Towards a Vision for Engineering Education in Science and Mathematics Standards

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Abstract

Improved education standards will not, by themselves, lead to the scientifically and technologically literate citizenry that we need for our nation to prosper in the 21st century. However, as we've learned in virtually every other professional field, standards can be an important first step to drive the changes that will lead to excellence and equity. It is now widely accepted that all students need to develop fundamental conceptual understanding and abilities in science, technology, engineering, and mathematics (STEM), but of those fields only science and mathematics have reserved seats in the K-12 curriculum. Unfortunately, previous efforts to integrate technology and engineering into science and mathematics standards have met with limited success. Most science educators have tended to focus only on aspects of national standards directly related to the science disciplines. And mathematics educators' interests in technology have been limited to tools for computation. Given that history, an open question is whether or not a new generation of science and mathematics standards that includes technology and engineering would bring about a different result. Although we cannot answer that question at present, we can consider how to go about developing a new vision of technology and engineering standards consistent with the "fewer, higher, clearer" guidelines that are driving the development of the next generation of standards. In the process we touch on three themes: the definitions of technology and engineering, the content of current technology and engineering frameworks, and a strategy for integrating these standards into core academic subjects so they are viewed as essential complements to the disciplines, rather than optional add-ons.

Introduction

Although the national standards movement has been underway for twenty years (since the publication of *Curriculum and Evaluation Standards for School Mathematics* in 1989, and *Science for All Americans* in 1990) our national penchant for states' rights has led each state to develop its own unique standards. The results have been roundly criticized as too broad, vague, repetitive, and poorly coordinated to define a clear and coherent pathway for textbook developers, assessment specialists and teachers to follow (Beatty 2008). Moreover, the sheer number of different types of standards intended to guide the work of generalist teachers (especially many K-5 teachers) made mastery unlikely. (Hudson and Overstreet, 2002, and Appendix A.)

Growing concern over the dismal performance of our students on national and international tests in mathematics and science and recognition that a patchwork of educational standards is at least partly to blame has led to a call for common state standards. Although still resistant to "federal" standards, state-elected officials are warming to the idea of "common standards" that would avoid the worst of the problems of the current system while allowing them to retain some control over the content of their state's standards. At this writing forty-six states have agreed in principle to adopt common standards in English and mathematics (McNeil 2009) and it's likely that science will be next on the agenda.

The prospect of a next generation of educational standards raises the possibility that there may be an opportunity to integrate technology and engineering standards in a way that may be more successful than previous attempts. However, there is still no universal agreement on the meaning of "technology" and

"engineering," let alone a vision for how these subjects can and should be integrated in our K-12 system. Given the current call for fewer, clearer, and higher standards, and the difficulty of including entirely new courses of study, especially at the high school level, it is unlikely that a separate set of standards for technology or engineering alone would be widely adopted by the states. Consequently, our best bet is to develop a clear and coherent vision for what exemplary standards in technology and engineering might be, and then consider where they might best fit within traditional K-12 subjects.

Developing a vision for fewer, clearer and higher engineering standards could be undertaken in a number of ways. One approach is to convene a workshop of engineers, educators, and other experts in related fields to determine the most important concepts and abilities that everyone needs to be effective citizens, workers, and consumers. That was the approach taken in developing chapters 3 and 8 of *Science for All Americans* in the 1980s, and it is the approach being taken now by the team writing a technological literacy framework for the National Assessment of Educational Progress. A second approach would be to comb the international literature using sources such as *Technology's Challenge to Science Education* (Layton 1993), which chronicles the evolution of technology in the national curriculum of England and Wales, and the series *Innovations in Science and Technology Education* (UNESCO, Volumes I-VIII, 1986-2003) which describe similar efforts in many industrialized and developing nations. A purpose of such a search would be to determine whether or not there is an existence proof for national standards that fully integrate technology and engineering with core subjects, and if so, what its characteristics appear to be. A third approach is to start with the standards that already exist in the United States, and imagine how they might be shaped in their next iteration so that they are perceived by practitioners as essential to core subjects. Ideally, all three methods would be used to triangulate on an optimal set of engineering standards.

Given limited time, this paper will skim the surface of the third approach by providing an overview of engineering standards in current frameworks, and suggesting a potential approach to synthesize these earlier efforts. First we turn first to definitions of these terms as they have been used in educational contexts.

Definitions of Technology and Engineering Education

Science for All Americans (AAAS 1990) was the first major document to set out a broad vision for science education that included a major role for technology and engineering. It defined these terms as follows:

> "In the broadest sense, technology extends our abilities to change the world: to cut, shape, or put together materials; to move things from one place to another; to reach farther with our hands, voices, and senses. We use technology to try to change the world to suit us better. The changes may relate to survival needs such as food, shelter, or defense, or they may relate to human aspirations such as knowledge, art, or control. But the results of changing the world are often complicated and unpredictable. They can include unexpected benefits, unexpected costs, and unexpected risks—any of which may fall on different social groups at different times. Anticipating the effects of technology is therefore as important as advancing its capabilities….
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> "Engineering, the systematic application of scientific knowledge in developing and applying technology, has grown from a craft to become a science in itself. Scientific knowledge provides a means of estimating what the behavior of things will be even before we make them or observe them. Moreover, science often suggests new kinds of behavior that had not even been imagined before, and so leads to new technologies. Engineers use knowledge of science and technology, together with strategies of design, to solve practical problems." (AAAS 1990, p. 23-24)

The definition of technology and its proposed role in the schools was further developed in *Benchmarks for Science Literacy* (AAAS 1993).

> "Technology is an overworked term. It once meant knowing how to do things—the practical arts or the study of the practical arts. But it has also come to mean innovations such as pencils, television, aspirin, microscopes, etc., that people use for specific purposes, and it refers to human activities such as agriculture or manufacturing and even to processes such as animal breeding or voting or war that change certain aspects of the world. Further, technology sometimes refers to the industrial and military institutions dedicated to producing and using inventions and know-how." (AAAS, 1993, p. 43)

The National Science Education Standards (NRC 1996), also gave technology a prominent place in science education, and defined the distinction between scientific inquiry and technological design:

> "Although these are science education standards, the relationship between science and technology is so close that any presentation of science without developing an understanding of technology would portray an inaccurate picture of science" (NRC 1996, p. 190).

> "As used in the Standards, the central distinguishing characteristic between science and technology is a difference in goal: The goal of science is to understand the natural world, and the goal of technology is to make modifications in the world to meet human needs. Technology as design is included in the Standards as parallel to science as inquiry. (NRC 1996, p. 24)

The *National Science Education Standards* also differentiated the roles of scientists and engineers:

> "*Scientists* propose explanations for questions about the natural world, and *engineers* propose solutions relating to human problems, needs, and aspirations." (NSES, p. 166)

In contrast to the science documents, which define technology broadly, mathematics documents define technology much more narrowly as electronic tools:

> "Calculators and other technological tools, such as computer algebra systems, interactive geometry software, applets, spreadsheets, and interactive presentation devices, are vital components of a high-quality mathematics education. With guidance from effective mathematics teachers, students at different levels can use these tools to support and extend mathematical reasoning and sense making, gain access to mathematical content and problem-solving contexts, and enhance computational fluency. In a well-articulated mathematics program, students can use these tools for computation, construction, and representation as they explore problems. The use of technology also contributes to mathematical reflection, problem identification, and decision making." (NCTM 2008)

In brief, mathematics documents use the term "technology" to refer to modern electronic tools, and do not typically refer to engineering at all except as one of many fields that require mathematics. The science frameworks use the term "technology" to refer to all of the ways that natural materials are modified to meet human needs and desires. These documents also make a distinction between science and technology, and between scientist and engineer, as primarily a difference in goal. This distinction is concisely stated in the following quote attributed to the famous engineer Theodore von Karman.

