and *Energy for the Future*. These modules were selected for review in light of their attention to design, engineering, and technology.

Engineering

Most of the attention in the first unit of instruction is on reverse engineering in the contexts of discovering how simple devices work, how they were manufactured, and how they address the needs of users. The second unit builds on reverse engineering by introducing the concept of redesign. The third unit under investigation focuses on energy concepts but it requires students to analyze their school's lighting system and present a proposal for utilizing a renewable energy resource (a.k.a., a feasibility study).

Design

Unlike many of the materials under investigation, the Ford PAS modules do not present students with a multistep model for doing design as well as a series of learning activities that take the students through a design process one step at a time. Instead, most of the focus is on reverse engineering and redesign. More specifically, students are presented with products and asked to analyze their design, understand how they work, uncover their subtleties, and decode why they look and work the way they do. Very simply, the students experience the design process in reverse. They start with a finished product (e.g., can opener) and ultimately define the problems that it was designed to solve and the needs that it was designed to fulfill. Furthermore, the students are also challenged to identify the problems and needs that the product did not address and to use their findings as a basis for improving their product's design (a.k.a., redesign).

One advantage to engaging students in reverse engineering is the fact that the learning process starts with something that is tangible and concrete (a physical product) in contrast to something that is intrinsically abstract (a problematic situation). Engaging students in reverse engineering and redesign is consistent with the idea engineers often use their knowledge and skills to make incremental improvements to existing designs over time (a.k.a., iteration). In such cases the engineering design process often start with something that already exists and the primary challenge is to make it better. The students' experience this aspect of engineering by reverse engineering a simple product, identify shortcoming and opportunities in its design, and making refinements through redesign. The process includes considering the marketplace demand, designing for multiple solutions, evaluating and selecting alternative solutions using a decision matrix, considering the product aesthetics (industrial design), representing the redesign with drawing, and presenting the new design to the rest of the class.

The attention given to design is more representative of industrial design than engineering design. This perception is based on the attention given to product design and absence of other kinds of engineering design contexts. Furthermore, the materials define industrial design as an "…aspect of product design that concerns the way a product looks and feels, and the way that customers interact with and use the product." Consequently, modules 10 and 11 engage students in activities that focus on the form and function of existing products. Most of the students' attention is directed toward how products work, what they look like, and why they look and work the way they do. A lot of emphasis is place on uncovering faults in their designs and ways to make them better. Modest attention is also given to improving the manufacturability of products (e.g., minimizing parts, combining parts, standardizing parts, designing parts for assembly). Focusing on industrial design allows the curriculum to start with a simple and familiar product that has subtle design features that students are likely to take for granted. This approach capitalizes on the students' prior experiences with everyday items to gain new insights about technology. Furthermore, analyzing a simple product from everyday life does not require as much domain knowledge as designing an analogous product from scratch.

Analysis

All three units of instruction require students to engage in a lot of analysis. In Module 10, *Reverse Engineering*, their inquiries include analyzing simple devices, comparing the features of analogous products, uncovering the processes used to manufacture products, dividing assembly processes into discrete and sequential steps, troubleshooting instructions, testing materials, and investigating design failures. Module 11, *Different by Design*, involves analyzing the designs of common products, identifying opportunities for making design improvements, and evaluating comparable products. Module 12, *Energy for the Future*, includes analyses of energy utilization patterns and energy conversion systems. The students also determine the feasibility of using alternative energy resources (e.g., availability, advantages, costs, impacts, efficiency).

Virtually all of these analysis activities are presented in the context of engineering and encourage engineering ways of thinking. The depth and breadth of these inquiries are consistent with grooming students to appreciate engineering and to be better consumers of engineering. However, they would be richer and more authentic if the concepts of systems, constraints, trade-offs, and optimization were addressed in a more overt and pervasive manner. Reading between the lines suggests a deliberate effort was made to moderate the technical content of these activities in the interest of serving the largest student population possible.

Constraints

In the first unit on reverse engineering the concept of constraints is touch upon when students are asked to consider the limitations of a manufacturing process in the production of a product. Students also uncover the limitations of materials by examine the bending characteristics of three different metals (i.e., copper, steel, brass) and the breaking points of different kinds of plastic. The attention given to the costs associated with bringing a product to market and the sales revenue generated over time implies there are financial constraints associated with product design. However, the concept of constraints is not targeted directly in the objectives, learning activities, or assessment items.

Modeling

The concept of modeling is not targeted in a direct and overt manner in the materials. The notion that models can be physical or mathematical representations of the problem that can be used to inform the design process was not addressed. The absence of models and modeling can be attributed, at least in part, to the emphasis on analyzing and improving simple devices from everyday life. The availability and simplicity of the objects minimize the need for other representations.

Optimization

The focus on reverse engineering and redesigning everyday products intrinsically calls for some form of optimization. However, the materials do not define and discuss the concept in a direct manner. It is embedded in the attention given to analyzing the design of simple products, identifying opportunities or shortcomings in their designs, and proposing ways to improve their design.

Like optimizations, the concept of trade-off is not addressed directly but it is likely to surface during the product analysis and design activities in *Reverse Engineering*. In *Different by Design*, the students read about the SC Johnson Administration Building, a famous Frank Lloyd Wright design, to explore the tension that exists between form and function.

Systems

The nature of systems and systems thinking is another subliminal concept that is embedded in these materials. The materials do not address the notion that devices are composed of parts that work together in interdependent ways to perform tasks that the individual parts alone can not achieve. However, during the analysis process, students are likely to recognize most of the parts that make up simple devices play critical roles in their functioning.

The concept that many technologies are systems that can be broken down into inputs, processes, and outputs was addressed in the analysis of the manufacturing process that go into making simple devices. It is also embedded in the case studies about how various energy conversion systems work. The potential of these examples was not deliberately tapped to illuminate the nature of technological systems and the use of systems thinking in reverse engineering. It does not appear in the learning goals, selected standards, assessment items, or glossaries of terms.

Science

The richest treatment of science content was found in Module 12, *Energy for the Future*. Most of the science concepts are used to help students understand energy conversion processes. The materials are written in a manner that suggests they are applying and reinforcing science concepts and skills rather than teaching them.

Mathematics

Most of the analysis in the first two modules is more qualitative (descriptive) than quantitative. However, the students are asked to test materials in a way that involves gathering modest forms of data and composing graphs. The purpose of this inquiry is to determine the relative strength of different metals. This is accomplished by illustrating the relationship between the amount of mass that is applied to the unsupported ends of different pieces of wire and their displacement (how much they bend). The results are used to characterize the limitations of different kinds of metal. They do not have any implications for a design problem.

The use of financial information to portray the relationship between costs and revenue over time represents a basic application of mathematics and mathematical reasoning. The composition and use of a decision matrix also has some mathematical properties. Although these examples are modest representations of important aspects of engineering, they do not introduce, apply, or reinforce high school level mathematics.

Modules 10 and 11 engage students in applying geometry concepts during the development of different kinds of technical drawings (e.g., isometric, orthographic, perspective). In this case, the mathematical principles play an integral role in learning how to communicate designs to others. However, they are embedded in lessons that are overwhelming about sketching and drafting techniques.

The richest treatment of mathematics was found in the module on *Energy for the Future*. It features numerous activities that require using simple formulas to calculate things like rate of change in the use of different energy resources, the amount of energy contained in pieces of biomass, the efficiency of energy conversion processes, the amount of work performed, and the cost of energy. Most of these examples of mathematics are used to quantify phenomena or to promote the understanding of science concepts. The only use of mathematics to inform an engineering design process (a feasibility study) can be found in the activity that asks students to compose a proposal for utilizing an alternative energy resource to aid in lighting the school. This assignment uses basic mathematics and algebra to determine the amount of energy that is currently being used and the cost-effectiveness of utilizing an alternative energy resource.

Technology

In many respects, the composition of the materials suggests great care was taken to minimize the need for domain knowledge to develop understandings about the nature of engineering. For example, most of the subjects of inquiry and investigations were simple objects from everyday life (e.g., can openers, training cups, model kits, clock radios, TV remotes). Furthermore, the examination of these items tended to be from a consumer's perspective that capitalized on the students' prior experiences. However, the materials also addressed relatively specific and sophisticated technical concepts in relatively superficial ways. For example, a lot of attention was given to materials and technological processes that go into manufacturing simple products. They included concepts like forging, casting, machining, blow molding, extrusion, injection molding, and sintering. Ironically, the materials ignored some of the simpler and more accessible processes like shearing, bonding, and finishing. The activities engaged students in reviewing Web sites for explanations and applications of these processes. They are then asked to use their new knowledge to "analyze products to determine what manufacturing processes were used to create them." They are also asked to "justify why a particular manufacturing process is appropriate for a product or a particular material and how changing the way a product is make may affect its usability, assembly, and/or cost. Addressing these tasks in a rich and credible way requires more than an encyclopedia-like awareness of selected materials and manufacturing processes.

In a subsequent activity, students are also asked to develop a flow-process diagram for manufacturing a simple device (a.k.a., a "gadget"). An example of a flow-process chart for manufacturing paper milk cartons is provided as a model. It lists manufacturing processes that are far more specific and specialized than the ones the students researched on the Internet (e.g., roll stand, splicer, decurl roller, corona treatment). Developing reasonably accurate flow-process charts for the manufacturing of household devices would require greater technical depth and breadth than what is suggested. To be successful, students would have to find rather specific explanations of how their devices were actually manufactured. Even simple kitchen tools can involve things like compression molding, rivets, sonic welding, press fits, grinding, chrome platting, composite materials, dip casting, and more.

Engaging students in the reverse engineering processes used to manufacture simple devices requires domain knowledge. Some of the devices that students are likely to analyze might require relatively sophisticated manufacturing processes despite the simplicity of the product under investigation. Engaging students in reading explanations, gathering pictures, and making posters to teach concepts that are essentially processes (doing things) is likely to result in a superficial understand and appreciation of the technology that goes into manufacturing products.

The materials do not acknowledge or recommend tapping the resources of technology education programs to enhance or enrich these units. The references to technology in the school curriculum refer to teachers and course offerings that are dedicated to computer literacy and computer science.

Treatment of Standards

All three modules cite numerous national standards that the authors state, "are directly taught and assessed." The list includes standards from English and language arts, mathematics, science, social studies, history, business, engineering, educational technology, technological literacy, and core skills. Furthermore, the materials clearly articulate how the activities in each module align with learning goals, selected standards, and assessment tools.

As a case in point, one of the standards that is being targeted in an activity is, "Students will develop an understanding of engineering design" (ITEA, 2000, p. 89). The following "learning goals" are aligned with this standard.

- Identify primary and secondary functions of various products.
- Analyze a product's usability.
- Analyze how well a product's design meets the needs of the intended users.
- Describe how to design a product for ease of assembly and use.

The learning activities ask students to "analyze a product's design for ease of use" (p.2). More specifically, students are to "explore the characteristics of different product designs to determine how they were designed to be used and who the intended users are" (p.2). They will also "search for examples of product designs that meet the intended users' needs" (p.2).

The items used to assess the achievement of the learning goals, as well as the standard in question, ask students to perform the following tasks.

- Make a sketch of the product and show how its components fit together.
- Identify the product's primary function and features along with its secondary functions.
- Critique the product's usability from the general public's point of view and list the users whose needs are met and those whose needs are not met.
- List and describe five ways to design a product for ease of assembly and then analyze the product in question for ease of assembly.

The continuity between the learning goals, the learning activities, and the assessment items has integrity. However, the achievement of the goals in question, by themselves, will not constitute an understanding of engineering design. Engineering design involves more than identifying functions, evaluating usability, and facilitating ease of assembly. While this module can contribute to the attainment of the espoused standard, its does not have the breadth or depth needed to address the ideas implied by the standard in question in a comprehensive manner.

Similar inconsistencies can be found with most of the standards cited in the modules. The correlations made between the contents of the materials and the standards cited do have some face validity if one looks only for loose connections based on common themes. The notion that dozens of standards "are directly taught and assessed" by each module could be easily misinterpreted. While the materials address some of the ideas and skills embedded in the standards cited, they were not designed to address the standards in their entirety.

Pedagogy

The Ford PAS curriculum uses hands-on activities, project-based learning, case studies, and student inquiry to facilitate the teaching and learning process. These activities engage students in work by themselves as well as working in groups. The lesson plans are basically sets of directions and lists of suggestions that guide and inform the implementation process. The materials do not present or follow a given instructional designs that formally address things like pre-assessment, set inductions, activating prior knowledge, potential misconceptions, etc. However, the teaching and learning process engages students in hands-on activities that employ questions to guide investigations, facilitate reflections and debriefing, and assess student understanding.

Implementation

The Ford PAS materials were designed to be part of a systemic effort to help students prepare for college and careers in a highly competitive and technologically sophisticated global society. The total program involves implementing five semester-long courses and requires participations from a variety of disciplines (e.g., social studies, economics, language arts, science).

Given the scope of the materials and the number of disciplines being addressed, program implementation requires a relatively large investment of time, money, and human capital. Furthermore, the modules are designed to build upon one another in a sequence. In its totality, it is designed to be a schoolwide initiative in contrast to being a collection of materials from which individual teachers can pick and choose. However, five of the modules were designed to be discrete units of instruction if schools chose to infuse these selected pieces of the program into their existing curricula.

The modules on *Reverse Engineering* (number 10) and *Energy for the Future* (number 12) are among those that can be integrated in existing courses without significant modifications or embellishments. The review of *Different by Design* (number 11) does suggest it is dependent on the introduction to reverse engineering that is provided in Module 10.

The Ford PAS program offers professional development workshops on selected modules during the summer. These workshops are approximately 3 days in duration, involve traveling to Dearborn, Michigan, and cost around $160. Implementation is also supported with on-line resources and a technical assistance service.

Purchasing the teacher guides for the three modules that comprise the course *Designing for Tomorrow* cost about $200. A classroom set of student materials (24) for all three modules would cost approximately $1,400. Most of the manipulatives and supplies needed to implement the course are relatively inexpensive when looked at as individual items. However, amassing complete collections for implementing all the activities could add up to thousands of dollars if purchased outright. The teacher guides includes potential sources for purchasing the items as well as strategies for saving money (at the expense of time).

Becoming a Ford PAS site involves making a significant commitment to the program. It involves establishing partnerships, assigning coordinators, obtaining resources, obtaining professional development, registering students on the Ford PAS Web site, gathering and sharing assessment data, and more.

Full Option Science System (FOSS)

Institution	FOSS Project Lawrence Hall of Science University of California Berkeley, CA 94720 Phone: 510-642-8941 Fax: 510 642-7387 Web site: http://www.lhsfoss.org/
Leaders	Linda De Lucchi, Co-director Larry Malone, Co-director Kathy Long, Assessment Coordinator Susan Kaschner Jagoda, Curriculum Developer Teri Dannenberg, Curriculum Developer Ann Moriarty, Curriculum Developer Brian Campbell, K-6 Specialist Don McKenney, K-6 Specialist David Lippman, Project Specialist Terry Shaw, Middle School Professional Developer Joanna Totino, K–6 Professional Developer Virginia Reid, K-8 Professional Developer Carol Sevilla, Publications Coordinator Susan Stanley, Senior Illustrator Arzu Orgad, Administrative Support
Funding	Lawrence Hall of Science (LHS) University of California at Berkeley National Science Foundation
Grade Levels	4-10
Espoused Mission	"The FOSS program materials are designed to meet the challenge of providing meaningful science education for all students in diverse American classrooms and to prepare them for life in the 21st century."

FOSS set out to achieve three important goals.

1. Scientific Literacy: Provide all students with science experiences that
   - are appropriate to their stages of cognitive development.
   - serve as a foundation for more advanced ideas that prepare them for life in an increasingly complex scientific and technological world.

2. Instructional Efficiency: Provide all teachers with a complete, flexible, easy-to-use science program that
   - reflects current research on learning, including collaborative learning, student discourse, and embedded assessment.
   - uses effective instructional methodologies, including hands-on active learning, inquiry, integration of disciplines and content areas, and multisensory methods.

3. Systemic Reform: Meet the community science-achievement standards and societal expectations for the next generation of citizens. FOSS continues to respond to the needs of systems moving away from passive exposure to scientific concepts toward real experiences for students that reflect the vision of the National Science Education Standards.

Organizing Topics

There are 35 discrete curriculum modules in the FOSS K-8 program that address a variety of science disciplines (e.g., life science, physical science, earth science). The module titled *Models and Designs* gives the greatest attention to engineering concepts and engineering ways of thinking. Therefore, it is the focus of this analysis.

Format

The module includes the following materials:

- A "teacher guide" that includes an introduction to the FOSS curriculum, an overview of the *Models and Designs* module, a description of the materials included in the kit, a series of lesson plans for orchestrating four investigations, a set of duplication masters for the handouts, an explanation of a variety of assessment strategies, a set of duplication masters for the assessment tools, recommendations for using the *Science Stories* included in the module, a list of resources for expanding and enriching the module, and directions for using the Web site for *Models and Designs*.

- A set of trade books featuring *Science Stories* that enables it to interface with the language arts curriculum (e.g., *Life on Earth 150 Million Years Ago, Henry Ford and His Model T, Smart Cars and Space Planes*).
- A set of *Science Notebooks* that provide instructions and templates for conducting and documenting the four investigations that make up the module.
- A "kit" that contains all the consumable materials needed to implement the module twice before it has to be restocked.
- A "teacher preparation video" that provides an overview of the module as well as recommendations for its implementation.

Pedagogical Elements

FOSS expects students to:

- Manipulate objects and materials.
- Design and construct conceptual and physical models.
- Look for relationships between structure and function of materials and systems.
- Organize and analyze data from investigations with physical objects and systems.
- Apply mathematics in the context of science.
- Acquire vocabulary associated with engineering and technology.
- Gain confidence in their abilities to solve problems.
- Learn that there is often more than one solution to a problem.
- Communicate ideas to peers and work in a collaborative scientific manner.
- Use scientific thinking processes to conduct investigations and build explanations: observing, communicating, comparing, organizing, and relating.

Maturity

FOSS has been designing curriculum and instruction materials for science education for over 20 years. The current editions of FOSS (2000–2003) are the result of a rich collaboration between the FOSS/LHS staff, a team at Delta Education, assessment specialists, educational researchers, classroom teachers, elementary students, building administrators, parents, and scientists.

Diffusion & Impact

The project did not conduct any formal assessments to determine the impact of the final curriculum on teachers, students, and programs. However, program leaders reported the Models and Designs unit is one of the least popular in the series.

Initiative **Full Option Science System**

Title **Models and Designs**

Grade Level Five and six

Broad Goals

Develop students' abilities to do and understand scientific inquiry.

- Use appropriate tools and techniques to gather, analyze, and interpret data.
- Develop descriptions, explanations, predictions, and models using evidence.
- Think critically and logically to make the connections between evidence and explanations.
- Recognize and analyze alternative explanations and predictions.
- Communicate procedures and explanations.
- Understand that scientists use different kinds of investigations and tools to develop explanations using evidence and knowledge.

Develop students' understanding of energy transfer.

- Energy is associated with electricity, mechanical motion, and sound. Electric circuits transfer electric energy.

Develop students' abilities in technological design.

- Design a solution or product.
- Implement a proposed design.
- Evaluate completed technological designs or products.
- Communicate the process of technological design.

Develop students' understandings about science and technology.

- Technological designs have constraints due to properties of materials and friction.
- Scientists and engineers work collaboratively in teams and use tools and scientific techniques to make better observations.

Salient Concepts & Skills

Math
- measuring
- locations and shapes
- analyzing data
- transforming data
- distance
- circumference

Science
- observation
- comparing data
- systems
- processes
- electricity
- resistance
- friction/traction

Technology
- design process
- drawing
- construction
- physical modeling
- collaboration
- computer programs

- rotation
- ratio
- spatial relationships

Enrichment

- dimensions
- fractions
- graphing
- multiplication
- sequencing
- averaging/ summing

- power
- inertia
- momentum

- variables
- circuit
- levers
- switch
- axle
- bearing

Science Stories

- simulations
- manufacturing
- automation

Engineering

This module introduces students to the following ideas about engineers and engineering.

- "Engineers use a five phase process to develop new products: design, construct, test, evaluate, and redesign."
- "Application of science for the benefit of people is called technology and it is the work of engineers."
- "People who design things… are called engineers."
- "The goal of an engineering project is clear at the outset; what is not known is how the goal will be achieved."
- "Problem solving that produces products is the domain of the engineer in our society."
- "An engineer uses scientific knowledge to design and build useful things."
- There is never a question in the engineer's mind whether or not the product is 'right' – either it does what it is supposed to, or it doesn't."
- "The question that… guides engineer's efforts is whether there is a better, more efficient, more durable way to get the same results."

Prominent Activities

The module features four investigations. They ask students to do the following things:

1. Make observations, models, and presentations regarding the internal working of a sealed black box.
2. Design and build a device that hums when a string is pulled and rings a bell when the string is released (a.k.a., hum dingers).
3. Design, build, test and improve a self-propelled cart.
4. Modify their self-propelled cart to perform tricks and make different maneuvers.

Investigation 1: The investigation begins with the definition of a black box as a metaphor for things in nature that cannot be easily studied. The students are given a plastic black box and asked to do the following:

1. Evaluate the box in groups of two.
2. Identify the possible objects inside the box.
3. Present their ideas to teacher in the form of drawings.
4. Combine and refine their ideas with those from other groups examining the same kind of black box.
5. Select the best explanation of what is going on inside their black box.
6. Build and test a physical model that represents their conception of what is inside their black box.

Students apply what they learned to another metaphorical black box. This time they are asked to figure out how a hidden device called a "drought stopper" works. More specifically, they have to determine how the output of the device produces more water than what is initially put into the system. To accomplish this task they must…

1. Observe how the drought stopper works.
2. Hypothesize what is inside of the drought stopper.
3. Conceptualize how it might work.
4. Draw diagrams explaining its internal workings.

Investigation 2: This investigation begins with a demonstration of a "hum dinger" that is concealed in a paper bag. The hidden device produces a humming sound when a string is pulled and a dinging sound when the string is released. After observing the mysterious device, students are asked to do the following things:

1. Working in groups, students take a bag of materials and evaluate each piece in search of objects that make the required sounds.
2. After locating the key objects, students explore how the objects might interact with each other, along with other materials, to produce the desired result.
3. They engage in designing, testing, and redesign to produce a working device.
4. During the course of the design process, problems are identified and discussed as a whole class.
5. Possible solutions to the problems are proposed and collaboration is encouraged.
6. Once the final designs are completed, they are recorded in a design journal.

Investigation 3: This investigation begins with a discussion of what a cart is and how it functions. A definition of design is also introduced and it is followed by the identification of people who design things. The students are then given the task to design a functioning go-cart. The following processes occur during the design procedure:

1. Initial designs for a go-cart are developed in small groups.
2. The students construct and test their designs with the aid of a ramp.
3. Problems are identified and refinements are made and recorded.
4. The refined designs are tested after the improvements have been made.
5. The go-carts are redesigned so they can self-propel with the aid of a rubber band.
6. Modifications are made to enable the go-carts run a distance of at least 2 meters
7. The designs are finalized and tested.

Investigation 4: This investigation is a continuation of the third investigation. Students are encouraged to follow an engineering design process (i.e., design, construction, test, evaluation, redesign) to enhance their go-cart so it will perform tricks and maneuvers. This process includes the following steps.

1. Writing out their design plans.
2. Obtaining approval for their plans.
3. Gather and configuring building materials.
4. Testing and evaluating their designs.

Salient Observations

Models and Designs is just one piece of a much larger kindergarten through eighth grade science program. This piece targets the concept of models as a methodology for characterizing and explaining scientific phenomena. It also addresses the concept of engineering things in an almost a separate vein.

It is important to note that the initial development of this module was conducted in the late 1980s. Therefore, it was designed before the introduction of national standards, the emphasis on outcomes-based evaluations, and the recent interest in engineering and design education. The materials were essential written by leaders in science education to improve the quality of science instruction with an emphasis on engaging students in scientific inquiry.

Engineering

This module introduces a lot of ideas about engineers and engineering that are too simple or incomplete to be truly accurate. For example, the materials stated, "the goal of an engineering project is clear at the outset." This is inconsistent with the challenges and ambiguities engineers often face with ill-defined problems. The materials also stated, "There is never a question in the engineer's mind whether or not the product is 'right'." This does not account for the new information, constraints, or problems that emerge during the design process that can inspire a new approach or a reconceptualization of the problem being addressed. Furthermore, the notion that an "engineer uses scientific knowledge to design and build useful things" ignores the important role that mathematics plays in engineering endeavors. It also does not address the fact that many engineering projects focus on things like people, processes, and managing the environment. Lastly, the statement that "Engineers take scientific ideas and use them to design and build useful objects" suggests the inspiration for engineering endeavors resides in science in contrast to problems or opportunities.

Design

This curriculum treats design as both a noun and a verb. As a noun, design is equated with a product. More specifically it is a document that represents a "plan for making something." According to the materials, the product can be a picture, a technical drawing, or a description. The concrete example provided to illustrate the nature of design is a "blueprint."

Although this definition is consistent with those presented in simple abridged dictionaries, it does not reflect how the concept is used in engineering contexts. A design is more than a plan or a document. A more accurate definition would reflect the idea that a design is an arrangement of elements (e.g., materials, people, processes) that fulfill a purpose. It would also be more appropriate to portray drawings, pictures, narratives, or models as simply tools for recording, visualizing, and communicating the actual design. The notion that these forms of documentation are the essence of design can lead to misconceptions and simplistic thinking.

As a verb, the materials define design as a "process of figuring out how to construct something." In this context, the materials state design involves "thinking, imagining, trying things out, and using materials wisely." The narratives, lessons, and assessment tools apply and reinforce the idea "engineers use a five phase process to develop new products: design, construct, test, evaluate, and redesign." These themes are a reasonable representation of engineering design given the population being served. However, teachers need to be told the problem-solving processes used by engineers are not this simple nor are they linear in nature. They need to understand that engineering beyond the walls of the school is more complex and dynamic. The development of solutions to problems tends to be more of an iterative process that progresses from ambiguity to a modicum of certainty. This journey from fog to clarity involves jumping back and forth among the basic steps of design.

The materials state, "Design is making stuff." The idea that design is limited to the development of new products is incomplete and underrepresents what engineers do. However, given the fact that this module was developed for grades five and six, this kind of concrete definition may be developmentally appropriate. Regardless, teachers are only presenting this narrow perspective on the nature of engineering. In the absence of a broader and more accurate view, teachers could inadvertently introduce or reinforce popular misconceptions about engineers and engineering.

Analysis

Students are engaged in doing analysis throughout the module. During the first half of the curriculum most of the analysis is conducted through the lens of scientific inquiry. For example, during the first two investigations students are given a representation of a system (a black box containing a marble and stationary geometric shapes that effect the movement of the marble). They are asked to make observations, formulate hypotheses, and construct a model that explains the contents of the black box. This process is presented in a manner that is analogous with how scientists create representations of our solar system, the atom, and more.

The balance of the curriculum and instruction is more representative of analysis in an engineering context. Students are introduced to the concept of analysis and asked to apply it in conjunction with designing, making, testing, and refining simple devices (the hum dinger and the go-cart). They will intrinsically engage in analysis when they strive to understand the problems posed and the materials provided. Furthermore, analysis emerges when they have to evaluate the alternative solutions generated by the other members of their group. Lastly, analysis would surface when they have to troubleshoot their designs because they do not perform in accordance to expectations.

Constraints

The idea of constraints is not among the main concepts that are addressed in this module. However, the notion of constraints is intrinsic to the nature of the materials that are given to students to fabricate solutions to problems and to the amount of time made available for students to address their design problems. A somewhat more direct treatment of the concept can be found in the design activities. However, instead of being variables that limit or govern the design, they tend to be expectations for the final design. For example, in the case of the "hum dinger" the students have to design and build a system that hums when a string is pulled and dings when the string is released. Another case asks students to develop a rubber band powered cart that can travel a distance of two meters. Although these expectations influence the design, they are more consistent with the concept of design specifications than constraints.

Modeling

The materials define a model as "an explanation or representation of an object, system, or process that cannot be easily studied." The materials go on to explain a "model is a sufficiently accurate and complete representation or explanation of an object or process that is to some degree inaccessible." The notion that a model can be a representation of a design (an arrangement of elements) that can be tested or used to communicate the design is more implied than defined.

Most of the discussion of models and modeling is presented in a science context. For example the materials state, "Scientists develop models to explain how systems work." The examples featured in the narratives include the solar system, dinosaur skeletons, the composition of the Earth's core, how one's lungs work, and the structure of an atom.

According to the materials, "The thinking processes that pervade both model building and engineering involve problem solving."

In the case of science, the problem is to discover the unknown. Toward that end, scientists strive to discover the unknown and use models to develop the best explanations of reality based on incomplete sets of data and observations. Engineers, on the other hand, make models to visualize solutions to technical problems. The example given is to "build a better mousetrap."

The first investigations use modeling for the purpose of representing or explaining something that cannot be observed directly and is based on the best scientific evidence at the time. The latter investigations engage students in solving a problem in a manner that requires them to make a physical representation (a.k.a., models).

The materials present the idea that "scientist use models" and "engineers make things." The notion that models can be used in engineering contexts to make design decisions is present in a section that provides teachers the "science" background knowledge needed to implement the module. The actual curriculum and instruction does not address this application in as direct a way as it does for scientific applications of models. However, the narrative titled "*Simulations"* in the book of *Science Stories* describes how scientists and engineers use models to test designs and train people.

The lack of recognition given to the role that models play in engineering is consistent with the propositions that models are science tools, using science to make things is technology, and making technology is the work of engineers. Each of these ideas is somewhat narrow and incomplete. They also put some intellectual distance between modeling and engineering. Consequently, the treatment of models and modeling is equally narrow and incomplete. A more comprehensive treatment of this concept would include the idea that scientists use models to describe and explain things that exist in the natural world and are hard to study. It would also make an equally sound case for the idea that engineers use models to study and test potential solutions to problems to inform the development of a design before it becomes part of the human-made world.

Optimization

The process of designing and redesigning devices contains opportunities for students to experience the concept of optimization. For example, friction is an inherent problem in designing and making the hum dinger and the go-cart projects. Furthermore, given the nature of the materials being used to make working models, repeatability is likely to be an issue. The analysis, tinkering, and refinements required to address these issues are akin to optimizing designs.

The curriculum also engages students in "redesign." For example, students are asked to initially make a free-rolling go-cart. Next they are prompted to use a rubber band to make their go-cart self-propelled. Then they are asked to improve their go-cart so it can travel a certain distance of two meters. This is followed by the request to modify their go-carts so they turn around an obstacle. Finally they are encouraged to make their self-propelled go-cart do tricks. The attention given to redesign is more about modifying the go-carts to address new challenges than it is about improving the performance of the design. However, the need to do things like reducing weight, prolonging the pull of the rubber bands, and minimizing friction are implied in the go-cart investigations.

During the course of these modifications students are likely to engage in optimization because each challenge is probably going to introduce unanticipated cause and effect relationships. For example, for the go-cart to travel a certain distance, the size of the wheels might have to be changed. If the size of the wheels is increased, the amount of force needed to propel the go-cart may have to be increased. If more tension is applied to the rubber bands to propel the cart a greater distance, traction is likely to become an issue. Additional tension is also likely to exacerbate the problem of friction. All of these scenarios will introduce the need to balance trade-offs within the design. However, the concept of trade-offs and balancing trade-off in the interest of optimization is not addressed directly in the materials.

Systems

The materials define systems as "two or more objects that work together in a meaningful way." Once again the curriculum contains numerous opportunities to address the concept of systems. For example, in the second investigation the students are presented a working hum dinger that is enclosed in a paper bag. The students are charged with the task of identifying potential parts of the system and how they might interact with one another. This analysis is following by a request to build and test a "hum dinger" of the students' own design. One important element in this investigation is the need for all the parts to work in a particular sequence to fulfill the design specifications. Another example is demonstrated in the go-cart investigation. The students must make a self-propelled go-cart. For the go-carts to perform in accordance with expectations, the students must understand the functions and behavior of each part and how it interacts with the other parts of the system. However, overall, the concept of systems is treated more subliminally than consciously.

Science

The investigations are rich with science content and scientific inquiry. Most of this attention is focused on the concept of scientific models and doing scientific inquiry (e.g., observation, hypotheses, data collection). The treatment of models in the context of science is especially rich (e.g., physical models, conceptual models, function of models). There is also some attention given to applying and reinforcing science content based on the assumption it was introduced in lessons prior to the implementing this module (e.g., electricity).

Much of the content presented under science is really technology if one separates ideas about the natural world from those about the human-made world. For example, things like circuits, levers, axles, and wheels are presented as science in contrast to being creations of human ingenuity (a.k.a., technology). The following understandings about the human-made world are also listed as "science content."

- "The way something is put together is its design."
- "Some land vehicles have wheels fixed to axles. Power turns the axles and thereby the wheels."
- "Problem solving involves designing, constructing, testing, evaluating, and redesigning based on evidence from testing."
- "Systems can be designed to perform specific functions."
- "All technological inventions have trade-offs such as safety, cost, efficiency, and appearance."
- "Transportation technologies have given many people goods and services that once were luxuries."
- "The assembly line was an important idea that improved productivity and efficiency and reduced cost."
- "Any invention is likely to lead to other inventions."

Mathematics

Most of the math is peripheral to the science investigations and design challenges. It is presented as an "extension" of the core activities. For example, during second investigation, students are asked to determine the amount of time it took for the fastest group to make their hum dinger, the amount of time it took the slowest group to make their hum dinger, the total amount of time taken for everyone to make their hum dingers, and the average amount of time needed to make a hum dinger. The mathematics performed does not have a direct impact on how the hum dingers were designed or made. A more authentic use of math, in the context of doing design, could have been applied to making decisions about the use of levers in the making of the hum dingers (e.g., distance traveled by the string on the input side of the lever versus the distance traveled by the output end of the lever).

Most of the math concepts presented in the *Science Stories* are used to describe and reinforce science concepts. Math also plays a modest role in engineering a solution to problems during the later investigations. When engineering is actually introduced there is a need for some math in order to ensure functionality of a product.

Technology

The essence of technology is described as a practical expression of science. More specifically, the materials state, "When science is put to work for people, we call it technology." They also state, "Technology is the enterprise of using science to develop objects, machines, and materials that are of use to society." These descriptions are consistent with the misconception that the development of technology is dependant on scientific understanding and ignores the historical evidence that many technologies have been developed without the benefit of a genuine understanding of the science involve (e.g., aspirin, radio, photovoltaic cells).

Again, the materials do not discriminate between science and technology. Most of the references to the human-made world are simply equated with science (e.g., vehicles, design, levers, axles, circuits, assembly lines, trade-offs, inventions).

The richest treatment of technology can be found in the "Science Stories" (the modest trade book that can be used to connect the module with the language arts curriculum). Approximately half of the stories in the reader are descriptions of noteworthy technologies (e.g., simulations, virtual reality, early automobiles, assembly line, industrial robots).

According to the *Teacher Guide*, there are profound ideas about technology (a.k.a., science content) embedded in the stories. One of these ideas is, "All technological inventions have trade-offs such as safety, cost, efficiency, and appearance." However, the questions used to debrief the students about the reading in question focuses on the improvements made to early automobiles in contrast to the trade-offs associated with the development of the automobile. Similarly, the *Teacher Guide* states that reading about *Henry Ford and His Model T* helps build the idea, "Transportation technologies have given many people goods and services that once were luxuries." Although the stories address this concept in a rich manner, the emphasis of the lesson is on comparing and contrasting two sources of information. While this is clearly a legitimate task under the auspices of complementing the language arts curriculum, it does not intrinsically draw out this important idea.

The readings also do an excellent job describing the kinds of problems that engineers address in their work. Again, most of the questions and discussions associated with these stories focus on reading comprehension. The potential of these stories to illuminate the nature of engineering and the work engineers do is not harnessed by the materials.

Treatment of Standards

The authors state the materials in question "support" the themes of "Science as Inquiry," "Physical Science," and "Science and Technology" in the "National Science Education Standards" (1996). A more detailed list of the standards that were addressed can be found under "Broad Goals" in this report. The notion that these materials can contribute to the achievement of these standards has tremendous face validity. However, upon closer inspection, there are some inconsistencies between the standards cited, the composition of the instruction, and the content of the assessment tools. For example, the materials aspire to address the concept that "Technological designs have constraints due to the properties of materials and friction." The concept of constraints is not among the "science concepts" being targeted or the tasks that students are asked to perform. It cannot be found in the lesson plans or in the glossary of the *Science Stories*. Lastly, it is not addressed in the various assessment tools (e.g., grading rubrics, objective test items, portfolio assessment).

Pedagogy

Very little is left to chance in the orchestration of quality instruction. The materials are very organized, comprehensive in nature, and easy to follow. The attention to detail in the instructional design of the curriculum is very impressive. Every investigation addresses the need for supplementing teacher content knowledge and engaging students in hands-on activities and scientific inquiry. Each lesson includes prompts and recommendations for engaging students in discourse, conducting debriefings, and facilitating reflection. Practical matters like lesson preparation, the distribution of materials, the establishment of groups, and the storage of projects are also addressed. The materials feature embedded assessments, formative assessments, and summative assessments for each lesson. They also provide teachers strategies and instruments for rating observations, conducting performance assessments, and checking for conceptual understanding.

Implementation

This module provides teachers a lot of support in light of the richness of the materials, the attention given to implementation details, and the comprehensive nature of the kit. However, all this attention to detail and support is expensive. One complete module (teacher guide, preparation video, trade books, science notebooks, hardware, and consumables) costs approximately $700. This kind of expense is beyond most elementary teacher's budgets. The purchase of these materials as an integral role of an elementary science program would require additional funding.

Beyond the materials and the kit, there is on-line support for teachers implementing this module. The cite in question provides resource ideas for enriching and expanding the scope of the unit, additional recommendations for implementing the curriculum, information for students and parents, and on-line learning activities that complement those in the classroom materials.

The Infinity Project

Institution

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Funding

Texas Instruments
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Grade Level

High School (grades 10 through 12)

Espoused Mission

To develop "… an innovative approach to applying fundamental science and mathematics concepts to solving contemporary engineering problems."

Organizing Topics

- *The World of Modern Engineering*
- *Creating Digital Music*
- *Making Digital Images*
- *Math You Can See*
- *Digitizing the World*
- *Coding Information for Storage and Secrecy*
- *Communicating with Ones and Zeros*
- *Networks from the Telegraph to the Internet*
- *The Big Picture of Engineering*

Format

The curriculum is presented in the following form:
- Textbook that contains nine chapters and 494 pages.
- Laboratory manual for students.
- Instructor's manual with a CD that contain images for instructional media.

Pedagogical Elements

The Infinity Project clearly outlines the pedagogical features of its materials. They are listed below:
- The use of four-color illustrations, diagrams, and photographs that "demystify engineering and technology concepts."
- Concrete examples that are interesting and relevant to young people.
- Textboxes that give special attention to important points and interesting facts (e.g., definitions, key concepts, historical references).
- Hands-on laboratory activities that enable students to explore, test, and apply many of the major concepts that are presented in the textbook.
- Hardware and software that simulate digital technologies that are prominent in young people's lives.
- Recommended exercises that check for comprehension, provide applications, and engage students in design thinking.
- Narrative reviews and summaries that include important ideas, key math and science concepts, useful equations, and additional references.

A comprehensive glossary of terms that defines most of the concepts presented in each chapter.

Maturity

The project started in 1999. It was pilot tested in a modest number of high schools in 2000. In 2001, the Texas Education Agency approved the course for an elective credit under the auspices of mathematics, science, career, or technology education. Field-testing on a larger scale began in 2003. Pearson Education Incorporated published the curriculum materials with a 2004 copywrite.

Diffusion & Impact

The materials developed by the Infinity Project are being…
- implemented in more than 300 high schools across the country,
- used in 5 different countries, and
- used as an introductory engineering course at the post-secondary level (e.g., SMU, DeVry).

The project reported that all of the students who completed the course would recommend it to a friend and over 60 percent plan to pursue engineering as a career.

Initiative **Infinity Project**

Title **The World of Modern Engineering**

Broad Goals None found

Salient Concepts & Skills

Math
- Moore's law
- binary
- binary numbers
- converting base 2 numbers to a base ten number
- representing a decimal number in binary form
- converting unit (nanoseconds to minutes)
- simple exponential functions
- algorithm
- bit
- byte

Science
- scientific method

Technology
- analog technologies
- digital technologies
- vacuum tubes
- digital age
- transistor
- integrated circuits
- block diagram
- inputs
- output
- prototype
- memory

Engineering This chapter introduces students to the "engineering design algorithm." The algorithm is a nine-step process that engineers "follow." It includes identifying the problem or objective, defining goals and constraints, researching and gathering information, creating potential design solutions, analyzing the viability of solutions, choosing the most appropriate solution, building and implementing the design, testing and evaluating the design, and repeating the steps as necessary. The chapter also introduces the concept of design constraints ("limits that are placed on a design problem").

Prominent Activities

1. Read about the engineering design process, the basics of modern technology (e.g., integrated circuits), and mathematical concepts like Moore's law.
2. Answer comprehension questions or perform tasks related to the main concepts presented in the reading (e.g., identify the design constraints associated with common technologies, write binary numbers in base-10 form, determine the number of picoseconds in an hour).
3. Complete exercises that use the concepts presented in the

chapter in the context of everyday applications (e.g., describe the advantages and disadvantages of common technologies, identify common technologies as being either digital or analog, use Moore's law to predict the year transistors will be the size of atoms, create a block diagram for an automobile braking system).

4. Review example applications for the mathematics presented in the chapter (e.g., converting a base-10 number to a base-2 number, predicting the number of transistors on a chip in the future, calculating how many people would it take to reach the moon).
5. Review a scenario for designing a solution to a problem (create a digital system that can produce movies based on key word imputed by a user).
6. Complete a lab to become familiar with the Visual Application Builder software (e.g., combine audio from a microphone with a cosine signal, test the video camera, create a sound echo, use an image delay to plot moving objects).

Initiative **Infinity Project**

Title

Creating Digital Music

Broad Goals None found

Salient Concepts & Skills

Math
- converting units
- sines and cosines
- using radians to measure angles
- adding sinusoids
- writing mathematical expressions
- spectrograms
- envelope functions
- square wave functions
- exponential functions
- bits per pixel
- spatial sampling
- spatial sampling rate
- sampling size
- temporal sampling rate
- approximation
- amplitude
- Hertz
- radian
- rate of decay
- exponential function

Science
- temperature
- sound
- notes, pitch, and frequency
- spectrum, amplitudes, and frequencies

Technology
- phonograph
- compact discs
- microphone
- loudspeaker
- Musical Instrument Digital Interface (MIDI)
- spectrum analyzer
- sound synthesis
- waveform synthesis
- additive synthesis

Engineering The focus of this chapter is on developing the domain knowledge needed to address an engineering design problem (e.g., cosine-generator block, making melodies with sinusoids, reverse spectrum analyzer, sound synthesis, wave form synthesis, additive synthesis).

Prominent Activities

1. Read about important engineering ideas associated with the creation of digital music (e.g., signals, MIDI, sound synthesis),

and how mathematical concepts like sines and cosines contribute to making electronic music.

2. Answer comprehension questions or perform tasks related to the main concepts presented in the reading (e.g., write specifications for designing common objects, name three ways to modify a sound signal, define sinusoid).
3. Complete exercises that use the concepts presented in the chapter in the context of everyday applications (e.g., plot examples of signals, calculate the speed of sound at 0 degrees C, write a list of instructions that would be found in a MIDI file based on a sequence of notes, draw the envelope of sound coming from a radio before and after the volume is turned down).
4. Review example applications for the mathematics presented in the chapter (e.g., plotting signals, computing Cartesian coordinates, plotting sines and cosines, adding two signals together, using time scaling to create mathematical expressions).
5. Review a scenario for designing a solution to a problem (design a new karaoke machine that improve the quality of any singing voice based on options selected by the user).
6. Complete a lab to experience how sines and cosines are fundamental to making computer generated music (i.e., take apart the sound of one's voice and analyze its structure, generate and adjust sounds using sines and cosines, model the sound of a tuning fork, build a sinusoidal MIDI player, use a spectrogram to see the frequency content of a signal over time, make musical sounds by multiplying two functions together, simulate an echo electronically, create sound effects with one's voice).

Initiative **Infinity Project**

Title

Making Digital Images

Broad Goals None found

Salient Concepts & Skills

Math
- determining colors and required bits
- determining pixel bit size
- determining pixel width
- calculating exposure time

Science

Technology
- animation
- digital imaging
- photography
- movies
- frame
- multimedia revolution
- pixel
- gray scale
- image enhancement
- image sampling
- sampling artifact
- spatial sampling
- spatial sampling rate
- special effects
- robot vision and navigational control
- exploration of space
- medical imaging systems
- field of view
- halftone image
- color printing
- halftoning
- color map
- palette
- quantization

Engineering The focus of this chapter is on developing the domain knowledge needed to address an engineering design problem.

Prominent Activities

1. Read about the basic technological and mathematical concepts related to digital imaging technology, capturing and storing digital photographs, and manipulating of digital images.
2. Answer comprehension questions or perform tasks related to the main concepts presented in the reading (e.g., What is a pixel? What does a pixel represent in a digital image? How is pixel size related to spatial sampling rate? What is false contouring? What causes false contouring? What is pointillist painting?).
3. Complete exercises that use the concepts presented in the chapter in the context of everyday applications (e.g., Bring pictures to class. Discuss how they were acquired and how they are used. If a color image is represented by 16 bits per pixel, what is the total number of colors that can be obtained?).
4. Review example applications for the mathematics presented in the chapter (e.g., determining sampling rate, determining colors and required bits, determining pixel bit size, determining pixel width, calculating exposure time).
5. Review a scenario for designing a solution to a problem (design an image recording system for a wild-animal refuge, which can count the number of animals that end and leave key areas within the refuge).
6. Complete laboratory activities related to capturing, storing, and displaying color digital images (i.e., image quantization, image sampling, aliasing in movies, color representation, resolution trade-offs).

Initiative	**Infinity Project**
Title	**Math You Can See**
Broad Goals	None found

Salient Concepts & Skills

Math
- image processing functions
- matrix
- matrix operations
- scalar
- calculating pixel and matrix elements
- addition, subtraction, and multiplication of image matrices
- average

Science
- hue

Technology
- image processing
- unsharp masking
- edge detection
- change detection
- image segmentation
- random noise
- impulsive noise
- computer graphics
- morphing
- chromakey
- quantization
- clipping
- mapping
- neighborhood operations
- texture
- threshold
- mask
- negative
- mapping
- filtering

Engineering

The focus of this chapter is on developing the domain knowledge needed to address an engineering design problem (e.g., design objectives for the automatic vision system; designing an object counter, a motion detector, and a blue screen chromakey system; designing image-processing systems).

Prominent Activities

1. Read about the basic technological and mathematical concepts related to digital image and video (e.g., images are treated as matrices, extracting information from images).
2. Answer comprehension questions or perform tasks related to the main concepts presented in the reading (e.g., What is the difference between edge detection and change detection?)
3. Complete exercises that use the concepts presented in the chapter in the context of everyday applications (e.g., What

property of an image can we use to segment an image that shows green apples, bananas, and oranges in a brown wooden bowel on a light-blue countertop? Make a block diagram for a system that would plot the cars traveling down a one-way residential street.).

4. Review example applications for the mathematics presented in the chapter (e.g., calculate pixels and matrix elements, brighten an image, change image contrast, compute results for a horizontal difference processor, find average values, find median values).
5. Review a scenario for designing a solution to a problem (design an image recording system for a wild-animal refuge, which can count the number of animals that enter and leave key areas within the refuge).
6. Complete laboratory activities related to capturing, storing, and displaying color digital images (i.e., brightness and contrast, threshold and negation, adding and subtracting images, adding and subtracting shifted images, sharpening filters, averaging and median smoothing filters).

Initiative **Infinity Project**

Title **Digitizing the World**

Broad Goals None found

Salient Concepts & Skills

Math
- converting numbers to decibels
- binary number system
- binary point
- most significant bit
- least significant bit
- binary fractions
- negative binary numbers
- Nyquist sampling theorem
- Nyquist rate
- signal-to-noise ratio

Science

Technology
- digitization
- digital signals
- sampling
- sampling period
- sampling rate
- sampling frequency
- bandwidth
- digital signal processing
- aliasing
- Moire patterns
- band limited
- lowpass filter
- antialiasing filter
- ASCII code
- digital yearbook
- semiconductor memory
- magnetic disks
- optical discs
- analog-to-digital conversion
- quantization
- dynamic range
- clipping
- quantization noise
- signal-to-noise ratio

Engineering The focus of this chapter is on developing the domain knowledge needed to address an engineering design problem.

Prominent Activities

1. Read about concepts related to computer security and encryption, redundancy of numbers and data compression techniques, and detecting and correcting errors in digital data.
2. Answer comprehension questions or perform tasks related to

the main concepts presented in the reading (e.g., What are four reason for which information is encoded into digital form? Name two different lossy compression methods and two different lossless compression methods. What is the smallest codeword length (in bits) that a codeword can have? What is the difference between even parity and odd parity?).

3. Complete exercises that use the concepts presented in the chapter in the context of everyday applications (e.g., Rounding is often used in engineering calculations to save storage space. How many bits are required in order to store the fractional part of a number when the fractional part is rounded to four significant decimal digits?).
4. Review example applications for the mathematics presented in the chapter (e.g., calculate relative frequency of text, average codeword length for a phrase, determine how much MP3 audio will fit on a single CD-ROM, pseudo-random number generator, compute powers of C modulo N).
5. Review a scenario for designing a solution to a problem (design a virtual garage where people can buy and sell personal items).
6. Complete laboratory activities that feature digital techniques for improving images and finding information within images. (e.g., speech compression, rotational encoder and decoder, pseudo-random number generator).

Initiative **Infinity Project**

Title

Coding Information for Storage and Secrecy

Broad Goals None found

Salient Concepts & Skills

Math
- compression ratio
- polynomials
- average codeword length
- entropy

Science
- entropy
- threshold of quiet
- threshold of feeling
- lower frequency threshold
- upper frequency threshold
- masking

Technology
- code
- encoding
- decoding
- formatting
- compression
- error detection
- error correction
- encryption
- codebook dictionary
- compression ratio
- subband coding
- permutation encoding
- public-key cryptography
- lossy compression
- lossless compression
- run-length coding
- relative frequency
- transparent compression
- parity
- parity bit
- decryption
- cryptography
- key
- password
- access codes
- personal identification numbers
- rational encoding
- identity coding
- permutation

encoding
- exclusive-OR operation
- pseudo-random-number generator
- modulo-N operation
- codeword
- MP3
- joint pictures experts group (JPEG)
- motion picture experts group (MPEG)
- seed

Engineering The focus of this chapter is on developing the domain knowledge needed to address an engineering design problem

Prominent Activities

1. Read about how information, in a variety of formats, (e.g., speech, text, music, images, video), can be acquired, converted, and stored in a digital form along with its applications, advantages, and disadvantages.
2. Answer comprehension questions or perform tasks related to the main concepts presented in the reading (e.g., A digital yearbook would contain what types of information? Name five advantages of a digital yearbook over a hard-copy yearbook. What is the definition of “Nyquist rate”? What is an antialiasing filter?).
3. Complete exercises that use the concepts presented in the chapter in the context of everyday applications (e.g., “A speech signal is sampled at a rate of 8,000 samples per second for a duration of two minutes. How many numbers are needed to represent the speech samples?”).
4. Review example applications for the mathematics presented in the chapter (e.g., finding values for s[n], converting a 4-bit, 5-bit, and 6-bit numbers, converting a decimal number to binary form, decoding an ASCII message, converting numbers into decibels).
5. Review a scenario for designing a solution to a problem (design a digital yearbook).
6. Complete laboratory activities that feature digital techniques for improving images and finding information within images. (e.g., aliased sinusoids, speech, and music; quantization and clipping).

Initiative **Infinity Project**

Title **Communicating with Ones and Zeros**

Broad Goals None found

Salient Concepts & Skills

Math
- determining transmission rate
- transmission speed

Science
- weak signals
- cochlea

Technology
- International Morse code
- Baudot code
- wireless transmitter
- radio transmitter
- wireless communications
- radio communications
- communication channel
- receiver
- bandpass filters
- transmitter
- noise
- tone
- interference
- mapping
- error rate
- prearrangement
- parallel binary method
- serial binary method
- frequency shift keying (FSK)
- American Standard Code for Information Interchange (ASCII)
- Unicode

Engineering The focus of this chapter is on developing the domain knowledge needed to address an engineering design problem (e.g., cost, speed, complexity, accuracy)

Prominent Activities

1. Read about the basic concepts behind wireless and radio communication systems (e.g., sines, cosines, bandwidth, data rate).
2. Answer comprehension questions or perform tasks related to the main concepts presented in the reading (e.g., What is the role of a transmitter in a communication system? What is the role of a receiver? When one person is talking to another, who is the transmitter, and who is the receiver?).
3. Complete exercises that use the concepts presented in the chapter in the context of everyday applications (e.g., What causes a single-tone-per-symbol audio communications system to fail? Outline all the ways that errors might be introduced using this communication system.).
4. Review example applications for the mathematics presented in the chapter (e.g., determine transmission rate, determine the length of the tone burst, determine the number of messages in two systems, determine binary transmission rate).
5. Review a scenario for designing a solution to a problem (design a communication system based on words instead of characters).
6. Complete laboratory activities that feature digital techniques for improving images and finding information within images. (e.g., communicating audio messages using one tone per letter, effects of weak signals and noise, difference codes, communicating audio using several tones per letter, communicating audio using serial binary transmission, touchtone telephone, communicating audio using two tones, how a facsimile works).

Initiative **Infinity Project**

Title **Networks from the Telegraph to the Internet**

Broad Goals None found

Salient Concepts & Skills

Math
- reducing the cost of a network

Science

Technology
- broadcast systems
- point-to-point systems
- full mesh networks
- relay point
- star configuration
- local area networks (LANs)
- store-and-forward network
- routing table
- router
- queue
- quality of service (QOS)
- guaranteed service
- switching
- Internet
- protocols
- access
- servers
- Internet service provider (ISP)
- access server
- content server
- intranet
- internetwork
- backbone network
- transport control protocol (TCP)
- Internet protocol (IP)
- packets
- simple mail transfer protocol (SMTP)

- multipurpose Internet mail extensions (MIME)
- hypertext transfer protocol (HTTP)
- file transfer protocol (FTP)
- uniform resource locators (URLs)
- domain name service (DNS)
- cache
- switching

Engineering

The focus of this chapter is on developing the domain knowledge needed to address an engineering design problem (e.g., store-and-forward networks, connection local ISPs, the Internet)

Prominent Activities

1. Read about computer networks and the Internet from a current and historical point of view, how the Internet is similar to other networks, and the economic trade-offs associated with system and network design.
2. Answer comprehension questions or perform tasks related to the main concepts presented in the reading (e.g., List at least five of the costs that should be examined when considering alternative network designs? Is your postal delivery person a router or a switch? What is a backbone network, and what type of service does it provide?).
3. Complete exercises that use the concepts presented in the chapter in the context of everyday applications (e.g., For a full mesh network with eight nodes, how many links are needed? Are the links one way or two way? Find a line of hypertext, and explain what it causes a Web browser to do.).
4. Review example applications for the mathematics presented in the chapter (e.g., comparison of a full mesh network with a central relay-point network).
5. Review a scenario for designing a solution to a problem (design a new network).
6. Complete laboratory activities that feature digital techniques for improving images and finding information within images. (e.g., multiple user networks with meshed connections, multiple user networks using a single router, multiple user networks using several routers, MUN with choice of transmission path, Internet performance, exploring the Internet).

Initiative **Infinity Project**

Title

The Big Picture of Engineering

Broad Goals None found

Salient Concepts & Skills

Math
- None found

Science
- None found

Technology
- aqueducts
- lighthouses
- printing
- refrigeration
- automobile development and manufacturing
- electrification
- Panama Canal
- space exploration
- television
- integrated circuits

Engineering

The chapter describes ten major engineering feats. Each description includes a discussion of the context in which the engineering occurred, the nature of the engineering performed, and the impact that the engineering had over time. These descriptions address the following engineering accomplishments.

- Roman aqueducts
- Lighthouse of Alexandra
- Gutenberg's printing press
- refrigeration
- the automobile
- electricity
- the Panama Canal
- space exploration
- television
- integrated circuits

This chapter also introduces the following basic fields of engineering:

- civil engineering
- materials engineering,
- agricultural engineering
- chemical engineering
- automotive engineering
- transportation engineering
- electrical engineering
- nuclear engineering
- biomedical engineering
- oceanographic engineering
- aerospace/aeronautical engineering
- environmental engineering
- computer engineering
- software engineering

Lastly, the chapter presents a modest discussion of the nature of engineering by addressing the following ideas:

- Engineering and science are not the same thing.
- Math and science are important, but engineering also requires creativity.
- There is a lot more to engineering than designing things.
- Degrees in engineering can lead to a wide range of careers.
- Engineering endeavors require people with different knowledge and skills to work together in a collaborative manner.
- Engineering work is an iterative process that rarely follows a pre-scripted plan because there are often unexpected problems and new ideas.
- While engineers appear to be unduly objective, they are also passionate about their work.
- Engineers work in a wide range of areas.

Prominent Activities

1. Read about ten great feats of engineering and the impacts that they had on society. Read about the nature of engineering work and popular misconceptions about engineering.
2. Complete exercises related to the concepts presented in the chapter (e.g., Pick a feat and list all the fields of engineering needed to develop, manufacture, and support it. Identify three well-known engineers and describe their contributions to society. Identify three famous people who are engineers by training and are doing things other than traditional engineering.).

Salient Observations

The Infinity Project is "sponsored and run by the Institute for Engineering Education at Southern Methodist University (SMU), with generous support from Texas Instruments, the National Science Foundation, and the Department of Education" (p. xv). The fundamental purpose of the curriculum is to encourage students to be curious about math and science by "connecting their relevance to prized personal technologies such as MP3, CD, and DVD players; cellular phones; pagers; and handheld video devices" (p. xv).

The focal point of the curriculum is on the "application of math and science concepts to the creative aspects of engineering design" (p. xvi) within the realm of digital technology. The preface states, the curriculum "focuses squarely on the math and science fundamentals of engineering during the information evolution and teaches students how engineers create, design, test, and improve the technology around them" (p. xvi).

Engineering

The opening and ending chapters focus on the role of engineers in the digital age and the heart of the text focuses primarily on the mathematics used to create digital technologies by engineers. Throughout the text, the science and math concepts discussed are done so through the lens of how engineers use these to create or change digital technologies.

Design

The first chapter introduces students to a nine-step engineering design process. It includes identifying the problem or objective, defining goals and constraints, researching and gathering information, creating potential design solutions, analyzing the viability of solutions, choosing the most appropriate solution, building and implementing the design, testing and evaluating the design, and repeating the steps as necessary. However, the materials do not use the linear nature of this paradigm to organize and orchestrate design projects and laboratory experiences. This can be attributed, at least in part, to the fact that the materials also try to portray engineering design as a dynamic and creative process.

The assumption that engineering design is essentially a synthesis level endeavor that requires domain knowledge is very evident throughout the materials. Each chapter begins with a design problem and a litany of questions that need to be addressed. For example, Chapter 2: "Creating Digital Music" begins with the notion of creating a "digital band." This challenge is followed by four questions: (1) What problem are we trying to solve? (2) How do we formulate the underlying engineering design problem? (3) What will we achieve if our design meets our goals? (4) How will we test our design? Each design question is followed by technical information, design criteria, or more specific design questions.

Each chapter goes on to explain and discuss the technical concepts that underpin the technology in question. A fundamental understanding of these technical concepts is also needed to design a viable solution to the problem being posed. In the case of Chapter 2, that narrative addresses ways to make music, the nature of sound, the transformation of sound into signals, the mathematics used to produce signals, and much more. All of these ideas could be applied to the problem of creating a digital band.

Lastly, each chapter culminates in a discussion of the design problem in more detail based on the technical content that was presented in the chapter. These closing discussions add additional layers of information and guidance to give the students a strong head start towards solving the problems at hand. The design problem in Chapter 2 is to "design a new and improved karaoke machine" (p. 95). According to one of the project's leaders, the extent to which students actually take on these design challenges is highly dependant on the teacher's content knowledge, comfort level, and initiative.

From a teaching and learning point of view, there appears to be little continuity between the problem that is posed at the start of each chapter and the problem that is posed at the end of the chapter. The format provides an opportunity to capture the students' attention with an interesting problem that they would like to solve, to leverage the problem to make the content presented in each chapter relevant and meaningful, and then to actually address the problem posed at the start of the chapter with the knowledge presented in the chapter. In the hands of a skilled teacher, this pattern could be used to implement problem-based learning. Furthermore, it could be used as a basis for anticipatory sets, advanced organizers, presentations of new knowledge, applications for new knowledge, and authentic assessments of the knowledge gained. However, the inconsistencies in the problems posed at the start and the ending of some of the chapters undermines the pedagogical potential of the instruction (see below).

At the Start of the Chapter	At the End of the Chapter
To "design a new device—a digital band—that will allow user to create a wide range of	To "design a new and improved karaoke machine—and 'Ultimate Karaoke

music without requiring user to have either extensive musical training or a complete music library" (p. 34).	Machine'—that would improve the quality of any singing voice fed to it" (p. 95).
To design "…a system to capture visual experience [in the problem it was a rock concert] and record it for later use" (p. 104).	"Design an image and video system to record local athletic events and theater performances" (p. 174).
"We want to design an imaging system that will provide information about the objects around the robot for use by the robot's action planner" (185).	"An image recording system for a wild-animal refuge must be designed to count the number of animals that enter and leave several important sites within the refuge" (p. 245).
To design a "digital yearbook" (p. 250).	To design a "digital yearbook" (p. 291).
"We want to design a digital scheme ['a digital backpack'] by which large amounts of information, in binary form, can be stored…" (p. 298).	"…to design a 'virtual garage' where people can buy and sell personal items" (p. 355).
"…to move multimedia information from one location to another. …as quickly as possible, receive it as accurately as possible and execute the process as cheaply as possible." (p. 360).	To design an "alternative communication system" that is "based on words rather than characters" (404).

Analysis

The materials do not engage students in doing analysis in the interest of identify problems, making design decisions, and evaluating solutions to problems. However, the presentation of design problems includes questions and design criteria that model the kinds of analysis engineers engage in. Most of the analysis being performed by students is directed toward understanding domain knowledge.

Constraints

The curriculum materials define constrains as "limits that are placed on a design problem." References to this concept include financial limitations, limitations imposed by the laws of nature, and parameters that make a technology useful.

Modeling The concept of modeling is not addressed directly in the materials. However, the block diagrams that are used throughout the materials to depict technological systems are clearly graphic models. Similarly, the representations of these same systems in the form of icons, lines, and displays on a computer monitor are also models. These models are used to explore how these systems work by bringing the mathematics at the core of these technologies to life in illuminating ways. Both the textbook and the laboratory software are very dependent on modeling to represent digital technologies and to engage students in assembling and testing digital technologies with the aid of the simulation software.

In this curriculum, models are used as tools for explaining, representing, creating, and testing digital communication and information processing systems. The curriculum does not try to teach the concept in a broader context nor does it give much attention to the nature of models and modeling in engineering endeavors (e.g., different kinds of models can be used to represent the same thing, the kind of model used in the work of engineers depends on the nature of the system being represented and the purpose of the model, models are not very useful it they are too simplistic or unduly complicated). In short, models and modeling are used to teach the content of the course in contrast to being salient pieces of content in the course.

Optimization The concept of optimization is not addressed in a targeted manner. However, lots of attention is given to balancing competing factors in developing solutions to problems. For example, in chapter 3, students have to address the trade-off between the quality of a digital image and the amount of storage space that it will require. Scenarios such as this are often presented to the students throughout the materials.

Systems The materials do not target the concept of a technological system directly. However, they do utilize a systems approach to explain how digital technologies work and to orchestrate laboratory experiences. Block diagrams are used in both the textbook and the virtual laboratory activities. Each block has an input, performs a process, and has an output. Again, systems and systems thinking are embedded tools that are used to teach the content of the course in contrast to being important pieces of content that has to be mastered.

Science The modest number of science concepts explored focus primarily on the physics of sound, the nature of light and color, and the biology of human hearing. These concepts are used to illustrate or explain specific digital technologies.

Mathematics A major focus throughout the text is on the mathematics involved in the creation of digital technologies, including binary numbers, matrix operations, and polynomials. The extent to which the materials uncover, examine, and apply the basic mathematical principles that underpin common digital communication and information processing technologies is impressive. The mathematical concepts and equations are presented as tools that are used by engineers to create or improve a given digital technology or system. Unlike many engineering courses, this one utilizes high school algebra and basic trigonometry.

Technology The materials are extremely rich in their treatment of domain knowledge. More specifically, they engage students in the study of digital information and communication technologies (e.g., photography, music, video, computer networks). Concepts like resolution, sound synthesis, compression, and encryption are systematically broken down into a logical series of subconcepts and subordinate details that are presented in the form of rich explanations of how these technologies work.

Treatment of Standards No attempt was made to cite national standards or to align the content in the materials with national standards. However, despite the lack of attention given to standards, it is very easy to recognize the role the materials could play in a science, technology, engineering, and mathematics (STEM) program that is attentive to national standards.

Given the emphasis on examining digital communication and information technologies from an engineering perspective, the curriculum goes far beyond the understandings recommended by the International Technology Education Association in the *Standards for Technological Literacy* (2000). For example, the idea that students should learn "information and communication technologies include the inputs, processes, and outputs associated with sending and receiving information" (p.173) would have to be achieved in the first few weeks of instruction in an *Infinity Project* classroom for students to progress beyond the introduction. Similarly, the notion that twelfth-graders should understand that "there are many ways to communicate information, such as graphic and electronic means" is remedial in comparison to the technical concepts that are addressed in this curriculum. However, these standards were developed with technological literacy in mind while the *Infinity Project* focused on preparing young people for the study of engineering at the post-secondary level.

In contrast to the ITEA standards, stronger correlations can be made with the standards published by American Association for the Advancement of Science (AAAS) in their book titled *Benchmarks for Science Literacy* (1993). For example, by end of twelfth grade students should know "the quality of communication is determined by the strength of the signal in relation to the noise that tends to obscure it (p. 199)." The textbook and laboratory manual address the concept of signal to noise ratio in a robust and detailed manner.

A similar alignment can be made between the concept of computer modeling and the laboratory activities that students are ask to perform throughout the curriculum. More specifically, the use of the *Infinity Project's* hardware and software is consistent with the belief that students need to develop the following understanding.

> Computer modeling explores the logical consequences of a set of instruction and a set of data. The instructions and data input of a computer model try to represent the real world so the computer can show what would actually happen. In this way, computers assist people in making decisions by simulating the consequences of different possible decisions. (p. 203)

It is important to note that the understanding outlined above is not targeted directly in the materials. However, students would experience the ideas embedded in this standard dozens of times during the course of their laboratory assignments. With a little extra attention from the instructor, it would be easy for students to recognize and formulate the generalization defined in this standard by virtue of its redundant treatment throughout the materials.

Pedagogy

According to the authors, the pedagogical features of the materials include things like four-color illustrations, real-world examples, a rich glossary, and hands-on laboratory activities. The kinds of pedagogical tools that are commonly found in lesson plans are not present in the materials (e.g., objectives, pre-assessment items, anticipatory set inductions, potential misconceptions, teaching methodologies, review strategies, debriefing techniques). However, to the materials' credit, they are extremely rich with questions and tasks that can be used to monitor and assess student understanding at the knowledge level as will as the application level. Furthermore, the text does a nice job of summarizing and chunking the content addressed at the end of each chapter.

The materials clearly present concepts and hands-on applications of digital communication and information processing technologies. Each chapter begins with a discussion of a design problem related to the subject matter being addressed in that section. The *Infinity Project* experiments are designed to apply the concepts being discussed in that section of the text. Most of the laboratory assignments involve building systems within the context of computer simulation, testing it see if it works, adding additional elements to enhance or expand the system, and changing one or more variables to see what happens. The purpose of these labs is to enable students to experience and apply the technical concepts presented in the text.

Implementation

The curriculum is designed to be a yearlong course that can be taught by a licensed math, science, or technology teacher. The prerequisites for the class include the successful completion of at least Algebra II and one laboratory science class.

For all practical purposes the materials in question are basically a textbook, laboratory manual, and teacher's guide. A classroom set of 30 textbooks would cost around $1,900 and, 15 laboratory manuals (one for each workstation) would cost an additional $330. These figures fall well within the norms for purchasing analogous materials for mathematics and science instruction.

The hardware and software needed to facilitate the laboratory activities come in a simple kit that is relatively inexpensive given its composition and capabilities. At around $400 a workstation, assuming appropriate computers are in place and the students will be working in pairs, it would cost around $6,000 to equip a lab for 30 students.

The *Infinity Project* provides teachers a 5-day professional development workshop to prepare them to implement the curriculum in their schools. They also provide on-line support for teachers implementing the course.

Invention, Innovation, and Inquiry (I^3)

Institution	International Technology Education Association (ITEA) 1914 Association Drive Reston, VA 20191 Tel: 703-860-2100 Web site: http://www.iteawww.org/i3 E-mail: itea@iteaconnect.org
Leaders	Daniel Engstrom, California University of Pennsylvania Kendall Starkweather, ITEA Thomas Wright, Ball State University Ian Finn, California University of Pennsylvania Matthew Anna, California University of Pennsylvania Nathan Hepler, California University of Pennsylvania
Funding	National Science Foundation International Technology Education Association California University of Pennsylvania
Grade Level	Five and six
EspousedMission	"The I^3 Project (Invention, Innovation, and Inquiry) was created to provide professional support for teachers interested in technological literacy in education, in particular, elementary curriculum."
Organizing Topics	*Invention: The Invention Crusade* *Innovation: Inches, Feet, and Hands* *Communication: Communicating School Spirit* *Manufacturing: The Fudgeville Crisis* *Transportation: Across the United States* *Construction: Beaming Support* *Power and Energy: The Whispers of Willing Wind* *Design: Toying with Technology* *Inquiry: The Ultimate School Bag* *Technology Systems: Creating Mechanical Toys*
Format	Each unit is present in a binder that contains the following basic elements.

- An introduction to the unit that features a summary (overview) and three to four learning goals
- Background information for the teacher that includes a brief presentation of the technical content and recommendations for implementing the learning activities.
- List of the technology and science standards and benchmarks that the author correlated with the unit.
- A list of key terms and their definitions.
- Suggestions for additional resources (e.g., books, Web sites, media).
- Instructions for implementing the unit that include an overview of the design challenge, suggestions for getting ready, a list of the tools and materials needed, an outline of the steps for conducting the unit, ways to extend the unit, strategies for assessing learning, an informative letter to parents, and transparencies masters.
- Materials for students that include reproducible masters for worksheets and assessment tools.

Pedagogical Elements

The units are designed to teach students “how inventions, innovations, and systems are created and how technology becomes part of people’s lives.” The authors state that each unit addresses content derived from standards, use a variety of teaching approaches (e.g., inquiry-based learning, project-based learning), and feature learning activities that include brainstorming, visualizing, testing, refining, and assessing technological designs that address an authentic need or scenario. The units are also designed to integrate science, mathematics, and language arts with the basic technology and engineering concepts.

Most of the units use teacher directed instruction and hands-on activities to facilitate the exploration and discovery of ideas about technology. Some of the units are more Socratic in nature. All of them engage students in doing design.

Maturity

The research and development phase began in 2002. The units were designed and developed in collaboration with elementary classroom teachers. They were piloted and field-tested at fourteen school in self-contained grades 4 and 5 classrooms as well as science classrooms. The units, in their final form, were made available through the International Technology Education Association in 2005.

Diffusion & Impact

According to project leaders, teachers with little background or experience with technology found the I3 units to be user-friendly and easy to implement with students from diverse backgrounds.

Initiative **Invention, Innovation, and Inquiry (I[3])**

Title

Invention: The Invention Crusade

Broad Goals

Students will:

- Explain and demonstrate how ideas can become inventions by using an engineering design process.
- Recognize that products are invented to meet specific needs and wants.
- Describe the general characteristics of famous inventors and their inventions.
- Document their inventive thinking with sketches and notations, in an Inventor's Journal.

Salient Concepts & Skills

Math	Science	Technology
• measurement		• Invention

Engineering

This unit of instruction introduces students to the following ideas about the nature of invention and inventors.

- Inventions involve identifying a challenge (a.k.a., a problem), exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others.
- Inventors "investigate the world around them, notice different needs, visualize creative solutions, explore many different ideas, never give up, and test their solutions."

Prominent Activities

1. Use common materials to create an invention that will make a household task easier to perform.
2. Arrange a series of inventions and inventors into chronological order.
3. Discuss how inventions have had positive and negative impacts on people's lives.
4. Research an invention or inventor using books, encyclopedias, and Web sites.
5. Discuss the characteristic of inventors and the roles that they play in the invention process.
6. Create a "Classroom Invention Museum" that features simple inventions brought from home (e.g., tea bags, instant coffee, Velcro, safety razor).
7. Work in teams to identify and present why a given invention was developed, how it works, and its positive and negative impacts.
8. Discuss and display ideas generated in response to the question, "Why do we invent things?"

9. Identify and discuss the steps required to invent something.
10. Hear about the "Engineering Design Process."
11. Discuss the characteristics of an inventor based on the acronym "I.N.V.E.N.T." (i.e., investigate the world around them, notice different needs, visualize creative solutions, explore many different ideas, never give up, test their solutions).
12. Participate in a "virtual mind walk" to identify household task that are difficult for young children.
13. Identify four ideas for a device that will help children live more independent lives in an adult world.
14. Examine the four ideas and select the solution that will be fully developed.
15. Develop a list of requirements that their final solution must fulfill to adequately address the problem at hand.
16. Develop drawings, identify materials, and list steps for making a product that will reflect their solution to the problem.
17. Use their plans to make their projects (a product that represents their solution to the problem).
18. Test and evaluate their product to determine how well it works.
19. Use the results of the testing process to make appropriate modifications.
20. Present the designs during an event called, "The Kid's Better Living Home Show."

Initiative **Invention, Innovation, and Inquiry (I^3)**

Title

Innovation: Inches, Feet, and Hands

Broad Goals

Students will:
- Demonstrate an understanding of basic design concepts as they relate to measurement and human form.
- Explain and demonstrate how an engineering design process can be used to improve technological devices.
- Describe limitations for a given device or design.
- Realize that with innovation, technological devices can be improved in many different ways.

Salient Concepts & Skills

Math	Science	Technology
• measurement	• science	• technology
• estimating	• anthropometrics	• invention
• uniform units (concept of)	• discovery	• innovation
• ruler reading		• serendipity

Engineering

This unit of instruction introduces students to the following ideas about the nature of science, technology, invention, innovation, discovery, and serendipity.
- Science is the "study of the natural world."
- Technology is the "study of the human-made world."
- Invention is "creating a new product, system, or process."
- Innovation is "the improvement of an existing product, system, or process."
- Discovery is "finding the answer to a question through experimentation."
- Serendipity is the "creation of a new product purely by accident."

Prominent Activities

1. Read a handout that describes the nature of science, technology invention, innovations, discovery, and serendipity.
2. Discuss the concepts of invention, innovations, discovery, and serendipity; identify examples of each; and describe their impacts on society.
3. Complete a worksheet regarding the concepts of science, technology, invention, innovations, discovery, and serendipity.
4. Interview a senior citizen about what life was like prior to modern technology.
5. Hear and discuss a definition of anthropometrics (the study of the human form as it relates to product design).

6. Hear about the "Engineering Design Process."
7. Measure distances related to the human hand (e.g., hand span, hand length, cubit, pointer finger, pinky finger).
8. Estimate the size of simple objects in the classroom (e.g., length of an unsharpened pencil, thickness of a desk top, width of a piece of paper).
9. Conduct measurements of the parts of the human body and make a graph that shows all the data.
10. Review an "Anthropometric Challenge" that involves improving a device that requires using one's hands (e.g., hair brush, screwdriver, door knob).
11. Identify a product that requires the use of one's hands and that can be improved.
12. Brainstorm ways in which the product in question can be improved.
13. Describe potential improvements using sketches and narratives.
14. Make a final drawing of the idea that will be made.
15. Build the "anthropometric innovation."
16. Have three people test the innovations and record their feedback.
17. Answer questions that require reflecting on the experience (e.g., What was the best and worst thing about your new product? How could you further improve your product?).
18. Prepare and deliver a short presentation that promotes the improvements made to the product.

Initiative **Invention, Innovation, and Inquiry (I^3)**

Title

Communication: Communicating School Spirit

Broad Goals

Students will:

- Compare and contrast how communication is affected by the chosen medium.
- Describe how marketing research is used to advertise a new product.
- Demonstrate how to design products like T-shirts to meet specific needs.
- Design and create a print and radio commercial using the Engineering Design Process.

Salient Concepts & Skills

Math	Science	Technology
• graphing		

Engineering

This unit of instruction has students go through the engineering design process in the context of developing verbal and visual messages (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).

Prominent Activities

1. Divide into teams and mock form advertising firms.
2. Review ideas related to advertising (e.g., definition, historical milestones, memorable slogans).
3. Discuss a scenario requiring the development of advertising to bolster school spirit.
4. Discuss design considerations for developing logos (e.g., symbols, initials, images).
5. Brainstorm names for make-believe advertising firms.
6. Develop potential names, logos, and mottos for the firms.
7. Select and present their team's name, logo, and motto to the class.
8. Conduct market research within the classroom to identify everyone's favorite colors and shapes.
9. Present data in the form of a chart or graph.
10. Develop potential multiple-choice questions for a survey.
11. Select and transform the questions into a survey instrument.
12. Administer the survey to the school population through interviews, e-mail, etc.
13. Compile the data collected into a chart or graph.
14. Write a paragraph summarizing the results of the market survey.

15. Discuss the design process and review the rubric that will be used to evaluate T-shirt designs.
16. Review examples of good graphic design in magazines and newspapers.
17. Discuss the basic principles of graphic design (e.g., balance, contrast, line, shape).
18. Develop a design for a T-shirt that will promote school spirit.
19. Use colored fabric markers or heat activated transfer paper to print the design onto a T-shirt.
20. Review the assignment and evaluation criteria for a "radio commercial."
21. Develop a script for a 30 second "radio commercial" that promotes school spirit.
22. Rehearse, time, and refine the radio commercials.
23. Record the commercial onto an audiocassette.
24. Evaluate the T-shirt designs and radio commercials.
25. Write a paragraph summarizing what was learned and how it can be applied in the future.
26. Present the ideas to the school through hallway displays or public address announcements.

Initiative **Invention, Innovation, and Inquiry (I^3)**

Title

Manufacturing: The Fudgeville Crisis

Broad Goals

Students will:

- Analyze the causes of change in food quality over time.
- Design a package that can extend the freshness of a food product.
- Design a production system for a food product and use it to produce shaped fudge.
- Recognize the importance of following and maintaining cleanliness with handling food products.

Salient Concepts & Skills

Math
- measurement
- graphing

Science
- bacterial growth

Technology
- primary processing
- secondary processing
- food preservation
- refrigeration
- drying
- canning
- fermentation
- curing
- smoking
- pasteurization
- aseptic packaging
- irradiation
- raw materials
- primary material
- secondary material
- craft production
- mass production
- quality control
- operation
- transportation
- inspection
- delay
- storage
- packaging

Engineering

This unit of instruction has students go through the engineering design process in the context of producing a product (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).