> "The scientist seeks to understand what is, the engineer seeks to create what never was." (Petroski 1997)

Additional insights about the relationship between science and technology in education, and the distinct role of engineers emerges from a series of papers delivered at various UNESCO conferences in the 1970s, surrounding the question of how best to organize science and technology education in developing countries. In one of these papers, Harold Foecke, then Director of Pre-University Science and Technology Education for UNESCO, urged the attendees to teach science and technology together, as basic education for all students. He further made the distinction between science and technology (and between scientist and engineer), as involving motivating forces [goals], processes and products:

> **"Motivating forces [goals]**: In science to know, explain, and predict, and in technology to find new and better ways of doing things;
>
> **"Processes**: In science the research process proceeds from the particular to the general, and in technology the design, problem-solving or decision-making process proceeds from the general to the particular; and
>
> **"Products**: Science results in new knowledge about the natural and man-made worlds while technology produces new materials, devices, techniques, processes, and systems to serve human needs."

Another theme of Foecke's papers concerns the role of engineers in society. In one of the papers (Foecke, 1970) the author lists many of the problems that plague humankind—natural disasters, shortages of food and water, disease, air and water pollution, and so on.

> "With respect to these human problems the scientists' role is to find out what is. The technologist's role is to determine what can be, and the engineer's role is to recommend what should be. Because the engineer's role in decision-making may profoundly affect society, engineers need to be well educated in the humanities and social sciences as well as in science, mathematics, and engineering design."

A third theme that emerges from this literature is a strategy for including science and technology as distinct but related subjects for all citizens. In *Fifty Years of UNESCO Leadership in Science and Technology Education* Foecke (1995) explains that the introduction of technology as a part of general education grew out of earlier efforts by UNESCO to integrate the various fields of science into courses of study that have practical value at all pre-university levels. However, initial efforts to introduce technology as separate courses in the curriculum were resisted because they were incorrectly perceived as "vocational" in nature, and some educators thought they were inappropriate for college-bound students. Consequently UNESCO adopted the strategy of integrating technology education with science education, while preserving the distinctions between science and technology. We will return to the question of strategy later. First, we will look at technology and engineering in current national and state standards documents.

Technology and Engineering in National Science Standards

1. *Benchmarks for Science Literacy* (AAAS 1993) was the first set of science education standards in the United States, describing what students should know in grades K-2, 3-5, 6-8, and 9-12. Chapter 3 The Nature of Technology, consists of three parts: Technology and Society; Design and Systems; and Issues in Technology. Chapter 8 The Designed World, consists of six parts: Agriculture, Materials and Manufacturing, Energy Sources and Use, Communication, Information Processing, and Health Technology. Although all of this material is relevant to understanding engineering and technology, in the interests of brevity Table 1 presents just the benchmarks in Chapter 3B Design and Systems. These are the statements closest to the heart of engineering. Notice that each statement is declarative. Although the authors of *Benchmarks* indicate that they expect students to learn by engaging in design and technology projects, the focus is on what students should *know* about engineering.

Table 1. *Benchmarks for Science Literacy*: Chapter 3B Design and Systems

Grades K-2	People can use objects and ways of doing things to solve problems. People may not be able to actually make or do everything they design.
Grades 3-5	There is no perfect design. Designs that are best in one respect (safety or ease of use, for example) may be inferior in other ways (cost or appearance). Usually some features must be sacrificed to get others. How such trade-offs are received depends on which features are emphasized and which are down-played. Even a good design may fail. Sometimes steps can be taken ahead of time to reduce the likelihood of failure, but it cannot be truly eliminated. The solution to one problem may create other problems.
Grades 6-8	Design usually requires taking constraints into account. Some constraints, such as gravity or the properties of the materials to be used, are unavoidable. Other constraints, including economic, political, social, ethical, and aesthetic ones, limit choices. All technologies have effects other than those intended by the design, some of which may have been predictable and some not. In either case, these side effects may turn out to be unacceptable to some of the population and therefore lead to conflict between groups. Almost all control systems have inputs, outputs, and feedback. The essence of control is comparing information about what is happening to what people want to happen and then making appropriate adjustments. This procedure requires sensing information, processing it, and making changes. In almost all modern machines, microprocessors serve as centers of performance control. Systems fail because they have faulty or poorly matched parts, are used in ways that exceed what was intended by the design, or were poorly designed to begin with. The most common ways to prevent failure are pretesting parts and procedures, overdesign, and redundancy.
Grades 9-12	In designing a device or process, thought should be given to how it will be manufactured, operated, maintained, replaced, and disposed of and who will sell, operate, and take care of it. The costs associated with these functions may introduce yet more constraints on the design. The value of any given technology may be different for different groups of people and at different points in time. Complex systems have layers of controls. Some controls operate particular parts of the system and some control other controls. Even fully automatic systems require human control at some point. Risk analysis is used to minimize the likelihood of unwanted side effects of a new technology. The public perception of risk may depend, however, on psychological factors as well as scientific ones. The more parts and connections a system has, the more ways it can go wrong. Complex systems usually have components to detect, back up, bypass, or compensate for minor failures. To reduce the chance of system failure, performance testing is often conducted using small-scale models, computer simulations, analogous systems, or just the parts of the system thought to be least reliable.

2. The *National Science Education Standards* (NRC 1996) was developed in response to a felt need in the nation for a clear set of goals. At the time just a few states had educational standards, and *Benchmarks for Science Literacy* was just one of two national documents in circulation in the early 1990s. The National Science Teachers Association initiated the *Scope, Sequence and Coordination* (SS&C) Project that aimed to replace the "layer cake" approach of teaching biology, chemistry, and physics in separate courses. The SS&C approach was to replace the entire middle and high school curriculum with a coordinated sequence of science units so that students took all of the sciences each year. Concepts within a field of science would build from year to year, and within a given year students would have opportunities to understand how learning in the different fields of science related to each other. These concepts were laid out in another set of standards called the *Content Core*. Many science educators chose to follow the SS&C route, while others followed the *Benchmarks* approach. Confusion between these two approaches led to a request to the National Research Council to bring the leaders of the science education community together with scientists to develop a definitive set of standards for the nation.

The National Science Education Standards (NSES), developed with input and support from the creators of the AAAS documents, plus many others, also gave technology and engineering a prominent place in science. However, the scope was considerably diminished in comparison with *SFAA* and *Benchmarks*. Perhaps responding to criticism that *SFAA* and *Benchmarks* were too broad, NSES limited inclusion of technology and engineering to concepts and abilities that were explicitly linked to science:

> "The science and technology standards in Table 6.5 establish connections between the natural and design worlds and provide students with opportunities to develop decision-making abilities. They are not standards for technology education; rather these standards emphasize abilities associated with the process of design and fundamental understandings about the enterprise of science and its various linkages with technology.

Nonetheless, many of the statements in NSES about what students should know and be able to do are similar to those in *Benchmarks*. Also, statements about technology were divided into two sections: what students were to know about technology and what students were to be able to do. The latter are summarized in Table 2.