Prominent Activities

1. Discuss the techniques used to process, preserve, and package food (e.g., drying, canning, curing).
2. Work in teams to research a product (e.g., When was it invented? How has it changed over time?).
3. Present the information gathered using posters.
4. Discuss the how the products have changed over time.
5. Hear about different types of food processing technologies (primary and secondary).
6. Read and review the scenario for the "Fudgeville Crisis."
7. Brainstorm and select names for mock companies.
8. Identify, discuss, and present how Hershey Kisses are made (e.g., ingredients, processes, packaging).
9. Explain how to make fudge (e.g., forming, cutting, packaging).
10. Discuss how food is handled during the manufacturing process.
11. Discuss safe food handling processes.
12. Make and display posters outlining safe food handling process.
13. Discuss how cookies are made from scratch (e.g., ingredients, processes).
14. Hear about primary and secondary processes.
15. Examine packaging materials and techniques that help keep food fresh (e.g., bags, foil, wax paper).
16. Hear about the engineering design process and how it can be applied to the development of a package.
17. Use the engineering design process to develop a package.
18. Review examples of different kinds of molded chocolates and discuss how they were formed.
19. Use the engineering design process to develop fudge-forming tools.
20. Outline a production system (the steps required) for forming and cutting fudge into six pieces.
21. Test the production system by weighing each group of six pieces to determine relative uniformity.
22. Review safe food handling techniques.
23. Develop and implement a production line for making, forming, cutting, and packaging fudge.
24. Conduct a "Fudge Festival" for parents and members of the school community to see displays from each mock company.

Initiative **Invention, Innovation, and Inquiry (I³)**

Title

Transportation: Across the United States

Broad Goals

Students will:

- Explain the significance of transportation in the westward expansion of the United States.
- Describe how inventions and innovations in technology can be modeled.
- Recognize that transportation systems comprise several subsystems.
- Design, construct, and test a prototype of a transportation vehicle by following the Engineering Design Process.

Salient Concepts & Skills

Math
- measurement
- scale

Science

Technology
- transportation
- commercial transportation
- personal transportation
- vehicle
- pathway
- support structure
- propulsion system
- structural system
- control system
- mock-up
- prototype

Engineering

This unit of instruction has students go through the engineering design process in the context of making a model of an early American means of transportation (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).

It also introduces students to the following ideas about the nature of models.

- "Model building is used to represent what something may look like."
- "Models are built either larger or smaller when compared to actual size of the object."
- "Graphic models include drawings, graphs, charts, and diagrams…"
- "Mathematical models show relationships in terms of

formulas."

- "Physical models are three-dimensional representations…"
- "Computer-generated models… can be used to develop and analyze a structure, mechanism, or product and provide very accurate data."

Prominent Activities

1. Identify how transportation has changed since the early 1800s.
2. Review a timeline for the development of transportation technology.
3. Complete a worksheet using the information presented in the timeline (e.g., most significant impact, examples of different modes of transportation, relative efficiency).
4. Discuss the role of transportation during the westward expansion of the United States.
5. Discuss the concepts of scheduling, routing, loading, transporting, unloading, and storing.
6. Complete a worksheet that asks students to reflect on the transportation processes related to getting to school.
7. Examine a model of a vehicle and discuss its basic systems (i.e., structure, propulsion, control).
8. Complete a worksheet that calls for descriptions of the structural, propulsion, and control associated with given vehicles.
9. Review a design challenge (research, draw, and build a model of a vehicle that made a contribution to the expansion and settlement of America).
10. Review the engineering design process (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).
11. Review how transportation contributed to the westward expansion of the United States.
12. Complete a worksheet that identifies the history, systems, and contributions of a vehicle that contributed to the westward expansion of the United States.
13. Sketch a drawing of the vehicle in question to scale (1" = 1'-0").
14. Review the sketches developed by the group and select one to be prototyped.
15. Develop a list of the materials needed to make a model of the vehicle in question.
16. Build and test the model and report the findings on a worksheet.
17. Prepare and deliver a written and oral presentation for the vehicle in question.

Initiative — **Invention, Innovation, and Inquiry (I^3)**

Title

Construction: Beaming Support

Broad Goals

Students will:

- Describe forces that act on structures.
- Explain how the size and shape of a beam will affect the ability to resist loads.
- Calculate the efficiency of a constructed beam.
- Design, construct, and test a variety of beams to determine which can support the most weight.

Salient Concepts & Skills

Math
- measurement
- ratio
- percent
- calculating efficiency

Science
- strength
- stress
- strain
- deal load
- live load
- tension
- compression

Technology
- beams
- columns
- laminated beam

Engineering

This unit of instruction has students go through the engineering design process in the context of developing laminated beams out of paper (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).

Prominent Activities

1. Review the design challenge ("…create the strongest beam possible").
2. Discuss the meaning of the word "beam."
3. Discuss why engineers record their ideas, drawings, and testing results.
4. Hear about the role of tension and compression in bending the materials in a structure.
5. Experience the concepts of tension and compression in simple activities (e.g., bend a sponge, stretch a rubber band, pull on linked fingers).
6. Record the difference between tension and compression in an engineering journal.
7. Summarize the concepts learned about beams and forces.
8. Discuss the difference between live and dead loads.
9. Identify and categorize things in the classroom that represented loads (live and dead).
10. Test and calculate the deflection of a yardstick suspending a

weight between two chairs (once lying flat and once on edge).

11. Repeat the deflection tests using two yardsticks that are taped together.
12. Record the results of the tests and the reflections they inspired in an engineering journal.
13. Discuss the engineering design process and review the challenge (make a paper beam that will hold 50 pennies).
14. Design and test paper beams.
15. Use the results of the testing process to redesign a second beam.
16. Calculate the efficiency of their final beam.
17. Present the beam design to the class.
18. Review the engineering design process.
19. Design and test paper beams while recording their ideas and results in their journals.
20. Present their final beam design including how it was build, tested, redesigned, and retested.
21. Reflect on the design experience (e.g., getting started, getting stuck, overcoming problems).

Initiative **Invention, Innovation, and Inquiry (I^3)**

Title

Power and Energy: The Whispers of Willing Wind

Broad Goals

Students will:
- Explain how energy is created, transmitted, and utilized in a home.
- Describe benefits and drawbacks of utilizing renewable energy.
- Design and develop a device that will harness wind and convert it into mechanical energy.

Salient Concepts & Skills

Math
- measurement
- ratio

Science
- energy resources
- geothermal
- natural gas
- petroleum
- nuclear
- solar
- hydro
- wind
- renewable
- non-renewable

Technology
- windmill
- blades

Engineering

This unit of instruction has students go through the engineering design process in the context of harnessing wind energy (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).

Prominent Activities

1. Research an energy resource (e.g., geothermal, natural gas, petroleum).
2. Create a poster that describes the energy resource in question (e.g., energy conversion process, characteristics, advantages, disadvantages).
3. Identify energy resources that have the smallest impacts on the environment.
4. Compare energy resources in terms of being renewable versus non-renewable.
5. Discuss the kinds of energy used in the home for heating, lighting, cooking, entertainment, etc.
6. Conduct a survey of 15 to 20 devices in the home that use energy (e.g., location, frequency of use, relative importance).
7. Review the engineering design process.

8. Discuss the role of wind power.
9. Discuss the design challenge (design a model windmill).
10. Gather information about windmills and windmill towers.
11. Sketch designs for the blades of a model windmill.
12. Sketch designs for a windmill tower.
13. Review the ideas of the group and select one for further development.
14. List the materials and procedures needed to construct a model windmill based on the design selected.
15. Build and test a model windmill (e.g., making a tower, making blades, mounting the blades onto the shaft).
16. Graph the results of the testing process (the amount of time required to coil a given length of string around the "propeller shaft").
17. Draw a new design based on reflections about the project (e.g. what would you change).
18. Present a presentation showing how the windmill was designed and how it works.
19. Discuss the advantages and disadvantages of harnessing the wind for electricity.

Initiative **Invention, Innovation, and Inquiry (I^3)**

Title

Design: Toying with Technology

Broad Goals

Students will:

- Describe and demonstrate how visualization and drawing techniques are used to document ideas using two- and three-dimensional representations.
- Explain how the engineering design process may be used to develop a new product such as a game.
- Recognize that effective marketing techniques can increase product success.

Salient Concepts & Skills

Math	Science	Technology
• measurement • basic geometric shapes • two-dimensional • three-dimensional		• model • prototype

Engineering

This unit of instruction has students go through the engineering design process in the context of developing a board game (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).

The unit also presents multiple definitions for key terms related to engineering design. The concept of design is defined as "to create and plan a solution to a problem or challenge" and it is defined as "taking ideas you develop in your mind and putting them on paper as drawings, words, or sketches." The concept of a model is defined as "a drawing, formula, or object that represents a device or design" and is also defined as "a graphic, mathematical, or physical representation of an object or design." A prototype is defined as "a full-size working model of an object or design" and is further defined as "a full-scale working model used to test a design concept by making actual observations and necessary adjustments."

Prominent Activities

1. Discuss board games and their features.
2. Define and discuss key terms (i.e., design, drawing, visualize, sketch, two-dimensional, three-dimensional, model, prototype, marketing, target audience, message, motto).
3. Discuss the engineering design process (i.e., identifying a challenge, exploring ideas, planning and developing a solution,

testing and evaluating the solution, and presenting the solution to others).

4. Complete a worksheet describing each step in the engineering design process.
5. Read about famous game and toy inventors (i.e., Ruth Handler, George Parker, Richard James, Lonnie Johnson).
6. Discuss trends in toy and game design.
7. Discuss the design challenge (design a new board game that is colorful, has different game pieces for each play, and has clearly written rules).
8. Define the specifications for the proposed game (e.g., age group, number of players, basic concept).
9. Present the concepts for the games and gather feedback from peers.
10. Discuss the key terms “design”, “drawing”, and “visualize” again.
11. Watch a demonstration about how to draw a square.
12. Engage in practice drawing squares and rectangles.
13. Watch a demonstration about how to draw a circle.
14. Engage in practice drawing circles of different sizes.
15. Apply drawing skills to draw a simple object (e.g., a wall clock).
16. Discuss the role of two-dimensional drawings in engineering design.
17. Draw a two-dimensional sketch of a design for a board game.
18. Discuss the steps in the engineering design process.
19. Select a design for a board game and develop ways to improve it.
20. List the materials needed to make the board game in question.
21. Discuss the key terms “model” and “prototype.”
22. Construct a prototype for the board game in question.
23. Discuss the key term “three-dimensional” in the context of making three-dimensional drawings.
24. Watch a demonstration on how to draw three-dimensional shapes.
25. Practice drawing three-dimensional objects.
26. Discuss the importance of measurements in drawings.
27. Draw three-dimensional representations of a game piece for the game in question.
28. Make prototype game pieces using modeling clay.
29. Outline the rules for playing the game in question.
30. Discuss and refine the rules for the game.
31. Write a set of rules for playing the game.
32. Exchange and test each other’s games.
33. Complete an evaluation form for the game they tested.
34. Study a print advertisement and determine its target audience

and main message.

35. Sketch a print advertisement to promote the game in question.

Initiative **Invention, Innovation, and Inquiry (I^3)**

Title

Inquiry: The Ultimate School Bag

Broad Goals

Students will:

- Describe how to assess the design of technological products by asking good questions.
- Explain the concepts of risk, benefits, and trade-offs.
- Use the finding of an inquiry process to design and produce an improved school bag by following an engineering design process.

Salient Concepts & Skills

Math	Science	Technology
• measurement	• scientific inquiry	• technology • assessing technology

Engineering

This unit of instruction has students go through the engineering design process in the context of developing "The Ultimate School Bag" (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).

The unit also addresses the concepts of trade-off, criteria, and risks in the context of engineering design. A trade-off is defined as "a decision involving one quality or feature selected over another." It is also defined as "an exchange of one thing in return for another, especially relinquishment of one benefit or advantage for another regarded as more desirable." Criteria are "desired specifications of a product or system." The word is also defined as "key or specific wants or needs according to personal or societal preferences in conjunction with the constraints" and it is defined as "…limits for the design by establishing what the product should do, look like, etc." Risks are "the chance of loss, harm, failure, or danger related to a product."

Prominent Activities

1. Address the question what is technology (e.g., everything that is made by humans, the way something is done or made).
2. Identify examples of technology during a walk.
3. Report and record observations about the technology encountered during the walk on chart paper.
4. Describe why specific examples of technology were developed.
5. Identify examples and non-examples of technology from a collection of devices that are on display.
6. Describe what specific technologies help them do.

7. Describe at least three technologies that they use everyday.
8. Post their examples of everyday technology on a bulletin board titled, “Technology Around Us.”
9. Brainstorm different technologies that are used to carry things like books, pens, pencils, and lunches.
10. Acknowledge a backpack is a popular option.
11. Explain the purpose of a school bag or backpack.
12. Hear about the advantages of using a school bag or backpack.
13. Address questions about what students used before school bags, what need school bags address, other applications for school bags, etc.
14. Discuss the role of criteria in engineering design.
15. Describe considerations when purchasing a school bag.
16. Define criteria for the design of a school bag.
17. Examine school bags and discuss their characteristics and why they are important.
18. Develop a list of characteristics or features for a school bag and some safety features a school bag should have.
19. Discuss the lists of characteristics and features as a class.
20. Discuss how to assess technology (e.g., identify why it was developed, define criteria, develop and answer questions, draw a conclusion).
21. Suggest ways to evaluate school bags using the criteria.
22. Review the criteria (e.g., at least three compartments, made of washable materials, costs less than 15 dollars).
23. Develop questions from the list of criteria.
24. Use the questions to evaluate school bags.
25. Discuss the concept of trade-offs (an exchange of one thing in return for another, especially relinquishment of one benefit or advantage for another regarded as more desirable).
26. Talk about why they have the school bag that they have, if it has all the features they want it to have, and what trade-offs were involved in its purchase.
27. Identify trade-offs that effect the selection of school bags.
28. Complete a worksheet for assessing a school bag.
29. Discuss the engineering design process.
30. Read a design brief for developing “The Ultimate School Bag.”
31. Study the requirements for “The Ultimate School Bag.”
32. Reflect back upon their assessment of school bags.
33. Select a school bag from within the group to be redesigned.
34. Develop a list of needs and wants for the redesign of the school bag in question.
35. Sketch ideas for the redesign of the school bag.
36. Choose the ideas that best contribute to the ultimate school bag.
37. Create a full-size appearance model or mock-up featuring their

ideas for the ultimate school bag.

38. Present the designs to the rest of the class.

Initiative — **Invention, Innovation, and Inquiry (I³)**

Title

Technology Systems: Creating Mechanical Toys

Broad Goals

Students will:

- Explain mechanical linkage function and movement.
- Explain how the Engineering Design Process is used when creating mechanical devices.
- Recognize that simple machines can be used with linkage mechanisms to create a mechanical system.

Salient Concepts & Skills

Math
- measurement
- linear
- rotary
- reciprocating
- ratios

Science
- motion
- velocity
- mechanical advantage
- force
- load
- power
- energy
- work

Technology
- technology
- machine
- simple machines
- complex machines
- levers
- gears
- wedge
- inclined plane
- screw
- wheel and axle
- pulley
- mechanisms
- linkages
- fixed point
- pivot point
- slider
- driver gear
- driven gear

Engineering

This unit of instruction has students go through the engineering design process in the context of developing a mechanical toy (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).

Prominent Activities

1. Discuss mechanisms and list examples (e.g., piston movement, salad tongs, folding chair, bicycle).
2. Watch a demonstration of different kinds of mechanisms (e.g., four-bar linkage, push-pull linkage, bell crank).
3. Make models of different kinds of mechanisms using

cardboard and brass fasteners.

4. Review the mechanical toy design challenge ("…design build and test a safe toy that incorporates simple machines and linkage mechanisms).
5. Discuss the engineering design process (i.e., identifying a challenge, exploring ideas, planning and developing a solution, testing and evaluating the solution, and presenting the solution to others).
6. Write a definition of the problem including the criteria (limitations) for their toy design.
7. Sketch ideas for a toy, select the best one, refine the idea, label its parts, and present the idea to the other members of the team.
8. Brainstorm ways to improve the design.
9. List the materials required to make a prototype of the toy.
10. Establish and utilize a class store for the acquisition of materials.
11. Build a prototype of the toy's design.
12. Test the prototype and recommend ways to improve its design.
13. Present the toy to the rest of the class.

Salient Observations

I^3 is short for Invention, Innovation, and Inquiry. The project's name is based on the notion that "invention and innovation are the hallmarks of technological thinking and action" and inquiry is integral to science. The program set out to teach students "how inventions, innovations, and systems are created and how technology becomes part of people's lives." The materials address this goal by engaging students in an engineering design process in the 10 different contexts (e.g., communications, manufacturing, energy and power, transportation).

Engineering

The curriculum and promotional materials state "the engineering design process is at the heart of each unit." The review suggests that that is indeed the case. All the units are based on the same model for engineering design and the only major difference from one unit to the next is the context in which the students will apply the process.

Design

The materials describe and define design in different ways throughout the program. Design is defined as "taking ideas you develop in your mind and putting them on paper as drawings, words, or sketches." The materials define the engineering design process as "a series of steps that allow designers to develop new and improved products."

All of the units present and utilize the same five basic steps that are used guide the engineering design process. The first step is to "identify a challenge." During this step students define the problems that needs to be solved along with the constraints, requirements, specifications and limitations that need to be addressed. The second step, "Exploring Ideas," involves describing several potential solutions to the problem at hand using drawings and written explanations. The third step in the process is to "Plan and Develop" the best solution. This step involves developing a final sketch of the design, identifying the tools and materials needed make the new product, and making a prototype. The next step is to "Test and Evaluate" the new product or process to see if meets the design specification and if it is acceptable to potential consumers. The last step in the process is to "Present the Solution" to others. In theory, this process should generate feedback that will inspire another cycle through the design process in the interest of improving the design.

Analysis

Most of the materials engage students in analyzing how well their designs perform. Only a few engage students in analyzing things to define design problems, specifications, and criteria. The richest example of this kind of analysis can be found in *Inquiry: The Ultimate School Bag*. It requires students to identify fundamental purpose of a school bag, its advantages over other things, and its other applications. They reflect upon, identify, and pool the considerations that they used to purchase their school bags. They use their experiences to define criteria for evaluating school bags and apply this information to the assessment of school bags. The results of these evaluations are used to design the "ultimate school bag."

Constraints The concept of constraints is not targeted in the instructional objectives, discussed in the background information, included in the list of key terms or addressed in the assessment items.

Modeling The materials define a model as "any graphic, mathematical, or physical representation of an object or design." Similarly, a mock-up is described as "a model that show how something will look or function." The concept of a model is defined as "a drawing, formula, or object that represents a device or design" and it is also defined as "a graphic, mathematical, or physical representation of an object or design." Similarly, a prototype is defined as "a full-size working model of an object or design." It is also defined as "a full-scale working model used to test a design concept by making actual observations and necessary adjustments."

Almost all of the units engage students in making physical models of one kind or another. Furthermore, they are used primarily to visualize and represent design ideas. Some of the models provide a basis for testing designs.

Transportation: Across the United States address the concept of models and modeling in the most depth. It also introduces ideas like "model building is used to represent what something may look like" and "models are built either larger or smaller when compared to actual size of the object." It also describes the nature of graphic mathematical, physical, and computer-generated models. However, the actual instruction and learning activities only deal with physical models in a modest way.

Optimization The concept of optimization is not addressed in the objectives, learning activities, or assessment tools in a direct manner. However, each unit asks students to look back upon their designs and think about what they would have liked to do differently. Then they are asked to use those ideas to draw a new and improved design.

The unit on *Inquiry: The Ultimate School Bag* focuses on the redesign and improvement of a backpack for school books and personal items. The spirit of redesign intrinsically involves optimization in a subliminal manner even though the concept is not addressed directly. The unit also introduces and applies the concept of trade-offs in the selection of school bags. However, the instructions that guide the redesigning process do not call attention to this concept nor do they require students to confront any trade-offs during the redesign process.

Systems The concept of systems is not targeted in the objectives, learning activities, and assessment tools in an overt manner. However, the idea that things going into processes and emerging from those processes with new attributes is embedded in storylines for different technologies. This kind of subliminal treatment of inputs, processes, and outputs can be detected in units on innovations, manufacturing, power and energy, and transportation.

The notion that technologies are composed of different parts that work together in interdependent ways was not targeted directly in any of the units. However the unit on *Transportation: Across the United States* does have students explore the basic parts of a transportation system. More specifically, it calls attention to the propulsion, structural, and control systems that can be found on vehicles.

Science The design of the materials aspired to "…integrate mathematics and science" during the course of the engineering design process. The topics and problems featured in the units contain opportunities for introducing, reinforcing, or applying science concepts and skills. However, the implementation procedures give very little attention to constructing scientific principles in the minds of learners. For example, in *Invention: The Invention Crusade* the materials refer to the need to introduce students to scientific concepts that apply to the materials prior to engaging in design. The examples provided include the concepts of stiffness, strength, elasticity, malleability, and ductility. However, these terms are not discussed in the background information nor are they defined in the list of key terms. Similarly, *Power and Energy: The Whispers of the Willing Wind* introduces concepts like energy, kinetic energy, potential energy, and electricity in a list of key terms but they are not addressed in the actual instruction.

Most of the emphasis is on engaging students in the five-step process for approaching engineering design in different contexts. The science associated with these contexts is typically presented as concepts that are defined and discussed in simple and brief ways under the auspices of providing the teacher background information.

The subject of scientific inquiry is included in the title and contents of *Inquiry: The Ultimate School Bag*. The treatment of the topic is presented in the background information for the teacher. The description focuses on finding and characterizing patterns inherent in nature. However, the actual instruction and learning activities focus on doing inquiry from a design perspective. More specifically, the students examine the features of their school bags, define the functions that they must serve, identify their design features and deficiencies, and much more. The results of these inquiries are used to inform the design of the "ultimate" school bag in contrast to modeling an aspect of nature or formulating "…explanations about the scientific phenomena being investigated."

Some of the science is not presented in a precise manner. For example, two of the objectives for *Power and Energy: The Whispers of the Willing Wind* state students will do the following: "Explain how energy is created, transmitted, and utilized in a home." "Design and develop a device that will harness wind and convert it into mechanical energy." The reference of creating energy instead of converting energy is problematic, especially when it is presented as one of the main thrusts of the unit. This kind of imprecise language contributes to the perpetuation of misconceptions among elementary school teachers and students. The notion of converting wind energy into mechanical energy is also problematic because wind energy is basically a form of mechanical energy. The technology in question harnesses the wind by converting linear mechanical energy into rotary mechanical energy. The conversion process is necessary because rotary motion is needed to do things like generate electricity, pump water, and prevent feed ponds from freezing.

Mathematics

Most of the mathematics that is built into the learning activities deals with taking measurements. Some of these measurements are used to make graphs that describe the performance of a given design. For example, in *Power and Energy: The Whispers of the Willing Wind* the students measure and graph the amount of time required for a model "windmill" to coil a length of string around the propeller shaft under two different simulated wind conditions. Another example was found in *Manufacturing: The Fudgeville Crisis*. In this unit students are asked to test their designs for food packaging by rating and comparing the freshness of marshmallows, one placed inside their package and one left out, over the course of five days.

Measurement is a prominent theme in the unit titled, *Innovation: Inches, Feet, and Hands*. This unit introduces students to the concept of anthropometrics (the measurement of the human form). This is followed by a series of labs that involve measuring one's hand span, hand length, cubit, and fingers; using one's hand to estimate the dimensions of given objects; measuring the same objects using a ruler; and comparing the estimated dimensions with the actual dimensions. Under the auspices of innovation, the students are then asked to improve the design of a device that has to fit and work well in a person's hand. However, anthropometrics does not appear to play a formal role in the redesign process. The design process involves identifying a product that needs to be improved, brainstorming ways to improve it, making sketches of the proposed improvements, developing a plan for making the improvements, asking three people for their impressions of the improvement, and presenting the final design to others. The opportunity to use anthropometric data to evaluate an existing design and make refinements is not an integral part of the design process that is outlined in the handouts for students.

Several units require students to do calculations to characterize the performance of their designs. For example, in *Construction: Beaming Support* the students have to compute the efficiency of their paper beams using a formula (efficiency = maximum load/beam weight x 100). *Power and Energy: The Whispers of the Willing Wind* asks students to determine the speed of their wind turbines by dividing the length of string (3 meters) by the amount of time (number of seconds) it takes to coil around the propeller shaft (length in meters/time in second = meters per second).

The review did not uncover any examples of using mathematics to inform the development of a design to a solution to a problem. The closest example was found in *Communications: Communicating School Spirit*. In this unit students are asked to plot the results of a survey about favorite colors, shapes, music, and more for the development of T-shirt designs and the composition of radio commercials. However, designing images for T-shirts and composing scripts for radio commercials are not engineering tasks.

Technology

Most of the content for the study of technology, or the domain knowledge associated with the problem being solved, is presented in the background knowledge for the teacher. For example, in *Construction: Beaming Support*, this section defines and describes the nature of beams and columns in three paragraphs. In *Transportation: Across the United States*, this section includes information about commercial versus personal modes of transportation; the basic parts of a transportation system; the nature of graphic, mathematical, and physical models; and the role of transportation during the westward expansion in American history.

The technology content also appears in the implementation procedure in the form of simple steps or questions that can be posed to students. For example, in *Manufacturing: The Fudgeville Crisis*, the teacher is told to display a bag of Hershey Kisses and ask students to think about how they are made. The teacher is asked to include things like the ingredients, the steps during production and distribution, and what other companies might be involved. According to the recommended procedure, the students list their ideas on a large sheet of paper and present them to the class. Lastly, the students watch a virtual tour of the actual manufacturing process on Hershey's Web site to confirm, correct, or expand their speculations.

The continuity between the background information for the teacher, the list of key terms for the unit, the implementation procedure, and the documentation for learning activities is often inconsistent. There can be several different definitions for the same key concept. For example, technology is defined as the "study of the human-made world by using knowledge and processes to develop products and systems." It is also defined a "human innovation in action that involves using knowledge and processes to develop systems that solve problems and meet human needs and wants." Some concepts are only explained in the list of key terms (e.g., live loads and dead loads). Other can be found in the transparency masters. In some cases, the procedures reference technology topics that are not included in the documentation. For example, in *Power and Energy: The Whispers of the Willing Wind*, one of the steps asks the teacher to "discuss the advantages and disadvantages of utilizing a windmill to generate electricity." It is not clear where the content would come from because the pros and cons of this technology are not described in the background information, the transparency masters, or the handouts.

There are some problems with how technology is portrayed in some of the units. For example, in *Power and Energy: The Whispers of the Willing Wind* the students are asked to test their "windmill blades" under different conditions that are characterized as a “Level 1 hurricane” and a “Level 5 hurricane.” In reality, wind turbines are engineered to rotate in a relatively consistent manner within a band of wind speeds. The probability of extreme wind conditions on a given site makes it a poor location for a wind turbine. Furthermore, most wind turbines have devices that render them relatively inert if wind conditions exceed their design parameters. Wind turbines are simply not designed for speed and they are not designed to work under extreme conditions.

The materials have to be studied thoroughly to uncover the technical knowledge needed to address the design problem that is at the core of each unit. In many cases, the content base needs to be supplemented by tapping the additional resources listed in each unit.

Treatment of Standards

The authors state that the units are based on the *Standards for Technological Literacy: Content for the Study of Technology* (ITEA, 2000). Some of the standards cited address the nature of design (e.g., it is a creative process, there is no perfect design, requirements for a design are made up of criteria and constraints) and abilities to apply the design process (e.g., improve design solutions, test, and evaluate designs). Others addressed topics related to the history of technology, the meaning of invention and innovation, and nature of technology. They also include more specific standards related to the context of each unit (e.g., information and communication, manufacturing, transportation).

Eight out of the ten units cite the *National Science Education Standard* that addresses “abilities of technological design” (e.g., identify appropriate problems, design a solution or product, implement a proposed design, evaluate… designs or products, communication the process of technological design). The design process used to guide the laboratory activities in these units runs parallel to these standards. However, the materials typically define the problem that needs to be solved in contrast to engaging students in an analysis that enables them to identify the problem for themselves.

The national standards for mathematics are not cited specifically. However, the materials do identify topics that connect the unit with the study of mathematics. The topic that appears the most in these listings is measurement. The other topics identified with less frequency are estimation, data analysis, number operations, scale and proportion, geometry, and problem solving. Although these topics can be found in the contents of their respective units, the treatment of these concepts and skills tends to be very modest.

More specifically, they involve applications and practice more than actual instruction that is designed to lead to mastery.

The standards related to the ability to do technological design had the strongest correlation with the contents of the units. The references to standards that address specific concepts also had high face validity. For example, *Innovations: Inches, Feet, and Hands* clearly addresses the benchmark that calls for knowing "invention is a process of turning ideas and imagination into deices and systems" and "innovation is the process of modifying an existing product or system to improve it." Most of the other standards have more of a thematic or coincidental relationship with their unit of instruction. For example, the design and testing of laminated beams in *Construction: Beaming Support* was aligned with the idea that students would learn "the selection of designs for structures is based on factors such as building laws and codes, style, convenience, cost, climate, and function." In this case and others, the scope of the standard cited goes beyond the depth and breadth of the content addressed in the unit.

Pedagogy

Most of the instruction is dedicated to guiding students through the design process. The design activities include brainstorming, visualizing, testing, refining, and assessing technological designs.

Each unit includes learning activities that prepare students for the main design problem. In most cases, these activities address some of the prerequisite knowledge needed to address the design problem. For example, in *Construction: Beaming Support*, the students perform a series of simple activities to explore the concepts of tension and compression prior to designing paper beams. In other cases, the activities are more complementary in nature. For example, in *Power and Energy: The Whispers of the Willing Wind,* the students profile different energy resources and survey devices that use energy in their homes before designing, building, and testing a model wind turbine.

The instructional design for each unit is presented in the form of outlines that list the main topics for each unit and the recommended steps for teaching each topic. Most of the units feature three to four main topics. Most of the steps are simple statements that begin with verbs like divide, assign, distribute, discuss, explain, list, and review. Some of the units emphasize teacher directed learning activities that enable students to discover and experience ideas while others utilize questions to facilitate the exploration of ideas and to guide investigations.

Each unit includes several tools that can be used to assess student achievement. Simple rubrics are presented to assess the completion and quality of learning activities. A short multiple-choice test is included to assess conceptual understanding. Lastly, all of the units include a performance assessment of problem solving skills that features a scenario and a challenge. For example, the scenario in *Innovation: Inches, Feet, and Hands* states "your grandmother has arthritis and she has difficulty opening doors." The challenge posed to the student is to design a doorknob that is easier to use, as the existing doorknob, and will work in the same way.

Implementation

Each unit was designed to last 8 to 10 days in duration for a class of 25 students. The documentation for each unit costs $15. It is available in hard copy form or on a compact disk. The entire set of 10 units can be purchased on a CD for $95. The developer states that a new start-up program with no basic supplies would only need $50 worth of materials to implement these units. Professional development training is available through the International Technology Education Association.

[EDITOR'S NOTE: This curriculum review has a different style and format than the others in this appendix. However, the information it contains mirrors that in the other reviews.]

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Leader	Robert Chang, Northwestern University

Materials World Modules

Northwestern University, Evanston, Illinois

The Materials World Modules (MWM) is a series of interdisciplinary modules based on topics in materials science. To date, the program offers modules on composites, ceramics, concrete, biosensors, biodegradable materials, smart sensors, polymers, food packaging, and sports materials. They are designed for implementation in middle and high school science, technology, and math classes. Their pedagogical approach centers on the principles of inquiry and design and utilizes hands-on learning activities that enable students to apply materials science concepts and skills to problems found in everyday life outside of school.

Inception and Development

Dr. Robert Chang launched the Materials World Modules (MWM) initiative in 1994 with a grant from the National Science Foundation. He is a Professor in the Department of Materials Science and Engineering at Northwestern University in Evanston, Illinois. He received his B.S. degree in Physics from the Massachusetts Institute of Technology and his Ph.D. in Astrophysics from Princeton University.

Prior to securing funding for the MWM project, Dr. Chang enjoyed "…being involved with teachers, learning from them, seeing how things work in their classrooms, and discovering the issues" that influence science education. One of the factors that helped inspire him to develop the MWM materials was the limited nature of the opportunities that were available for his own two children to cultivate an interest and appreciation for science. Another factor was a latent desire to attract students to the materials science program at Northwestern University. However, the need to simply improve the quality of science education overshadowed these earlier motives.

Dr. Chang said, "I started out working with the school districts to make changes but that is like climbing Mount Everest. I wouldn't see any genuine change in my lifetime. So, I decided to make these modules — something that might make a difference."

The project set out to develop, field test, and disseminate a series of supplementary materials for high school teachers and students. Given the pervasiveness of materials in everyday life, the project's authors felt the study of materials would facilitate students' discovery of the interconnections between science, technology, and society (STS). The authors also felt organizing instruction around topics from materials science would help students see how science relates to their lives. Therefore, they established teams of university faculty, high school teachers, professional editors, and graphic designers to develop instruction modules that center around the themes of materials science and engineering. Their goal was to engage students in scientific inquiry in the contexts of solving design problems that required knowledge of materials science. They wanted to create modules that required students to "…ponder design problems that scientists and engineers encounter every day in the workplace."

"My premise for what I do is to improve science literacy. Not everyone is going to be a scientist. A majority of the population… does need to appreciate the importance of science. We study music and art so we can appreciate things like music and art. We just want to bring science to the same level."

Robert Chang

Mission and Goals

The **mission** of the Materials World Modules is to improve science education by engaging students in the intellectual processes of inquiry and design. Consistent with this mission, the modules are 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.

The Materials World Modules program was developed to address the following goals. The authors purport that these goals are consistent with those published by the National Research Council (1996) in the *National Science Education Standards*.

- Develop the abilities necessary to do scientific inquiry. These include the ability to generate questions, design and conduct scientific investigations, formulate models, analyze alternative models, and communicate and defend explanations.

- Understand scientific inquiry. Understand that scientific inquiry is focused on logically consistent explanations, grounded in current knowledge and augmented by mathematics and technology.

- Become familiar with materials science. Develop an understanding of materials science by applying knowledge from physical, life, and earth sciences to create materials for specific purposes.

- Take part in iterative design. Provide opportunities to identify technological problems, propose designs, choose between alternative solutions, implement and evaluate a solution, redesign the product, and communicate the problems, process, and solution.

- Understand the relationship between science and technology. Understand the difference between the purposes and nature of scientific and technological studies and the interrelationship between the fields.

- Understand contemporary problems. Appreciate the use of science and technology to meet local, national, and global challenges, including problems of personal and community health, natural resources, environmental quality, and human-induced hazards.

- Present a historical perspective. View the history and nature of science as a human endeavor, producing new knowledge, supported by developing technology.

The MWM materials were also designed to address two complementary sets of goals for student achievement. One set of goals addresses content while the other targets skills. More specifically, the content goals target the science and technology principles. The process goals focus on the skills associated with thinking like a scientist, technologist, or an engineer. Together, these two sets of goals informed and guided the design of the activities that students performed in each module.

The content goals for the program are as follows:

- Learn scientific and mathematical principles by applying them to solve real-world problems
- Develop an understanding of the science and engineering of materials by applying knowledge from physical, life, and earth sciences to create materials for specific purposes
- Learn about the interrelationship between science and technology and their influences on local, national, and global environments
- Understand contemporary problems in society, including problems of personal and community health, natural resources, environmental quality, and human-induced hazards and appreciate the use of science and technology to meet these challenges
- View the history and nature of science as a human endeavor, producing new knowledge, supported by developing technology

The process goals for the modules are listed below.

- Ask and refine researchable, productive questions
- Plan and conduct a quantitative, hands-on laboratory investigation, using journals to guide investigation and record progress
- Work within a collaborative team to complete a design project
- Develop solutions through iterative design: challenge, problem definition comparing options, implementation, reflection, and redesign
- Develop a designer's eye to analyze trade-offs and decisions an engineer may encounter in creating artifacts

Conceptual Framework

Materials science is the study of the characteristics and uses of various materials, such as metals, ceramics, and polymers that are employed in science and technology. It is an interdisciplinary subject that employs and integrates concepts and techniques from a variety of disciplines, including chemistry, biology, physics, and mathematics.

The MWM program is an ongoing project that is dedicated to developing instructional materials that enrich existing high school science curricula with learning activities that show concrete linkages between the concepts and skills from various science disciplines and everyday life. Towards that end, the project structured its modules around topics that the authors believed were "critical" to a technological society. They also want to show how modern materials can be viewed as systems and disclose how they impact society. To date, nine modules have been published and the collection available to teachers includes the following titles.

- Biodegradable Materials
- Biosensors
- Ceramics
- Composites
- Concrete
- Food Packaging
- Polymers
- Smart Sensors
- Sport Materials

The following were recently developed and field-tested, but have not as yet been published.

- Bonding & Polarity
- Materials & the Environment
- Lights & Color
- Motion & Forces: Inquiry into Sports Equipment
- Properties of Solutions: Real-World Applications
- Biotechnology
- Electrical Conductivity
- Environment Catalysis
- Structure & Properties of Matter
- Introduction to the Nanoscale: Surface Area & Volume

The following two modules are currently undergoing field-testing.

- Manipulation of Light in the Nanoworld
- Nanoinvestigations: Measurement

Content

The following content analysis is limited to the modules that have been published.

Biodegradable Materials Students examine the attributes, advantages, and applications of biodegradable materials during this module. During the course of the module they will compare biodegradable and non-biodegradable packing materials, identify examples of biodegradable materials in everyday life, test the strength and compressibility of two gelatin-based films of varying density, measure the degradation rates of biodegradable materials, research biodegradable materials, design a device for delivering medicine, and develop a new biodegradable material. The science concepts addressed include the meaning of the word biodegradable, natural versus synthetic polymers, natural degradation processes (i.e., microorganism, enzymes, hydrolysis, ultraviolet light), the nature of gelatin, the effects of temperature and pH on degradation rates, and the cross-linking of polymer chains. The technology content includes the invention of gelatin capsules and development biodegradable polymers.

Biosensors This module focuses on the nature and uses of biological molecules and biosensors. The lessons and activities include experimenting with biological molecules and bioluminescence, investigating enzymes and indicator molecules, making a peroxide biosensor, teaching a cholesterol biosensor, evaluating a home-use cholesterol biosensor, researching biosensors, and designing a glucose biosensor. The science addressed includes concepts related to bioluminescence and chemiluminescence (e.g., luciferase, luciferin, oxyluciferin), biological molecules (e.g., proteins, carbohydrates, lipids, nucleic acids), enzymes, peroxidase-catalyzed reactions, and cholesterol. The technology content includes the development and applications for common biosensors (e.g., home-use pregnancy tester, blood glucose tester for diabetics, testing for environmental contaminants, cholesterol testing).

Ceramics This module looks at the functions and properties of ceramics. The activities include categorizing materials like glass, metal and plastic based on their properties; identifying examples of ceramic objects and their applications; experimenting with ZnO powder; and exploring ways to eliminate porosity through slip casting. Students also examine how firing ceramics turns a weak, soft, and porous object into a dense, strong, and solid object. The design projects involve developing a low-clamping voltage suppressor and synthesizing a high-temperature superconductor. The salient science content includes classifying materials based on their properties (electrical conductivity, electrical resistively, thermal conductivity, chemical reactivity), the composition and characteristics of ceramics (especially, ZnO), the concepts of density and porosity. Some of the technology content focuses on historical as well as modern applications for ceramic materials. It also includes hydroplastic forming and slip casting. Lastly, the composition of semi-conductors is described and examined.

Composites During this module students study the characteristics, advantages, and application of composite materials. The activities include comparing pure ice with ice reinforced with paper, identifying examples of composite materials in everyday things, testing the strength and stiffness of a simple composite material, researching composite materials, designing a composite fishing pole, and developing a new composite material. During these activities, students study science concepts like natural versus synthetic composites, compressive and tensile forces on atoms, and strength versus stiffness. There is also a passing reference to covalent bonds, ionic bonds, metallic bonds, hydrogen bonds and van der Waals forces. The technology content focuses defining the term “composite materials,” the different types of composite materials (i.e., particulate, laminar, fiber reinforced), the difference between structural and functional composite materials, historical examples of composite materials, and contemporary applications for composite materials.

Concrete The characteristics, advantages, and applications of concrete are the subjects of this module. It asks students to identify objects made of concrete in their surroundings; discover the physical and chemical changes in cement as it cures; compare the density, strength, and brittleness of different formulations of concrete; experiment with reinforced concrete. The design projects include developing a concrete roofing tile and creating a new product made out of concrete. The science content includes different kinds of cement and the concepts of hydration, compression, tension, and strength. The technology addressed in this unit includes the concept of infrastructure, historical and modern applications for concrete, the composition of concrete (i.e., cement, water, aggregates), and the concept and advantages of reinforcing concrete.