Table 2. *National Science Education Standards*: Abilities of Technological Design

Grades K-4	**Identify a simple problem:** In problem identification, children should develop the ability to explain a problem in their own words and identify a specific task and solution related to the problem. **Propose a solution.** Students should make proposals to build something or get something to work better; they should be able to describe and communicate their ideas. Students should recognize that designing a solution might have constraints, such as cost, materials, time, space, or safety. **Implementing proposed solutions.** Children should develop abilities to work individually and collaboratively and to use suitable tools, techniques, and quantitative measurements when appropriate. Students should demonstrate the ability to balance simple constraints in problem solving. **Evaluate a product or design.** Students should evaluate their own results or solutions to problems, as well as those of other children, by considering how well a product or design met the challenge to solve a problem. When possible, students should use measurements and include constraints and other criteria in their evaluations. They should modify designs based on the results of evaluations. **Communicate a problem, design, and solution.** Student abilities should include oral, written, and pictorial communication of the design process and product. The communication might be show and tell, group discussions, short written reports, or pictures, depending on the students' abilities and the design project.
Grades 5-8	**Identify appropriate problems for technological design**. Students should develop their abilities by identifying a specified need, considering its various aspects, and talking to different potential users or beneficiaries. They should appreciate that for some needs, the cultural backgrounds and beliefs of different groups can affect the criteria for a suitable product. **Design a solution or product.** Students should make and compare different proposals in the light of the criteria they have selected. They must consider constraints—such as cost, time, trade-offs, and materials needed—and communicate ideas with drawings and simple models. **Implement a proposed design**. Students should organize materials and other resources, plan their work, make good use of group collaboration where appropriate, choose suitable tools and techniques, and work with appropriate measurement methods to ensure adequate accuracy. **Evaluate completed technological designs or products.** Students should use criteria relevant to the original purpose of need, consider a variety of factors that might affect acceptability and suitability for intended users or beneficiaries, and develop measures of quality with respect to such criteria and factors; they should also suggest improvements for their own products, try proposed modifications. **Communicate the process of technological design.** Students should review and describe any completed piece of work and identify the stages of problem identification, solution design, implementation, and evaluation.
Grades 9-12	**Identify a problem or design an opportunity**. Students should be able to identify new problems or needs and to change and improve current technological designs. **Propose designs and choose between alternative solutions**. Students should demonstrate thoughtful planning for a piece of technology or technique. Students should be introduced to the roles of models and simulations in these processes. **Implement a proposed solution**. A variety of skills can be needed in proposing a solution depending on the type of technology that is involved. The construction of artifacts can require the skills of cutting, shaping, treating, and joining common materials—such as wood, metal, plastics, and textiles. Solutions can also be implemented using computer software. **Evaluate the solution and its consequences**. Students should test any solution against the needs and criteria it was designed to meet. At this stage, new criteria not originally considered may be reviewed. **Communicate the problem, process, and solution**. Students should present their results to students, teachers, and others in a variety of ways, such as orally, in writing, and in other forms—including models, diagrams, and demonstrations.

3. *Standards for Technological Literacy* (ITEA 2000) is perhaps the most fully developed standards for technology and engineering education. The document was developed by the International Technology Education Association in collaboration with the National Academy of Engineering. The *Standards for Technological Literacy* (STL) is an organized set of twenty standards patterned largely on the framework of *SFAA* and *Benchmarks*, but further elaborated. The twenty standards are broken down into benchmarks for grades K-2, 3-5, 6-8, and 9-12. The twenty standards are grouped into five major areas, as shown below:

The Nature of Technology

1. The characteristics and scope of technology.
2. The core concepts of technology.
3. The relationships among technologies and connections with other fields.

Technology and Society

4. The cultural, social, economic and political effects of technology.
5. The effects of technology on the environment.
6. The role of society in the development and use of technology.
7. The influence of technology on history.

Design

8. The attributes of design.
9. Engineering design.
10. The role of troubleshooting, R&D, invention, innovation and experimentation in problem solving.

Abilities for a Technological World

11. Apply the design process.
12. Use and maintain technological products and systems.
13. Assess the impact of products and systems.

The Designed World

14. Medical technologies.
15. Agricultural and related biotechnologies.
16. Energy and power technologies.
17. Information and communication technologies.
18. Transportation technologies.
19. Manufacturing technologies.
20. construction technologies.

Notice that standards 1-13 correspond to many of the ideas in *Benchmarks* Chapter 3 The Nature of Technology, and that standards 14-20 correspond to *Benchmarks* Chapter 8 The Designed World. However, the detailed descriptions for what students are expected to know and be able to do are more explicit in *STL* than in Benchmarks.

Although the *Standards for Technological Literacy* is now almost a decade old, it remains the most comprehensive set of standards for technology and engineering education yet developed, and should provide an excellent pool from which to draw ideas for the next generation of standards. The standards that primarily concern engineering are 8, 9, 10, all under "Design," and standard 11, which is classified under "Abilities for a Technological World." These are shown in Table 4.

Table 3 *Standards for Technological Literacy*: Standards 8, 9, 10, and 11

	Standard 8. Students will develop an understanding of the attributes of design.
Grades K-2	Everyone can design solutions to a problem. Design is a creative process.
Grades 3-5	The design process is a purposeful method of planning practical solutions to problems. 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.
Grades 6-8	Design is a creative planning process that leads to useful products and systems. There is no perfect design. Requirements for design are made up of criteria and constraints.
Grades 9-12	The design process includes defining a problem, brainstorming, researching and generating ideas, identifying criteria and specifying constraints, exploring possibilities, selecting an approach, developing a design proposal, making a model or prototype, testing and evaluating the design using specifications, refining the design, creating or making it, and communicating processes and results. Design problems are seldom presented in a clearly defined form. The design needs to be continually checked and critiqued, and the ideas of the design must be redefined and improved. Requirements of a design, such as criteria, constraints, and efficiency, sometime compete with each other.
	Standard 9. Students will develop an understanding of engineering design.
Grades K-2	The engineering design process includes identifying a problem, looking for ideas, developing solutions, and sharing solutions with others. Expressing ideas to others verbally and through sketches and models is an important part of the design process.
Grades 3-5	The engineering design process involves defining a problem, generating ideas, selecting a solution, testing the solution(s), making the item, evaluating it, and presenting the results. When designing an object, it is important to be creative and consider all ideas. Models are used to communicate and test design ideas and processes.
Grades 6-8	Design involves a set of steps, which can be performed in different sequences and repeated as needed. Brainstorming is a group problem-solving design process in which each person in the group presents his or her ideas in an open forum. Modeling, testing, evaluating, and modifying are used to transform ideas into practical solutions.
Grades 9-12	Established design principles are used to evaluate existing designs, to collect data, and to guide the design process. Engineering design is influenced by personal characteristics, such as creativity, resourcefulness, and the ability to visualize and think abstractly. A prototype is a working model used to test a design concept by making actual observations and necessary adjustments. The process of engineering design takes into account a number of factors.