Food Packaging This module examines the properties and functions of food packaging. It begins with students taking apart and analyzing a bag for microwave popcorn. This is followed by analyzing different kinds of food packaging (e.g., the types of materials used, their properties, the function they serve), researching the materials used in food packaging, designing a protective package for tomato, and testing the insulating properties of packaging materials. The design project involves making a package that will keep a potato hot and developing an environmentally friendly package for a food item. The science content includes how various materials react to microwaves, concepts related to protecting food (e.g., potential energy, kinetic energy, absorbing energy), and concepts related to heat transfer and thermal conductivity (i.e., conduction, convection, radiation). The technology includes old as well as modern examples of food packaging, the materials used for food packaging, the environmental impact of food packaging, the protection function of packaging, and the techniques used to retain heat.

Polymers The subject of this module is the nature of polymers and their applications. During this unit students look at the absorption properties of polymer pellets and their potential use in gardening. They also identify common products made of polymers, compare the viscosity of liquids, and test the strength and water absorption of different polymer films. The design problems include designing a humidity sensor and developing a new product made out of a polymer. The science content includes the molecular composition of polymers and their ability to absorb water, natural versus synthetic polymers, the concepts related to polyethylene chains (e.g., linear polyethylene, branched polyethylene, cross-linked polyethylene), the relationship between molecular weight and viscosity, the factors that effect the strength of polymer film, and why adding polymers to paint provides a water barrier. The technology content includes different applications for types of polymers, how polymer films are manufactured, and the development of paint.

Smart Sensors Students study the features and applications of smart sensors in this module. Students begin by experimenting with a commercial piezoelectric motion detector and then they explore other kinds of sensors (their inputs, outputs, composition, and potential applications). The next lesson and activity engages them in making a piezoelectric microphone. This activity is followed by examining the piezo effect and the peizoelectric and pyroelectric responses of the polymer polyvinylidene fluoride (PVDF) film. The design problems involve developing a device that will count coins and inventing a new kind of sensor. The science content examines the sensitivity of materials to infrared radiation, plants that sense stimulus, the human ear as a natural sensor, the chemical structure of a piezoelectric material, and how PVDF works. The technology content looks at human-made sensors (piezoelectric sensors), practical applications for sensors, and the role of sensors in technological systems.

Sport Materials This module focuses on the characteristics of materials used for sports applications. Students study the features of different kinds of balls and speculate why they are made of different materials. Next, students measure the rebound of various balls using a drop test and investigate how materials absorb through deformation. They also look at how surfaces can impede how far a ball rolls and how well different kinds of balls roll across the same surface. Lastly, they compose a report about the materials used in a piece of sport equipment of their own choosing. The design problems include developing a mini-golf game and inventing an innovative piece of sports equipment. The science looks at the laws of nature acting on a golf ball, quantifying the performance of a ball by calculating its coefficient of restitution, the exchange of energy when a ball bounces, how molecular bonds absorb and release energy, and the impact of friction on the movement of objects (i.e., sliding friction, rolling friction, static friction). The technology looks at the composition of a golf ball and how its design reduces drag.

Most of the science concepts are presented in explanations that are similar to those one would find in an encyclopedia or trade book. The concepts are broken down into small pieces and presented in a logical sequence that progresses from simple to complex. Most of the explanations are supported with easy to understand analogies, common examples, and clear illustrations.

All of the modules feature scientific investigations that require students to declare their ideas by formulating hypotheses or making predictions. These hypotheses or predictions are tested with simple manipulatives that involve making observations, taking measurements, analyzing data, and presenting conclusions.

Most of the mathematics content is embedded in the various investigations that the students conduct (e.g., measurements, data analysis, graphing the relationship between two variables). The materials do not attempt to teach the mathematics that is required to quantify phenomena, to perform calculations, to analyze data, or to present results.

Engineering concepts and ways of thinking can be found in the culminating design problems at the end of each module. They all require students to apply what they have learned in previous lessons and laboratory activities to the development of a solution of a practical problem. The problems are typically presented in the context of a company that needs a new product. These problems often include a list of design constraints and, in some cases, minimum specifications for a successful design. The solutions developed by the students are always in the form of physical models that are constructed out of simple materials that are listed materials. More importantly, they can be tested and thus provide the data needed to determine the effectiveness of the design. In every case, students are asked to keep a design log that shows their brainstorming, thought processes, drawings, predictions, evaluation criteria, testing procedures, data, reflections, and results.

> *"The process we are using is relevant to teaching engineering. We pique their curiosity. They do some measurement. Once they get the feel of it, we try to get them to put it into words or simple equations. They develop a model and they test the model.."*
>
> Robert Chang

Pedagogical Principles

Each module in the series has three basic elements. First, instruction is initiated with an opening activity that is designed to create interest in the topic at hand. The introductory activity also requires the students to formulate a hypothesis about a cause and effect relationship related to the topic in question. Second, the introduction is followed by four or five hands-on learning activities that introduce the students to key principles, ideas, and methods related to the topic under study. Students conduct these activities in the context of one or more design problems. Lastly, each module culminates in a design project that requires the development of a prototype product as well as the application of the key materials science concepts and skills.

The contents and the design of the materials suggest the authors were attentive to the need for **scaffolding**, **continuity**, and **coherence**. All the modules clearly start with something relatively simple and they progress to more complex concepts and tasks in a very incremental and deliberate manner. Furthermore, each lesson features a series of modest narratives that link it to the previous lesson, describes how it connects to the next lesson, and ultimately how it applies to the culminating design problem.

Each module features a series of lessons that model basic pedagogical principles. More specifically, the lessons include clearly defined objectives, interest building strategies for initiating instruction, brief overviews, sequential learning activities, potential multidisciplinary connections, strategically placed reviews, ways for engaging students in reflection and lastly, strategies for assimilating content.

A Socratic approach to teaching and learning underpins the lesson instruction and students' learning activities. Questions can be found throughout the materials and they play prominent roles initiating lessons, exploring examples, guiding investigations, reviewing results, identifying applications, informing design projects, and checking for understanding.

All of the Materials World Modules are based on the pedagogical principle of "**inquiry through design**." More specifically, they are designed to engage students in scientific inquiry that helps them discover how materials science concepts and skills are applied to everyday design problems.

One of the fundamental premises underpinning the modules is the notion that doing scientific inquiry and addressing design problems can work together in a synergistic manner to help students to better understand science principles and develop scientific habits of mind. The authors believe engaging students in scientific inquiry helps them to uncover the important scientific principles that they need to address their design problem. Inversely, engaging students in design activities creates a genuine need to explore the scientific principles that will inform their solution to the design problem. This approach unites the abstract, quantitative methods of scientific inquiry with the concrete methods of technological design, helping students develop and integrate these complementary skills in a unique way.

"*What is unique about the US is we have the freedom to do this and that. We had to tap into that freedom to explore and try things. But we discovered we had to train students and adults how to ask good questions.*"

Robert Chang

The design problems are presented to students in scenarios that are typically framed in the context of a fictitious company that has a problem that needs to be solved. The teachers are given specific and detailed lists of the tools and materials that need to be available for the students to address the problem. Some of the design problems require students to develop multiple solutions to the problem, to test each prototype against the design criteria, and use the results to develop the optimal solution. Each design problem culminated with some form of reporting the thought processes, design, and testing results.

"I grew up with electronics — making radios from kits — going to the electronics store and finding things to make. I wanted the students to build something."

Robert Chang

Interdisciplinary education is another pedagogical principle that underpins the MWM materials. Mathematics, chemistry, physics, biology, and technology are typically taught as discrete subjects at the high school level. The architects of the MWM program espoused that the "compartmentalization of knowledge leads students to understand these fields as sets of decontextualized techniques and facts rather than integrated disciplines that complement each other and that are frequently used as instruments to solve real problems." Therefore, the MWM program strives to use materials science as an integrating context for studying science, mathematics, technology, and society. Instead of teaching principles of chemistry, physics, and mathematics in isolation of each other, the MWM program frames the instruction around real problems and societal issues that require students to draw on several disciplines at once. Furthermore, according to the projects leaders, "approaching science and technology with a social context helps students see how science is relevant to their lives, empowering them to make better decisions as citizens of the world."

Curriculum Implementation

The Materials World Modules project offers workshops that are conducted by master teachers that have experience with the MWM materials. These workshops are conducted in what the MWM project calls "hub sites." A hub site is a central location with approximately a 50-mile radius where 15 to 20 teachers can gather for training. The number of modules, the length of the training session, and number of teachers in attendance can vary from site to site. The agenda can include things like guest speakers from industry or the research community, feedback from field tests, discussions about reflective practice, demonstration of iterative design, techniques for composing questions, and classroom video clips.

Each workshop provides participants an overview of the pedagogical principles that were used to design the instruction in modules. The workshops also provide teachers an opportunity to experience the hands-on activities in the modules. The activities enable teachers to experience the scientific and technological techniques used in the module. The facilitators strive to familiarize teachers with the activities that their students will be doing in class. Due to their experience with the modules, they provide advice on how to best use the materials, address student misconceptions, encourage design ideas, and capitalize on interdisciplinary connections.

The teacher network provides a natural conduit for continuous exchange among the practitioners of the Materials World Modules (MWM). MWM is committed to establishing and cultivating informal communication and support networks among developers and users of these materials science modules. This kind of linkage is absolutely essential for supporting and stimulating teachers who implement curricular reform and for achieving long-term impact.

The MWM listserv provides a mechanism for ongoing dialog between the project staff, seasoned teachers, and teachers implementing the materials for the first time. Teachers use the listserv to exchange project design ideas, ask questions, and develop lessons. The network provides a medium for collaboration across schools, states, and even countries.

There are some costs associated with integrating one or more of the Materials World Modules into an existing curriculum. First, the teacher's edition for each module costs $40. Student editions cost $14 each and a classroom set of 24 would cost about $336. Starter kits for conducting the laboratory activities cost between $142 and $417 depending on the module being implemented. Similarly, the refill kits for replacing consumables cost between $33 and $379.

Implementing a module can require one to three weeks of class time depending on the module being implemented, the number of enrichment activities included in the instruction, and the scope of the design project presented to the students. They can also be implemented in one of two ways. Selected modules can be used as self-contained units of instruction that supplement an existing high school or middle school science, math, or technology class. They can also be linked together in a series to form a one-year class. In light of the interdisciplinary nature of the modules, the course would be akin to those developed under the auspices of the Science, Technology, and Society (STS) movement.

Diffusion and Impact

The module on Composites was the first one developed, and it has been implemented in the widest range of high school and middle school classes. Smart Sensors, Biodegradable Materials, Concrete, and Sports Materials are also popular among various disciplines due to their interdisciplinary nature. The high school subjects that used the modules with the greatest frequency are chemistry, general science, and biology. Lastly, the Department of Defense Education Activity is currently implementing MWM modules in a STS curriculum in overseas high schools.

The Materials World Modules project reported that over 40,000 students in schools nationwide have used its materials. Extensive field-testing in 48 states has enabled the developers of the MWM program to solicit feedback from a wide range of teachers and students. Teachers in all subject areas reported that the use of the modules enabled students to make connections between concepts from the traditional curriculum and the world around them more frequently than ever before. They also identified numerous skills that students have demonstrated, both during and after the experience of using the modules in class. These skills fall into several categories, including:

- Laboratory skills: measuring, manipulating equipment, recording data, graphing, performing mathematical computations, devising and conducting controlled experiments, making predictions
- Communication skills: collaborating to achieve shared goals, brainstorming, explaining ideas to others, persuading, employing problem-solving strategies, working to reach a consensus, translating observations into discussion, employing new terminology and vocabulary in group work, leading other students
- Application of scientific and mathematical knowledge: exploring new ways to integrate scientific, mathematical, and technological concepts; synthesizing information to create a new product or design; preparing technical reports on computers using programs like Excel.

The latest round of field-testing focused on eight of the ten recently developed modules. *Environment Catalysis* and an *Introduction to the Nanoscale: Surface Area*

& Volume were not included because of conceptual differences in content and design. According to Dr. Chang, these results can be generalized to the original nine modules because they follow the same format and instructional design.

The modules in question were field-tested in 118 science classrooms addressing a wide range of topics (e.g., physical science, AP chemistry, biotechnology, physics, introduction to engineering). The field-test sites were randomly selected from 42 states representing six different regions of the nation. The project secured data representing 2,026 students with a return rate of 88.2 percent. Project leaders reported the following findings from their analysis of the data collected.

- The students across the 118 classrooms demonstrated an average gain of 31.75% in subject matter knowledge as a result of completing the modules.
- At least half of the students in each of the 118 classrooms reported improvements in the areas of teamwork, connecting science to everyday life, planning design projects, analyzing data, understanding science concepts, and overcoming failures.
- The teachers in the 118 classrooms reported their students improved in the areas of discussing design issues and design constraints, planning design projects, working as a member of a team, analyzing and overcoming failures, retaining science concepts, and being able to discuss materials science concepts.
- The students demonstrated statistically significantly gains on items that assess the level of "science esteem" in a classroom (e.g., science classes are interesting, I talk about science with my friends, I enjoy designing useful things, science labs help me overcome my own mistakes).
- Students liked the design projects more than the other module activities.
- Female students demonstrated higher achievement and design scores than their male counterparts.
- The field-test teachers felt the modules required teaching a lot of material in a two-week period of time. They also reported the modules were very professional, enriched their curricula, added depth to the concepts being addressed, and were engaging for their students.
- Most of the teachers reported that they planned to use the modules in the future. There was also feedback that suggests the money and time required to implement the modules was at odds with pressure to prepare students for standardized tests.
- Most of the teachers recognized how the module can be aligned with the National Science Education Standards, especially in the areas of Science Inquiry and Abilities of Technological Design.
- There wasn't a relationship between student achievement and the teachers' level of experience, but there was a correlation between class performance and teachers having Master's degrees.

PLTW: Gateway to Technology

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Grade Level
Middle School (6-8)

Espoused Mission
"…to show students how technology is used in engineering to solve everyday problems."

Organizing Topics
The curriculum is divided into five discrete units that have the following titles:

- *Design and Modeling*
- *The Magic of Electrons*
- *The Science of Technology*
- *Automation and Robotics*
- *Flight and Space*

Format
Each unit is divided into a series of lessons and each lesson has the following elements.

- A preface that presents an introduction to the lesson (e.g., expectations).
- Several key concepts that are presented in the form of sentences that declare the big ideas in the lesson.
- Learning activities that are presented in a day-by-day sequence that include links to support materials (e.g., handouts, assessment tools, PowerPoint presentations).

Pedagogical Elements

The authors set out to use a "project-based learning" approach that engages students in working in teams on hands-on activities. Most of the lessons engage students in seeking out references, gathering information, demonstrating comprehension, and making and testing devices.

Maturity

The initial five units that comprise the *Gateway to Technology* program were developed between 2004 and 2006. At the time of this report, the curriculum was undergoing its first revision. During the course of this revision, a new unit titled *Energy and Environment* was added to the program. The revised units and new unit will be field tested during the 2009/10 school year and will be available to participating schools in the fall of 2010.

Diffusion & Impact

Approximately 1090 schools are implementing the *Gateway To Technology* program. However, Project Lead the Way does not have a formal assessment tool in place for *Gateway to Technology*. Therefore, its impact on students, teachers, and schools has not been assessed.

Initiative **PLTW: Gateway to Technology**

Title

Design and Modeling

Broad Goals

It is expected that students will:

- Compare and contrast technology and science.
- Describe impacts that technology has had on society.
- Explain the purpose and function of technology.
- Describe the design process and how it is used to aid in problem solving.
- Explain how to measure in different contexts.
- Demonstrate the ability to measure.
- Describe the purpose and importance of working in a team.
- Use the design process to solve a technological problem.
- Recognize thumbnail sketches, isometric, orthographic, one- and two-point perspective drawings and accurately interpret what they see.
- Communicate ideas for a design using various sketching methods, sketches, and different drafting views.
- Develop thumbnail sketches, orthographic drawings, and isometric drawings using manual and computer-assisted processes.
- Identify basic geometric relationships of shapes and solids.
- Use coordinate system to express geometric relationships.
- Create a three-dimensional (3D) model of an object.
- Demonstrate the ability to produce various documentation drawings from a 3D model.
- Produce the annotations to document various drawings made from a 3D model.
- Interpret the relationship of orthographic and auxiliary views to their parent 3D models.
- Identify what a prototype model is and how it is used.
- Create a three-dimensional (3D) prototype model of an object.
- Demonstrate the ability to produce various documentation drawings from a 3D model.
- Describe how a prototype model is used and how its fabrication aids in the design process.

Salient Concepts & Skills

Math
- measurement
- common units
- metric system
- English system
- decimals

Science
- …is the study of the natural world
- field of science (biology, chemistry,

Technology
- …is the study of how humans develop new products to meet needs and wants

- geometric shapes can be combined to form objects
- X- and Y-axis
- three-dimensional
- descriptive geometry
- geometric relationships
- dimensions
- reducing fractions
- tenths of an inch
- thousandths of an inch
- hundred thousandths of an inch

physics)

- scientific method (define a problem, researching and developing a hypothesis, testing the hypothesis, analyzing data, forming a conclusion, reporting results)

- inventions
- innovations
- artifacts
- processes
- systems
- precision measurement
- micrometer
- dial calipers
- thumbnail sketches
- isometric drawings
- orthographic drawings
- one- and two-point perspective drawings

Engineering

The following espoused concepts have implications for the study of engineering:

- The use of technology can have cultural, economic, environmental, political, and social consequences.
- The development and use of technology can create ethical issues.
- The design process includes identifying problems and opportunities, brainstorming and sketching, investigating and researching, generating multiple solutions, choosing the best solution, modeling and prototyping, testing and evaluating, redesigning and improving.
- Design is a creative planning process that leads to useful products and systems.
- Designs are never perfect.
- Requirements for a design include criteria and constraints.
- Design involves a series of steps that can be performed in different sequences and are often repeated several times.
- Engineers use pictures to express design ideas and potential solutions to problems.
- Brainstorming is used to generate numerous ideas about how to solve a problem.
- Making a virtual prototype allows the designer to see the product as a three-dimensional object.
- Virtual prototypes are used to test the functionality of a design.

Prominent Activities

In the first lesson, the *Introduction to Technology*, students are engaged in the following activities.

1. Receive an overview of the curriculum (i.e., Design and Modeling, Magic of Electrons, Science of Technology, Automation and Robotics).
2. Explore the meaning of the word “technology.”
3. Discuss the roles that people, information, capital, time, energy, tools/machines, and materials play as resources of technology.
4. Identify examples for all the different types of resources (.e.g., people, information, capital, time energy).
5. Discuss the need to prepare and maintain an “Engineer’s Notebook” (e.g., notes, research, sketches, drawings, journal entries).
6. Examine the impacts that technology has on society.
7. Describe the importance of technology in everyday life.
8. Discuss the major areas of technology (e.g., communication, production, transportation, biotechnology).
9. Examine the meaning of the word technology.
10. Explore how science and technology are similar and how they are different (e.g., the study of the “natural world” versus the study of the “human-made world,” deals with “what is” versus “what can be”).
11. Develop concept maps for technology (students draw a picture of their thinking related to what the word technology means to them).
12. Develop concept maps for a topic related to technology (e.g., printing press, automobile, medical, environmental).
13. Research a technological invention (e.g., what does it do, how does it work, what does it look like, who invented it, when was it invented, where was it invented, why was it invented).

In the second lesson, the *Design Process*, students are engaged in the following activities.

14. Hear about he concept of teamwork and identify first, second, third, and fourth choice for engineering partners.
15. Be introduced to the concept of measurement (e.g., match attributes of an object with a quantity of standardizes units, metric versus English, counting units, and reducing fractions).
16. Explore the history of measurement (i.e., cubit, fathom, hand span, pace, girth, palm).
17. Be introduced to precision measurement and precision measurement tools that use decimals (i.e., micrometer, digital caliper, dial caliper).
18. Measure the length, width, and height of objects using rulers and creative units of measurement (e.g., paper clips).
19. Identifying the parts of a dial caliper and interpret the readings on illustrations of calipers.

20. Use measurement skills to make an “air racer” (a project that requires laying out and folding paper).
21. Hear about the design process (i.e., identifying problems and opportunities, brainstorming and sketching, investigating and researching, generating multiple solutions, choosing the best solution, modeling and prototyping, testing and evaluating, redesigning and improving).
22. Discuss the basic elements of design (e.g., line, form color, light and shadow, space, materials, texture).
23. Develop a concept map that features the elements of design.
24. Hear about the problem-solving method (i.e., define the problem, set goals and consider specifications, gather information, develop alternatives, select the best solution, implement the solution, evaluate the results).
25. Use the technical problem-solving process to “design a solution” to a problem (design a poster for a band).
26. Identify and solve a “community technical problem” (the example given is the problem that people with arthritis have opening jars).
27. Design and build a model crane from simple materials (e.g., drinking straws, paper clips, string, masking tape) that address the problem of lifting toy animals over a barrier).

In the third lesson, the *Sketching and Views*, students are engaged in the following activities.

28. Be introduced to the concept of sketching and different types of sketches (e.g., thumbnail sketching, isometric sketching, perspective sketching, multiview sketching).
29. Be led through the process of sketching (technique, tool use, expectations).
30. Discuss thumbnail sketches, one- and two-point perspective, and orthographic drawings,
31. Make orthographic (multiview) drawings.
32. Discuss how different types of drawings are used in engineering endeavors.

In the fourth lesson, the *3D Computer Modeling*, students are engaged in the following activities.

33. Be guided through basic descriptive geometry as well as the use of a coordinate system (e.g., X-axis, Y-axis).
34. Learn how to used 3D modeling (computer-aided design) software (e.g., line sketch tool, geometric constraint tool, dimension constrain tool, extrusion dialog box, dynamic rotation).
35. Sketch a plane cube.
36. Be introduced to the concept of reverse engineering (e.g.,

looking at an object and trying to determine what shapes make up its composition so it can be reproduced using computer-aided design software).

37. Learn how to draw multiview drawings (a.k.a., orthographic projections) using reverse engineering (converting a isometric representation of an object into a multiview drawing).
38. Be introduced to parts assembly (combining object that were drawn separately on CAD).
39. Make drawings for a “Peg Board Toy” and other objects (e.g., bracket, electric switch plate, hair brush).

In the fifth lesson, the *Prototype Fabrication*, students are engaged in the following activities.

40. Be introduced to the problem and specifications associated with the design of a model dragster that is power by compressed air.
41. See examples of dragsters.
42. Follow the steps laid out for making a prototype dragster on the computer using solids modeling software.
43. Develop thumbnail sketches for their model dragster.
44. Draw the basic body of their dragster using solids modeling software.
45. Draw three side view sketches of potential designs for their dragster.
46. Chose one design over the others for further development.
47. Draw the side view of their dragster’s design using solids modeling software.
48. Hear how to use the “project geometry tool” in the software.
49. Sketch an orthographic projection of their dragster’s design that includes dimensions.
50. Draw the top view of their dragster using solids modeling software.
51. Hear how to use the “work plane tool” in the software.
52. Assemble their dragster (i.e., wheels, axle, body) using solids modeling software.
53. Create and print working drawings of their dragster’s design.
54. Make entries in their engineer’s notebook.

Initiative **PLTW: Gateway to Technology**

Title

The Magic of Electrons

Broad Goals

It is expected that students will:

- Demonstrate the movement of electrons and electronegativity in atomic structure diagrams
- Explain the difference between static electricity and current electricity.
- Measure conductivity levels of various materials using a digital multimeter and classify them as conductors or insulators.
- Explain what part of the electron, protons, and neutrons of an atom play in the generation of electricity.
- Explain the term electromotive force and the parts that make up a motor.
- Demonstrate their knowledge of DC motor operations by explaining how electricity is generated.
- Demonstrate the ability to follow directions in the assembly of a simple motor.
- Assemble series, parallel and combination series/parallel circuits.
- Use schematic symbols to diagram electric and electronic circuits.
- Test and prove the relationship between voltage, current, and resistance as stated in Ohm's law.
- Understand common electric and electronic load devices, their schematic symbols, and describe the function of each device.
- Describe the use of a transistor and its use as a switch or amplifier.
- Demonstrate the correct use of a digital multimeter.
- Recognize and translate resistor color codes and resistor resistance metering.
- Utilize reading comprehension techniques to discern important information from a passage on digital electronics and apply that information in later assignments.
- Understand and apply their knowledge of truth tables and logic gates to solve digital electronic problems.
- Design and prototype solutions to digital electronics problems.
- Understand inputs, outputs, and sensors and their uses in digital electronics.

Salient Concepts & Skills

Math	Science	Technology
• binary numbers	• energy comes in different forms	• electrolyte
• truth tables		• DC motor

- logic problems

- structure of an atom
- different materials have different properties
- Periodic table
- insulators
- conductors
- static electricity
- current electricity
- electrons
- protons
- neutrons
- electromotive force

operation
- series circuits
- parallel circuits
- schematics
- electrical components
- bread boarding
- printed circuit boards
- routing diagram
- soldering
- digital electronics
- open and closed loop systems
- controls
- ASCII code
- logic gates
- AND gates

Engineering

The following espoused concepts have implications for the study of engineering:

- The components of an electrical system perform different functions.
- Models are used to test new designs and processes.

Prominent Activities

In the first lesson, the *Science of Electricity*, students are engaged in the following activities.

1. Research careers that require only a high school diploma, high school and some post-secondary education, and four or more years of college (e.g., job title, job description, salary projection, demand).
2. Watch a video titled "Electricity: The River of Invisible Energy."
3. Watch a demonstration (simulation) regarding the flow of electricity using aquarium tubing and marbles.
4. Compare static electricity (electricity that is standing still) and current electricity (electricity that is moving) by making an electroscope and making and wiring batteries into a circuit.
5. Discuss the periodic table.
6. Use a periodic table to identify materials that are good conductors versus insulators.
7. Learn how to use a digital multimeter.
8. Test different kinds of materials to determine their ability to conduct electricity.

In the second lesson, the *Electromotive Force*, students are engaged in the following activities.

9. Watch a demonstration of a hand generator.
10. Write an explanation of electromotive forces in their engineer's notebook.
11. Explore the "How Stuff Works" Web site to learn about how a motor works.
12. Hear about how a DC motor is constructed
13. Watch a demonstration of how a motor's speed can be tested with a strobe light.
14. Assemble and test a simple DC motor.

In the third lesson, the *Circuit Design and Fabrication*, students are engaged in the following activities.

15. Be introduced to series circuits, parallel circuits, and breadboard systems.
16. View a demonstration on how to use a breadboard to construct different kinds of circuits.
17. Build and test an electrical circuit.
18. Be introduced to the different symbols used to represent electrical components.
19. Be introduced to the concept of resistance.
20. View a demonstration of the doping process (pouring salt into water to reduce its resistance).
21. Calculate the resistance of different resistors.
22. Be introduced to Ohm's law and how unknown values can be determined with mathematical formula.
23. Discuss the differences between calculated values and metered values (e.g., human error, meter error, resistor tolerances, poor connections).
24. Be introduced to transistors and how they are used in electronic systems (e.g., switch, amplifier)).
25. Take notes in their engineer's notebook.
26. Watch a video titled, "Transistorized" and take notes in the form of a "graphic organizer."
27. Hear about the difference between a schematic and a routing diagram.
28. Be introduced to different kinds of electronic components and hear about their function (e.g., transistor, diode, LED, photocell, thermistor).
29. Watch a demonstration on how to center punch and drill tiny holes in a printed circuit board.
30. Use a routing diagram to trace the circuit they are going to construct on printed circuit board.

31. Watch a demonstration about how to safely solder electronic components.
32. Watch a demonstration on how to orient and install electrical components correctly.
33. Build a working circuit on a printed circuit board,
34. Watch a demonstration on how to troubleshoot circuit boards.

In the fourth lesson, the *Digital Electronics*, students are engaged in the following activities.

35. Be introduced to digital systems, binary numbers, bits and bytes.
36. ASCII code, transistors as switches, logic gates, and truth tables.
37. Hear about AND gates.
38. Take notes in their engineer's notebook.
39. Use a web quest to learn how electronic gates work.
40. Discuss how truth tables are used to predict how a digital logic circuit will work.
41. Hear explanations of how different kinds of sensors work (e.g., microphone, photocell, thermistor, slide switch, push switch).
42. Complete truth tables and wire circuits for a series of logic circuit problems (e.g., manage an incubator's temperature, summon a nurse only during the day, fire alarm that is triggered by heat or smoke)

Initiative **PLTW: Gateway to Technology**

Title

The Science of Technology

Broad Goals

It is expected that students will:

- Be capable of comparing and contrasting kinetic and potential energy.
- Be capable of identifying and explaining the function of systems and subsystems.
- Correctly identify the six simple machine and explain their applications.
- Identify a machine as something that helps use energy more efficiently.
- Be able to classify energy sources as renewable and nonrenewable.
- Be able to explain the environmental impact of future career opportunities with the energy field.
- Be able to describe and follow the steps necessary to create a prototype.
- Explain the importance of building a working prototype before beginning full scale fabrication of a product.

Salient Concepts & Skills

Math

- standard unit of measurement
- measuring time in seconds
- measuring distance in meters
- calculate speed based on distance and time
- calculate acceleration based on changes in speed and time
- calculate force based on mass and acceleration

Science

- potential energy
- kinetic energy
- systems in nature
- energy sources
- energy can not be created or destroyed
- Newton's law of gravity
- Newton's laws of motion (inertia, acceleration, action and reaction)
- speed
- acceleration
- force

Technology

- system
- prototype
- inclined plane
- lever
- wedge
- screw
- pulley
- wheel and axle

Engineering

The following espoused concepts have implications for the study of engineering:

- "Energy source development has an environmental impact that must be taken into consideration."

- "Prototyping is a very important step in the design process and provides the designer with a scaled working model."
- "Full size fabrication should only be done when a viable prototype has been built and tested."

Prominent Activities

In the first lesson, the *Mechanics of Motion*, students are engaged in the following activities.

1. Identify positive and negative impacts for different families of technology (i.e., communication technology, production technology, transportation technology, biotechnology).
2. Identify some of the subsystems associated with given systems (e.g., universe, ecosystem, automobile, house or apartment, computer, stereo, middle school, technology lab).
3. Read about the difference between open-loop systems and closed-loop systems.
4. Be introduced to the six simple machines (i.e., inclined plane,. lever, wedge, screw, pulley, wheel and axle).
5. Watch a video about simple machines, record the types of machines described and identify examples of each.
6. Discuss the scientific principles associated with machines, what machines do, and what is inside machines that make them work.
7. Disassemble everyday devices (electric pencil sharpeners, mixers, drills, etc.) to understand the concepts force, motion, and work.
8. Draw the simple and compound machines found in the disassembled device and show the directions of forces and motion using arrows.
9. Be introduced to the terms potential and kinetic energy.
10. Hear about Rube Goldberg; inventor and cartoonist.
11. Design, make, troubleshoot, and present a Rube Goldberg device made of everyday tools and materials.

In the second lesson, the *Energy Conversion Systems*, students are engaged in the following activities.

12. Discuss different kinds of energy resources and their impacts on the environment.
13. Brainstorm how different energy resources are changed to do work.
14. Hear about the difference between renewable and nonrenewable energy resources.
15. Create and present posters that describe an energy resource in terms of it historical development, whether it is renewable or non-renewable, and its impact on the environment.
16. Make a PowerPoint presentation about a specific engineering

career (aerospace, agriculture, architectural, etc.) that includes a job description, work tasks, skills and abilities, education/training requirements, wages, job outlook, and why it is appealing.

In the third lesson, the *Prototyping and Fabrication*, students are engaged in the following activities.

17. Hear about Newton's laws (gravity, inertia, acceleration, action and reaction).
18. Hear how to calculate speed, force, and acceleration.
19. Receive an introduction to the compressed air dragster project.
20. Review the procedures for safely using the tools and equipment that will be used to make a compressed air dragster.
21. Fabricate a compressed air dragster using drill presses, scroll saws, band saws, and belt sanders.
22. Race the compressed air dragsters and record data
23. Use the data collected to calculate velocity, average velocity, acceleration, average acceleration, and force.
24. Receive an introduction to the "maglev fabrication" project.
25. Be introduced to the tools and equipment that will be used to make a maglev vehicle.
26. Design and fabricate a maglev vehicle in accordance to a set of given specifications.
27. Run their maglev vehicles and record data
28. Use the data collected to calculate velocity and the average velocity of all the vehicles tested.
29. Be introduced to the concept of structures.
30. Identify the similarities between the human skeleton and the structural skeleton of a high-rise building.
31. Watch a demonstration about the relative strength and stability of triangular and square structures made out of pencils linked together with tubing.
32. Design and construct a tower using Fischertechnik parts.

Initiative **PLTW: Gateway to Technology**

Title

Automation and Robotics

Broad Goals

It is expected that students will:

- Develop an understanding of the various ways robots are used in today's world and the impact their use has on society.
- Investigate an engineering career and determine the requirements for entering the field.
- Investigate and understand various mechanisms to determine their purpose and application.
- Be able to apply their knowledge of mechanism to solve a unique problem.
- Understand and program open-loop and closed-loop systems.
- Be able to troubleshoot a malfunction using a methodological approach.

Salient Concepts & Skills

Math
- ratios

Science
- force
- torque

Technology
- universal joint
- bevel gear assembly
- crown and pinion
- rack and pinion
- worm and wheel
- leadscrew
- gear train with idler
- cam and follower
- belt and pulley
- crank and slider
- icon-based programming

Engineering

The following espoused concepts have implications for the study of engineering:

- "Invention is a process of turning ideas and imagination into devices and systems."
- "Some technological problems are best solved through experimentation."

Prominent Activities

In the first lesson, the *Robotics in Today's World*, students are engaged in the following activities.

1. Watch a video about robots and what they are used for.
2. Draw a diagram of a robotic arm in their engineering notebooks.

3. Discuss the many types and uses of "end effectors" that can be installed at the end of a robotic arm.
4. Make a prototype of end effectors from the sketches in their engineering notebooks.
5. Research an engineering career and develop a brochure that describes the "responsibilities, salary range, locations, advantages and disadvantages of the job" in question. Or, make a PowerPoint presentation about a specific engineering career (aerospace, agriculture, architecture, etc.) that includes a job description, work tasks, skills and abilities, education/training requirements, wages, job outlook, and why it is appealing.
6. Hear about the social implications of using automation and robotics in industry.
7. Identify the pros and cons of (e.g., efficiency, worker displacement, retraining, relocation, job orientation).

In the second lesson, the *Mechanical Gears and Energy Transfer*, students are engaged in the following activities.

8. Hear an explanation about how mechanisms have inputs and outputs; how they can be used to change direction, speed, force, or torque; and how they can change one type of movement (rotary) into another (reciprocating).
9. Look at examples of mechanism in a PowerPoint presentation (e.g., crown and pinion gear, bevel gear and worm gear, gear train with idler gear).
10. Complete a worksheet regarding torque versus speed in the context of a bicycle.
11. Be introduced to different kinds of Fischertechnik components (a sophisticated form of Legos), how they can be used, and how they are assembled.
12. Hear an explanation of how to calculate gear ratios.
13. Use the Fischertechnik components to make different kinds of mechanisms (e.g., universal joint, bevel gear assembly, rack and pinion, worm and wheel, leadscrew, gears with idler, cam and follower).
14. Address questions regarding speed, direction, and motion.
15. Calculate gear ratios.

In the third lesson, the *Fischertechnik Parts and Programming*, students are engaged in the following activities.

16. Hear about the problem-solving method (i.e., define the problem, set goals and consider specifications, gather information, develop alternatives, select the best solution, implement the solution, evaluate the results).
17. Watch a demonstration on how to set-up the Fischertechnik

interface between the computer and the model they will build.

18. Review the basic principles of orthographic and isometric sketching via a PowerPoint presentation.
19. Watch a PowerPoint presentation about how to program a Fischertechnik model.
20. Explore how icons can be used to represent actions and how icons can be linked together to string a set of actions together to form a program.
21. Be introduced to a flow chart for troubleshooting a Fischertechnik interface, model, and program.
22. Get into teams of three and assign job responsibilities (e.g., computer engineer, electrical engineer, and mechanical engineering).
23. Address a series of problems by making, programming, and demonstrating Fischertechnik models that represent viable solutions.
24. Brainstorm different types of robots.
25. Research a robotic machine (e.g., what it looks like, how it works, what it does).
26. Prepare and present a two- to three-minute report to the class in the form of a video, poster, PowerPoint, or oral presentation.
27. Hear an explanation of flexible manufacturing systems.
28. Develop, program, and demonstrate a model assembly line for manufacturing a block of materials that has given features (e.g., slots, holes, chamfers).

Initiative **PLTW: Gateway to Technology**

Title

Flight and Space

Broad Goals

It is expected that students will:

- Apply their knowledge of research techniques to investigate the history of an aerospace vehicle.
- Utilize language arts skills to write a script for a commercial promotion of an aerospace vehicle.
- Experience the flight characteristics of kits, whirly gigs, model airplanes, hot air balloons, and model rockets.
- Apply their knowledge and experience gained in Activity 2.1 to design an airfoil that will generate lift during the wind tunnel test.
- Utilize proper data collection skills and language arts skills in engineering notebook entries.
- Learn about Newton's three laws of motion and how they relate to propulsion.
- Design, construct, and launch a water bottle rocket and make predictions of the rocket's altitude.
- Calculate the average altitude and relate Newton's three laws of motion to height the rocket achieved.
- Parts of a model and parts of a model rocket engine have specific functions during a rocket's flight.
- The forces of weight, thrust, drag, and lift interact differently on a rocket in flight than one an aircraft in flight.
- Newton's three laws of motion (inertia, F=ma, and action-reaction) can be used to describe and predict events during each phase of a rocket launch.
- Rocket design features are interrelated and determine how well a rocket will perform during powered flight.

Salient Concepts & Skills

Math
- cubes
- spheres
- cylinders
- prisms
- irregular shapes
- vectors
- measuring distance
- measuring time
- measuring angles
- calculating altitude

Science
- force
- thrust
- lift
- drag
- weight
- velocity
- buoyancy
- acceleration
- aerodynamics
- center of pressure
- mass

Technology
- airfoil
- propulsion
- propellant
- oxidizer
- weather cocking
- kites
- hot air balloons
- helicopters
- gliders
- rockets
- lighter-than-air

	based on a angle and a distance	• Newton's 3 laws of motion • potential energy • Bernoulli's principle	• heavier-than-air • airfoil • angle of attack

Engineering

The following espoused concepts have implications for the study of engineering:

- "Engineering designs in aerospace exploration evolve as they are developed."
- "Teamwork is needed to effectively complete an activity."

Prominent Activities

In the first lesson, the *Evolution of Flight*, students are engaged in the following activities.

1. Receive an overview of the expectations, criteria, and constraints associated with the lesson.
2. Conduct a "web quest" to research how various forms of flight developed (e.g., kites, hot air balloons helicopters, gliders, rockets) and use the information gathered to answer 41 low-level questions (e.g., The first person to fly solo, non-stop across the Atlantic was…, The Red Baron's real name was…).
3. Select a vehicle from a list of options (i.e., kites, hot air balloon, helicopters, gliders, rockets) and address a series of questions (e.g., When was it invented, Who invented it, How was it to be used).
4. Research the difference between lighter-than-air and heavier-than-air vehicles.
5. Receive an overview of the Flying Aerospace Vehicles Project.
6. Construct, test fly, and refine an aerospace vehicle from a list of options (i.e., kites, hot air balloon, helicopters, gliders, rockets) and keep notes in their engineering notebooks.
7. Produce a 60-second video commercial that informs an audience about the features and attributes of a "futuristic aerospace vehicle" based on the model they constructed and flew in the previous activity (e.g., develop a format, slogan, facts, jingle, and video clips into a script; rehearse, record and edit the commercial).
8. Develop a simple timeline illustrating the important dates in the history of aerospace technology.

In the second lesson, the *Airfoil Research, Construction and Testing*, students are engaged in the following activities.

9. Watch a three to five minute video clip related to aviation that will "grab" the students' attention.
10. Discuss aircrafts that fit under the categories of lighter-than-air and heavier-than-air.