	Standard 10. Students will develop an understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving.
Grades K-2	Asking questions and making observations helps a person to figure out how things work. All products and systems are subject to failure. Many products and systems, however, can be fixed.
Grades 3-5	Troubleshooting is a way of finding out why something does not work so that it can be fixed. Invention and innovation are creative ways to turn ideas into real things. The process of experimentation, which is common in science, can help solve technological problems.
Grades 6-8	Troubleshooting is a problem-solving method used to identify the cause of a malfunction in a technological system. Invention is a process of turning ideas and imagination into devices and systems. Innovation is the process of modifying an existing product or system to improve it. Some technological problems are best solved through experimentation.
Grades 9-12	Research and development is a specific problem-solving approach that is used intensively in business and industry to prepare devices and systems for the marketplace. Technological problems must be researched before they can be solved. Not all problems are technological, and not every problem can be solved using technology. Many technological problems require a multidisciplinary approach.
	Standard 11. Students will develop the abilities to apply the design process.
Grades K-2	Brainstorm people's needs and wants and pick problems that can be solved through the design process. Build or construct an object using the design process. Investigate how things are made and how they can be improved.
Grades 3-5	Identify and collect information about everyday problems that can be solved by technology, and generate ideas and requirements for solving a problem. The process of designing involves presenting some possible solutions in visual form and then selecting the best solution(s) from many. Test and evaluate the solutions for the design problem. Improve the design solutions.
Grades 6-8	Apply a design process to solve problems in and beyond the laboratory-classroom. Specify criteria and constraints for the design. Make two-dimensional and three-dimensional representations of the designed solution. Test and evaluate the design in relation to pre-established requirements, such as criteria and constraints, and refine as needed. Make a product or system and document the solution.
Grades 9-12	Identify the design problem to solve and decide whether or not to address it. Identify criteria and constraints and determine how these will affect the design process. Refine a design by using prototypes and modeling to ensure quality, efficiency, and productivity. Evaluate the design solution using conceptual, physical, and mathematical models at various intervals of the design process to check for proper design and to note areas where improvements are needed. Develop and produce a product or system using a design process. Evaluate final solutions and communicate observation, processes, and results of the design process, using verbal, graphic, quantitative, virtual, and written means, in addition to three-dimensional models.

4. *Engineering Frameworks for a High School Setting* (Koehler et. al. 2005) is an updated set of engineering standards intended as an improvement on the engineering standards in *Benchmarks*, *National Science Education Standards* and *Standards for Technological Literacy*. The document is similar in many ways to the previous frameworks although they focus only on high school engineering standards. This document uses the following outline:

I. Content Standards

- A. Information and Communication
  - 1. Instruments
  - 2. Mediums
- B. Sources of Power/Energy
- C. Transportation
- D. Food and Medicine
  - 1. Engineering in Food
  - 2. Engineering in Medicine

II. Engineering Tools

- A. Engineering Paradigm [engineering design process]
- B. Science and Mathematics
- C. Social Studies
- D. Computer Tools

Part I is similar to the content in Chapter 8 The Designed World from *Benchmarks*, whereas Part II is similar to Chapter 3 The Nature of Technology. It is also similar to Technology and Science in the National Science Education Standards. Since Part II seemed to be closest in spirit to the engineering standards described previously, these have been included in Table 4. The authors of this framework used it successfully as a way to compare the content of standards in 49 states. (Koehler et. al. 2006)

Table 4. *Engineering Frameworks for a High School Setting*: Part II Tools

A. The Engineering Paradigm is a systematic methodology that allows a technically literate person to gain perspective into the logical decomposition of a problem and its iterative procedure toward a solution. The topics covered in these content standards can only be explicitly understood in this context. More specifically, this is the fundamental tool for exploration, understanding, and improvement of the content covered in the Standards. In addition, this Engineering Paradigm provides an analytical thought process that can be extended to addressing other problems beyond the traditional scope of engineering and technology. Finally, it is imperative that a technically iterate society be able to compare and contrast the products that it uses. This paradigm enables consumers to evaluate the functionality and capabilities of products in terms of design optimization and the trade-offs inherent in satisfying multiple constraints. This paradigm is outlined below. • Problem recognition and definition • Problem decomposition • Piecewise analysis • Preemptive generation of possible solutions • Consideration of constraints • Iterative revision of possible solutions • Iterative prototyping until an acceptable product • Final design optimization
B. Science and Mathematics. All technology is ultimately derived from the application of scientific and mathematical principles. Therefore, a solid foundation in these disciplines is essential for facilitating a comprehensive understanding of the content standards. The following should be covered in the course of a high school education. • Science Disciplines Math Topics • Biology Geometry • Chemistry Algebra • Physics Trigonometry • Calculus
C. Social Sciences. Engineering, as a discipline, is focused on improving society by satisfying its ever-changing technological needs. Thus, while technology is derived from scientific and mathematical principles, its development is predominantly driven by sociological motivation and constraints. It is important that these factors be considered in the study of any technical system. Furthermore, the Engineering Paradigm outlines an iterative approach toward final design optimization. This process is by no means limited to technical constraints but must also satisfy its sociological requirements. It is important that the Content Standards, and their sociological optimization, are studied in the context of sociology, economics, ethics, and politics
D. Computer Tools. Our society is inextricably bound to the computer infrastructure that supports it. Technical literacy thus increasingly requires proficiency with various computer tools and applications to effectively interact within our technologically advanced environment. However, the engineering community is absolutely dependant on its computer tools for system development. Because of the complexity of these systems, such as those covered in the Content Standards, the use of computer tools greatly enhances their meaningful and thorough exploration. Students should have a working knowledge of the following computer tools. General computing Word processing Spreadsheet Communication tools Presentation tools Familiarity with operating systems Computer Programming Algorithmic synthesis and decomposition Implementation of computer-based models Computer aided drafting / drawing

Technology and Engineering in National Mathematics Standards

5. ***An Agenda for Action*** (NCTM 1980) was released in response to the 'back to basics' movement of the late 1970s, and became the first major document to set out a vision of mathematics education in modern times. It called for an emphasis on problem-solving over drill and practice, and encouraged mathematics educators to use calculators and computers with students in the earliest practical grade. Other recommendations included the creation of student-centered classrooms where students explore mathematical concepts rather than complete worksheets. The message on computational technology was clear: the K-12 mathematics curriculum should take advantage of calculating devices rather than the traditional focus on paper-and-pencil algorithms. It was in this report that the mathematics education community equated knowledge of technology with knowledge of appropriate use of calculators and computers.

6. ***Curriculum and Evaluation Standards for School Mathematics*** (NCTM 1989) was developed by a mathematics education community that had become weary of the pendulum swings in mathematics curriculum between basics and reform and the focus on the best and brightest. The purpose of this document was to proactively define what all students should know and be able to do. The National Council of Teachers of Mathematics (NCTM) Commission overseeing the task had two charges:

> "Create a coherent vision of what it means to be mathematically literate both in a world that relies on calculators and computers to carry out mathematical procedures and in a world where mathematics is rapidly growing and is extensively applied in diverse fields.
>
> "Create a set of standards to guide the revision of the school mathematics curriculum and its associated evaluation toward this vision." (NCTM 1989, p. 1)

What emerged was more detail on how teachers should teach than specific content that students should learn. There are three aspects of mathematics featured in the document:

- "…'knowing' mathematics is 'doing' mathematics. A person gathers, discovers, or creates knowledge in the course of some activity having a purpose….
- "The Computer's ability to process large sets of information has made quantification and the logical analysis of information possible in such areas as business, economics, linguistics, biology, medicine, and sociology…However, the fundamental mathematical ideas needed in these areas are not necessarily those studied in the traditional algebra-geometry-precalculus-calculus sequence, a sequence designed with engineering and physical science applications in mind. Because mathematics is a foundation discipline for other disciplines and grows in direct proportion to its utility, we believe that the curriculum for all students must provide opportunities to develop an understanding of mathematical models, structures, and simulations applicable to many disciplines.
- "Changes in technology and the broadening of the areas in which mathematics is applied have resulted in growth and changes in the discipline of mathematics itself…The new technology not only has made calculations and graphing easier, it has changed the very nature of the problems important to mathematics and the methods mathematicians use to investigate them. (NCTM, 1989, p. 7- 8)

In one of the few overt references to engineering cited above, the *Curriculum and Evaluation Standards* deliberately seek to broaden the mathematical pre-college curriculum beyond the educational needs of prospective scientists and engineers. Nonetheless, the following standards have some relevance to engineering education, even though they are not described from such a perspective.

Table 5: *Curriculum Standards in School Mathematics*

	Mathematics as problem-solving
Grades K-4	The study of mathematics should emphasize problem solving so that students can: • Use problem-solving approaches to investigate and understand mathematical content; • Formulate problems from everyday and mathematical situations; • Develop and apply strategies to solve a wide variety of problems; • Verify and interpret results with respect to the original problem; • Acquire confidence in using mathematics meaningfully.
Grades 5-8	The mathematics curriculum should include numerous and varied experiences with problem solving as a method of inquiry and application so that students can: • Use problem-solving approaches to investigate and understand mathematical content; • Formulate problems from situations within and outside mathematics; • Develop and apply a variety of strategies to solve problems, with emphasis on multistep and non-routine problems. • Verify and interpret results with respect to the original problem situation; • Generalize solutions and strategies to new problem situations; • Acquire confidence in using mathematics meaningfully.
Grades 9-12	The mathematics curriculum should include the refinement and extension of methods of mathematical problem solving so that all students can: • Use, with increasing confidence, problem-solving approaches to investigate and understand mathematical content; • Apply integrated mathematical problem-solving strategies to solve problems from within and outside mathematics; • Recognize and formulate problems from situations within and outside mathematics; • Apply the process of mathematical modeling to real-world problem situations.
	Mathematical Connections
Grades K-4	The study of mathematics should include opportunities to make connections so that students can: • Link conceptual and procedural knowledge; • Relate various representations of concepts or procedures to one another; • Recognize relationships among different topics in mathematics • Use mathematics in other curriculum areas; • Use mathematics in their daily lives.
Grades 5-8	The mathematics curriculum should include the investigation of mathematical connections so that students can: • See mathematics as an integrated whole; • Explore problems and describe results using graphical, numerical, physical, algebraic, and verbal mathematical models or representations; • Use a mathematical idea to further their understanding of other mathematical ideas; • Apply mathematical thinking and modeling to solve problems that arise in other disciplines; such as art, music, psychology, science, and business; • Value the role of mathematics in our culture and society.
Grades 9-12	The mathematics curriculum should include investigation of the connections and interplay among various mathematical topics and their applications so that all students can: • Recognize equivalent representations of the same concept; • Relate procedures in one representation to procedures in an equivalent representations; • Use and value the connections among mathematical topics; • Use and value the connections between mathematics and other disciplines.

7. *Principles and Standards for School Mathematics* (NCTM, 2000) is an updated version of the earlier mathematics standards. Several factors motivated this volume; for example, the original consensus supporting the 1989 standards collapsed into bitter debate, some of which highlighted ways in which the original rhetoric was misinterpreted or misguided as well as the need to widely solicit input from an array of constituencies.

Chapter 2 includes six principles—equity, curriculum, teaching, learning, assessment, and technology—that describe features of high-quality mathematics education, PreK-12. In the remaining chapters, there are five standards—number and operations, algebra, geometry, measurements, and data analysis and probability—that describe mathematical content goals. There are also five process standards—problem solving, reasoning and proof, connections, communication, and representation—for each of the grade bands, PreK-2, 3-5, 6-8, and 9-12.

Here again, the document uses a purely mathematics lens. This is not surprising coming from the professional association of teachers of mathematics and recognizing that the field has long been in the spotlight. Apart from the math wars, assessments are regularly administered to ascertain students' achievement levels in mathematics. Progress—or lack thereof—in mathematics is often in the news.

Nonetheless, *Principles and Standards* covertly acknowledged technology and engineering education. In the Technology Principle, technology—in the narrow sense of computes and calculators—is again described as a tool to enhance the teaching and learning of mathematics.

> "The effective use of technology in the mathematics classroom depends on the teacher. Technology is not a panacea. As with any teaching tool, it can be used well or poorly…Technology not only influences how mathematics is taught and learned but also affects what is taught and when a topic appears in the curriculum…" (NCTM 2000, pp. 25-26)

Among the process standards, problem solving is perhaps closest to engineering education. Students must be able to: (1) build new mathematical knowledge through problem solving, (2) solve problems that arise in mathematics and in other contexts, (3) apply and adapt a variety of appropriate strategies to solve problems, and (4) monitor and reflect on the process of mathematical problem solving. (NCTM 2000, p. 52-54 and elaborated elsewhere in the document).

The Connections standard addresses the potential of multi-discipline learning. NCTM calls on teachers and students to recognize and apply mathematics in contexts outside of mathematics. "The link between mathematics and science is not only through content but also through process. The processes and content of science can inspire an approach to solving problems that applies to the study of mathematics." (NCTM 2000, p. 66).

8. Guiding Principles for Mathematics Curriculum and Assessment (NCTM, 2009)
With work underway to create a common core of standards in English and mathematics, the NCTM recently released a document urging that the common core be grounded in existing work. The document concludes:

> "…any curriculum must be linked to assessments based on standards. A curriculum should provide a rich, connected learning experience for students while adding coherence to the standards, and standards must align with the curriculum rather than be separate, long lists of learning expectations. Alignment and coherence of these three elements—curriculum, standards, and assessment—are criti-

> cally important foundations of mathematics education." (NCTM, available on-line http://www.nctm.org/standards/content.aspx?id=23273)

The predominant theme is mastery of mathematics; no mention is made of learning through technology or engineering.

Technology and Engineering in State Standards

The No Child Left Behind law of 2001 required that all states develop challenging academic content and student achievement standards in mathematics and science by the 2005-2006 school year. So as not to lose federal funds for education, all states have complied. In this section we'll first look at how technology and engineering fared in science standards, and then in mathematics standards.

Recognizing the importance of technological literacy for all citizens, a number of states have incorporated technology and engineering standards within their science standards. Massachusetts, for example, includes a K-12 strand for Technology/Engineering alongside (and equal in importance to) strands for physical science, life science, and Earth and space science. However, the content of technology and engineering standards included in state science frameworks has been uneven. An analysis of the science frameworks in 49 states (Koehler et. al. 2005, 2006) found that nearly all states now include technology in their standards, but the content of those standards is far from what it needs to be.

> ". . .the nexus between engineering concepts and states science frameworks revolves around socioeconomic issues. This may be in part due to the influence of the science, technology and society (STS) movement in science education that began in the 1980s. Particularly, the socioeconomic content is described as how economics, politics and ethics coupled with technological development permeates the discipline of science. It is the means by which state science frameworks incorporate technology into their curriculums. While STS has been the traditional link between science content and technology, it is not a sufficient means to introduce engineering education and technical literacy into the high school setting. Instead, it is vital that science education focus on actual technology-based content integrated into the science curriculum as a means to promote technical literacy. (Koehler et. al. 2006)

When STS standards were left out of the analysis, regional differences emerged, with Northeastern states including the greatest number of technology and engineering standards, and Southeastern and Mountain states the fewest.