11. Receive an overview of the key concepts and terms in the lesson (e.g., aerodynamics, airfoil, angle of attack).
12. Hear about the three main activities they will be doing, the expectations they need to meet, and the assessments that will be used.
13. Watch a demonstration of the Bernoulli principle and hear about the forces that effect flight (e.g., buoyancy, lift, drag, gravity, thrust).
14. Work in teams of three or four to explore Bernoulli principle and hear about the forces that effect flight (e.g., buoyancy, lift, drag, gravity, thrust).
15. Make sketches and write definitions related to Bernoulli principle and hear about the forces that effect flight (e.g., buoyancy, lift, drag, gravity, thrust).
16. Be introduced to an activity that involves testing different shapes in a tabletop wind tunnel.
17. Predict, wind tunnel test, and document the lift and airflow around different shapes (e.g., cubes, spheres, cylinders, prisms, irregular shapes).
18. Be introduced to an activity that involves testing different airfoil shapes in a tabletop wind tunnel.
19. Use Internet resources and a computer simulation package (FoilSim II) to research the factors that affect the lift of a wing (e.g., thickness, area, camber, angle of attack, airspeed).
20. Discuss what shapes work the best for airfoils.
21. Be introduced to an activity that involves designing, making, and testing different airfoil shapes in a tabletop wind tunnel.
22. Design, make, and test an airfoil in a tabletop wind tunnel and record their design and test results in their engineering notebook.
23. Make short presentations explaining their airfoil design, how well it worked, and why it did or did not work well.

In the third lesson, the *Propulsion Systems*, students are engaged in the following activities.

24. Watch a PowerPoint presentation on aerospace terminology (e.g., force, propulsion, thrust, lift, drag, weight, vectors, velocity, acceleration) and Newton's laws of motion.
25. Hear excerpts from books about Sir Isaac Newton or have students read books about flight.
26. Make a CD describing what they have learned about Sir Isaac Newton, write an essay presented to two views about Sir Isaac Newton's work, or write an essay about the positive and negative impacts of flight.
27. Be introduced to an activity related to Newton's second law about mass and force.

28. Determine the effect that changing the amount of force has on the acceleration of an object (the compressed air dragster) with a relatively constant mass.
29. Uncover the effect that changing mass of an object (the compressed air dragster) has on its acceleration with the force remaining relatively constant.
30. Discuss Newton's second law of motion.
31. Be introduced to an activity related to Newton's third law about action and reaction.
32. Determine how far one can travel on a scooter by throwing a medicine ball in the opposite direction.
33. Discuss how Newton's third law of motion applies to propelling aircraft and rockets.
34. Be introduced to an activity that addresses Newton's three laws using water bottle rockets.
35. Design, make, and prepare the water bottle rockets, the rocket launcher, and the altitude tracker.
36. Launch water bottle rockets, track their altitude, and record data in engineering notebooks.
37. Answer comprehension question related to their experiences with the water bottle rockets.
38. Discuss how Newton's three laws of motion apply to the water bottle rockets.
39. Watch a demonstration of a solid rocket on a testing fixture that illustrated thrust.

In the fourth lesson, the *Aeronautics and Rocketry*, students are engaged in the following activities.

40. Receive an overview of the key concepts and terms in the lesson (e.g., acceleration, drag, torque, trajectory, vector).
41. Review around nine Web sites about the history of rockets to answer over two-dozen low-level questions (e.g., Rockets were first used for…, First mammal in space was…, First man in space was…, First American in space was…, First women in space was…, First man on the moon was…).
42. Be introduced to the activity on researching rockets.
43. Review NASA's Web page called the Beginner's Guide to Aeronautics to become familiar with essential terms and concepts (e.g., parts of a model rocket, parts of a model rocket engine, forces that affect a rocket's flight).
44. Watch PowerPoint presentations on the parts of a model rocket, model rocket engines, and the flight of a model rocket.
45. Discuss the key terms and concepts related to model rockets.
46. Conduct experiments to determine the reaction of effervescent antacid tablets under different conditions (e.g., whole tablet, crushed tablet, cold water, hot water).

47. Build and test paper/film canister model rockets that are powered by effervescent antacid tablets and water.
48. Be introduced to the activity that involves simulated model rockets.
49. Use computer simulation software (Rocket Modeler II) to explore how different rocket design features affect a model rocket flight performance (e.g., velocity, vector, altitude).
50. Be introduced to the model rocket construction activity.
51. Work in a team to construct a model rocket from a kit.
52. Assign roles to be performed during the launch of their model rockets (i.e., launcher, timer, recorder, spotter, observers).
53. Launch their rocket in accordance with the safety guidelines outlined by the National Association of Rocketry.
54. Address questions related to their rockets flight profile (e.g., under power, acceleration, coasting, altitude, decent, deceleration, touchdown).

Salient Observations

Gateway to Technology is an "activity oriented" curriculum. Most of the emphasis is on engaging students in rich and familiar learning experiences that can be implemented with popular software, simple manipulatives, easy to work materials, and common supplies. There is very little evidence that suggests the curriculum is based on a systematic breakdown of engineering ideas and the learning activities are designed to reconstruct the ideas in the minds of students in an iterative and scaffolding manner.

The materials appear to have been developed with more of a naturalistic approach than a systematic one. The composition of the curriculum suggests the development process started with units of time; in this case 10 weeks. Each chunk of time was assigned a topic or theme. Some of the topics appear to be aligned with the high school coursed offered by Project Lead the Way (see table below). A series of popular learning activities were configured to fit into each unit (e.g., compressed air dragsters, water bottle rockets, maglev vehicles). The divisions of time within each unit vary in duration depending on the demands of the learning activities.

Middle School Units	**High School Courses**
Design and Modeling	Introduction to Engineering Design
Magic of Electrons	Digital Electronics
Science of Technology	Principles of Engineering
Automation and Robotics	Computer Integrated Manufacturing
Flight and Space	Aerospace Engineering

The contents and graphic design of the materials reflect more of a "grassroots" effort than a formal research and development process. The lessons and learning activities read like they were originally developed by teachers for their own use and then configured into bundles so other teachers could benefit from them. The lessons are not unduly formal, comprehensive, or interdependent. Most of the emphasis is placed on engaging students in reading and comprehending resources than doing hands-on activities.

The overall format of the curriculum follows a hierarchical structure that is similar to that found in many teachers' filing cabinets. The course is divided into five discrete topics. In this analogy, they would be the left-tab file folders. Each topic is subdivided into three to five lessons. These would be the center-tab file folders. Peripheral materials that include things like handouts, lab sheets, homework assignments, PowerPoint presentations, assessment tools, and optional assignments support each lesson. All of these would be stored in the right-tab file folders. In reality, the progression from one level to the next is facilitated with hyperlinks between computer files that are stored on a compact disk.

The "lessons" are not really lesson plans in the traditional sense. The breadth and depth of their contents is more consistent with unit plans. They have a syllabus-like appearance that defines several broad concepts, presents dozens of related standards, announces several performance objectives, outlines a series of activities that require five to 29 days for implementation, and more. Some of the activities for a given day are described in just one to three sentences while others are linked to handouts, media, assessment tools, and additional support materials for the teacher to follow and use.

Some of the lessons in each unit have a direct relationship with the topic in question while others appear to be included to address important ideas that have implications beyond the topic being addressed. For example, *Design and Modeling* begins with activities related to the nature of technology and the difference between science and technology. It is presented in such a way that it could be inserted in any of the other units. Similarly, the activities related to careers in the different fields of engineering are presented in the unit on *Automation and Robotics*. They too could be relocated in other units. Lastly, the making of a 60-second commercial on a futuristic vehicle requires a relatively rich treatment of marketing concepts and communication technology that is well beyond the scope of aerospace technology (e.g., defining a format. developing a slogan, selecting a jingle, plan video clips, writing a script, rehearsing parts, recording segments, assembling, and editing).

Very little actual content is presented in the curriculum. The content outlines list the topics and the activities in contrast to presenting taxonomies of key concepts, subordinate concepts, and specific details. The handouts are primarily instructions for assignments and learning activities. In most cases, teachers and students are directed to things like Web sites and videos for the substance of the lessons and activities. In some cases, the PowerPoint slides that support some of the lessons provide details about the content that is being addressed.

Engineering

The curriculum does not target engineering principles and engineering ways of thinking directly. Instead, most of the focus is on presenting learning activities that engage students in contexts and experiences that can be related to engineering in one way or another. Making connections between the learning activities and the work that engineers do is left to the teacher with the aid of a few debriefing questions at the end of each activity.

For the most part, engineering is a word that refers to the people that address problems in a technological enterprise. For example, in *Automation and Robotics* the students work in teams of three to design, build, and test mechanisms that are programmed to address a problem (e.g., mock up a spinning sign for a sandwich shop that feature an emergency stop, program a model of a traffic light). Each member of the team is assigned a role using different fields of engineering. The mechanical engineer assembles the physical components, the electrical engineer wires the system, and the computer engineer writes the program. These assignments are used primarily to divide the work among the members of the team. However, given the nature of the tasks that they are asked to perform, they could be called mechanical technicians, electronic technicians, and computer programmers with equal validity.

Design

The materials define design as both a verb and a noun. As a verb, it is "an iterative decision-making process that produces plans by which resources are converted into products or systems that meet human needs and wants or solve problems." As a noun, it is "the product of the planning, creating, and devising process."

The materials also address design from a variety of perspectives. One lesson presents design from an aesthetic point of view by focusing on the "elements of design" (i.e., line, form, space, color, texture, light, and shadow). Another reference to the "elements of design" addresses the ideas that design is purposeful, based on certain requirements, systematic, iterative, creative, and has many possible solutions. An additional definition states it is "a systematic way of finding a solution to a given problem efficiently." Lastly, design is discussed as a process that features a series of activities that are presented in a "loop." All of these definitions, a part from the two discussions of the elements of design, are relatively analogous. However, the various titles and differences in wording could be a source of confusion for both teachers and students.

Design Process	**Elements of Design**	**Problem-solving Method**	**Designing a Solution**
Identify problems and opportunities	Line	Define the problem	Define the problem
Brainstorming and sketching	Form	Set goals and consider specifications	Goal setting and specifications
Investigating and researching	Color	Gather information	Gather information
Generating multiple solutions	Light and Shadow	Develop alternatives	Alternatives
Choosing the best option	Space	Select the best solution	Optimum solution
Developing a solution	Material and Texture	Implement the solution	Implement the solution
Modeling and prototyping	Shape *	Evaluate the results	Monitor and evaluate
Testing and evaluating	Rhythm *		
Redesigning and improving	Proportion *		
	Balance *		

* These concepts were included in the lesson's list of "key terms" but they were not addressed in the media or learning activities.

The materials state that the design process (a.k.a., the design loop) shares characteristics with the scientific method. More specifically, they portray a problem as being the starting point for both science and design. They equate the process of conducting research and formulating a hypothesis in science with brainstorming, sketching, investigating and researching in design. Hypothesis testing in science is paired with generating multiple solutions in design. The analysis of data in science is likened to choosing the best solution, developing the solution, modeling and prototyping the solution, testing and evaluating the solution.

Lastly, formulating a conclusion and reporting results in science is associated with redesigning and improving in the design process. This analogy is unduly simplistic, has poor face validity, and could lead to misconceptions about the nature of science and engineering design.

Analysis

Engineers engage in analysis to identify problems, evaluate potential solutions, predict performance, test prototypes, and much more. In the *Gateway to Technology* materials most of the analysis is directed toward uncovering how things work. For example, in the *Automation and Robotics* unit students construct and study simple mechanism to uncover how they transmit force and movement. In the *Flight and Space* unit students use online simulations to explore the affect different variables have on the performance of model rockets (i.e., water bottle rockets, conventional model rockets). Lastly, students disassemble simple devices (like a can opener) to identify simple machines and trace the path of force and motion.

Analysis is likely to be an intrinsic part of other activities. For example, during the making of a Rube Goldberg machine students would inevitably encounter problems and failures that require some form of analysis. However, for the most part, analysis from an engineering perspective is more implied than defined.

Constraints

The materials define constraints as things that limit the design process. More specifically, “constraints may be such things as appearance, funding, space, materials, and human capabilities.” They are also described as “rules or limitations that restrict the position or relationship between parts of a whole.” The word “criteria” is defined as “a desired specification (element or feature) of a product or system” and “a list of restrictions to be considered and used in the development of a solution.” Lastly, the term “specification” is described as “a detailed statement of a requirement pertaining to a project.” All of these terms can be used to define the boundaries and specifications for designing a solution to a problem. However, most of the learning activities simply state the parameters for a successful solution to a problem.

Students are not asked to study and identify the constraints embedded in a problematic situation. Instead, most of the constraints are presented to the students as sets of rules that need to be followed in a game. For example, students encounter this kind of constraint with rules that must be followed while designing their compressed air dragsters. Compliance with the design specifications ensures the dragsters will interface with the launcher (the manifold that applies the compressed air) that is used to propel the dragsters. These specifications also provide a common basis for making analytical and competitive comparisons between dragsters.

Modeling

The verb modeling is defined as “the process of creating three-dimensional representations of design solutions.” Similarly, computer modeling is defined as “the use of computer software applications that allows the used to visualize an idea in a three-dimensional format.” Lastly, the noun model is defined as “a three-dimensional representation of an object.” Consistent with all of these definitions, the curriculum engages students in making things that help them visualize designs and test solutions to problems.

For example, the lesson on 3D computer modeling stresses the advantages of creating drawings of objects using software in contrast to traditional drafting methods (e.g., easy of revisions, ability to rotate objects, can generate multiple views, it is a precursor to manufacturing with programmable machines). The learning activities focus on how to use the software to draw objects using specific tools and commands.

Models play important roles in many of the learning activities featured in *Gateway to Technology*. In some cases the construction and testing of a model is the primary vehicle used to facilitate hands-on experiences. For example, the students design and test model dragsters that are propelled by compressed air. The final product reflects their ideas about aesthetics, aerodynamics, and efficiency (use as little material as possible to minimize mass and maximize speed). Their models’ performance during testing provides tangible feedback regarding the effectiveness of their ideas as well as the quality of their fabrication.

In other cases models are used to illustrate or demonstrate basic laws of nature. For example, water bottle rockets are constructed and tested to illustrate Sir Isaac Newton’s three laws of motion (i.e., objects in motion tend to stay in motion and objects at rest tend to stay at rest, the sum of external forces acting on an object is equal to the mass of the object times its acceleration, for every action there is an equal and opposite reaction).

Despite the prominent use of models in learning activities, the curriculum does not use models or modeling in the context of doing engineering design in an overt manner. More specifically, the materials do not engage students in making or using physical models to generate the data that informs the design of a solution to a problem.

The *Flight and Space* unit does take advantage of two online programs that simulate the flight of rockets (i.e., water rocket, conventional model rocket). These programs allow students to alter features of a rocket (e.g., number of fins, angle of the fins, location of the fins) and determine their impact on flight performance. The students use the data collected to make decisions about the design of their model rockets prior to their fabrication. However, the materials do not call attention to the fact that these simulation packages are based on mathematical models and they are similar to those used by engineers to make informed design decisions before making and testing prototypes.

Optimization

The materials define optimization as "an act, process, or methodology used to make a design or system as effective or functional as possible with the given criteria and constraints." They go on to define trade-offs as "an exchange of one thing in return for another, especially relinquishment of one benefit or advantage for another regarded as more desirable."

Although there are several assignments that involve uncovering the positive and negative impacts of various technologies, students do not have to directly address the balance between competing factors. For example, from a student's point of view, the main goal associated with the compressed air dragster activity is to design the fastest vehicle possible. In this case, speed is a function of the vehicle's mass assuming the propulsion force remains constant. However, mass also contributes to the vehicle's stability. The materials do not require students to deliberately confront the trade-offs that exist between the vehicle's mass, its stability, and its speed.

Systems

The materials define a system as "a group of interrelated components designed collectively to achieve a desired goal." One of the learning activities also addresses the concept that systems often contain subsystems; they have inputs, processes, and outputs; and they can be either open-loop or closed-loop (contain provisions for feedback). However, the learning activities do not engage students in designing systems. Instead, the attention given to systems and systems thinking is directed toward understanding the nature of technological systems. One of the learning activities involves the disassembly and analysis of simple mechanical devices (e.g., egg beater). It focuses on identifying simple machines and tracing the path of force and movement through the device. Modest attention (two sentences) is given to redesigning the mechanism in question so it uses fewer parts; assuming it is not an optimal design and it can actually be made with fewer parts.

The richest treatment of systems and system thinking is embedded in an activity that asks students to build a "Rube Goldberg" device. The purpose of the Rube Goldberg activity is to engage students in creating a network of simple machines and devices that work together to perform a simple task in as complex and comical a way possible. The design process involves brainstorming and sketching. However, there isn't any evidence that the students are required to engage in any formal engineering. Ironically, creating a Rube Goldberg device is the antithesis of most engineering endeavors because the goal is be as complex and inefficient as possible. However, the pursuit of complexity and entertainment does require creativity and systems thinking (e.g., being silly, sequencing inputs and output, accounting for the interdependence among parts).

Another opportunity for systems thinking can be found in the unit titled *Automation and Robotics*. It contains a lab that asks students to construct a series of mechanisms that transmit and convert motion and force. These mechanisms include things like gear chains, belts and pulleys, cranks and cams, and more. However, this lab does not engage students in any genuine engineering. Instead, students build a series of mechanisms in accordance with drawings and note how they transmit and convert force and motion (e.g., changes in direction, changes in speed, changes in distance). Students are not asked to design and configure mechanisms that will produce a given output based on a given input. The emphasis is on experiencing the different kinds of mechanisms that are commonly found in mechanical systems (e.g., universal joint, rack and pinion, cam and follower, crank and slider).

Science

In *Designs and Models*, most of the attention is on how to discriminate between science and technology. Science is portrayed as "the study of our natural world" while technology is characterized as "the study of our human-made world." The espoused differences are addressed in a slide presentations, a comprehension worksheet, and a concept mapping activity.

This unit also depicts the scientific method as a problem-solving process in contrast to a rational pursuit of knowledge that supports or refutes tentative ideas about nature. It suggests scientific endeavors are initiated in response to problems that have to be solved without attending to the idea that it is often the pursuit of knowledge for its own sake.

One of the most direct treatments of science content is found in the units titled *The Science of Technology* and *Flight and Space*. They target Newton's laws of motion. In the *Science of Technology* the laws of inertia and acceleration are applied to a model car (a dragster) that is propelled by the release of compressed air. The speed of the cars is used to calculate their acceleration. Once the acceleration is determined, it is used to determine the amount of force used to propel the cars. In this case, the making and testing of the cars is being used to reinforce concepts (e.g., mass, speed, acceleration, force). It is important to note that these science concepts are not being used to predict the cars' performance or inform their design. In an authentic engineering context that involves designing a vehicle for speed, the students would have use the relationship between force and acceleration to understand the importance of minimizing their vehicles' mass prior to prototyping. Similarly, in *Flight and Space* the students conduct activities that are intended to illuminate Newton's three laws of motion, but they do not provide a basis for a design.

Mathematics

Many of the learning activities involve taking measurements in the context of making and testing models. These measurements include things like distance, angles, and time. The data derived from testing is used to calculate unknowns using given formulas. In most cases, mathematics is used to quantify and explain relationships between variables. The most salient example of the use of mathematics can be found in the *Science of Technology* where students are asked to calculate the velocity, acceleration, and force associated with their compressed air dragsters. It is important to note that these calculations are used to understand these science principles in contrast to informing the design of the model dragsters.

Technology

The curriculum addresses several sophisticated topics (e.g., the nature of technology, solids modeling, digital electronics, magnetic levitation vehicles, alternative energy, automation, robotics, aerospace technology). However, very little attention is given to teaching domain knowledge. Some of the lessons include references to online resources for domain knowledge and others do not. For example, students are asked to investigate the Internet, books, and CDs to obtain the content needed to compose informational posters about alternative energy resources. In contrast, the lesson that addresses automation and robotics asks students to identify three positive attributes and three negative attributes of using robots in the workplace under the headings of "efficiency, work displacement, retaining, relocation, and job orientation." It is not clear where these headings came from and where the students would find creditable answers (e.g., from the videos, teacher presentations, the Internet). The answers to these questions are not presented in the content outlines for the lesson. Furthermore, students are asked to formulate "conclusions" in response to the following questions.

1. "What do you think is the greatest concern that should be considered before converting a factory from a human workforce to a robotic work force? Why?"
2. "If the use of robotics in industry continues to climb, will we be able to keep pace with the need for workers?"

In absence of technical content or creditable references, the answers to these questions are likely to contain different opinions as well as several misconceptions. The curriculum does not include any recommendations for anticipating and addressing simplistic or incorrect ideas about this controversial technology.

Treatment of Standards

The materials state that they were "written and designed to be based on the national standards for technology, science, mathematics, and English." The use of the word "based," suggests the selected standards provided the basis on which the curriculum was developed and they are the targets of the instruction. However, the materials do not reflect orchestrated breakdown of ideas within the standards cited. Nor do they represent a systematic approach to construct knowledge and skills embedded in the standards in the minds of learners. Instead, they include matrices that show when a particular standard contains one or more concepts that "correlate" with those in a given lesson. Furthermore, the narrative states "the ideas and concepts may not be directly addressed," but they are supported or implied in the lesson and activity. The composition of the matrices suggests the relationship between lessons and the standards is more vicarious than symbiotic.

The breadth and depth of the standards cited exceed those of the objectives that the lesson is designed to achieve. For example, the *Introduction to Technology* lesson in the *Design and Modeling* unit espouses to address the following standards in conjunction with enabling students to "describe impacts that technology has had on society."

- "The use of technology affects humans in various ways, including safety, comfort, choices, and attitudes about technology's development and use.
- "Technology, by itself, is neither good nor bad, but decisions

about the use of product and systems can result in desirable or undesirable consequences."
- "The development and use of technology poses ethical issues."
- "The use of inventions and innovations has led to changes in society and the creation of new needs and wants."
- "Many different people in different cultures have made and continue to make contributions to science and technology."
- "Perfectly designed solutions do not exist. All technological solutions have trade-offs, such as safety, cost, efficiency, and appearance."

The intellectual richness of these standards intrinsically calls for the achievement of objectives beyond just being able to describe the impacts of technology on society. The lesson in question has three modest objectives and it embraces dozens of standards. The imbalance between the standards and the objectives associated with the lessons suggests there is a relatively loose relationship between the two types of outcome statements.

Most of the curriculum is dedicated to facilitating learning activities that the authors believed will provide students engineering-like experiences. The richness of the activities contains numerous opportunities to address a wide range of standards from technology, science, mathematics, and English. Thus the alignment between the standards and curriculum appears to be based on the potential capacity of learning activities in contrast to the actual instruction.

Pedagogy

Each unit contains collections of bits and pieces from numerous authors, which were assembled together. There is a tremendous amount of flexibility built into the materials. The lessons are not unduly formal, comprehensive, or interdependent. Some of learning activities are intended to be optional. Most of the emphasis is placed on engaging students in reading and comprehending resources and doing hands-on activities.

The primary audience for the materials is classroom teachers. The core documentation for each lesson features lists of standards, objectives, essential questions, vocabulary terms, learning activities, and support documents (e.g., handouts, PowerPoint presentations, assessment tools, additional references).

Most of the "essential questions" presented in each lesson can be used as advanced organizers because they alert the teachers to the big ideas that students should develop over the course of the activities. They can also be used at the end of learning activities to encourage reflection and facilitate debriefing.

A lot of attention is given to technical terms. The vocabulary lists and the glossaries include key words (or concepts) that are used in the learning activities. Some of the words appear to be included in the lists because students might encounter them on the Internet or in the references. Many of the learning activities (e.g., worksheets, presentations, projects) and assessment items emphasize understanding technical terminology.

The pedagogical strategies that are embedded in the materials also include introductions that provide background information that can be used to frame the learning activities that follow. In some cases they provide a modest rationale for the instruction. In other cases they present a fictitious problem that has to be solved.

The instructional media reflects the grassroots nature of the curriculum. Most of the PowerPoint slides try to present too much information. Some of the concept load and density of the slides can be attributed to an effort to convey key ideas in a standalone manner. A conscientious teacher would need to modify and edit most of the slides to bring them into compliance with the basic rules of media (e.g., composition, simplicity, brevity).

Implementation

Gateway to Technology is not a curriculum that one can simply pick up and read from cover to cover. The curriculum does not provide detailed scripts or lesson plans for orchestrating the teaching and learning process. Instead, it is a framework that contains collections of resources that teachers can use to facilitate instruction. These collections include scenarios that can be used to frame lessons, potential standards that can be addressed, lists of vocabulary terms that can be taught, assignments that can aid comprehension, handouts that can engage students in hands-on learning activities, media presentations that present concepts, assessment tools that can be use to check for understand or the accomplishment of tasks, and more. A conscientious teacher needs to develop daily lesson plans that connect and fill in the gaps between the various collections in the framework. In light of this need, the curriculum also includes materials (or tutorials) that provide teachers with recommendations for developing lessons and additional assessment tools.

Teaching *Gateway to Technology* would be like implementing a series of short courses that one has never taught before based on a colleague's materials. Despite the shear mass the materials provided, there are unwritten stories, explanations, and details that reside between the lines of the curriculum's documentation. The curriculum is presented in loosely connected sets of activities that provide the teacher a lot of flexibility. *Project Lead the Way's* approach appears to be one that points teachers in a given direction and provides them the basic resources needed to implement instruction while leaving ample room for developing personal ownership of the curriculum.

Project Lead the Way's emphasis on professional development is clearly justified. Formal training is needed to understand the ideas, eccentricities, and expectations that are embedded in the materials. The required workshop provides a forum for receiving additional direction, resolving ambiguities, filling in the gaps that reside between the elements, and adopting the curriculum to different situations.

Obtaining and implementing the curriculum requires schools to make a significant commitment to the program. The formality of this commitment includes signing memos of understanding, obtaining recommended tools and materials, having faculty complete an in-service workshop, and undergoing a review to ensure adequate implementation. The financial demands of the program involve tens of thousands of dollars.

PLTW: Introduction to Engineering Design

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Funding
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Grade Level
High School (9-10)

Espoused Mission
"The major focus of the IED [Introduction to Engineering Design] course is to expose student to design process, research and analysis, teamwork, communications methods, global and human impacts, engineering standards, and technical documentation."

Organizing Topics
The Introduction to Engineering Design course is divided into the following units.

- *Introduction to Design*
- *Design Solutions*
- *Reverse Engineering*
- *Design Problems*

Format
Each unit is divided into a series of lessons and each lesson has the following elements.

- A preface that presents an introduction to the lesson (e.g., expectations).
- Several key concepts at are presented in the form of sentences that declare the big ideas in the lesson.
- Learning activities that are presented in a day-by-day sequence

that include links to support materials (e.g., handouts, assessment tools, PowerPoint presentations).

Pedagogical Elements The authors set out to use a "project-based learning" approach that engages students in working in teams on hands-on activities. Most of the lessons engage students in using tools and computer-aided design software to develop solutions to authentic problems.

Maturity An *Introduction to Engineering Design* course is one of the first courses developed in the *Project Lead the Way* program. It is also the most widely implemented course in the program. It was reviewed and revised for 2008.

Diffusion & Impact Over 1,400 schools in 50 states and the District of Columbia are participating in the *Project Lead the Way* (PLTW) program. Participation involves making formal commitments with PLTW, dedicating resources to the program, having teachers and guidance counselors complete training programs, implementing multiple courses, and more. Consistent with the project mission, an analysis of 171 college transcripts showed 40 percent of the students that completed *Project Lead the Way* classes pursued further education in technology and engineering fields as first year college students.

Initiative **PLTW: Introduction to Engineering Design**

Title

Introduction to Design

Broad Goals

It is expected that students will:

- Apply engineering notebook standards and protocols when documenting their work during the school year.
- Identify and apply group brainstorming techniques and the rules associated with brainstorming.
- Research a product's history, develop a PowerPoint presentation, list chronologically the major innovations to a product, and present finding to a group.
- Use outline and published works to research aspects of design problems.
- Identify the design process steps used in given scenarios and be able to list the steps, if any are missing.
- Identify, sketch, and explain the function of points, construction lines, object lines, and hidden lines.
- Plot points on grid paper to aid in the creation of sketches and drawings.
- Explain how an oblique view of simple geometric solids differs from an isometric view.
- Sketch one-point, two-point, and three-point perspectives of simple geometric solids.
- Describe the concept of proportion as it relates to freehand sketching.
- Sketch multiview drawings of simple geometric solids.
- Determine the front view for a given object.
- Research and design a CD cover or book jacket on the origins of the measurement system.
- Measure and record linear distances using scale to a precision of 1/16 inch and 1 mm.
- Measure and record linear distances using a dial caliper to a precision of 0.001 inch.
- Add and subtract U.S. standard and metric linear measurements.
- Convert linear distance measurements from inches to millimeters and vice versa.
- Apply linear dimensions to a multiview drawing.
- Calculate the mean, mode, median, and range of a data set.
- Create a histogram of recorded measurements showing data elements or class intervals, and frequency.
- Brainstorm and sketch possible solutions to an existing design problem.

- Select an approach that meets or satisfies the constraints given in a design brief.
- Create simple extruded solid Computer Aided Design (CAD) models from dimensioned sketches.
- Generate dimensioned multiview drawings from simple CAD models.
- Measure and fabricate parts for a functional prototype from the CAD multiview drawing.
- Assemble the product using the CAD modeling software.
- Test and evaluate the prototype and record results.
- Apply geometric and numeric constraints to CAD sketches.
- Identify the purpose of packaging in the design of consumer products.

Salient Concepts & Skills

Math
- measurement
- depth
- ellipse
- height
- proportion
- scale
- width
- size
- grid
- data
- data set
- frequency
- mean
- measure
- median
- mode
- normal distribution
- statistics
- variation
- two-dimensional
- three-dimensional
- histogram
- class interval
- plane

Science

Technology
- design brief
- innovation
- invention
- standard
- design
- product change lifecycle
- ergonomic design
- model
- prototype
- construction line
- isometric sketch
- line conventions
- line weight
- manufacture
- multiview drawings
- object line
- hidden line
- projection line
- oblique sketch
- orthographic projection
- projection plane
- vanishing point
- dimension lines
- extension lines
- American National Standards Institute

(ANSI)
- dial calipers
- International Organization for Standardization (ISO)
- mock-up
- design brief
- extrusion
- computer-aided design
- computer-aided drafting (CAD)
- model
- prototype
- packaging
- scale model
- solid modeling
- numeric constraint
- geometric constraint
- assembly drawing

Engineering

The following espoused concepts have implications for the study of engineering:

- "There are many design processes that guide professionals in developing solutions to problems."
- "A design process most used by engineers includes defining a problem, brainstorming, researching, identifying requirements, exploring possibilities, selecting an approach, developing a design proposal, making a model or prototype, testing, refining, making, and communicating results."
- "Engineers create sketches to quickly record, communicate, and investigate ideas."
- "Engineers apply dimensions to drawings to communicate size information."
- "Statistical analysis of measurements can help verify the quality of a design or process."
- Engineers use Computer Aided Design modeling systems to quickly generate and annotate working drawings."
- "Pictorials and tonal shading techniques are used in combination to give sketched objects a realistic look."
- Designers use isometric, oblique, perspective, and multiview sketching to maintain an object's visual proportions."
- "A multiview projection is the most common method of

communicating the shape and size of an object that is intended for manufacture."

- "Measurement systems were developed out of the need for standardization."
- "Manufactured parts are often created in different countries, where dimensional values are often converted from one standard unit to another."
- "The amount of variation that can be measured depends on the precision of the measuring tools."
- "Engineers use graphics to communicate patterns in recorded data."
- "Three-dimensional forms are derived from two-dimensional shapes."
- "The results of the design process are commonly displayed as a physical model."
- "Engineers develop models to communicate and evaluate possible solutions."
- "Geometric and numeric constraints are used to define the shape and size of objects in Computer Aided Design (CAD) modeling systems."
- "Packaging not only protects a product, but contributes to that product's commercial success."

Prominent Activities

In the first lesson, *Introduction to a Design Process*, students are engaged in the following activities.

1. Hear an overview of the lesson, which contains key terms and questions.
2. Watch a PowerPoint presentation about engineers.
3. Obtain or create an engineer's notebook.
4. Discuss acceptable and unacceptable engineering notebook entries based on samples each.
5. Watch a PowerPoint presentation about the nature of engineering notebooks.
6. Discuss how products have changed society.
7. Discuss how two or three major inventions have made life easier.
8. Review an assignment that calls for the redesign of a beverage container.
9. Watch a presentation about the rules of brainstorming.
10. Brainstorm ways to improve a simple beverage container.
11. Present ideas about how to improve a simple beverage container to the class.
12. Discuss the steps in the design process and the constraints associated with redesigning an item.
13. Watch a PowerPoint presentation about the evolution of a products design.

14. Review and discuss an assignment that involves researching the history of a product, developing a PowerPoint presentation about evolution of a product, and presenting it to the class.
15. Research the evolution of a product.
16. Compose a PowerPoint presentation depicting the history of a product.
17. Present PowerPoint presentations to the class.
18. Review and discuss an example of the design process.
19. Watch a PowerPoint presentation that provides an overview of the design process.
20. Review and discuss an assignment that uses the Gossamer Condor (a human-power aircraft) to explore the nature of design.
21. Watch a documentary about *The Flight of the Gossamer Condor* and address questions about the design process depicted in the film.
22. Discuss the iterative nature of design and the design process that will be used throughout the course.

In the second lesson, *Introduction to Technical Sketching and Drawing*, students are engaged in the following activities.

23. Hear an overview of the lesson, which contains key terms and questions.
24. Watch a PowerPoint presentation about line conventions.
25. Watch a PowerPoint presentation about isometric pictorials
26. Use isometric graph paper to sketch isometric drawings of objects that are presented isometric format.
27. Watch a PowerPoint presentation about oblique pictorials.
28. Use graph paper to sketch oblique drawings of simple objects.
29. Watch a PowerPoint presentation about perspective sketches.
30. Sketch perspective drawings of simple objects.
31. Watch a PowerPoint presentation about multiview sketching.
32. Hear about the use of hidden lines and center lines in technical drawings.
33. Sketch multiview drawings of simple objects.

In the third lesson, *Measurement and Statistics*, students are engaged in the following activities.

34. Hear an overview of the lesson, which contains key terms and questions.
35. Watch a PowerPoint presentation about the history of measurement.
36. Complete a Web quest on the history of measurement (e.g., units, tools, people).
37. Review how to use a fraction to decimal conversion chart.
38. Watch a PowerPoint presentation about how to read an English

scale.

39. Complete a worksheet on English and metric linear measurement.
40. Watch a PowerPoint presentation about how to use and read a dial caliper.
41. Use a dial caliper to measure dimensions of objects presented in technical drawings.
42. Watch a PowerPoint presentation about dimensioning practices.
43. Complete a worksheet that calls for dimension drawings of objects.
44. Watch a PowerPoint presentation about basic descriptive statistics.
45. Measure a batch of wooden cubes and calculate their mean, median, mode, and range.

In the fourth lesson, *Puzzle Cube*, students are engaged in the following activities.

46. Hear an overview of the lesson, which contains key terms and questions.
47. Review an assignment that calls for the development of a puzzle that utilizes small hardwood cubes.
48. Hear a review of the design process.
49. Brainstorm and sketch ways to arrange three, four, five, and six cubes.
50. Review examples of puzzle part solutions.
51. Watch a PowerPoint presentation about marketing.
52. Design a package that will contain and promote the puzzle.

Initiative **PLTW: Introduction to Engineering Design**

Title

Design Solutions

Broad Goals

It is expected that students will:

- Identify common geometric shapes and forms by name.
- Calculate the area of simple geometric shapes.
- Calculate the surface area and volume of simple geometric forms.
- Identify and explain the various geometric relationships that exist between the elements of two-dimensional shapes and three-dimensional forms.
- Identify and define the axes, planes, and sign conversions associated with the Cartesian coordinates system.
- Apply geometric and numeric constraints to CAD sketches.
- Utilize sketch-based, work reference, and placed features to develop solid CAD models form dimensioned drawings.
- Explain how a given object's geometry is the result of sequential additive and subtractive processes.
- Explain the difference between size and location dimensions.
- Differentiate between datum dimensioning and chain dimensioning.
- Identify and dimension fillets, rounds, diameters, chamfers, hoes, slots, and screw threads in orthographic projection drawings.
- Explain the rules that are associated with the application of dimensions to multiview drawings.
- Identify, sketch, and explain the difference between general tolerances, limit dimensions, unilateral, and bilateral tolerances.
- Differentiate between clearance and interference fits.
- Sketch and model an auxiliary view of a given object to communicate the true size and shape of its inclined surfaces.
- Describe the purpose and demonstrate the application of sectional lines and cutting plane lines in a section view drawing.
- Sketch a full and half section view of a given object to communicate its interior features.
- Identify algebraic relationships between the dimensional values of a given object.
- Apply assembly constraints to individual CAD models to create mechanical systems.
- Perform part manipulation during the creation of an assembly model.

- Explain how assembly constraints are used to systematically remove the degrees of freedom for a set of components in a given assembly.
- Determine ratios and apply algebraic formulas to animate multiple parts within an assembly model.
- Create and describe the purpose of the following items: exploded isometric assembly view, balloons, and parts list.
- Brainstorm and sketch possible solutions to an existing design problem.
- Create a decision-making matrix.
- Select an approach that meets or satisfies the constraints given in a design brief.
- Create solid computer-aided design (CAD) models of each part from dimensioned sketches using a variety of methods.
- Apply geometric numeric and parametric constraints to form CAD modeled parts.
- Generate dimensioned multiview drawings from simple CAD modeled parts.
- Generate dimensioned multiview drawings from simple CAD modeled parts.
- Assemble the product using the CAD modeling software.
- Explain what constraints are and why they are included in a design brief.
- Create a three-fold brochure marketing the design solution for the chosen problem, such as a consumer product, a dispensing system, a new form of control system, or extend a product design to meet a new requirement.
- Explain the concept of fluid power, and the difference between hydraulic and pneumatic power system.

Salient Concepts & Skills

Math
- geometric shapes
- area
- surface area
- volume
- calculating the area of circles
- ellipses
- major and minor axis
- polygons (triangle, rhombus, trapezoid)
- right triangle
- acute triangle

Science
- mass
- weight

Technology
- CAD
- solid modeling
- solid model
- wireframe model
- dimensioning
- tolerancing
- unidirectional dimensioning
- aligned dimensioning
- size dimensions
- location dimensions
- chain dimensioning

- obtuse triangle
- inscribed triangles
- circumscribed triangles
- calculating area of triangles
- quadrilaterals (square, rhombus, trapezoid, trapezium)
- parallelograms (square, rectangle, rhombus, rhomboid)
- calculating area of parallelograms
- polygons (pentagon, hexagon, octagon)
- calculating area of polygons
- Boolean operations
- angle
- axis
- basic shapes (e.g., circle, square, rectangle, prism)
- Cartesian coordinate system
- two-dimensional
- three-dimensional
- parametric equations
- degree of freedom
- datum
- datum dimensioning
- coordinate method
- angular method
- dimensioning (e.g., lengths, curves, arcs, diameters, chords, chamfers)
- limit dimensions
- unilateral and bilateral tolerances
- general tolerance
- total tolerance
- clearance fit
- interface fit
- transition fit
- baseline dimensioning
- dual dimensioning
- reference dimension
- working drawings
- work points
- work planes
- work axis
- parameters
- geometric constraints
- parametric constraints
- assembly constraints
- foreshortened face
- auxiliary distance
- true height
- depth auxiliary
- height auxiliary
- width auxiliary
- short and long breaklines
- half section
- full section
- offset section

- assembly constraints
- mate constraint
- flush constraint
- insert constraint
- tangent constraint
- base component
- grounded component
- pattern component
- replace component
- editing components
- subassemblies
- trail
- transformations (linear, rotational, directional)
- animation
- balloons
- parts lists

Engineering

The following espoused concepts have implications for the study of engineering:

- "Geometric shapes describe the two and three dimensional contours that characterize an object."
- "The properties of volume and surface area are common to all designed objects and provide useful information to the engineer."
- "CAD systems are used to increase productivity and reduce design costs."
- "Geometric and numeric constraints are used to define the shape and size of objects in CAD modeling systems."
- "Solid CAD models are the result of both additive and subtractive processes."
- "Working drawings should contain only the dimensions that are necessary to build and inspect an object."
- "Objects require specialized dimensions and symbols to communicate technical information, such as size."
- "There is always a degree of variation between the actual manufactured object and its dimensioned drawing."
- "Engineers specify tolerances to indicate the amount of dimensional variation that may occur without adversely affecting an object's function."
- "Tolerances for mating parts features are determined by the type of fit."