State mathematics frameworks use a different definition of the term "technology" than state science frameworks. In a descriptive analysis of the mathematics grade-level expectations in 42 states, the term "calculators/technology" refers to the use of electronic devices as tools to communicate concepts or solve problems. (Reys 2006) Of the 31 states that mention calculators 7 states specify that students should not use them, and "all of the documents referring to calculators/technology are explicit in emphasizing that these tools do not replace the need for computational fluency." (Reys 2006, p. 6) The authors conclude that the use of computational technology is relatively unimportant in state standards. This is a key issue in the 'math wars,' so it is not surprising that others disagree with this conclusion:

> "One of the most debilitating trends in current state math standards is their excessive emphasis on calculators. Most standards documents call upon students to use them starting in the elementary grades, often beginning with Kindergarten. Calculators enable students to do arithmetic quickly, without thinking about the numbers involved in a calculation. For this reason, using them in a high school science class, for example, is perfectly sensible. But for elementary students, the main goal of

> math education is to get them to think about numbers and to learn arithmetic. Calculators defeat that purpose. With proper restriction and guidance, calculators can play a positive role in school mathematics, but such direction is almost always missing in state standards documents." (Klein 2005, p. 1)

Relevant to this paper, we see that the warring parties tend to see technology as a tool to learn mathematics, rather than an end learning goal.

Engineering or Technology Standards?

Building on the growing use of the term "engineering" in education, Robert Wicklein (2003) proposed that a focus on engineering was a more effective strategy for changing education than the older focus on technology for the following reasons:

- Engineering is more easily understood and valued than technology.
- Engineering elevates the field to a higher academic level.
- Engineering provides a solid framework to design curriculum.
- Engineering is ideal for integrating mathematics and science.
- Engineering provides a focused career pathway for students.

Wicklein's arguments suggest that developing "engineering" rather than "technology" standards may be a way to overcome a number of barriers, such as avoiding the "vocational" label, and the common misperception that technology is limited to electronic devices like computers and cell phones. This line of reasoning recently persuaded the state of Oregon to join Massachusetts and adopt "engineering design" as one of four organizing principles of its science standards document. (Oregon DOE, 2009).

While Wicklein offers thoughtful arguments the jury is still out regarding whether "technology" or "engineering" is the better term from a strategic point of view. Both New Hampshire and Washington State chose to include a strong component of engineering in their standards, but both preferred the term "technological design" rather than "engineering design" because of the expectation that teachers feared engineering as a subject they may not be able to comprehend, but were comfortable with the pairing of terms "science and technology." Also, a new framework for a national test of technological literacy beginning in 2012 is currently being developed (NAGB in press).

In Search of an Effective Strategy

As illustrated in the previous section, the current science standards documents include technology and engineering, albeit with evolving definitions of the terms "technology" and "engineering." However, most practitioners have ignored those standards and focused instead just on the traditional science disciplines. Mathematics standards use an even narrower definition of "technology" as limited to computational tools, and there are strong debates within the mathematics community about whether or not to include technology at all.

If the next attempt at integrating technology and engineering standards into the mainstream subject standards is to be more successful, some thought needs to be given to terms and definitions. Wicklein suggested using "engineering" as a more promising strategy than "technology." Although there are misunderstandings about both terms we agree that the range of people's conceptions about engineering is probably somewhat less than about technology. However, this suggests that one element of a strategy is certainly to develop clear definitions of both terms with relevant examples.

A second strategy is to conduct case studies of successful implementation of engineering standards. For example, the state of Massachusetts has a network of school district teams aimed at implementing their state's technology/engineering standards at the district level. The teams share challenges and successes, and borrow ideas from each other. A recently developed curriculum, *Engineering is Elementary* provides materials that can be integrated with reading and social studies lessons at the elementary level, along with science learning activities. Several evaluation studies have been conducted using the materials and the curriculum is being used in all 50 states. The state of New Jersey has had a very active professional development program for teachers for several years focused on technological design. Project Lead the Way is a rigorous high school engineering program that has been implemented in more than 1,000 high schools nationwide. These and other educational projects can and should be reviewed for lessons on how best to integrate engineering into the curriculum for all students, and how standards can support those efforts.

A third strategy is to develop a small set of big ideas that we want students to understand at a deep level, to remember for many years after leaving high school, and to find useful in everyday life. These big ideas would provide a means of deciding what is included and what is excluded from the standards. The practice of starting with big ideas to establish a framework is not new (McCarthy and Comfort 1993). However it has gained recent attention in two influential publications from the National Research Council (Duschl et. al. 2007, and Michaels et. al. 2008). In order to be more successful than previous attempts it will be important for the big ideas in engineering to clearly complement the core subjects so they are viewed by practitioners as central, and not as add-ons. For example: in science engineering can be used to illustrate why science is important and how engineering design problems can help students understand and apply physical, life, Earth and space science concepts; and in mathematics engineering problems can engage students in solving problems that sharpen their mathematics abilities.

Establishing a common language for science and mathematics educators when discussing engineering would be challenging, but it could be done. A next step would be to further vet the list of big ideas, either by consulting with engineers, educators, and other experts, researching the literature on educational research, or making international comparisons.

Table 6 offers a recommendation for big ideas in three dimensions of engineering education: critical *knowledge* about the engineering design process, *skill sets* that enable students to apply the process, and *habits of mind* that frame the way students think about how to approach problematic situations. The meaning of these big ideas and how they might play out at the elementary, middle and high school level is elaborated in Appendix B.

Table 6. A Vision of Engineering Standards in terms of Big Ideas

Knowledge	1. Engineering design is an approach to solving problems or achieving goals.
	2. Technology is a fundamental attribute of human culture.
	3. Science and engineering differ in terms of goals, processes, and products.
Skills	4. Designing under constraint.
	5. Using tools and materials.
	6. Mathematical reasoning.
Habits of Mind	7. Systems thinking.
	8. Desire to encourage and support effective teamwork.
	9. Concern for the societal and environmental impacts of technology.

A set of big ideas such as these has the potential to make engineering standards more concise and focused, and to emphasize both the connections and distinctions among the fields of science, technology, engineering and mathematics.

Conclusion

The ideas offered here are preliminary, and do not even begin to address the deeper issues of implementation. Massachusetts enacted the strongest set of technology and engineering standards in the nation in 2001. Although considerable progress has been made in many school districts to implement the standards, change at the classroom level required significant efforts of time and funding by a number of governmental and private organizations in the state. Nonetheless, although educational systems have a great deal of inertia, they can be moved. Recent discussions about accountability in the forthcoming reauthorization of the Elementary and Secondary Education Act include the need to be "…comprehensive, incorporating indicators of the many fields of knowledge and skills that young people need to be successful." (A Broader, Bolder Approach, available on-line at http://www.boldapproach.org/report_20090625.html) If enacted into law, this philosophy may help motivate change as well.

We are optimistic in suggesting that if a clear and concise vision for engineering education can be developed and integrated into the fabric of state standards within the core subjects of science and mathematics then implementation of engineering education will begin to take hold.

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Appendix A

The *2000 National Survey of Science and Mathematics Education* by Susan B. Hudson, Kelly C. McMahon, Christina M. Overstreet, provides a wealth of data, based on responses from 5,765 science and mathematics teachers across the United States. (Hudson 2002) This volume contains tables of frequencies for each item on the questionnaire, copies of the instruments, and detail on data collection and analysis. Results are available online at: http://2000survey.horizon-research.com/reports/tables.php.