- "Solid modeling programs allow the designer to create quality designs for production in far less time than traditional design methods."
- "Engineers use CAD models, assemblies, and animations to check for design problems, verify the functional qualities of a design, and communicate information to other professionals and clients."
- "Auxiliary views allow the engineer to communicate information about an object's inclined surfaces that appear foreshortened in basic multiview drawings."
- "Designers use sectional views to communicate an object's interior features that may be difficult to visualize from the outside."
- "As individual objects are assembled together, their degrees of freedom are systematically removed."
- "Engineers create mathematical formulas to establish geometric and functional relationships within their designs."
- "A title block provides the engineer and manufacturer with important information about an object and its creator."
- "A part list and balloons are used to identify individual components in an assembly drawing."
- "Design solutions are created while working in teams and sometimes as an individual."
- "Engineers use design briefs to explain the problem, identify solution expectations, and establish project constraints.
- "Teamwork requires constant communication to achieve the goal at hand."
- "Engineers conduct research to develop their knowledge base, stimulate creative ideas, and make informed decisions."
- "Engineers use a design process to create solutions to existing problems."
- "Fluid power concepts can be used to enhance design solutions."
- "The use of fluid power, hydraulics, and pneumatics is used as an enhancement to solving problems with electrical control systems."

Prominent Activities

In the first lesson, *Geometric Shapes and Solids*, students are engaged in the following activities.

1. Hear an overview of the lesson, which contains key terms and questions.
2. Watch a PowerPoint presentation about geometric shapes and area.
3. Take linear measurements of different items using a scale or dial caliper (e.g., chalk board eraser, sugar cube, door wedge).
4. Identify the basic shapes that comprise different items.

5. Sketch and calculate area for different items.
6. Compare measurement data and observations with peers.
7. Sketch and calculate area for a variety of shapes (e.g., square, rhomboid, obtuse triangle, circle, ellipse).
8. Watch a demonstration on how to use the tools associated with a CAD solid modeling program.
9. Make a sketch using the tools featured in a CAD program.
10. Watch a PowerPoint presentation about additive and subtractive sold modeling.
11. Use CAD software to create six three-dimensional geometric objects using additive and subtractive techniques.
12. Develop orthographic and isometric drawings of the objects.
13. Compose step-by-step instructions for recreating one of the objects.
14. Trade instructions with a peer and use them to create another object.

In the second lesson, *Dimensions and Tolerances*, students are engaged in the following activities.

15. Hear an overview of the lesson, which contains key terms and questions.
16. Watch a PowerPoint presentation about the basic rules used to dimension objects.
17. Identify and correct errors and omissions in the dimensioning of several drawn objects.
18. Review and discuss errors and omission in dimensioning.
19. Watch a PowerPoint presentation about dimension standards that were established by different organizations (e.g., ANSI, ISO, DIN).
20. Review the general rules for dimensioning.
21. Dimension orthographic representations of six three-dimensional objects.
22. Watch a Power Point presentation about tolerancing.
23. Analyze drawings, identify tolerances, and explain their meaning.

In the third lesson, *Advance Modeling Skills*, students are engaged in the following activities.

24. Hear an overview of the lesson, which contains key terms and questions.
25. Watch a PowerPoint presentation about work points, axes, and planes.
26. Review and discuss two projects that require the development of working drawings (an arbor press or toy train).
27. Examine the difference between numeric and geometric constraints and the application of parametric equations for

numeric values.
28. Watch a PowerPoint presentation about parametric modeling.
29. Use algebraic formulas in place of numeric values in conjunction with the development of three-dimensional solid model with CAD.
30. Watch a PowerPoint presentation about creating and using auxiliary views.
31. Draw auxiliary views that show the true size and shape of inclined surfaces on three different objects.
32. Watch a PowerPoint presentation about sectional views.
33. Make full and half section drawings for different objects.
34. Watch a PowerPoint presentation about basic assembly.
35. Assemble a simple device using CAD.
36. Watch a PowerPoint presentation about exploded CAD assembly models.
37. Watch a demonstration on how to explode an assembly.
38. Watch a PowerPoint presentation about animating assembly models and exporting video using CAD.
39. Watch a demonstration on how to animate assembly models.
40. Watch a demonstration on developing dimensioned multiview drawings for a given project (drawings for an arbor press or toy train).
41. Watch demonstrations regarding auxiliary views, centerlines, dimensions, and tolerances in the context of drawing an arbor press or toy train.
42. Watch a PowerPoint presentation about adding balloons and parts lists using CAD.
43. Watch a demonstration on how to add balloons and a parts list to drawings for an arbor press or toy train.
44. Complete sets of drawings for an arbor press or toy train.

In the fourth lesson, *Advanced Designs*, students are engaged in the following activities.

45. Hear an overview of the lesson, which contains key terms and questions.
46. Watch a PowerPoint presentation about teamwork (e.g., benefits, development, mission, norms).
47. Watch a PowerPoint presentation about fluid power (e.g., definition, examples, advantages, applications components, systems).
48. Review a design process (i.e., define the problem, brainstorm, research and generate ideas, identify criteria and specify constraints, explore possibilities, select an approach, develop a proposal, make a model or prototype, test and evaluate the design, define the design, make the solution, communicate processes and results).

49. Study five design briefs and select the one that will be addressed as a team (e.g., a desk organizer for basic office supplies, a container for emergency supplies for the trunk of a car, a hand-held candy dispensing device).
50. Follow the steps in the design process to develop a solution to the problem.
51. Sketch potential design solutions on isometric graph paper.
52. Develop three possible solutions to the problem.
53. Watch a PowerPoint presentation about developing and using a decision-making matrix.
54. Use a decision-making matrix to identify the final solution to the problem.
55. Develop a set of working drawings for the solution to the problem.
56. Compose a three-fold flyer to market the solution to the problem.
57. Present the final solutions to the class.

Initiative **PLTW: Introduction to Engineering Design**

Title

Reverse Engineering

Broad Goals

It is expected that students will:

- Identify visual design elements within a given object.
- Explain how visual design principles were used to manipulate design elements within a given object.
- Explain what aesthetics is, and how it contributes to a design's commercial success.
- Identify the purpose of packaging in the design of consumer products.
- Identify visual design principles and elements that are present within marketing ads.
- Identify the intent of a given marketing ad and demographics of the target consumer group
- .
- Identify the reasons why engineers perform reverse engineering on products.
- Describe the function of a given manufactured object as a sequence of operations through visual analysis and inspection (prior to dissection).
- Describe the differences between joinery, fasteners, and adhesives.
- Identify the types of structural connections that exist in a given object.
- Use dial calipers to precisely measure outside and inside diameter, hole depth, and object thickness.
- Identify a given object's material type.
- Identify material processing methods that are used to manufacture the components of a given commercial product.
- Assign a density value to a material, and apply it to a given solid CAD model.
- Perform computer analysis to determine mass, volume, and surface area of a given object.
- Write design briefs that focus on product innovation.
- Identify group brainstorming techniques and the rules associated with brainstorming.
- Use decision matrices to make design decisions.
- Explain the difference between invention and innovation.

Salient Concepts & Skills

Math	Science	Technology
• surface area	• mass	• system
• volume	• stress	• mechanism

- centroid
- principal axes
- tension
- torsion
- compression
- hypothesis
- renewable resource
- non-renewable resource
- moments of inertia
- product of inertia
- principal moments
- radii of gyration
- black box models
- adhesive bonding
- fastener
- mechanical fastener
- manufacturing process
- snap fit
- joinery
- part interaction
- invention
- innovation

Engineering

The following espoused concepts have implications for the study of engineering:

- "Visual design principles and elements constitute an aesthetic vocabulary that is used to describe an object independent of its formal title, structural, and functional qualities."
- "Tangible design elements are manipulated according to conceptual design principles."
- "Aesthetic appeal results from the interplay between design principles and elements."
- "A design's visual characteristics are influenced by its structural and functional requirements."
- "Visual appeal influences a design's commercial success."
- "Graphic designers are concerned with developing messages that make people in a target audience respond in a predictable and favorable manner."
- "Engineers perform reverse engineering on products to study their visual, functional, and structural qualities."
- Through observation and analysis, a product's function can be divided into a sequence of operations."
- "Products operate as systems, within identifiable inputs and outputs."
- "Objects are held together by means of joinery, fasteners, or adhesives."
- "Precision measurement tools and techniques are used to accurately record an objects geometry."
- "Operational conditions, material properties, and manufacturing methods help engineers determine the material makeup of a design."
- Engineers use reference sources and computer-aided design (CAD) systems to calculate the mass properties of design objects.

- "Engineers analyze designs to identify shortcomings and opportunities for innovation."
- "Design teams use brainstorming techniques to generate large numbers of ideas in short time periods."
- "Engineers use decision matrices to help make design decisions that are based on analysis and logic."
- "Engineers spend a great deal of time writing technical reports to explain project information to various audiences."

Prominent Activities

In the first lesson, *Visual Analysis*, students are engaged in the following activities.

1. Hear an overview of the lesson, which contains key terms and questions.
2. Watch a PowerPoint presentation about visual design elements (i.e., line, color, form, shape, space, texture, value) and visual design principles (i.e., balance, rhythm, emphasis, proportion, scale, unity).
3. Review examples of products, art forms, and print media that feature various design elements and principles.
4. Identify objects that utilize different visual design elements and exemplify different visual design principles.
5. Explain the visual design elements and principles found in different examples.
6. Perform a visual analysis of a product that involves photographing the object from different perspectives and composing captions that describe its visual design features.
7. Complete a quiz that involves matching principles with modest descriptions and listing the basic elements.
8. Watch a PowerPoint presentation about graphic design (e.g., audience analysis, human factors, key characteristics).
9. Analyze and evaluate the graphic design of two different print advertisements.
10. Present and defend the results of their graphic design analysis.

In the second lesson, *Functional Analysis*, students are engaged in the following activities.

11. Hear an overview of the lesson, which contains key terms and questions.
12. Watch a PowerPoint presentation about reverse engineering and functional analysis (e.g., definition, applications for, stages of).
13. Review an example of a functional analysis of a simple device (a stapler).
14. Conduct a functional analysis of a simple object (e.g., purpose, size, shape, features, operation, inputs, processes, outputs).

In the third lesson, *Structural Analysis*, students are engaged in the following activities.

15. Hear an overview of the lesson, which contains key terms and questions.
16. Watch a PowerPoint presentation about assembling wood components (e.g., joinery, fasteners, adhesives).
17. Match specific examples of fasteners (e.g., nails, screws, and adhesives) with their names.
18. Match the names of different kinds of wood joints and their parts with their descriptions.
19. Match the words nail, screw, and adhesive with their characteristics.
20. Match the names of different kinds of metal fasteners and bonding techniques with their descriptions.
21. Match specific examples of fasteners (e.g., bolts, screws, and nuts) with their names.
22. Match different kinds of adhesives (i.e., cyanacrylates, epoxies, urethanes, anaerobics) with their characteristics.
23. Match different kinds of welding (e.g., hot gas, ultrasonic, laser, spin) with their description.
24. Match specific examples of plastic fasteners and bonding techniques (e.g., snap-fits, mechanical fasteners, plastic assemblies, bonding agents) with their names.
25. Watch a PowerPoint presentation about product disassembly (e.g., why disassemble something, it relationship with reverse engineering, process and tools, inquiry).
26. Disassemble a product, identify the parts, and note their size, function, material, quantity, and relationship with other parts.
27. Complete a product disassembly chart that lists the parts as well as their quantity, dimensions, function, material, texture, finish, interaction, etc.
28. Watch a PowerPoint presentation about conducting a mass property analysis (e.g., volume, surface area, density, mass, moments of inertia, products of inertial).
29. Conduct a mass property analysis for two or more examples of parts made of different materials (e.g., calculate volume and surface area, determine the density of the material, compute the mass).
30. Draw all the parts of their object with modeling software and complete mass property analysis for each.
31. Develop a tri-fold post to display the parts of their product and to present the results of their mass property analysis.
32. Conduct a three-minute presentation of their product disassembly and analysis display.

In the fourth lesson, *Product Improvement by Design*, students are engaged in the following activities.

33. Hear an overview of the lesson, which contains key terms and questions.
34. Watch a PowerPoint presentation about writing a design brief (defining things like features, purpose, issues, appearance, client, consumer, and constraints).
35. Analyze a given product and write a design brief that would have launched its original creation.
36. Put the steps in the design process in an appropriate sequence on a quiz.
37. Label the parts of a given design brief on a quiz.
38. Address questions about the nature of the design process and design briefs on a quiz.
39. Watch a video presentation of a group of experts that are asked to design a solution to a problem in a modest amountt of time and answer a series of comprehension questions.
40. Watch a PowerPoint presentation that correlates the basic step of the design process with the process depicted in the video.
41. Discuss the differences between invention and innovation.
42. Identify the visual, structural, or functional problems associated with an object.
43. Compose a design brief that identifies the problem, outlines the criteria for a successful solution, and lists the constraints that have to be addressed.
44. Brainstorm potential solutions to the problem and utilize a design matrix to inform the selection process.
45. Develop the solution to the problem in the form of a solid model using CAD.
46. Watch a PowerPoint presentation about writing technical reports (e.g., importance of writing report, the nature of technical writing, composition of a technical report).

Initiative **PLTW: Introduction to Engineering Design**

Title

Design Problems

Broad Goals

It is expected that students will:

- Create a brainstorming list of different products made from common materials that are used daily.
- Research and construct a product impact timeline presentation of a product from the brainstorming list and present how the product may be recycled and used to make other products after its life cycle is complete.
- Identify the five steps of a product's life cycle and investigate and propose recyclable uses for the material once the life cycle of the product is complete.
- Explain why teams of people are used to solve problems.
- Identify group norms that allow a virtual design team to function efficiently.
- Establish file management and file revision protocols to ensure the integrity of current information.
- Use Internet resources, such as e-mail, to communicate with a virtual design team member throughout a design challenge.
- Create a Gantt chart to manage the various phases of their design challenge.

Salient Concepts & Skills

Math	Science	Technology
• exponential rate	• ecosystem	• ergonomics
	• carcinogen	• recycle
		• raw material
		• product life cycle
		• refurbish
		• Gantt chart

Engineering

The following espoused concepts have implications for the study of engineering:

- "The material of a product, how the material is prepared for use, it durability, and ease of recycling all impact a product's design, marketability, and life expectancy."
- "All products made, regardless of materials type, may have both positive and negative impacts."
- "In addition to economics and resources, manufacturers must consider human and global impacts of various manufacturing process options."
- "Laws and guidelines have been established to protect humans and the global environment."

- "A conscious effort by product designers and engineers to investigate the recyclable uses of materials will play a vital role in the future of landfills and the environment."
- "Teams of people can accomplish more than one individual working alone."
- "Design teams establish group norms through brainstorming and consensus to regulate proper and acceptable behavior by and between team members."
- "Engineers develop Gantt charts to plan, manage, and control a design team's actions on projects that have definite beginnings and end dates."
- "Virtual teams rely on communications other than face-to-face contact to work effectively to solve problems."
- Each team member's strengths are a support mechanism for the other team members' weaknesses."
- "Conflicts between team members is a normal occurrence, and can be addressed using formal conflict resolution strategies."

Prominent Activities

In the first lesson, *Engineering Design Ethics*, students are engaged in the following activities.

1. Hear an overview of the lesson, which contains key terms and questions.
2. Watch a PowerPoint presentation about impacts, ethics, design, and product life cycle.
3. Create a PowerPoint series that explains the product life cycle for a given consumer product.
4. Select and research a ethical issues related to a specific scientific or technological endeavor (e.g., stem cell research).
5. Develop a design brief for the study of the ethical issues related to the chosen topic.
6. Compose a CD cover, book cover, or poster depicting the results of the research regarding the ethical issues surround the topic in question.

In the second lesson, *Design Teams*, students are engaged in the following activities.

7. Hear an overview of the lesson, which contains key terms and questions.
8. Review a list of potential design briefs that can be addressed (i.e., design a modular table for a coffee shop, design supports for mounting speakers to a concrete wall, design fixtures for a drill press to perform operations on a part, design a bicycle storage system for an apartment, design a prairie style stained glass window using Frank Lloyd Wright inspired geometry, a storage organizer for dog supplies, design an organizer for a school locker).

9. Review the evaluation tools that will be used to assess designs, teammates, presentations, and more.
10. Watch a PowerPoint presentation about teamwork (e.g., definitions, benefits, development, group norms).
11. Work with partners to develop group norms for conduct, communication, management, decision making, and conflict resolution.
12. Draft a timeline for the design project.
13. Develop sketches for potential solutions to the problem and exchange with partners electronically.
14. Develop a set of working drawings for the solutions to the design problems.
15. Compose and present a PowerPoint presentation describing a solution to the design problem.
16. Conduct evaluations of each team's solution to the problem in terms of its visual, structural, and functional qualities.

Salient Observations

Project Lead the Way is a very prominent and prolific curriculum initiative that is dedicated to introducing the study of engineering knowledge and skills at the secondary level. According to Richard Blais, the project's founder, the initiative was born out of a desire to address the workforce problems that face the United States in a high-tech, highly competitive, and global economy. More specifically, it was established to better prepare students for entry into two- and four-year post-secondary programs that lead to careers in technology and engineering.

The program offers a series of courses for grades 6 through 12. All the courses are designed to "complement math and science college preparatory programs to establish a solid background in engineering and technology." The middle school curriculum is called *Gateway To Technology* and the sequence for the high school level is called *Pathway to Engineering*.

Pathway to Engineering is a four-year sequence of high school courses which, when combined with traditional mathematics and science courses, espouses to introduce students to the scope, rigor, and discipline of engineering before entering college. The program strives to engage students in "hands-on, real-world projects" that helps them see "how the skills they are learning in the classroom can be applied in everyday life." The approach is characterized as using "activities-based learning, project-based learning, and problem-based learning." More specifically, the curriculum endeavors to engage students in "rigorous and relevant" projects over an extended period of time. These projects often require working cooperatively in small groups and integrating mathematics, science, technology, and English language arts while solving complex problems. The sequence of classes features three foundation courses, four specialization courses, and a capstone course.

The foundation courses are *Introduction to Engineering Design, Principles of Engineering,* and *Digital Electronics.* The *Introduction to Engineering Design* course teaches problem-solving skills using an engineering design process. During this course students design, analyze, and communicate solutions to problems using solid modeling software. *Principles of Engineering* is designed to help students explore various technological systems and manufacturing processes while learning how engineers and technicians use math, science, and technology to solve problems. *Digital Electronics* engages students in the study of digital circuits and devices as well as their applications.

The specialization courses include *Aerospace Engineering*, *Biotechnical Engineering*, *Civil Engineering and Architecture*, and *Computer Integrated Manufacturing.* The *Aerospace Engineering* course engages students in hands-on engineering projects that help them learn about aerodynamics, astronautics, space-life sciences, and systems engineering. *Biotechnical Engineering* introduces students to biotechnology, bioengineering, biomedical engineering, and biomolecular engineering. *Civil Engineering and Architecture* provides an overview of the roles civil engineers and architects play in project planning, site planning, building design, project documentation, and project presentations. *Computer Integrated Manufacturing* builds on the computer modeling skills develop in the foundation courses by having students use CNC equipment to produce models of their three-dimensional designs, study the basic concepts of robotics, and learn about design analysis.

The capstone course is called *Engineering Design and Development*. It requires students working in teams to research, design, and construct a solution to an open-ended problem. They apply the principles developed in the foundation courses under the guidance of a mentor from the community. The teams present progress reports, submit a final written report, and ultimately defend their solutions to a panel of experts.

Given the scope of the program and based on a recommendation from *Project Lead the Way*, this review focused on an *Introduction to Engineering Design*. It is one of the most widely implemented classes in the program and it has recently undergone a formal revision.

The curriculum for the *Introduction to Engineering Design* course follows a hierarchical structure. It is divided into four discrete topics that are subdivided into lessons. The lessons include things like handouts, lab sheets, homework assignments, PowerPoint presentations, assessment tools, and optional assignments. Navigating from one level to the next is accomplished by activating hyperlinks that open specific files on a compact disk.

The “lessons” are not really lesson plans in the traditional sense. The breadth and depth of their contents is more consistent with unit plans that outline the instruction over the course of weeks in contrast to individual class periods. The lessons in an *Introduction to Engineering Design* run between 4 to 25 days in duration. They follow a syllabus-like format that lists key concepts, presents dozens of related standards, announces several performance objectives, outlines a series of activities, and more. The directions for the learning activities range from several simple sentences to handouts, media, assessment tools, and additional support materials for the teacher to follow and use.

The course starts with an *Introduction to Design* that provides a modest overview of the history of design, the steps in the design process, basic sketching techniques, and how to use common measurement tools. This segment culminates with students using their new knowledge to solve a simple design problem.

The next section is called *Design Solutions* and it addresses concepts and skills related to basic geometric shapes and solids, conventions for dimensioning drawings and communicating tolerances, and using three-dimensional modeling software (CAD). This segment also asks students to apply their new skills to solving a simple design problem.

The unit on *Reverse Engineering* asks student to break down and analyze an existing product. The product and its parts are studied to determine how they work and to identify opportunities to make improvements. This work culminates in a proposal for making refinements to the product's design.

The last unit is called *Design Problems* and it requires students to apply the knowledge and skills that they developed in the class to design a solution to an authentic problem. They work in virtual teams to develop their solutions.

Engineering

The materials define an engineer as "a person who is trained in and uses technological and scientific knowledge to solve practical problems." Consistent with this definition the curriculum teaches students how to used contemporary tools to design solutions to problems.

A lot of emphasis is placed on developing knowledge and skills that are very technical in nature. For example, a significant portion of the curriculum is dedicated to teaching students how to use computer-aided design software to develop drawings and computer models. Attention is also given to using precision measurement tools (e.g., dial calipers), standards for dimensioning and tolerancing objects, and material fastening techniques (e.g., joinery, adhesives, mechanical fasteners).

Each unit features a list of key concepts that address the nature of engineering as well as technical details. For example, the unit about *Design Solutions* states, “Engineers use design briefs to explain the problem, identify solution expectations, and establish project constraints.” Similarly, it states, “Engineers conduct research to develop their knowledge base, stimulate creative ideas, and make informed decisions.” In a more technical vein, the list includes statements like, “As individual objects are assembled together, their degrees of freedom are systematically removed.” These ideas and many more are embedded in the lessons and learning activities. Some of these ideas are addressed in details while others are simply sampled.

A significant portion of the curriculum is dedicated to the concept of reverse engineering. It is defined as “the process of taking something apart and analyzing its workings in detail, usually with the intention to understand function, prepare documentation, electronic data, or construct a new or improved device or program, without actually copying from the original.” Consistent with this definition, students are asked to disassemble an existing product, study the attributes of each part, and uncover the role they play in the system.

Design

The materials address the concept of design from a variety of perspectives. It is described as “an iterative decision-making process that produces plans by which resources are converted into products or systems that meet human needs and wants or solve problems.” It is also defined as “a plan or drawing produced to show the look and function or workings of something before it is built or made.” Lastly, it is equated with a “decorative pattern.” All three perspectives are addressed in the course.

Most of the emphasis is on describing and experiencing design as a problem solving process that features a sequential series of 12 steps that are presented in loop. The sequence was adopted from the *Standards for Technology Literacy* that was published by the International Technology Education Association in 2000. The steps in the design process are:

1. Define a problem
2. Brainstorm
3. Research and generate ideas
4. Identify criteria and specify constraints
5. Explore possibilities
6. Select an approach
7. Develop a design proposal
8. Make a model or prototype
9. Test and evaluate the design use specifications

10. Refine the design
11. Create or make the solution
12. Communicate processes and results

The notion that a design is a plan for a new product is also addressed throughout the unit. All the units include lessons and learning activities that require students to develop drawings and models using computer-aid design software.

The materials also deal with design from an aesthetic point of view by focusing on "design elements" (i.e., line, form, space, color, texture, light and shadow) and "design principles" (e.g., balance, rhythm, emphasis, proportion, scale, unity). The examples used to illustrate the different design elements and principles came from product, graphic, and architectural design. The activities include a visual analysis of an existing product and several advertisements.

Analysis

Analysis can be used to identify problems, evaluate potential solutions, to gather the data need to inform designs, predict performance, test prototypes, and much more. *Introduction to Engineering Design* utilizes analysis in specific and focused ways. More specifically, the materials define analysis as a "detailed examination of the elements or structure of something."

The section on *Reverse Engineering* deals with analyzing the visual, functional, and structural features of an existing product. The visual analysis lesson focuses on the aesthetic features of a product. The lesson that targets the functional aspects of the product asks students to determine how an everyday device works and to map its inputs and outputs. The structural analysis lesson has students taking a simple device apart, studying the individual parts, and determining their physical attributes (e.g., volume, surface area, density, mass).

Constraints

The materials define constraints as a "limitation or restriction" that is imposed on the design process. More specifically, "constraints may be such things as appearance, funding, space, materials, and human capabilities." Most of the learning activities present the students with the criteria and constraints for developing a successful solution to the problem at hand. Even the design challenges at the end of the course outline some expectations and limitations for the solutions to the posed problems. For example, one of the challenges asks students to develop a system for organizing common items that are stored in school lockers. The final product has to fit inside the locker, be easy to install, must hold 20 pounds of books and binders, and be made out of nonflammable materials. As the students progress through the sequence of courses, they take a more active role in defining limitations and defining the characteristics of a successful solution.

Modeling

The materials define a model as “a visual, mathematical, or three-dimensional representation in detail of an object or design” that is often “smaller than the original.” The materials go on to state a “model is often used to test ideas, make changes to a design, and to learn more about what would happen to a similar, real object.

Most of the modeling in the course is done on computers using computer-aided design (CAD) software. It is the primary tool used to develop, visualize, and represent solutions to problems. For example, students use CAD to generate three-dimensional objects by creating, adding, and subtracting geometric shapes. They also develop computer models for the parts of an existing product to facilitate an analysis of their structural composition. Lastly, students create computer models to represent solutions to a variety of posed problems (e.g., design a candy dispenser, design a desk organizer for office supplies, design a locker organizer, design a modular table for a coffee shop, design a fixture that can be used on a drill press).

Physical models play important roles in several learning activities. For example, the *Introduction to Design* unit requires students to design, prototype, and package a puzzle based on small hardwood cubes. The unit on *Reverse Engineering* utilizes existing products as models for analysis and designing improvements.

Optimization

The materials do not address the concept of optimization in a direct and overt manner. However, optimization is an intrinsic part of the lesson called *Product Improvement by Design*. In this lesson the students have to identify the visual, functional, or structural shortcomings of the product that they analyzed under the auspices of reverse engineering. They then compose a design brief that describes an opportunity to improve the product in the form of a problem statement along with design criteria and constraints. The students then brainstorm potential refinements, use decision matrices to select the most promising ideas, develop the ideas into product improvements, and communicate their designs in technical reports. On a basic level, these activities are consistent with the concept of optimization even though it is not targeted under the major concepts, performance objectives, essential questions, or key terms.

Systems

The materials define a system as “a group of interacting, interrelated, or interdependent elements or parts that function together as a whole to accomplish a goal." The most prominent treatment of systems and system thinking can be found in the unit on *Reverse Engineering*. It asks students to break an existing product down into its basic parts and determine its purpose, features, operation, inputs, processes, and outputs. The concepts of interaction, interrelated, and independent are not addressed in an overt manner. The modest attention given to systems appears to be an introduction and the topic is addressed in more detail in the *Principles of Engineering* course.

Science

The materials include several references to science concepts. In some cases, they are simply scientific terms that are used in conjunction with explanations of technical things. For example, an explanation of a product's life cycle in the unit on *Reverse Engineering* references the concepts of carcinogen and ecosystem. In other cases, science concepts are integral to a learning activity. For example, the same unit requires students to perform a "mass property analysis" for the parts of an existing product.

The richest and most direct treatment of science content is found in the unit on *Reverse Engineering.* It features a PowerPoint presentation that addresses science concepts like density, mass, moments of inertia, products of inertia, and radii of gyration. The slides in question impart simple definitions for these concepts along with supporting formulas and complementary illustrations. For example, mass is defined as "the amount of matter in an object or the quantity of the inertia of the object." Density is described as "mass per unit volume." The sophistication of these concepts and the relative simplicity of their treatment suggests the lesson is intended to be a review of key concepts that were addressed in a more thorough manner in a prerequisite or concurrent science course. It is important to note that these science concepts are being used to describe a product that was designed in contrast to designing a new product.

Mathematics

The curriculum includes instruction that applies descriptive statistics, geometry, and algebra in technical contexts. For example, an *Introduction to Design* engages students in measuring dozens of hardwood cubes and using the data collected to quantify and describe their variability in terms of the mean, median, mode, and range. The unit on *Design Solutions* deals with a variety of geometric shapes and how to calculate their area. It goes on to address how objects can be created by adding geometric shapes together and by subtracting geometric shapes from one another. The *Reverse Engineering* unit uses basic algebra to calculate things like mass, volume, and surface area under the auspices of a mass property analysis. Most of the mathematics is used to describe objects and to create objects. The use of mathematics to design solutions to problems is not address directly but it is likely to surface during the course of solving one of the problems at the end of the course.

Technology

The curriculum addresses several topics that can be considered domain knowledge in technology. The most pervasive example is the attention given to teaching students how to use the basic tools, commands, and capabilities of computer-aided design software to make drawings, develop three-dimensional models, and to conduct analyses. Another area of domain knowledge that is addressed in the course is the basic techniques used to assemble parts that are made out of different materials. The unit on *Reverse Engineering* includes details about the joinery, fasteners, and adhesives used to make things out of wood (e.g., biscuit joints, dado joints, lap joints, nails, screws, animal glues, contact cement). It also addresses similar content for assembly objects made of plastic (e.g., snap fits, self-tapping screws, solvent bonding) and metal (e.g., nuts and bolts, rivets, brazing).

Treatment of Standards

The materials clearly list the national standards and the related benchmarks that are “addressed” in each lesson. The standards cited include the Standards for Technological Literacy, the National Science Education Standards, the Principles and Standards for School Mathematics, and the English Language Arts Standards. The treatment of these standards is outlined in matrices that show when a particular standard contains one or more concepts that “correlate” with those in a given lesson. The materials go on to state that “the ideas and concepts may not be directly addressed,” but they are supported or implied in the lesson and activity. The contents of the matrices suggests the lessons and the standards run parallel to one another and share common themes in direct and indirect ways.

The breadth and depth of the standards cited often exceed that of the objectives that the lessons are designed to achieve. For example, the objectives for the *Functional Analysis* lesson in the *Reverse Engineering* unit requires students to “identify the reasons why engineers perform reverse engineering on products” and “describe the function of a given manufactured object as a sequence of operations through visual analysis and inspection.” The achievement of these objectives is correlated with the following standards and benchmarks:

- “Students will develop an understanding of the attributes of design.”
- “Requirements for a design include such factors as the desired elements and features of a product or system or the limits that are placed on the design.”
- “Design is a creative planning process that leads to useful products and systems.”
- “Students will develop abilities to apply the design process.”
- “Evaluate final solutions and communicate observations, processes, and results of the entire design process, using verbal, graphic, quantitative, virtual, and written means, in addition to three-dimensional models.”

The intellectual implications of these standards go beyond being able to explain why engineers engage in reverse engineering and how a simple device works. The lesson has two objectives but it is aligned with more that 20 standards and benchmarks. The imbalance between the standards and the objectives in terms of their conceptual depth and breadth provides further evidence that there is a relatively loose relationship between them.

Most of the curriculum is dedicated to facilitating learning activities that engage students in engineering-like experiences. The richness of these activities provides numerous opportunities to address a wide range of standards from technology, science, mathematics, and English. The alignment between the standards and curriculum appears to be based on the potential capacity of learning activities in contrast to the actual instruction.

From a broader perspective the curriculum seems to chip away at the standards identified in contrast to targeting them directly. This is supported by the fact that many of the same standards are listed in multiple lessons in different units of instruction that the students encounter over the course of the program.

Pedagogy

The curriculum clearly states it uses an activity-based, project-based, and problem-bases approach to facilitating student learning. Operationally, most of the lessons follow a basic linear pattern that begins with presenting the main concepts, key terms, and essential questions that run through the instruction for a given topics (e.g., measurement and statistics, geometric shapes and solids, structural analysis). This is often followed by an introduction to the labs students will need to perform, the projects they will need to complete, or the problem that they will need to solve. The next step typically involves PowerPoint presentations that introduce students to the concepts that will be applied in a hands-on activity.

The next phase engages students in one or more hands-on activities. Most of the learning activities include several questions that ask students to look back on their activities and share some of the things that they learned from the experience. Lastly, all the lab activities, projects, and design problems culminate in a concrete product that can be evaluated.

The primary audience for the materials is classroom teachers. The core documentation for each lesson features lists of standards, objectives, essential questions, vocabulary terms, learning activities, and support documents (e.g., handouts, PowerPoint presentations, assessment tools, additional references).

Most of the "essential questions" presented in each lesson can be used as advanced organizers because they alert the teachers to the big ideas that students should develop over the course of the activities. They can also be used at the end of learning activities to encourage reflection and facilitate debriefing.

A lot of attention is given to technical terms. The vocabulary lists and the glossaries include key words (or concepts) that are used in the learning activities. Some of the words appear to be included in the lists because students will encounter them and use them in the learning activities. Many of the learning activities (e.g., worksheets, presentations, projects) and assessment items emphasize understanding technical terminology.

The pedagogical strategies that are embedded in the materials also include introductions that provide background information that can be used to frame the learning activities that follow. In some cases they provide a modest rationale for the instruction. In other cases they present a fictitious problem that has to be solved.

Most of the PowerPoint slides present a large amount of information. According to *Project Lead the Way*, the slides are designed to provide as much support as possible for teachers who are new to the curriculum or even the profession. The heavy concept load and visual density of the slides can be attributed to an effort to convey key ideas in a comprehensive and standalone manner. A conscientious teacher would need to modify and edit most of the slides to bring them into compliance with the fundamental principles of media (e.g., composition, simplicity, brevity).

Implementation

Introduction to Engineering Design presents a rich framework for updating a high school computer-aided drafting class while infusing aspects of design. The materials do not provide detailed narratives or lesson plans for executing the teaching and learning process. Instead, they provide teachers with lists and resources that can be used to guide and facilitate instruction. The lists provide the backbone for each chunk of instruction. They include the big ideas that can be targeted, the standards that can be addressed, the vocabulary terms that can be taught, the questions that can be posed, and the objectives that can be addressed. The resources that are attached to lists include definitions for the key terms, scenarios that can be used to frame lessons, handouts that can engage students in hands-on learning activities, media presentations that present concepts, assessment tools that can be use to measure the accomplishment of tasks, and more.

A conscientious teacher needs to develop daily lesson plans by drawing on selected pieces of the framework. In light of this need, the curriculum also includes materials (or tutorials) that provide teachers with recommendations for developing lessons and additional assessment tools.

Obtaining and implementing the curriculum requires schools to make a significant commitment to the program. The formality of this commitment includes signing memos of understanding, obtaining recommended tools and materials, having faculty complete professional development workshops, and undergoing reviews to demonstrate the integrity of the curriculum's implementation. The financial demands of the program involve tens of thousands of dollars.

A World in Motion® Elementary

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Toyota Motor Corporation

Grade Levels
4-6

Espoused Mission
"The *A World in Motion*® (AWIM) curriculum joins together teachers, students, and industry volunteers in an exploration of physical science while addressing essential mathematic and scientific concepts and skills. Industry volunteers play an essential role in motivating the next generation to pursue careers in science, technology, engineering, and math by bringing their everyday experiences into an AWIM classroom."

Organizing Topics
- *Skimmer* (paper sailboats)
- *JetToy* (balloon-powered toy cars)
- Electricity and Electronics (i.e., static electricity, batteries, capacitors)

Format
The curriculum is distributed in the form of a CD that contains a curriculum guide for the unit in question. Each curriculum guide

includes the following elements.

1. An overview of A World in Motion program.
2. A description of the design paradigm that underpin the units.
3. A table that aligns the unit's objectives with national standards.
4. Recommendations for teaching the program.
5. Instructions for requesting materials.
6. A guide for working with volunteers from industry.
7. An introduction to the design challenge in question.
8. A section that provides an overview of the technical aspects of the unit (e.g., the problem, the context, the science principles)
9. A letter describing a problematic scenario from a fictitious company.
10. Lesson plans, student handouts, and assessment tools.

Pedagogical Elements

The design of the instruction is very comprehensive and detailed. Attention is given to the following things.

- Justifying lessons with a modest rationales
- Supporting the teacher's content knowledge
- Using volunteers from business and industry
- Managing materials, activities, and students
- Using cooperative learning strategies
- Anticipating problems students are likely to encounter
- Engaging students in scientific inquiry
- Conducting class discussions.
- Preparing for lessons (e.g., materials, props, examples).
- Implementing lessons in a sequential manner
- Processing learning activity materials to obtain the best results.

Maturity

1990 - *A World In Motion*® was introduced as a supplemental curriculum to be used in grades 4-6

2000 - The *Skimmer* & *JetToy* (Challenge 1) were introduced as supplemental elementary school curriculum

2003 - Elementary & Electronics (Challenge 4) was introduced for use in elementary, middle, and high school

Diffusion & Impact

- It is utilized in all 50 states and in 10 of Canada's 13 provinces/territories.
- Over 60,000 AWIM kits have been shipped to schools since 1990.
- It is estimated that over 3.75 million students across North America have participated in AWIM programs.
- More than 15,000 volunteer engineers have been involved in AWIM programs.

Initiative *A World in Motion®*

Title

Skimmer Design Challenge

Grade Level 4

Broad Goals

Under the auspices of "Engineering Design," the materials cite the following objectives.

- Using the Engineering Design Experience as a context for teaching and learning.
- Using the Engineering Design Experience to fulfill a specific goal.

Under the heading of "Science," the materials cite the following objectives.

- Formulating appropriate questions for scientific investigation.
- Conducting scientific research using appropriate methods.
- Interpreting scientific evidence.
- Communicating results of scientific investigations.
- Understanding forces acting on a moving object.
- Understanding simple machines.
- Understanding the difference between science and technology and use of design process and skills.

In support of "Technology Education," the materials cite the following objectives.

- Applying scientific understanding to a design problem.
- Designing to optimize one or more variables.
- Creating design specifications, drawings, and models.
- Testing and evaluating a design.
- Exploring properties of materials.

Salient Concepts & Skills

Math
- shapes
- symmetry
- measuring weights and distances
- estimating area
- calculating area
- using graphing paper to determine area for irregular shapes

Science
- friction
- force
- torque
- motion
- difference between science and technology
- formulating questions investigation

Technology
- hull
- sail
- mast
- applying scientific understanding to a design problem
- designing to optimize one or more variables
- design

	• metric units of measurement (centimeter and meter) • perpendicular	• conducting scientific research • interpreting scientific evidence • communicating the results • understanding forces acting on a moving object • understanding simple machines • friction, forces, and the effect of surface area are some of the physical phenomena students encounter in this challenge • understanding the difference between science and technology and use of design process and skills	specifications • drawings • models • testing and evaluating a design • exploring properties of materials

Engineering

The materials are designed to use “The Engineering Design Experience” to address the following concepts and skills.

- Develop skills in scientific inquiry (i.e., experimental thinking, analyzing systems, reasoning logically, drawing conclusions).
- Design prototypes, test and modify designs in response to constraints and side effects.
- Communicate their design ideas and plans both orally and in writing.

Prominent Activities

During the course of this unit, students…

1. Study and discuss a problem and set of design specifications outlined in a letter from a fictitious company.
2. Make paper sailboats and determine how they work.
3. Test different sizes and shapes of sails.
4. Experiment with the orientation and placement of the sail and mast on the hull.
5. Determine the effect of friction on vessel performance.

6. Gather, organize, and interpret the data derived from each experiment.
7. Use the information gathered to design a vessel that fulfills the design specifications outline in the letter.
8. Presents the results of their work to an audience.

Initiative *A World in Motion®*

Title

JetToy Design Challenge

Grade Level 5

Broad Goals

Under the auspices of "Engineering Design," the materials cite the following objectives.

- Using the Engineering Design Experience as a context for teaching and learning.
- Using the Engineering Design Experience to fulfill a specific goal.

Under the heading of "Science," the materials cite the following objectives.

- Formulating appropriate questions for scientific investigation.
- Conducting scientific research using appropriate methods.
- Interpreting scientific evidence.
- Communicating results of scientific investigations.
- Understanding forces acting on a moving object.
- Understanding simple machines.
- Understanding the difference between science and technology and use of design process and skills.

In support of "Technology Education," the materials cite the following objectives.

- Applying scientific understanding to a design problem.
- Designing to optimize one or more variables.
- Creating design specifications, drawings, and models.
- Testing and evaluating a design.
- Exploring properties of materials.

Salient Concepts & Skills

Math
- circumference
- diameter
- metric units of measurement (meter)

Science
- energy
- acceleration
- air resistance
- forces
- balanced forces
- unbalanced forces
- friction
- kinetic energy
- pressure
- potential energy

Technology
- alignment
- balloon motor
- chassis
- nozzle
- propulsion
- prototype
- axle
- bearing
- hub
- wheel

- Newton's second law
- hypothesis
- nozzle

Engineering

The materials are designed to use "The Engineering Design Experience" to address the following concepts and skills.

- Develop skills in scientific inquiry (i.e., experimental thinking, analyzing systems, reasoning logically, drawing conclusions).
- Design prototypes, test and modify designs in response to constraints and side effects.
- Communicate their design ideas and plans both orally and in writing.

Prominent Activities

During the course of this unit, students…

1. Study and discuss a problem and set of design specifications outlined in a letter from a fictitious company.
2. Make balloon power vehicles and determine how they work.
3. Test the effect the inflation of the balloon has on vehicle speed and distance.
4. Experiment with the size and orientation of the nozzle used to release the pressure from the balloon.
5. Determine the effect that wheel alignment and friction have on vehicle performance.
6. Gather, organize, and interpret the data derived from each experiment.
7. Use the information gathered to design a balloon power vehicle that fulfills the design specifications outlined in the letter.
8. Present the results of their work to an audience.

Initiative *A World in Motion®*

Title **Electricity and Electronics** (elementary school)

Grade Level 4-6

Broad Goals The Electricity and Electronics unit is designed to…

- demonstrate the force of static electricity using familiar materials and illustrate electric attraction and repulsion.
- create awareness of storing charges and the basic construction of capacitors and batteries.

Salient Concepts & Skills

Math

- numeric scales (on the multimeter)
- higher scale
- lower scale
- units of measurement (volt, amp, farad)

Science

- electrical energy
- atoms
- electrons
- protons
- neutrons
- static electricity
- static charge
- charge
- positive charge
- negative charge
- electrochemical reaction
- chemical reaction
- oxidization
- reduction
- conductors
- insulators
- voltage
- current
- alternating current
- direct current
- resistance
- electrostatic
- spark or arc
- poles
- electrostatic activity
- free electrons
- zinc
- copper ions

Technology

- galvanic cell
- battery
- electrolyte
- Leyden jar
- capacitors
- separating dielectric
- power supply
- diode
- anode
- cathode
- LED (light-emitting diode)
- making electrical circuits
- using a multimeter

- dielectric
- describing experiments
- making observations
- drawing conclusions

Engineering All the activities involve building and testing simple devices.

Prominent Activities

1. Make a variety of devices and play simple games that illustrate "…how static electricity is everywhere, how charge can either attract (move toward) or repel (move away from), and how things can be charged using different materials" (i.e., magic wand, boar races, electroscopes, a versorium, electric golf, balloons, and snakes).
2. Make a simple battery using dissimilar metals suspended in a salt water solution. Use a small speaker to sense electricity and a multimeter to measure current.
3. Conduct an electroplating experiment to demonstrate a conversion of electrical energy into electrochemical energy.
4. Make a Leyden jar (home-made capacitor) that will produce an electrical spark or arc when it comes in proximity to a ground.
5. Charge a capacitor across a battery and then discharge it across an LED (light-emitting diode).
6. Make and test a capacitor out of foil, paper, and tape that will produce an electrical spark or arc when it comes in proximity to a ground.

Salient Observations

The Society of Automotive Engineers developed three discrete challenges (or units of instruction) that enable teachers and students to address mathematics, science, and technology in the context of doing engineering design. The first two deal with designing and testing simple model vehicles performance in accordance with the design specifications outline in a problematic scenario. The third challenge deals with basic principles of electricity as well as the components used to make electrical circuits.

The *Skimmer* and *JetToy* challenges are very similar in composition, format and pedagogical approach. The *Electricity and Electronics* materials are organized and presented in a different format. In contrast to engaging students in design, most of the attention is on making and testing simple electrical devices in accordance with sets of directions. These learning activities are more project-based than design-based. Treatment of engineering is limited to building domain knowledge. Therefore, the following discussion will focus primarily on the *Skimmer Design Challenge* and the *JetToy Design Challenge*.

Engineering

Overall, the *Skimmer* and the *JetToy* design challenges do a nice job of blending scientific inquiry with engineering design. They also incorporate aspect of engineering that include the need for collaboration within a design team, the applications of science and mathematics, and the use of models and modeling as sources of data. The students vicariously do the work of engineers by conducting detail analysis prior to design, documenting their investigations and design processes, and ultimately communicating their designs in the form of drawings, narratives, and oral presentations.

Design

Both the *Skimmer* and the *JetToy* units do a nice job of introducing the nature of design. They ask the teacher to confront how design is commonly discussed in the context of something's appearance. The teachers are then asked to expand this concept by discussing how engineers must also address considerations of function, feasibility, and impact. More specifically, (i.e., who is it for, what needs will it address, how will it be used, what kinds of materials are needed to make it, how much will it cost to make, how much will it cost to buy, what kinds of impacts might it have on the environment).

The *Skimmer* and the *JetToy* units teach and employ a five-phase process for doing engineering design. Both sets of materials state that the process is "similar" to the one engineers use to design things. The first phase deals with setting goals based on the review of a problem that is presented in a scenario. In both cases, the problem is introduced in the form of a letter from a toy company (Earth Toy Designs, Inc.). The contents of the letter outline the problem, the specification for the final solution (e.g., features, performance), and the expectations for a presentation of the design.

The second phase is, by far, the longest and most detailed step in the design process. It involves building a model and using it to figure how it works. This is followed by a sequence of manipulating one variable at a time and determining their effect on their vehicles performance (e.g., stability, direction, distance). In this context, the models provide the data needed to uncover the scientific factors as well as the technological features that effect vehicle performance.

In phase three, students use the data gathered and the knowledge gained during the previous phase to design their vehicle, plan its construction, and predict its performance. This phase involves making drawings as well as describing and justifying design features.

Phase four is all about building and testing the vehicles (the *Skimmers* and *JetToys*). The building and testing enables students to observe directly how their integration and application of scientific principles and engineering design influence vehicle performance.

The last phase, number five, asks students to prepare and give a design presentation to an audience. These student presentations have to include how the design addressed the design specifications presented in the letter, how their vehicle design translates into performance, and what they learned during the course of the design process.

Throughout the process, the students are required to make entries in their "design logs." The purpose of the design logs is to maintain a record of the design ideas, observations, and performance data. These entries include drawings, notes, predictions, graphs, tables, and reflections.

Analysis

The materials do a very nice job of blending scientific inquiry with engineering design in an almost symbiotic way. It would be easy for teachers to recognize the concepts and skills that are consistent with doing inquiry in the name of teaching science. This is especially evident with the emphasis that is placed on testing only one variable at a time (e.g., sail size, sail shape, sail orientation), formulating hypotheses, making observations, collecting data, and drawing conclusions based on evidence. At the same time, it would be equally easy to identify concepts and skills from an engineering point of view. This is because the inquiry in question focuses on human-made objects under the auspices of solving a specific problem based on a given set of design specification for the solution. One of the core concepts embedded in the analysis is finding the optimal vehicle design among competing variables (e.g., friction, propulsion, weight, speed, distance, stability). The materials alert teachers that engineers need to predict how a design will perform before it is built. All of the investigations inform the design characteristics of the final vehicles before they are made.

Constraints

The concept of constraints is not one of the main ideas presented in the units of instruction. More specifically, it cannot be found in the objectives, the glossary of terms, the lesson plans, the learning activities, or the evaluation tools. However, the investigations that the students conduct do uncover many of the natural variables that govern vehicle performance (e.g., friction, forces, weight). Furthermore, constraints are intrinsic to the activities in light of the materials provided for the fabrication of vehicles and to the amount of a time allotted for conducting investigations and designing vehicles. Despite these opportunities to address the concept of constraints in an overt manner, its treatment is rather subliminal.

The letters from the fictitious the toy company do outline expectations for the final designs. For example, in the case of the Skimmer it has to be designed to “travel at least 60 centimeters in a straight line.” It also has to include sail configurations that will enable the vessel to turn. In the case of the *JetToy*, the final design needs to have adjustable performance characteristics (e.g., speed, distance, payload). Although these expectations influence the vehicle design, they are more consistent with the concept of design specifications than constraints.

Modeling

The concept of models and modeling is not among the core concepts being addressed in these materials. However, in all three pieces of instruction, students engage in making and testing models. Furthermore, in the case of the *Skimmer* and *JetToy* challenges, the models are the primary sources for data for making design decisions. This application of models is consistent with how modeling is used in engineering contexts. The overdependence on physical models, in contrast to mathematical models, is appropriate given the developmental nature of the population being served.

Optimization Optimization plays an integral role in both the *Skimmer Design Challenge* as well as the *JetToy Design Challenge*. However, the concept of optimizations is more embedded in these activities than it is formally targeted. The word is only used a few times in the narratives. It is not presented in the objectives, the glossary of terms, the laboratory handouts, or in the evaluation tools. Despite its absence, in many ways, optimization is part of the essence of these activities.

The sequence of investigations and analysis in the *Skimmer Design Challenge* leads to making informed decisions about the size, shape, and position of a sail. More specifically, the students confront the trade-offs between the size of the sail and vessel speed, distance, and stability. They also have to address the relationship between a vessel's weight and its speed, distance, and stability. Lastly, orientation of the sail on the mast and the location of the mast on the hull must be addressed.

In the case of the *JetToy Design Challenge*, the laboratory activities direct students toward finding the optimal relationship between balloon inflation, nozzle diameter, and the amount and duration of propulsion force. They also have to find the optimal vehicle weight in relation to the vehicle's speed and the distance that it can travel. The tuning process is informed by data that describes how each variable (nozzle size, balloon inflation, vehicle weight, and friction) affects the vehicle performance (speed and distance). The optimization process is also informed by more intuitive observations. For example, students are likely to encounter how the shape and orientation of the nozzle affects their vehicle's propulsion (it needs to be straight and parallel with the floor for maximum effect).

Systems The concept that both the *Skimmer* and the *JetToy* are systems is not targeted in the materials in a direct manner. In both instances, the notion that all the parts have to work together in interdependent ways is not formally addressed in the lessons and learning activities of these units. However, an overwhelming part of the inquiry is directed toward making informed decisions about configuring all the parts of a vehicle in an optimal way to maximize its performance. The concept of systems and systems thinking resides between the lines and in the background of the curriculum.

Science

The science content in the *Skimmer* and the *JetToy* challenges includes concepts like force, friction, pressure, energy, and motion. Furthermore, these ideas are applied to the design of vehicles that address a problem and fulfill design criteria. The design process requires students to recognize the role these scientific concepts play in vehicle design and performance.

The treatment of science also includes the development of inquiry skills. More specifically, the instruction and learning activities engages students in formulating questions, designing investigations, controlling variables, gathering data, interpreting evidence, and communicating results. The main purpose of these activities is to understanding how forces act on a moving object.

Mathematics

The mathematics in both design challenges include measuring distance, measuring time, organizing data in tables and graphs, interpreting patterns within data, and drawing conclusions from multiple sources and representations of data. Given the grade levels being address, the amount of mathematical reasoning is sophisticated. More importantly, the use of mathematics is integral to making design decisions. There is a symbiotic relationship between the mathematics being performed, the nature of the scientific investigations being performed, and the engineering decisions that need to be made to configure the optimum design.

The construction and testing of the vehicles also requires the application and development of geometric reasoning. More specifically, in both units students are engaged in transforming two-dimensional developments (or patterns) into three-dimensional objects. The making and testing of sails also involves calculating the area of simple shapes using dimensions and estimating the area for irregular shapes using a grid approach with the aid of graph paper.

Technology

The technology that is addressed in these units is limited to the anatomy of the vehicles. Both activities require the development of a common language for designing, building, testing, discussing, and describing the salient features of the *Skimmers* and the *JetToys*. Therefore, students apply or expand their understand of the terms hull, mast, sail, chassis, axle, hub, wheel, bearing, etc.

Treatment of Standards

According to the authors, the objectives for the *Skimmer Design Challenge* and the *JetToy Design Challenge* "correlate" with the National Science Education Standards of the National Research

Council (NRC) and the Benchmarks for Science Literacy of the American Association for the Advancement of Science (AAAS). A matrix aligning the unit's objectives with each set of standards is presented in both units of instruction. The basis on which these correlations were made is not explained. However, a review of the standards along side the materials suggests these alignments have merit. For example, the objective that states students will "understand forces acting on a moving object" is correlated with the following AAAS standard (1993, p. 89).

> By the end of the 5th grade, students should know that
> - Changes in speed or direction of motion are caused by forces. The greater the force is, the greater the change in motion will be. The more massive an object is, the less effect a given force will have.
> - How fast things move differs greatly. Some things are so slow that their journey takes a long time; other move too fast for people to even see them.

Both the objective and the standard deal with motion. However, the materials only address the first bullet of the standards cited. For example, in the case of the *Skimmer Design Challenge*, the students do not deliberately alter the speed of the fan to determine the effect that an increase or decrease in force has on their skimmer's speed. As a matter of fact, students are encouraged to keep the fan speed the same in the interest of keeping this variable constant. But they do address the impact that surface area has on harnessing the force coming off the fan on the motion of the vessel. They also note that the amount of force available diminishes as the vessel moves away from the fan and results in a loss of motion. The introduction of weight in the vessel has a dramatic affect on motion of the vessel despite the fact that the force applied remains relatively constant. Lastly, teachers are instructed to call attention to the strength of the air coming off the fan relative to the orientation of the sail on the mast. A similar alignment can be made between the first bullet in the standard and the relationship between force and motion in the *JetToy Design Challenge*.

It is important to note that the materials do not claim to address the standards in question. The authors simply plot the correlations that exist between the objectives of the units and selected national standards. That is to say, they point out what the standards and the units have in common. Thus, teachers can choose to use the materials, along with others, in their efforts to address the standards.

Pedagogy

The *Skimmer* and the *JetToy* activities start with an engineering scenario, much the way engineers in a real company would. The company is given a name and the engineering problem. The students are given the task of refining the skimmer toy. The toys need to travel specific distances. The students test, engineer, design and document the services required for the product to move to the next stage of development.

The technical content knowledge required to address these challenges presented in the scenarios is explained in surprising detail in encyclopedia-like narratives. The narratives also describe the kinds of problems students are likely to encounter and outline the steps required to conduct the learning activities in detail. As a result, teachers should be able to prepare for lessons in an efficient and confidence-building manner.

The instruction in both units is very Socratic in nature. The materials are dominated by the use of questions to direct learning, to implement activities, conduct debriefing, assess understanding, and facilitate student reflections.

A lot of emphasis is place on collaboration. More specifically, the students have to work in teams to develop designs, to gather and synthesize information, to construct and test models, and to prepare presentations of their final designs. The recommendations for establishing the climate for collaboration include team-building activities. The need for collaboration is reinforced with strategies for fostering mutual accountability for the knowledge developed and the work performed. Lastly, in the spirit of cooperative learning, each member of the design teams is given a title and job description. Job titles and descriptions are as follows:

- Project Engineer: He or she is responsible for helping members of the team understand the task the at hand, leading the team in discussions, maintaining safety at all times, and monitoring the team's progress.
- Facilities Engineer: He or she is in charge of collecting materials, directing model construction, conducting cleanup, and storing building materials and models.
- Test Engineer: He or she provides leadership in the area of recording and organizing the data derived from experiments and test runs.

Implementation

The materials provide rich recommendations for the following aspects of the curriculum's implementation.

- Soliciting and utilizing industry volunteers.

- Orchestrating design and scientific inquiry.
- Establishing collaborative teams and encouraging teamwork.
- Using, monitoring, and evaluating design logs.
- Facilitating interdisciplinary teaming among teachers.
- Preparing, managing, and storing materials.
- Managing the classroom activities.
- Anticipating technical difficulties students might have.
- Posing questions and conducting classroom discussions.

Unlike most curricula, the curriculum and laboratory materials are free from upon request. All teachers have to do is complete and submit a simple two-page form to the headquarters for *A World in Motion*. The Society of Automotive Engineers (SAE), through its Foundation for Science and Technology Education, absorbs the cost of the materials.

A World in Motion® Middle School

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Toyota Motor Corporation

Grade Levels
5-8

Espoused Mission
"The *A World in Motion*® curriculum joins together teachers, students, and industry volunteers in an exploration of physical science while addressing essential mathematic and scientific concepts and skills. Industry volunteers play an essential role in motivating the next generation to pursue careers in science, technology, engineering and math by bringing their everyday experiences into an AWIM classroom."

Organizing Topics
The middle school program is divided into the following units of instruction:

- *Motorized Toy Car* (electric gear driven toys)
- *Glider* (model airplane)
- *Electricity and Electronics* (i.e., series & parallel circuits, magnetism, introduction to electronics)

Format

The curriculum is distributed in the form of a CD that contain a curriculum guide for the unit in question. Each curriculum guide includes the following elements.

1. An overview of *A World in Motion*® program.
2. A description of the design paradigm underpins the units.
3. A table that aligns each unit's objectives with national standards.
4. Recommendations for teaching the program.
5. Instructions for requesting materials.
6. A guide for working with volunteers from industry.
7. An introduction to the design challenge in question.
8. A section that provides an overview of the technical aspects of the unit (e.g., the problem, the context, the science principles).
9. A letter describing a problematic scenario from a fictitious company.
10. Lesson plans, student handouts, and assessment tools.

Pedagogical Elements

The design of the instruction is very comprehensive and detailed. Attention is given to the following things.

- Justifying lessons with a modest rationale.
- Supporting the teacher's content knowledge.
- Using volunteers from business and industry.
- Managing materials, activities, and students..
- Using cooperative learning strategies.
- Anticipating problems students are likely to encounter.
- Engaging students in scientific inquiry.
- Conducting class discussions.
- Preparing for lessons (e.g., materials, props, examples).
- Implementing lessons in a sequential manner.
- Processing learning activity materials to obtain the best results.

Maturity

1996 - The *Motorized Toy Car* (Challenge 2) was introduced as a supplemental middle school curriculum.

1998 - The *Glider* (Challenge 3) was introduced as a supplemental middle school curriculum.

Diffusion & Impact

- It is utilized in all 50 states and in 10 of Canada's 13 provinces/territories.
- Over 60,000 AWIM kits have been shipped to schools since 1990.
- It is estimated that over 3.75 million students across North America have participated in AWIM programs.

More than 15,000 volunteer engineers have been involved in AWIM programs.

Initiative *A World in Motion®*

Title

Motorized Toy Car

Grade Levels 7

Broad Goals

Under the heading of "Science," the materials cite the following objectives.

- Students begin to develop an understanding of acting on moving by exploring the design of a moving toy.
- Students extend their understanding of simple machines through their explorations of gears, axles, wheels, and motors.
- Students begin to understand the differences between science and technology by developing the ability to use technological design processes and skills.

Under the heading of "Mathematics," the materials cite the following objectives.

- Students extend their understanding of rates and ratios as a relationship between numbers.
- Students systematically collect, organize, and describe data; draw graphs; and develop an appreciation for statistical methods as decision-making tools.
- Students use physical materials to build conceptual development of algebraic variables and relationships.

Under the heading of "Technology Education," the materials cite the following objectives.

- Students use development and use production processes to solve a technological design problem.
- Students learn to create design briefs, sketches, and models.
- Students explore properties of materials in designing a product.

Under the heading of "Social Studies," the materials cite the following objectives.

- Students develop research skills through conducting interviews and gathering data on consumers.
- Students develop marketing skills through an understanding of consumer needs.

Under the heading of "Language Arts," the materials cite the following objectives.

- Students develop writing skills through a variety of writing products, such as design logs, journals, and proposals.

- Students develop oral language skills through the preparation and execution of formal presentations.
- Students develop communication skills through performing collaborative tasks with their peers.

Salient Concepts & Skills

Math	Science	Technology
• ratio • multiplying fractions • metric units of measurement • organizing data • interpreting data • graphing	• speed • force • Newton • torque • Newton meters	• gears • axle • collar • sprockets • drive gear • driven gear • compound gear trains • chassis • motor • model • prototype

Engineering

The following concepts are related to the study of engineering:

- Design Brief

Prominent Activities

During the goal-setting phase of the design process (pages 1 to 42), students perform the following activities.

1. Read, analyze, and discuss a request for proposals from a fictitious manufacturing company that is looking for a new design and prototype for a motorized gear driven toy.
2. Talk to an engineer (a guest speaker) about the nature of engineering design, working in design teams, and maintaining a design log.
3. Research the kinds of work engineers do and interview other engineers about the nature of design.
4. Form design teams, discuss how to work in teams, and define roles for team members (e.g., equipment manager, design manager, construction manager, recorder).
5. Collect and present example of company logos, icons, and slogans from magazines and newspapers.
6. Identify, discuss, and analyze the nature and use of company logos, slogans, and icons.
7. Design a logo and slogan for their design team (e.g., brainstorming, sketching, selecting).
8. Review and discuss an example of a “design log entry” (e.g., what does it say, what is the problem being addressed, what kind of information is recorded, why was this entry made, why would one record ideas that do not work, what role does it play in an engineer’s work).

9. Discuss things that need to be recorded during the design process (e.g., plans, decisions, assumptions, tests, data, questions, ideas, discoveries).
10. Review the request for proposals and determine who is going to buy the toy, what they might want from the toy, what they already know about the consumer, and how to gather more information.
11. Review the request for proposals and determine what needs to be made, what does the company want, what needs to be shown to the company, what needs to be done, what resources are available, etc.
12. Define the objectives that need to be achieved and the criteria that will be used to determine how well they are achieved.
13. Develop a list of tasks that have to be performed to fulfill the request posed in the letter.
14. Assign roles to be played by specific members of the design teams.

During the knowledge-building phase of the design process (pages 43 to 176), students perform the following activities:

15. Analyze a bicycle to explore how gears can be used to change speed and torque (e.g., what sprocket combination would result in the fastest speed? How far would a bicycle travel with each rotation of the pedals? What sprocket combination would be best for climbing a hill?).
16. Plot a web diagram illustrating what they already know about gears (e.g., what do they look like, what are they used for, what kinds of machines use them).
17. Examine simple devices that use gears (e.g., where are they used, what do they do, why are they being used).
18. Use the materials provided (e.g., frame, gears, axles, collars) to explore how different combinations of gear can change the rate and direction of rotation.
19. Build different gear chains, draw each gear chain, determine the number of teeth on each gear, and count the number of revolutions of each gear.
20. Determine the gear ratio associated with different gear chains based on gear rotations (gear ratio = number of rotations of the drive gear versus the number of rotations of the driven gear) as well as the number of teeth on each gear (gear ratio = number of teeth on the drive gear versus the number of teeth on the driven gear).
21. Use the formula for determining gear ratios to calculate unknown values based on given values (e.g., if the drive gear has 15 teeth and the gear ratio is one to four, how many teeth on the driven gear? How many rotations of the driven gear

based on one rotation of the drive gear? How many rotations of the driven gear?).

22. Calculate ratios based on the diameter and circumference of wheels and gears (e.g., circumference versus diameter, diameter versus the number of teeth, number of teeth versus rolling distance).
23. Learn how to build and troubleshoot gear chains that include a motor and wheels.
24. Build motorized test vehicles with given gear ratios and use them to gather data regarding their performance (e.g., speed over three meters, force measured of the wheel).
25. Discuss compound gear chains that feature more than one gear on an axle.
26. Build and test compound gear chains and determine gear ratios.
27. Measure the performance of test vehicles that feature compound gear chains (e.g., speed over three meters).
28. Use fractions to calculate the overall gear ratio in compound gear chains.
29. Investigate the relationship between drive gear size and the amount of force produced (e.g., predict the force for three sizes of drive gear, measure the force produced by three sizes of drive gears, plot the relations on a graph).
30. Determine the amount of torque produced by three different drive gears by multiplying the lever arm of each gear (the radius of the gear) times the force it produced.
31. Review and discuss what has been learned about gears thus far and how the knowledge might be used to design motorized and gear driven toys (e.g., gear ratios, rotational speed, compound gears, gear ratios and torque, gear ratios and speed).
32. Explore how different materials can be used to make a body for toy vehicles that are strong, durable, and aesthetically pleasing.
33. Discuss how information from potential consumers (or users) can be used during the design process.
34. Develop a series of interview questions to gather information about the appearance and performance characteristics of a motorized toy.
35. Conduct interviews of children or parents of children using the questions and forms they developed.
36. Survey parents and children to gather additional information about potential consumers and the features their toy should have.
37. Organize the data from the surveys, tally the responses, calculate percentages, and make charts and graphs.
38. Analyze the results of the survey and describe how they can be used to make decisions about the design of motorized toys.

During the design phase of the design process (pages 177 to 192), students perform the following activities:

39. Review and discuss the information gathered thus far (e.g., expectations defined in the request for proposals; the nature of gear ratios, torque, and speed; the nature of toy consumers)
40. Compose design briefs that define the specifications for the toy in question (e.g., type of toy, features, appearance, performance, materials).
41. Design a gear train for a prototype toy based on the performance specifications outlined in the design brief (e.g. speed, climbing ability).
42. Develop drawing for the body that will be place over the vehicle drive train (e.g., orthographic drawings, three-dimensional drawings, color illustrations).

During the building and testing phase of the design process (pages 193 to 208), students perform the following activities:

43. Build a prototype based on the drawing made for the gear train that will meet the performance specifications outlined in the design brief.
44. Test the prototype to determine how well it addresses the design specifications for vehicle performance.
45. Compose a report that describe the test performed and report the data in written, numeric, and graphic form.
46. Interpret the test data to determine if the performance specifications have been met, the factors that are impeding performance (if any), and what changes need to be made to bring the design within specs (if any).
47. Conduct focus group evaluations of the body designs and report the findings in written form.

During the model finalizing phase of the design process (pages 209 to 248), students perform the following activities:

48. Use simple materials (e.g., cardboard) to make a mock-up of the body that will be placed over the vehicle's chassis and drive train.
49. Construct the body that will be placed over the vehicle's chassis and drive train based on the drawings, the consumer survey findings, the nature of the materials selected, and the mock-up designs.
50. Mount the body on the chassis and conduct tests to determine if it still fulfills the specifications outlined in the design brief.
51. Review the request for proposals to determine what needs to be included in the final proposal.
52. Discuss what tasks need to be done to complete the written proposal as well as what tasks need to be done to prepare the

verbal presentation.

53. Outline and compose the written proposal (e.g., an introduction of the team, a description of the team's design, a description of how the team addressed the challenge, a summary of the work performed, a summary of the market research).
54. Compose resumes that can be included in the final proposal (e.g., demographic information, hobbies and interests, experience with design).
55. Prepare an oral presentation that introduces the team members, describes the team's design, explains how the team addressed the challenge, summarizes the market research, demonstrates how the prototype performs, and makes an argument in favor of the team's design over others.

During the presentation phase of the design process (pages 249 to 258), students perform the following activities:

56. Present their final designs to their peers and a panel of reviewers.
57. Discuss the engineering process and review the activities the performed during each phase.
58. Reflect upon each phase of the design process as well as the interdisciplinary nature of engineering design (the use and role of mathematics, science, social studies, language arts, technology, and art).

Initiative *A World in Motion®*

Title **Gliders**

Grade Levels 8

Broad Goals Under the heading of "Science," the materials cite the following objectives.

- Students begin to develop an understanding of the relationship between forces acting on objects and their motion, and that the relative strength and position of forces determine the motion of an object.
- Students begin to develop an understanding of the effects of the interaction of forces of weight and lift on the flight of a gliding toy.
- Students learn to use diagrams to express the strength and position of forces.
- Students conduct formal scientific experiments to control for a single variable.
- Students begin to understand the effects of changing a single variable, to investigate the interrelationship of two variables, and to appreciate the concept of dynamic equilibrium.
- Students begin to understand the differences between science and technology by developing abilities to use technological design processes and skills that apply scientific knowledge.

Under the heading of "Mathematics," the materials cite the following objectives.

- Students systematically collect, organize, and describe data; draw graphs; search for patterns in data; and make predictions and inferences based on data.
- Students investigate the optimization of two variables.
- Students develop an appreciation for statistical methods as decision-making tools.
- Students use concrete materials to build conceptual development of algebraic variables and relationships.

Under the heading of "Technology Education," the materials cite the following objectives.

- Students develop and use production processes to solve a technological design problem.
- Students learn to create design briefs, sketches, and models.
- Students explore properties of materials while designing a

product.

Under the heading of "Language Arts," the materials cite the following objectives.

- Students develop their writing skills by creating written products, such as design logs and instructions.
- Students design a book.
- Students communicate technical information to a specified audience.
- Students develop communication skills through collaborative tasks with their peers.

Under the heading of "Social Studies," the materials cite the following objectives.

- Students analyze data on consumer preferences.
- Students design and use instruments to gather consumer data.
- Students develop marketing skills by investigating customer needs.

Salient Concepts & Skills

Math

- metric units of measurement
- collect, organize, analyze, and interpret data
- measures of central tendency
  - range
  - median
  - mean
  - mode
- frequency counts
- percent
- ratio
- angles
- cross-tabulations
- graphs
- compare subsets of data (boy versus girls)
- making inferences from data
- assessing data
- finding averages
- identifying patterns

Science

- weight
- drag
- Newton's laws of motion
- equilibrium
- dynamic equilibrium
- acceleration
- weight
- terminal velocity
- forces acting on a projectile
- lift
- angle of attack
- air flow
- air pressure
- low air pressure
- high air pressure
- stall
- relationship between lift and speed
- relationship between life and wing area

Technology

- glider
- wing
- camber
- uncambered wing
- wind tunnel
- vertical stabilizer
- horizontal stabilizer
- elevator
- control surfaces
- rudder
- ailerons
- positive setting angle
- neutral setting angle
- wing loading (weight the wing must support divided by the area of the wing)
- bank (turning an aircraft)
- control surface
- pitch

- making predictions
- linear relationships between variables
- inverse relationship between variables
- hyperbolic curve
- interpolate
- curve fitting (drawing smooth lines or curves to plot relationships)
- area
- span
- scale
- wing load
- balance
- center of gravity (a.k.a., center of balance, center of mass)
- relationship between center of gravity and lift
- thrust
- glide angle
- glide ratio
- momentum
- yaw
- delta wing
- flight path
- fuselage
- leading edge
- propulsion
- roll
- trailing edge

Engineering

The following concepts are related to the study of engineering:

- The "engineering design experience begins with a challenge" (p. 4).
- Real engineers typically work in design teams that address projects assigned by their company.
- Engineers consider more than appearance in their work.
- Design means to "plan very completely what they are going to build before they build it" (p. 5).
- Engineers must consider the needs that the object will address.
- Engineers must consider "how it will be used, who will use it, what materials will be used in building it, how much it will cost to manufacture and to buy, and its impact on the environment and on social relationships' (p. 5).
- Recognizing "all manufactured things… were designed by people" and everything "started out as an idea" (p. 5).
- "People who design airplanes are called aeronautical engineers" (p. 5).
- The design process goes through several phases that include setting goals, building knowledge, designing, building and testing, finalizing the model, presenting, and assessment.
- Engineering work is very creative and engineers must use knowledge from other fields to design things.
- Maintaining accurate records in an important part of the design process (e.g., ideas, notes, drawings, data, reflections).
- One of the challenges in engineering design is to develop a product that addresses the preferences and needs of its users.
- Engineers frequently need to use quantitative relationships between variables to make predictions.
- "Mathematical analysis is essential in designing full-size

aircraft, for which the balance points cannot easily be measured" (p. 194).

- Engineers draw straight line and curves to represent relationships between variables on a graph even if it misses a few data points (a.k.a., curve fitting).
- Design engineers have to account for constraints that are placed on the design.

Prominent Activities

During the goal-setting phase of the design process (pages 1 to 38), students perform the following activities.

1. Read, analyze, and discuss a letter from a fictitious publishing company that wants to produce a book of design for toy gliders.
2. Explore the meaning of the word design from an engineering point of view (e.g., more than appearance, involve careful planning, human-made things are designed).
3. Learn basic phases of engineering design (i.e., set goals, build knowledge, design, build and test, finalize the model, present, assess).
4. Write a paragraph about what they had to consider while designing a manufactured object.
5. Review the materials that will be available to design, build, and test glider designs.
6. Look at examples of children's books about gliders.
7. Discuss the nature of the challenge (e.g., what needs to be produced, what resources do we have, how will we know we are successful).
8. Brainstorm the kinds of things that they will need to do in order to address the challenge (developing a book of glider designs for children).
9. Develop a list of tasks that have to be performed to fulfill the request posed in the letter.
10. Identify the resources needed to complete each task.
11. Form design teams, discuss how to work in teams, and define roles for team members (e.g., equipment manager, design manager, construction manager, recorder).
12. Collect and present examples of company logos, icons, and slogans from magazines and newspapers.
13. Identify, discuss, and analyze the nature and use of company logos, slogans, and icons.
14. Design a logo and slogan for their design team (e.g., brainstorming, sketching, selecting).
15. Meet an engineer and hear about how engineers do design, the importance of working in teams, and the role of keeping detailed records.
16. Research the kinds of work engineers do, interview other

engineers about the nature of design, and write a thank you note to the guest speaker.

17. Review and discuss an example of a "design log entry" (e.g., what does it say, what is the problem being addressed, what kind of information is recorded, why was this entry made, why would one record ideas that do not work, what role does it play in an engineer's work).
18. Discuss things that need to be recorded during the design process (e.g., plans, decisions, assumptions, tests, data, questions, ideas, discoveries).

During the knowledge-building phase of the design process (pages 39 to 266), students perform the following activities:

19. Identify things that fly and discuss the characteristics of things that fly.
20. Identify things that glide and discuss the characteristics that enable them to glide (e.g., heavier-than-air, light in weight, no propulsion system, large wings).
21. Develop an operational definition for "gliding."
22. Generate data by answer simple survey questions (e.g., How many times have you been to an airport? Have you ever made a paper airplane?).
23. Develop cross-tabulation tables to divide the data into subsets and make comparisons using frequencies and percentages.
24. Make appropriate tables to represent the data collected in the survey.
25. Interpret what the data means (e.g., What is the range and what does it tell us about the sample?)
26. Discuss the concept of a "target market" and its role in designing and redesigning products.
27. Discuss the strategies used to collect information from groups of consumers and potential consumers (e.g., sales records, telephone surveys, mail surveys, interviews, warranty registration cards).
28. Identify target markets based on the information presented in advertisements and product brochures.
29. Identify and discuss important details regarding the target market for a children's book about gliders (e.g., interests).
30. Study the data and findings presented in a given market research report that features information about child development, spending habits of children, respondent demographics, experience making toys from directions, experience making flying toys, etc.
31. Use the data presented in the market research report to describe a target market for a book about gliders.
32. Identify design strategies that will address the needs and

preferences of the target market.
33. Conduct additional market research to gain additional information about the target market (e.g., develop questions, identify methodology, collect and interpret data, report findings).
34. Sketch potential designs for model gliders and select the best design for making a model.
35. Build a model glider based on a drawing using the materials provided (e.g., polystyrene foam, balsa, modeling clay, rubber bands, tape).
36. Work in teams to conduct test flights of their gliders (e.g., launcher, retriever, recorder).
37. Make and record observations about their glider flight path.
38. Make modifications based on observations in order to improve their glider's flight path and to uncover cause and effect relations related to their glider's design.
39. Prepare a report describing their glider's design, performance, and modifications.
40. Present their preliminary glider designs to the class (e.g., inspiration, expectations, problems, modifications, future changes).
41. Conduct and observe demonstrations of preliminary design models to uncover features that aid or inhibit flight performance (e.g., size, wing placement, weight, weight distribution).
42. Redesign preliminary models, modify their preliminary model to reflect the revised design, and test their new designs.
43. Interpret and present the results of their redesigning process to the class.
44. Build and test a "standard model" to determine the effects that changes in wing placement, stabilizer adjustment, and weight placement have on flight performance.
45. Interpret and present the results of the testing process (e.g., configurations tested, identification of the best configuration, best launching technique).
46. Identify the characteristics that effect flight performance (e.g., weight of clay, position of the clay, position of the wing, position of the stabilizer assembly, amount of thrust applied with the rubber band launcher).
47. Design experiments to test one variable at a time while holding all the other variables constant.
48. Conduct test flights based on the modification of one variable (e.g., flight distance versus nose weight, flight distance versus wing position).
49. Record glider specifications (i.e., weight at the nose, nose to wing distance, nose to stabilizer distance, the amount of stretch

applied to the rubber band launcher) and record the flight path and distance.

50. Use basic statistics to interpret the data collected during test flights (e.g., assess the quality of the data, calculate averages, graph averages, identify patterns, make predictions).
51. Identify forces acting on a glider that is simply held in the air in a static position, predict how the glider will behave if released, and describe the behavior of the glider when it is released (dropped) from a static position.
52. Find their glider's center of gravity using a pushpin and string.
53. Explore and discuss how the center of gravity is affected by changes in weight and how it affects flight.
54. Predict and test effects of wing position relative to the center of gravity (e.g., fly level. pitch upward, pitch downward).
55. Develop graphs that illustrate the relationship between the center of gravity of a glider relative to its nose weight and wing position (e.g., increasing nose weight decreases the distance between the center of gravity and the nose, decreasing the nose weight increases the distance between the center of gravity and the nose, increasing the distance between the nose and the wing increases the distance between the nose and the center of gravity proportionally).
56. Use the graphs to make predictions (e.g., optimal location for wind over the center of gravity given a specific nose weight).
57. Conduct a series of experiments to determine the effect the launching force (the amount of thrust applied to the glider by virtue of how far the rubber band is stretched) has on a glider's flight distance and the flight path.
58. Discuss how the optimal launcher force (how far the rubber band is stretched) is dependant on other variables (i.e., light weight gliders with large wings need less thrust, heavy gliders with small wings need more thrust).
59. Determine, compare, and contrast the mathematical properties of different wing shapes (e.g., cord: the distance from the front to the back of the wing, mean cord length: the average distance from the front to the back of the wing, aspect ratio: wing span divided by the mean cord length).
60. Discuss how wing properties like area, shape, span, cord, and aspect ratio might affect the flight path of a glider.
61. Design experiments to test wings configurations one variable at a time.
62. Test the impact of a given wing configuration on flight performance (i.e., flight distance, flight path).
63. Interpret and report finding regarding wing designs to the class.
64. Study basic concepts about graphic design (e.g., proportion, formal balance, informal balance, typeface, margins, white

space).
65. Analyze and discuss examples of page designs and develop a layout for their pages in the final book.
66. Introduce the concept of "dynamic equilibrium" (changing one thing changes everything else).
67. Propose adjustments to a glider that has a short flight path due to a heavy nose (e.g., remove weight, increase thrust).
68. Discuss how the setting for optimal weight, wing position, and launcher force are relative to one another.
69. Complete a table outlining how to adjust the variables associated with standard model based on it performance (i.e., pitches up, pitches down).

During the design phase of the design process (pages 267 to 290), students perform the following activities:
70. Read and study a letter that contains the requirements for the book that the students will develop (e.g., gliders must be adjustable, user must be able to change the center of gravity, instructions must be readable for children between the ages of 8 and 12).
71. Discuss the implications of requirements on the design of gliders and the development of the book.
72. Discuss the consumer's preferences regarding the appearance and performance of gliders as well as the continuity between the consumer's preferences and the publisher's expectations.
73. Compose a design brief that defines the characteristics of the gliders that they plan to design for the book in question (e.g., appearance, performance, materials, dimensions).
74. Develop detailed drawings of their designs that include features and dimensions.