	Mathematics Standards How familiar are you with the NCTM *Standards*?
Grades K-4	38% of respondents "Not at all familiar" 31% of respondents "Somewhat familiar" 21% of respondents “Fairly familiar” 10% of respondents “Very familiar
Grades 5-8	27% of respondents "Not at all familiar" 24% of respondents "Somewhat familiar" 30% of respondents “Fairly familiar” 19% of respondents “Very familiar
Grades 9-12	15% of respondents "Not at all familiar" 31% of respondents "Somewhat familiar" 35% of respondents “Fairly familiar” 19% of respondents “Very familiar
	2a. How familiar are you with the *National Science Education Standards*, published by the National Research Council?
Grades K-4	67% of respondents "Not at all familiar" 22% of respondents "Somewhat familiar" 9% of respondents “Fairly familiar” 2% of respondents “Very familiar
Grades 5-8	42% of respondents "Not at all familiar" 31% of respondents "Somewhat familiar 19% of respondents “Fairly familiar” 8% of respondents “Very familiar
Grades 9-12	37% of respondents "Not at all familiar" 34% of respondents "Somewhat familiar" 18% of respondents “Fairly familiar” 10% of respondents “Very familiar

Appendix B: DRAFT

A Vision of Engineering Standards in terms of Big Ideas

Cary Sneider, Associate Research Professor, Portland State University
Based on earlier work at the Museum of Science, Boston

One way of developing standards that are clear, coherent, focused, and rigorous is to first identify a small set of big ideas that we want students to understand at a deep level, to remember for many years after leaving high school, and to find useful in everyday life. These big ideas would provide a means of deciding what is included and what is excluded from the standards. Following is a suggestion for big ideas in three dimensions of engineering education: critical *knowledge* about the engineering design process, *skill sets* that enable students to apply the process, and *habits of mind* that frame the way students think about how to approach problematic situations.

Knowledge	1. Engineering design is an approach to solving problems or achieving goals.
	2. Technology is a fundamental attribute of human culture
	3. Science and engineering differ in terms of goals, processes, and products.
Skill Sets	4. Designing under constraint.
	5. Using tools and materials.
	6. Mathematical reasoning.
Habits of Mind	7. Systems thinking.
	8. Desire to encourage and support effective teamwork.
	9. Concern for the societal and environmental impacts of technology.

In the remainder of this appendix we list learning expectations for the elementary, middle, and high school levels for each of these big ideas, skill sets, and habits of mind. We use the term *benchmarks* to denote what students should know and be able to do at the 5th, 8th, and 12th grade levels, provided they have had adequate opportunities to learn the engineering design process. These learning expectations are based on prior national standards (*NSES, Benchmarks,* and *STL*), and our own experience in developing and evaluating K-12 curriculum materials in technology and engineering.

Knowledge

Three big ideas characterize what students need to know about the engineering design process: 1) that it is an approach to defining and solving problems; 2) technology is a fundamental attribute of human culture; and 3) engineering and science are different but mutually reinforcing endeavors. Learning expectations for each of these big ideas are listed below.

1. Engineering design is an approach to solving problems or achieving goals. Problems and goals can be defined so that they can be tackled in a systematic manner, and satisfying solutions can be found.

> **Grades K-5:** Elementary school children understand that everyone can design a solution to a problem. Given a problem statement, they can ask questions to clarify the problem and learn what others

have done, imagine what some solutions might be, create a plan and test a possible solution, then improve the design and communicate it others.

Grades 5-8: At the middle school level students can more thoroughly describe how the engineering design process would be applied to a problem situation. They can describe a set of steps that can be performed in different sequences and repeated as needed. Although there are slightly different descriptions of the process in the literature, most converge on a set of steps like the following: 1) define the problem, 2) research how others have solved it, 3) generate several alternative solutions, 4) select the most promising solution, 5) make a prototype then 6) test and evaluate it. 7) Communicate the results, then 8) redesign based on feedback.

Grades 9-12: When asked to describe technologies around them, high school students recognize that almost everything that they see, touch, hear, or otherwise experience has been designed by people using the engineering design process. One way of demonstrating this knowledge is by "reverse engineering" some everyday example of technology. They also understand that the engineering design process is a highly flexible approach to recognizing, defining and solving problems, or meeting human needs or desires.

2. Technology is a fundamental attribute of human culture. We define human cultures largely in terms of the technologies that people in those cultures engineer and use.

Grades K-5: At the elementary level students can distinguish things found in nature from things that are made by people. They can also give examples of how naturally occurring materials such as wood, clay, cotton, and animal skins may be processed or combined with other materials to change their properties in order to solve human problems and enhance the quality of life.

Grades 5-8: Middle school students can explain how technologies such as spear points, grinding bowls, and pottery provide evidence of how people who lived long ago solved problems, how they must have lived, and even something of their creativity and sense of aesthetics. They can give examples of historical periods that have been named for the dominant technology, such as the Iron Age, the Bronze Age, or the Industrial Revolution. Further, they are able to give examples of the vast number and variety of technologies that pervade modern society, as well as technologies that are particular to the students' own cultural communities.

Grades 9-12: High school students can describe some of the evidence in support of the statement that "As long as there have been people, there has been technology." They can also cite evidence that technology has been a powerful force in the development of civilization, by giving examples of how technology has shaped values, commerce, language, and the arts. High school students should also be able to describe the rapid pace of technological change in their own era, as well as modern civilization's dependence on technological systems, such as the electrical power grid, transportation systems, and food production and distribution.

3. Science and engineering differ in terms of goals, processes, and products. Science is a means for learning about the natural world, while engineering is a process for changing it. Technological advances may enable new scientific discoveries, while scientific understanding sometimes results in new or improved technologies.

Grades K-5: Students are able to distinguish the questioning, observing, and experimenting process of scientific inquiry from the problem-solving process of engineering design. They can give examples of how a scientist might go about studying the life cycle of a butterfly; and how an engineer might go about designing a better car. They can also give examples of how engineers apply since in their work, and how scientists rely on technologies developed by engineers.

Grades 5-8: Middle school students can explain the differences in goals, processes and products of scientists and engineers. They can also give examples of why engineering is essential to science (e.g. for gaining access to outer space, for observing very small or very distant objects) and why science is

essential to engineering (e.g. for helping engineers understand why things work, such as how airplanes fly, so that they can be improved). They can also describe a wide variety of engineering professions, and recognize that both men and women from different ethnic and cultural backgrounds have chosen to be engineers.

Grades 9-12: Students at the high school level will be able to express a richer sense of the relationships linking technology and science. They can give examples of how technological problems sometimes create a demand for new scientific knowledge, and new technologies make it possible for scientists to extend their research in new ways or to undertake entirely new lines of research. Most important, they can cite modern examples of the complementary relationship between science and technology from fields such as medical research and nanotechnology, and they can describe the educational pathway that individuals would need to follow if they choose to enter such fields.

Skill Sets

Although many skills contribute to a person's capability to do engineering design, we have identified the following skill sets as the most essential: 4) designing under constraint; 5) using tools and materials; and 6) mathematical reasoning. Although this brief section does not define the level of skill performance that should be expected, a major goal of this study will be to specify those levels and figure out how teachers can determine their students' skill levels through embedded assessments.

4. Designing under constraint is the ability to apply all of the steps of the engineering design process in real-world contexts.

Grades K-4: Elementary school students can learn that the problem definition phase of engineering design includes identifying desired characteristics of the solution (criteria), as well as limits (constraints). Young children can learn about constraints such as safety, time, cost, school policy, space, availability of materials, and other realities that restrict possible solutions. Teachers can point out that adults also face constraints when they design things, and that the real challenge, for adults or children, is to devise solutions that give good results in spite of the restrictions. However, elementary students should not be faced with problems that involve too many variables at one time. When generating possible solutions young children have a tendency to go with their first idea. Learning to suspend judgment until other ideas for solving the problem have been generated can be very challenging for elementary students, but is a very important element of the decision-making process.