During the building and testing phase of the design process (pages 291 to 304), students perform the following activities:
75. Build prototype gliders based on their engineering drawings (e.g., select materials, transfer dimensions from drawings to materials, cut out and assemble parts).
76. Test prototypes to determine if they meet the specifications outlined in their design briefs.
77. Troubleshoot and adjust the prototypes to improve their flight paths.
78. Continue the process of testing, evaluating, and adjusting (and possibly redesigning) until the prototypes fulfill the design specifications outlined in the design briefs.
79. Exchange prototypes and test them to determine if they will perform consistently for other people.

During the model finalizing phase of the design process (pages 305 to 346), students perform the following activities:

80. Plan the organization of the book that will feature their designs for gliders (e.g., title, cover design, table of contents, introduction, glider designs, glossary of terms).
81. Assign responsibilities to individuals (e.g., table of contents, introduction, glossary, building instructions, drawings, flying instructions, adjustment instructions, explanations).
82. Plan the production of the book (e.g., number of copies to be produced, covering the cost of paper and duplication, binding, distribution).
83. Study examples of published design instructions to uncover strategies for writing their own instructions (e.g., organization, use of numbering, contents, illustrations).
84. Compose instructions on how to build, fly, and adjust gliders using narrative and illustrations (e.g., naming their glider, listing tools and materials, providing an introduction, integrating words and illustrations, adjustment instructions, flight path drawings, explanations about flight, pre-flight checklist).
85. Develop scale drawing that can be included in the instructions and enlarged by the reader and used as templates to make gliders.
86. Present and demonstrate the final designs to the class (e.g., design brief specifications, technical drawings, consumer data, test flight results, reflections about the process).

During the presentation phase of the design process (pages 347 to 365), students perform the following activities:

87. Conduct a “book signing” event for peers, parents, and guests that features displays, presentations, demonstrations, and autographing.
88. Reflect upon each phase of the design process as well as the interdisciplinary nature of engineering design (the use and role of mathematics, science, social studies, language arts, technology, and art).

Initiative *A World in Motion®*

Title **Electricity and Electronics** (middle school)

Grade Levels 7-8

Broad Goals To…

- Discover how circuits and electricity can be used and controlled to create different functions.
- Explore terms used in electric circuits and how measurements and mathematics can be used to calculate the action of different circuits.
- Introduce Ohm's law and Kirchoff's law to calculate voltage, resistance, and current flow.
- Discover terms such as series, parallel, series-parallel, open, closed, and short.
- Explore both a drawing and a schematic diagram of the experiment.
- Demonstrate electromagnetism and explore terminology associated with magnets and electromagnets.
- Duplicate Hans Christian Oerstead's original experiment that led to the development of the science of electromagnetism.
- Introduce Lenz' law and Faraday's law.
- Discover terms such as magnetic flux, lines of forces, magnetic fields, poles, ferromagnetic retentivity, hysteresis, induction, and saturation.
- Include both pictorial and schematic diagrams of the experiments.
- Demonstrate an introduction to transistors and electronics.
- Explore terminology associated with transistors.
- Introduce active circuits.
- Discover terms such as semi-conductor transistor, emitter, base, collector, bias, correct basing, alternating current, and oscillation.

Salient Concepts & Skills

Math

- algebra (using simple algebraic equations to solve for unknown values given to two known values)
- units of

Science

- Ohm's law
- Kirchoff's law
- lodestone
- magnetism
- line of flux
- induction
- electromagnetism

Technology

- circuit
- series circuits
- parallel circuits
- series-parallel circuits
- breadboard
- fuses

measurement
- tolerance

- retentivity
- paramagnetic
- diamagnetic
- direct current
- alternating current
- resistance
- voltage
- current
- torque

- light emitting diodes (LEDs)
- coil
- electromagnet
- circuit breakers
- using a multimeter
- semiconductor
- buzzer
- solenoid
- galvanometer
- semi-conductor
- integrated circuits
- silicon chip
- n-type materials
- p-type materials
- p-n junction
- transistor
- bi-polar transistor
- NPN device
- PNP device
- emitter
- base
- collector
- bias
- forward biasing
- reverse biasing
- correct basing
- oscillation
- electric motor
- commutator

Engineering

This unit focuses on introducing basic domain knowledge regarding the nature of electricity and electronics.

Prominent Activities

1. Read about how a breadboard works.
2. Read about Ohm's law, Kirchoff's law, series circuits, and parallel circuits.
3. Construct a series circuit featuring six resistors, measure individual resistors using a multimeter, calculate total resistance, measure total resistance, and compare calculated and measured resistance.
4. Construct a series/parallel circuit featuring six resistors, measure individual resistors using a multimeter, calculate total resistance, measure total resistance, and compare calculated and measured resistance.

5. Build a series/parallel circuit featuring LEDs, measure the voltage across each set of resistors and LEDs, and notice how voltage divides across the loads in a series circuit.
6. Build a “light sensor” that is essentially a series/parallel circuit that features an LED, several resistors wired in parallel, and light dependent resistor.
7. Take measurements at various points in the light sensor circuit and notice how changes in light result in changes in resistance and changes in the LED.
8. Build a “polarity detector” that is essentially a series/parallel circuit that features two LEDs.
9. Introduce voltage at various points in the polarity detector circuit and notice which LEDs light depending on the polarity of the power supply.
10. Build a “switched dimmer” that is essentially a series/parallel circuit that features an LED, a switch between two parallel branches with different resistances.
11. Notice how the intensity of the LED changes depending on the position of the switch and the amount of resistance in the selected branch of the circuit.
12. Build a “buzzer volume” control circuit that is essentially a series of resistors in line with a buzzer.
13. Introduce voltage at various points along the circuit and notice how increasing the resistance prior to the buzzer affects its volume.
14. Construct a simple electro-magnet and use it to create a working solenoid switch.
15. Wire and test a galvanometer using a coil, a compass, two resistors, and a power supply.
16. Build and test a simple electric motor.
17. Build and test a circuit featuring “flashing lights” using LEDs, resistors, capacitors, and transistors.
18. Take measurements at various points in the circuit to confirm the existence of alternating current and oscillation.
19. Build and test a “transistor LED driver” (a simple touch switch) using a transistor, an LED, two resistors, and a power supply.

Salient Observations

The Society of Automotive Engineers developed three units of instruction for the middle grades that enable teachers and students to apply mathematics, science, and technology. The first unit is framed in the context of designing a motorized and gear driven toy car. It was developed with seventh-grade students in mind. The second unit focuses on designing toy gliders and it was written for eighth grade students. Both units deal with designing and testing simple model vehicles that need to perform in accordance with the design specifications that are outlined in research and development scenarios. Furthermore, these two units are very similar in composition, format, and pedagogical approach.

The third unit of instruction addresses basic principles of electricity as well as the components used to make electrical devices and circuits. The *Electricity and Electronics* materials (a.k.a., *Challenge 4*) are organized and presented in a different format. In contrast to engaging students in engineering design, most of the attention is on making and testing simple electrical devices and circuits in accordance with sets of directions. These learning activities are more demonstration-based than design-based. The treatment of engineering is limited to building domain knowledge. Therefore, the following discussion will focus primarily on the *Motorized Vehicle* unit (a.k.a., *Challenge 2*) and the *Gliders* unit (a.k.a., *Challenge 3*).

Engineering

Overall, the design challenges in *Motorized Vehicle* and *Gliders* engage students in scientific inquiry in conjunction with doing engineering design. They both incorporate aspect of engineering that include the need for collaboration within a design team, the applications of science and mathematics in solving problems, and the use of models and modeling as sources of data for making design decisions.

Both units engage students in engineering-like experiences by having them conduct detail analyses, document their investigations and design processes, and communicate their designs with drawings, narratives, and presentations. However, very little attention is directed toward engineering concepts and the nature of engineering in the *Motorized Vehicle* unit. Most of the emphasis in this unit is on the concept of ratios as a relationship between numbers, the science and technology of gear trains, and the role of inquiry in making design decisions.

In contrast, the *Gliders* unit encourages teachers to provide students glimpses into the nature of engineering and the kinds of work that engineers do. These insights into engineering are typically followed by learning activities that engage students in analogous engineering tasks in an almost role-playing like way. For example, one of the lessons in *Gliders* states the following.

> Engineers frequently need to use a quantitative relationship between variables. When engineers know a quantitative relationship between two variables, they can calculate and predict, for example, the effect of a change in weight on the center of gravity, without actually balancing the aircraft every time. Mathematical analysis is essential in designing full-size aircraft, for which the balance points cannot easily be measured (p. 194).

This insight into the nature of engineering leads into an activity where students measure, graph, and discover the inverse relationship between the amount of weight applied to the nose of a glider and the location of the center of gravity along the body of the glider. They also have to gather, plot, and study similar data to determine the linear relationship between the center of gravity and the location of the wing along the body of the glider. Ultimately, in later lessons, they must use these interdependent relationships to configure their gliders and optimize their flight paths (the distance, direction, and duration of flight).

Despite the rich treatment of engineering in *Gliders*, the study of engineering was not a priority in the development of the materials. According to the project's director, Mathew Miller, the aim was to use engineering as a framework for delivering and enhancing the study of mathematics and science in the core curriculum. The curriculum's architects only intended to use an engineering approach to create rich and authentic situations for using math and science concepts and skills in practical and meaningful ways.

Both units also address the role that communication plays in engineering endeavors. This is substantiated by rich use of logbooks, technical drawings, narrative descriptions, written instructions, graphic design, and verbal presentations. In addition to be attentive to the needs of an audience, the materials frequently require students frame their communications in the context of the design specifications. For example, the narrative descriptions of the gliders have to account for the expectations outlined in the letter that came from "Mobility Press, Inc." Presentations of the glider designs during the "Book-Signing Event" also need to address how they address the design specifications.

Design

The *Motorized Vehicle* and *Gliders* units use a design process to structure and sequence the instruction and student learning activities. None of the lessons in the *Motorized Vehicle* unit actually target the nature of design. However, there are several lessons in *Gliders* that address the nature of design in a direct manner. More specifically, they ask the teacher to confront how design is commonly discussed in the context of something's appearance. Teachers are then asked to expand this concept by discussing how engineers must also address considerations to function, feasibility, and impact. More specifically, teachers pose a series of questions that help students think like engineers (i.e., who is it for, what needs will it address, how will it be used, what kinds of materials are needed to make it, how much will it cost to make, how much will it cost to buy, what kinds of impacts might it have on the environment).

The *Motorized Vehicle* and the *Gliders* units use a design process that features six phases. The first phase deals with setting goals based on the review of a problem that is presented in a scenario. In both cases, the problem is introduced in the form of a letter from a toy company (i.e., Mobility Press, Inc., Mobility Toys, Inc.). The contents of the letters outline the problems that need to be solved, the specifications for the final solutions (e.g., features, performance), and the expectations for presenting the final designs.

The second phase is, by far, the longest and the most detailed step in the design process. It begins with building a model and using it to figure how it works. This task is followed by a sequence of activities that require the manipulation of one variable at a time and determining its effect on their vehicle's performance (e.g., stability, direction, distance). In this context, the models provide the data needed to uncover the scientific factors as well as the technological features that effect vehicle performance.

In phase three, students use the data gathered and the knowledge gained during the previous phase to design their vehicle, to plan its construction, and to predict its performance. This phase involves making drawings as well as describing and justifying the design features.

Phase four is all about building and testing the vehicles (the motorized cars, the gliders). The building and testing enables students to observe directly how their integration and application of scientific principles and engineering design influence vehicle performance.

The fifth phase asks students to take what they learned during the building and testing phase to make the final product. In the case of *Gliders*, the students need to compose an entry for a book on gliders. In the *Motorized Vehicle* unit the students must prepare a proposal for a new toy. This stage is about bringing everything together into one package.

The last phase, number six, engages students in preparing and giving presentations to an audience. In addition to showing and explaining their designs, student must demonstrate how their model performs in accordance to expectations. The student presentations have to include how their design addressed the design specifications present in the original problem, how their vehicle's design translates into performance, and what they learned during the course of the design process (e.g., how gears work, how aircraft fly, how to design solutions to problems).

Analysis

The analysis process in both units starts the problem. The *Gliders* unit asks students to read a letter from a publisher requesting designs that can be featured in a book. The *Motorized Vehicle* unit has students study a "Request for Proposals" from a toy manufacturing company. In both cases, the scenarios outline the specifications for the final products and the analysis of the problem requires little more than basic reading comprehension.

Analysis receives a much stronger emphasis during the process of "Building Knowledge," the second phase in the design process. During this phase, the materials blend scientific inquiry with engineering design in an almost symbiotic way. It would be easy for teachers to recognize the concepts and skills that are consistent with doing inquiry in the name of teaching science. This is especially evident with the emphasis that is placed on testing only one variable at a time (e.g., weight applied to the nose of the glider, the location of the wing on the glider). The testing process includes formulating hypotheses, conducting tests, making observations, collecting data, and making inferences based on evidence.

It is also easy to recognize concepts and skills from an engineering perspective. This is because the inquiry in question focuses on human-made objects under the auspices of solving a specific problem based on a given set of design specification for a viable solution. One of the core concepts embedded in the analysis is finding the optimal vehicle design among competing variables (e.g., location of the wing on the glider, the amount of weight applied to the nose of the glider, the glider's center of gravity).

The materials alert teachers that engineers need to predict how a design will perform before it is built. Thus, all of the investigations inform the design characteristics of the final vehicles before they are made.

Analysis is also an integral part of the design, building, and testing processes in third and fourth phases of the design process. Here the emphasis is on addressing the design specifications and using test data to inform design decisions, to make modifications, and to refine designs.

Constraints

The concept of constraints is not one of the main ideas presented in the units of instruction. More specifically, it cannot be found in the objectives, the glossary of terms (in *Gliders*), the lesson plans, the learning activities, or the evaluation tools. However, the investigations that students conduct do uncover many of the natural variables that govern vehicle performance (e.g., friction, forces, weight). Furthermore, constraints are intrinsic to the activities in light of the materials provided for the fabrication of vehicles and the amount of a time allotted for conducting investigations and designing vehicles. Despite these opportunities to address the concept of constraints in an overt manner, its treatment is rather subliminal.

The correspondence from the fictitious companies outline the expectations for the final designs. For example, in the case of the *Motorized Vehicle* unit, students have to design a gear train that will enable a model car to travel a given distance (three meters) in a given period of time (three seconds), climb a given slope (30 degrees) for a given distance (one meter), or climb a given slope (15 degrees) over a given distance (1 meter) in a given amount of time (2 seconds). In the case of the *Gliders*, the final product, a narrative for a book, needs to present a glider design that is constructed out of given materials (polystyrene foam and balsa sticks), featuring interesting shapes, and adjustments that alter flight performance (aerobatic stunts). Although these expectations influence the vehicle design, they are more consistent with the concept of design specifications than constraints.

Modeling

The concept of models and modeling is not among the core concepts being addressed in these materials. However, models play integral roles in both units of instruction. They enable students to visualize their design ideas in a tactile and concrete manner. However, most of the attention is on using models to discover basic laws of nature (e.g., mechanical advantage, center of gravity). Furthermore, from an engineering point of view, the models that students build and test provide the data needed to make informed design decisions. This application of models is consistent with how modeling is used in many engineering contexts. The use of physical models is very appropriate given the age and development of the population being served.

The *Gliders* unit features a modest treatment of mathematical modeling. More specifically, students are required to graph the location of the center of gravity in relation to the amount of weight added to the nose of the glider. The graph is subsequently used to illustrate an inverse relationship that can be represented by an algebraic equation ($P = a/(W=b)$). Furthermore, the graph is also used to predict optimal flight performance by defining the appropriate nose weight that locates the center of gravity closest to the centerline of the wing. The same line of inquiry is used to establish the linear relationship between a glider's center of gravity and the location of the wing. Once again, the graph is used to predict the location of these variables for the optimal flight performance.

Optimization

Optimization plays an integral role in the *Motorized Vehicle* unit and the *Gliders* unit. However, the concept of optimization is more embedded in these activities than it is formally targeted. The word optimization is only used a few times in the narratives. It is not addressed in the objectives, the glossary of terms, the laboratory handouts, or the evaluation tools. Despite its absence, in many ways, optimization is part of the essence of these activities.

Both of the units ask students to balance the trade-offs between competing variables. The sequence of investigations and analysis in the *Motorized Vehicle* unit leads to making a vehicle that strikes a balance between a gear ratio that maximizes torque and gear ratio that maximizes speed. The *Gliders* unit requires finding the best glider configuration based on wing placement, the amount of weight on the nose, and the glider's center of gravity. In both cases, mathematics plays a critical role in determining the optimal balance between variables that intrinsically interact with one another. In both cases, the results of the mathematical determinations can be validated through testing. However, it is important to note that these units do not formally call attention to the fact that the students are using mathematical models in pursuit of the optimal design in a manner that is analogous that used by engineers. Instead, the emphasis is on uncovering and applying science and math principles in the context of doing inquiry.

Systems The lessons do not address the concept of systems and systems thinking in a direct manner. More specifically, they are not salient themes in the objectives, glossary of terms, lesson plans, or assessment tools. However, they are embedded in both units of instruction. For example, technological systems are often described as collections of things that work together in interdependent ways to do work. The concept of interdependence among parts is examined in the *Gliders* unit. One lesson asks teachers to introduce the concept of "dynamic equilibrium"– changing one thing in a system changes everything else. Students discover changing the weight on the nose of a glider alters the center of gravity and moves the optimum location for the wing. Inversely, adding or subtracting weight at the nose of the glider can counter the effects of changing the location of the wings in relation to the center of gravity.

In the case of the *Motorized Vehicle* unit, systems and systems thinking is intrinsic to mechanisms. Gear trains have inputs and outputs. A given amount of force (or speed) is applied to one gear and a different amount of force (or speed) is produced by another, as long as they are connected to one another. The gears in a gear train are interdependent on one another. A failure or misplacement of any gear in the gear train compromises the whole system. However, the emphasis in this unit is on the science and mathematics associated with gear trains and little attention is given to the nature of systems.

Science The science content in *Motorized Vehicle* and *Gliders* addresses concepts related to force, motion, torque, and speed. Furthermore, these ideas are applied to the design of vehicles that address a problem and fulfill design criteria. The design process requires students to recognize the roles that these scientific concepts play in vehicle design and performance. Furthermore, the incremental and detailed nature of the investigations make it very difficult to gloss over these concepts and simply pursue success through tinkering and trial and error. Attending to the science is an integral part of the design process in both units.

The treatment of science also includes the development of inquiry skills. More specifically, the instruction and learning activities engage students in formulating questions; designing investigations; controlling variables; gathering, organizing, and analyzing data; interpreting evidence; and communicating results. In the case of the *Motorized Vehicle* unit, the focus is on determining relationships between force and distance. Similarly, in *Gliders* the purpose of the inquiries are to explore how the center of gravity, along with other variable, effect flight. Both units are very focused in their treatment of specific science concepts and skills. More specifically, the students study a limited number of ideas over an extended period of time in a manner that progresses from simple to complex. The same can also be said for the role inquiry plays throughout the units. In other words, the emphasis is clearly on depth in contrast to breadth when it comes to science content.

Mathematics

The mathematics in these units includes things like measuring distance and time, organizing data in tables and graphs, interpreting patterns within data, and using data to make design decisions. Given the grade levels being addressed, the amount of mathematical reasoning is relatively sophisticated. There is an interdependent relationship between the mathematics being performed, the nature of the scientific investigations being conducted, and the engineering decisions that need to be made to configure the optimum design. For example, in the *Motorized Vehicle* unit, students must apply the concept of ratios to strike a balance between torque and speed to achieve design specifications. The *Gliders* unit calls for the representation of relationships between variables in the form of verbal statements, line graphs, and algebraic equations to achieve desired flight paths.

Technology

Both units address the need to develop domain knowledge. A lot of attention is placed on technical vocabulary (e.g., the names of gears in a gear train, the anatomy of gliders). The attention given to vocabulary is appropriate given the need to develop a common language for designing, building, testing, describing, and discussing the two types of vehicles and how they perform. Virtually all of the terms introduced are tied to their function in the design of a vehicle (i.e., motorized cars, gliders). Furthermore, there is a mutually dependent relationship between the science and the technology. The concept of a drive gear, driven gear, gear ratio, force, speed, and direction are networked together to form a holistic body of knowledge. The same can be said for ideas about lift, drag, thrust, gravity, center of gravity, wing placement, nose weight, and glide angle in the context of gliders.

Treatment of Standards

The curriculum for *Motorized Vehicle* and *Gliders* appears to have embraced the idea forwarded by the National Research Council (NRC, 1996) that middle school students could conduct scientific investigations in conjunction with activities that are meant to meet a human need, solve a problem, or develop a product. As a result of these activities, students should develop abilities in the area of technological design and come to understand the nature of science and technology. According to the NRC (1996), the skills in question should include the ability to identify an appropriate problem for technological design, to design a solution or a product, to implement a proposed design, to evaluate completed designs or products, and to communicate the process to others. The only skill that was not cited in the materials was the ability to "identify appropriate problem for technological design." The other attributes were presented in the margins along side the goals of each unit of instruction. The abilities outlined in the standards can be correlated with the salient theme embedded in the curriculum's goals.

It is important to note that the materials have the potential to address other sets of standards that address concepts related to math, design, systems, models, and communication. For example, the units could be use to address the following standards from *Benchmarks for Science Literacy* (1993) by the American Association for the Advancement of Science.

- Engineers, architects, and others who engage in design and technology use scientific knowledge to solve practical problems
- Mathematical statements can be used to describe how one quantity changes when another changes.
- Thinking about things as systems means looking for how every part relates to others.
- Inspect, disassemble, and reassemble simple mechanical devices and describe what the various parts are for; estimate what the effect that making a change in one part of a system is likely to have on the system as a whole.
- Know why it is important in science to keep honest, clear, and accurate records.
- Organize information in simple tables and graphs and identify relationships they reveal.
- Read simple tables and graphs produced by others and describe in words what they show.

Pedagogy

The *Motorized Vehicle* and the *Gliders* activities start with problematic scenarios that are somewhat analogous to those engineers confront in a real company. In response to these problems, students are put into teams, they give their team a name, and they proceed with engineering a solution to the problem. Their process includes testing, experimenting, designing, and documenting their solution to problems throughout the development process.

The technical content knowledge required to address the challenges presented in the scenarios is explained in surprisingly detailed encyclopedia-like narratives. These narratives also describe the kinds of difficulties students are likely to encounter and outline the steps required to conduct the learning activities. As a result, teachers should be able to prepare for the lessons in an efficient and confidence-building manner.

The instruction in both units is very Socratic in nature. The materials are dominated by the use of questions to direct learning, to implement activities, to conduct debriefings, to assess understanding, and to facilitate student reflections.

A lot of emphasis is placed on collaboration. More specifically, the students have to working in teams to develop designs, to gather and synthesize information, to construct and test models, and to prepare presentations of their final designs.

Implementation

The materials provide rich recommendations for the following aspects of the curriculum's implementation.

- Utilizing volunteers
- Orchestrating design and scientific inquiry
- Establishing collaborative teams and encouraging teamwork
- Using, monitoring, and evaluating design logs
- Scheduling and managing the classroom activities
- Addressing mathematics through collecting, analyzing, and displaying data

Unlike most curricula, the curriculum and laboratory materials are free upon request. All teachers have to do is complete and submit a simple two-page form to the headquarters for *A World in Motion*®. The Society of Automotive Engineers (SAE), through its Foundation for Science and Technology Education, absorbs the cost of the materials.

Young Scientist Series

Institution Education Development Center, Inc.
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Funding National Science Foundation

Grade Levels Pre-kindergarten through kindergarten (ages 3-5)

Espoused Mission "The Young Scientist series makes science the work and play of exploring materials and phenomena, while providing opportunities for children to learn from that experience."

Organizing Topics There are three curriculum topics that are addressed in the *Young Scientist Series*. They are represented in the following titles:

- *Discovering Nature with Young Children*
- *Exploring Water with Young Children*
- *Building Structures with Young Children*

Building Structures with Young Children addressing engineering concepts and ways of thinking the most and thus, it is the focus of this analysis.

Format The *Young Scientist Series* consists of teacher guides, comprehensive professional development packages. The materials for *Building Structures with Young Children* includes two soft-cover books and a videotape.

Pedagogical Elements	• Hands-on science inquiry projects. • Teachers guide children's explorations to deepen their understanding of the physical science of building structures. • Teachers encourage the students to focus their observations and clarify their questions. • Open explorations that get the students to play with various building materials. • Focused explorations that give students more guidance in the context of solving a problem or meeting a challenge. • Teachers are trained to monitor student activities and asked questions about their work. • Teachers encourage students to discuss, express, represent, and reflect in order develop theories and understandings from their active work. • Teachers encourage students to learn from each other through “walkabouts” and “science talks.”
Maturity	The materials were field-tested across the nation in 2001 and 2002. The books were copyrighted in 2004 The video’s copyright is 2003.
Diffusion & Impact	A team of early childhood educators at the Educational Development Center, Inc., developed the *Young Scientist Series*. This project was nationally field tested from 2001-2002.

Initiative Young Scientist Series

Title

Building Structures with Young Children

Grade Level Pre-kindergarten through kindergarten

Broad Goals *Building Structures with Young Children* guides children's explorations to deepen their understanding of the physical science present in building block structures—including concepts such as gravity, stability, and balance. Children will do the following:

- Learn to build with a variety of different materials.
- Experience the ways forces such as gravity, compression, and tension affect a structure's stability.
- Build an understanding about how the characteristics of materials affect a structure's stability.
- Develop scientific dispositions including curiosity, eagerness to explore, an open mind, and delight in being a builder.

Salient Concepts & Skills

Math

Describing objects in terms of their
- shape
- size
- quantity
- patterns
- standard measurements
- non-standard measurements
- directionality
- order
- position

Science

Science concepts taught to teachers include
- gravity
- tension
- compression
- balance
- stability
- observations

Technology
- building
- structures
- tower
- walls
- foundation
- roof
- materials
- stories (of a building)

Engineering The curriculum is intended support the study of science. However, under the auspices of science, the materials focus on building structures for reasons that include strength, safety, durability, and stability. The teaching and learning process includes planning a structure, building the structure, observing the structure, collecting information about the structure, and using sketching to record their designs.

Prominent The curriculum features "open" and "focused" explorations.

Activities

The open explorations serve as introductory activities that are designed to help students become familiar with the various building materials and to discover how they work together to make structures. The following learning activities fall under the open explorations:

1. Discussing prior experiences with building blocks and other construction materials.
2. Explaining the rules for building structures (e.g., how to take building blocks off shelves, how to take structures apart, how to put building blocks away).
3. Engaging in "block play" to learn how to use the building materials.
4. Acknowledging the structures built during block play, talking to children about their structures, and introducing new vocabulary during discussions (e.g., upstairs, downstairs, walls, roof, foundation).
5. Sharing building experiences through questions (e.g., Do you remember when you rebuilt it here at the bottom? How did you change it?).
6. Introducing new building materials (e.g., new blocks) and new props (e.g., toy horses that need a home).
7. Engaging in additional block play and acknowledging the children's structures.
8. Conducting a "walkabout" where children study and talk about each other's structures.
9. Conducting a "science talk" where children share their thought about making structures in response to questions (e.g., Tell us about your building? Which parts of it wiggled or fell down? How did you keep it up?).

The "open explorations" are followed by "focused explorations." During this phase of the curriculum students are given more guidance and the building activities are designed to address a challenge or problem.

10. Discussing prior experiences with building something that is tall.
11. Introducing children to the challenge of building a tall tower.
12. Discussing the safety issues associated with making something tall (e.g., wearing hard hats).
13. Observing and acknowledging children's work while building tall towers (ask questions about stability and balance).
14. Conducting a "walkabout" where children study and talk about each other's towers.
15. Conducting a "science talk" where children share their

experiences while making towers (e.g., Tell us about your tower? Could it be taller without falling down? What would happen if you used the thinner side of each block?).

16. Examining and discussing pictures of tall buildings.
17. Conducting a "walkabout" around the school to uncover the features of tall structures.
18. Making representational drawings of their towers.
19. Using different strategies and objects to measure their towers (e.g., counting blocks, using string, photographing students next to their towers).

The same pattern of activities is used to engage students in making structures that are essentially enclosures (e.g., discussing prior experiences, challenge children to make enclosures, observing and acknowledging children's work, conducting walkabouts, conducting science talks).

Salient Observations

The audience for this curriculum includes pre-school teachers, kindergarten teachers, and teacher trainers. Over half of the documentation is directed toward the teacher trainers that conduct workshop on how to implement the curriculum. The workshop materials include outcomes, objectives, timelines, handouts, activities, and reproducible masters.

The balance of the documentation is directed toward the teachers that will implement the curriculum in their classrooms. It features teaching plans, recommendations, examples, questions, assessment tools, learning outcomes, and information about additional resources.

Engineering

The materials clearly espouse enriching the study of science. They do not deliberately target ideas about engineering, invention, or technology. However, in its treatment of science content and inquiry the curriculum inadvertently addresses basic engineering principles and ways of thinking that are appropriate for young children.

Design

The materials do not address the concept of engineering design directly. However, they do ask children to create solutions to problems. For example, They may be asked to build a house for a dog (possibly represented by a plastic toy). In this context, they would be encouraged to make sure their dog will fit in the house (a design specification) and their dog will not get hurt by a falling roof (another design specification). Other potential problems include building a tall tower, making a house for a turtle, and erecting a structure that will withstand the wind.

During the course of solving these problems the students are encourage by their teachers to practice inquiry skills under the auspices of science. In simple vernacular these skills include doing things, noticing things, wondering about things, and questioning things. More specifically, the children are asked to engage in following activities:

- Explore how things work (tinkering with building blocks).
- Investigate ideas (staking blocks and seeing what happens).
- Collect data (counting the number of blocks).
- Record observations and experiences (drawing pictures).
- Reflect on experiences (answering questions).
- Communicate the results (sharing ideas and experiences).

Even though these activities are presented in the context of scientific inquiry, they are also consistent with thinking like an engineer. How do these blocks fit together? What will happen if you use this block? Should the big block be on top or on the bottom? What would happen if you put the big block on top? Is your tower taller than you or shorter than you? How many stories did you build? Is that space big enough for your turtle? Addressing questions such as these can be construed as being more consistent with engineering than science because most of the emphasis is on solving problems in contrast to uncovering laws of nature. The context of the work is more attentive to the human-made world than the natural world. The approach is consistent with engineering in the sense that the children address a problem, gather information, implement and test ideas, document their ideas and work in the form of drawings, and communicate their work to others.

Analysis

Analysis appears to be highly dependent on the nature of the dialog between the teacher and the students. The materials clearly recommend using questions to guide students in noting the nature of the building materials, making observations about the structures they build, detecting the features of their structures relative to what they do or represent, connecting what they have seen with what they have built, and assessing the ability of their structures to fulfill their functions (e.g., making a doghouse that will not fall down).

Constraints

Constraints are subliminally imposed on the children by the nature of the materials that are available for them to use. Very simply, the size, shape, weight, and strength of the materials intrinsically influence what can be made. The characteristics and limitations of the materials would inevitably surface during the course of the children's thinking, experimenting, building, and explaining. For example, they may discover something has to be built without the benefit of a piece of material that has a given size, shape, or strength because it is not available, there is not enough, or another child is using it. During the course of their building the children will also discover what the materials can and cannot do. These discoveries would have to be taken into accounted during subsequent building attempts.

Given the nature of children and the scope of early childhood programs, the children would be given finite amounts of time to create their structures. Therefore, time is likely to be another constraint that may or may not be addressed in an overt manner.

Modeling

The concept of modeling is addressed in both indirect and direct ways. Indirectly, the curriculum clearly engages children in making lots of models with simple modeling materials without addressing the concept. The process of imaging a way to stack blocks, actually stacking the blocks as conceived, observing what happens in terms of balance and stability, and reconfiguring the blocks based on success or failure suggests modeling is informing the design process. In many ways it is a four-year-old's version of an aeronautical engineer gathering data from a model airplane in a wind tunnel.

In a more targeted sense, the materials suggest both teachers and children use the word "model" during their interactions. Furthermore, the materials recommend engaging children in making models of their models. This step requires the children to study their models made of relatively large blocks to build a smaller (table-top) version from easy to work materials (e.g., cardboard, pieces of foam). However, this kind of modeling is being presented in the interest of having children produce multiple representations of their ideas as a way to deepen understanding.

Regardless of the intent, making models, studying models, and talking about models constitutes a valid, although subliminal, treatment of the concept because the blocks, straws, and wires that the children work with are representing things that are, in reality, much bigger. Thus, implementing the curriculum as written would "get students to talk about how the things they play with relate to real things in the world" (AAAS, 1993, p. 268). These activities would intrinsically help children realize "a model of something is different from the real thing but can be used to learn something about the real thing" (AAAS, 1993, p. 268). However, it is important to note that these ideas reside between the lines of the curriculum and they are not represented in the lists of learning outcomes.

Optimization

Optimization is another concept that is embedded in the curriculum. The materials clearly guide children through multiple rounds of thinking, building, observing, and explaining. The use of iterations is presented in the context of scaffolding the teaching and learning process. However, during this process the children are also revising and improving their structure to meet a challenge or solve a problem. If the curriculum were implemented as written, teachers would implicitly guide and encourage children to optimize their structures (e.g., make it tall, make it stronger, make it more stable, make the opening bigger).

There are some modest references to the concept of trade-offs in the recommendations for learning activities. More specifically, the materials encourage the teacher to prepare and ask questions about the advantages and disadvantages associated with different design options. For example, in the context of building a model house, teachers are encouraged to entertain ideas like making the roof from something light will require less support but it is not likely to be strong. If children chose to make a strong roof, they might also need to build in more support.

Systems The materials do not address the concept of systems in an explicit manner. Nevertheless, by default, students are likely to uncover the fact that parts work together to do things that individual parts alone cannot do. Furthermore, they are liable to discover structures can fail if a part is installed wrong, missing, or removed. Despite the richness of the materials, the notion of deliberately looking at structures as systems is not among the recommendations for engaging students in inquiry or asking questions about their designs.

Science *Building Structures with Young Children* espouses helping teachers guide children's explorations that deepen their understanding of the physical science of building structures. The materials were clearly developed with science in mind. The activities are constantly asking the students to explore, question, and investigate. Furthermore, they are in a sense, collecting data through the use of their senses and their observations, and experiences tell them how to build a better building. They are recording and representing their data (and ideas) by making drawings of what they have built.

The curriculum purports to look at science "in a new way" without giving this methodology a name. Through this novel approach the curriculum strives to develop "important science inquiry skills such as questioning, investigating, discussing, and formulating ideas and theories." It endeavors to build these skills through exploring, designing, and building structures.

Given the amount of attention dedicated to exploring the human-made world, in contrast to the natural world, one could argue it fosters skills more in the context of doing engineering than doing science. The instruction targets concepts like gravity, stability, and balance while teaching children, "…how to make things strong, tall, or elegant." The symbiotic blending of science and technology is, in part, the essence of engineering. The materials approach science in such a way that one could replace the word "science" with the word "engineering" with relative ease without compromising validity. Therefore, one could characterize this new approach as "children's engineering."

Mathematics

The curriculum does not teach math directly but it does apply and reinforce a variety of foundational concepts and skills. For example, teachers are trained to use questions to engage children in dialogs about their structures. These questions are intended to lead children into describing their buildings using things like quantities, shapes, features, patterns, sizes, and more. The materials also recommend using questions to nurture the children's understanding of the directionality, order, and position of objects.

Measurement is another theme that can be found in the materials. The recommended activities employ both standard and non-standard forms of measurement for the length, height, or area of objects and structures. Standard units of measurement include things like "my tower is ten blocks high" and non-standard units of measurement could include things like "my tower is as tall as me" or "my tower is as tall as this string." In these examples, measurement is being used to assess the extent to which the structure addresses the problem posed (build a tall tower).

Technology

During the course of their activities children are asked to think about, make, test, and talk about the parts of their structures. These parts include things like foundations, walls, roofs, supports, and more. The attention given to the basic anatomy of buildings enables children to apply, practice, and expand their technical vocabulary (a.k.a., domain knowledge).

The activities also address building techniques that are technological in nature. This is especially evident in the process of having student examine buildings and study pictures of buildings to uncover the techniques that they can use to build their structures. These include things like overlapping blocks, making strong corners, and keeping walls from falling down. Their experiences with stacking blocks will be analogous to the techniques used to build real structures, especially masonry buildings. Consequently, the learning activities enrich the children's knowledge of how things are done and subsequently, how to do things.

Treatment of Standards

The materials present rich sets of outcomes for science inquiry, mathematical reasoning, social behavior, learning skills, and language development. Although they read like standards, no attempt is made to reference national standards or correlate these outcomes with national standards. Despite the lack of attention given to standards, it is very easy to envision using the materials as an integral part of an early childhood program that is designed to address standards.

The learning activities outlined in *Building Structures with Young Children* are consistent with standards recommended by the American Association for the Advancement of Science (AAAS) *in Benchmarks for Science Literacy* (1993). For example, according to AAAS, by the end of second grade students should be able to "make something from paper, cardboard, wood, plastic, metal, or existing objects that can actually be used to perform a task." Making a structure that provides shelter for a toy turtle could make a valid contribution toward the attainment of this standard.

The questioning and debriefing strategies that are recommended throughout the materials are also consistent with developing students' ability to "Describe and compare things in terms of number, shape, texture, size, weight, color, and motion." Similarly, the role that sketching plays in the teaching and learning process can help children develop an ability to "Draw pictures that correctly portray at least some features of the thing being described."

Inversely, targeting the following standards about systems could have added additional ideas and new lines of inquiry that can enrich the dialog between teachers and students.

- "Most things are made of parts" (p. 264).
- "Something may not work if some of its parts are missing" (p. 264).
- "When parts are put together, they can do things that they couldn't do by themselves."

Pedagogy

The materials are well laid out and easy to follow. They ask teachers to address the study of structures from multiple perspectives. Attention is given to configuring the learning environment to encourage exploration, conducting neighborhood tours that involve examining and discussing real structures, using books to inspire and inform designs, incorporating guest speakers, helping students learn from one another, and debriefing students about their experiences. Attention is also given to establishing schedules and routines that support learning, facilitating core experiences, offering suggestions for making connections to families, surveying the children's work during classroom "walkabouts," conducting group discussions during "science talks", using books and pictures to inform designs, and more.

All of the learning activities include the same elements that are organized into a logical sequence. The instruction is consistent with constructivist pedagogy in the sense that it asks teachers to activate prior experience, introduce new concepts, engage students in using existing knowledge in conjunction with new knowledge, employ tactile experience to support active learning, use questions for acknowledging ideas and guiding the development of new ones, and ask students to represent their ideas in multiple ways.

The curriculum and instruction is extremely Socratic in nature. Posing questions is the primary tool used to implement the teaching and learning process. Emphasis is placed on thoughtfully observing students, formulating questions based on their work, using question to access their thought processes, posing questions to leverage experience and guide the incremental develop of understandings, and using questions to reflect upon and learning experiences. In short, questions are used to encourage student to discuss, express, represent, and reflect in the interest of helping them construct understanding from their active work.

Implementation

Building Structures with Young Children, clearly capitalizes on materials and supplies that early childhood teachers are likely to have in their classrooms (e.g., building blocks, craft supplies, toys representing people and animals). However, the implementation of the curriculum at the scale described in the materials could easily require more supplies and manipulatives than teachers have on hand. Therefore, implementation is likely to require additional expense for capital improvements (e.g., purchasing additional maple building blocks) and consumables (e.g., buying craft supplies).

More than half of the documentation for the program focuses on facilitating teacher training. Tremendous attention is given to informing and developing teachers' abilities to prepare the learning environment, to observe children building, to use carefully crafted questions to uncover thought processes and guide thinking, to engage children in composing multiple representation of their ideas, to engage children in looking back on their experiences, and to debrief children about their learning. Therefore, the greatest challenge associated with implementing this curriculum is allocating the time and resources needed for the professional development of teachers.

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