Grades 5-8: Middle school students should develop skill in defining problems in which there may be competing interests and values. They should learn to use brainstorming as a means for generating diverse solutions, and develop analytical tools for choosing among several possible ideas even in cases where the data are unclear or incomplete. One of the most important tools that they should learn to use is the idea of trade-offs—designs that are best in one respect (safety or ease of use, for example) may be inferior in other ways (cost or appearance). The students should be able to justify decisions in terms of trade-offs, and acknowledge that other individuals may make different, but also justifiable solutions to the same problem. Middle school students should also have experience in prototype testing as a way to transform ideas into practical solutions. Finally, they should have experiences in which they communicate their ideas using drawings and simple models, receive feedback on their ideas, and then redesign their solutions in light of that feedback.

Grades 9-12: High school students should have opportunities to define solvable problems, with clearly identified criteria and constraints, in situations that may at first seem chaotic. Once a solvable problem is defined, and the students brainstorm alternative solutions, they need to be able to make decisions about which solutions are best in light of uncertain or partial data. Good engineering design is distinguished by the ability to make the best possible decision in light of real-world uncertainties.

The use of a Pugh chart is an especially helpful analytic tool in comparing various solutions against criteria and constraints. High school students should also be more sophisticated than middle school students in their abilities to build and test prototypes, or simulate technological systems, to come up with the best possible solution.

5. Using tools and materials involves the selection, testing, and use of appropriate tools and materials to solve a problem or meet a human need.

Grades K-5: In early years, students develop simple skills using tools and materials, such as how to measure, cut, connect, switch, turn on and off, pour, hold, tie, and hook. Beginning with simple instruments, students can use rulers to measure the length, height, and depth of objects and materials; thermometers to measure temperature; watches to measure time; beam balances and spring scales to measure weight and force; magnifiers to observe objects and organisms; and microscopes to observe the finer details of plants, animals, rocks, and other materials. Children should also develop skills in selecting among different materials to choose those most useful for a given purpose.

Grades 5-8: Middle school students should have a broad view of Earth materials as the solid rocks and soils, water in liquid and ice forms, and the gases of the atmosphere. These varied materials have different physical and chemical properties, which make them useful in different ways, for example, as building materials, as sources of fuel, or for growing the plants we use as food. 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 with the other parts. Middle school students should also exhibit capabilities in the use of computers and calculators for solving problems.

Grades 9-12: In addition to the above experiences with tools and materials, high school students should have opportunities to illustrate their ideas through the use of engineering drawings, using Computer Aided Design (CAD) systems if possible. They should also have opportunities to use a variety of tools and materials to construct prototypes of their own design, and to test the design concept by observing its function in representative situations, so that it can be redesigned for manufacturing.

6. Mathematical reasoning involves the use of fundamental mathematical skills as applied to the solution of problems or the building of prototypes.

Grades K-5: Young children should develop the capability of making measurements to answer questions about objects such as "How tall is it?" "How much does it hold?" "How big is it?" They should also encounter situations in which they need to use simple arithmetic operations to solve problems related to a design challenge.

Grades 5-8: At the middle school level students can make more varied and precise measurements as well as more challenging estimates. They are also capable of understanding more abstract measurement concepts, such as the idea of a "measurement unit," the conversion of units from one system to another, and the limitations of measurements made with different instruments. Negative numbers, fractions and decimals can now be used in the service of solving problems. Students should demonstrate their capability not only to carry out operations accurately, but also to choose the appropriate operation, and or level of estimation or precision of measurement for a given situation.

Grades 9-12: While high school students can be expected to bring additional skills (algebra, geometry, trigonometry and possibly elementary calculus) to the engineering design process, the major focus should be on determining whether or not students have developed further skills in determining the most appropriate operations to address the various steps of the process—defining problems quantitatively, creating engineering drawings with scale factors, using tools to accurately measure materials, setting up a testing apparatus that allows for quantitative comparison of different materials and structures, etc.

Habits of Mind

The process of engineering design requires a different mind set from science, mathematics, or any other academic field. We've divided these "habits of mind" into three areas: 7) systems thinking; 8) teamwork; and 9) societal and environmental impacts of technology.

7. Systems thinking is a way of approaching problems with a recognition that all technologies are systems of interacting parts; and they are in turn embedded in larger systems. While it may be argued that systems thinking is both a big idea and a set of skills, we have chosen to list it as a habit of mind to emphasize that systems thinking is—more importantly—a worldview.

> **Grades K-5:** Young children can learn that things consist of interacting parts. Our bodies, for example, are natural systems that contain many different parts that act together to keep us alive and active. They should consider many other systems as well, including both technological and natural systems. Further, young children can learn that everything is connected to everything else, so that damage to one part of a system may affect the function of the system as a whole. Food webs are frequently presented to elementary students as systems; but many other examples should be presented as well.

> **Grades 5-8:** Middle school students can learn that complex technological systems require control mechanisms. The essence of control is comparing information about what is happening to what people want to happen and then making appropriate adjustments. This procedure requires sensing information, processing it, and making changes. The common thermostat can serve as a model for control mechanisms. Students should explore how controls work in various kinds of systems—machines, athletic contests, politics, the human body, and so on. Students should also try to invent control mechanisms that they can actually put into operation. As a habit of mind, understanding systems at a middle school level means that whenever students approach a new problem they consider the system as a whole, how it functions, and how it is controlled.

> **Grades 9-12:** High school students should have opportunities to explore more complex technological systems, including the ways that technologies interact with social and cultural systems. They should be aware that complex systems have layers of controls. Some controls operate particular parts of the system and some control other controls. Even fully automatic systems require human control at some point. High school students should also be able to analyze technological systems using the ideas of universal design and life cycle analysis. The universal design model involves analysis of goals, inputs and outputs, internal processes, feedback and control. Life cycle analysis of a device or process involves how it will be manufactured, operated, maintained, replaced, and disposed of and who will sell, operate, and take care of it. As a habit of mind, students are able to break out of the narrow definition of a problem, and reflect on the relevant systems and how they affect, and in turn are affected by, new and improved technologies.

8. Desire to encourage and support effective teamwork is a hallmark of capable engineering work, since no single individual is likely to bring to a problem situation all of the desirable knowledge and skills that will be needed for a good solution.

> **Grades K-5:** A predisposition to work with others and contribute effectively on a team takes many years to develop and is best started in elementary school. In the early elementary years it is challenging for students to consider other students' ideas, especially where they conflict with their own ideas. By the end of fifth grade students should be able to do this well and to reflect what they like about working on teams, and conflicts that they try to avoid. They should also be aware that their own teams are like those of scientists and engineers in which different individuals with different capabilities and talents are able to combine their efforts and arrive at a better solution as a team than they could as individuals.

Grades 5-8: Middle school students should be aware that most of the work of engineers involves working as a member of a team. Further, one of the strengths of teams is that they may include a wide diversity of talent and points of view from women and men of various social and ethnic backgrounds with different interests, capabilities, and motivations. Evidence of effective teamwork might include full participation with other students on teams, ability to communicate ideas clearly, but also active listening to other teammates, and willingness to work with a wide diversity of individuals.

Grades 9-12: High school students should move to higher levels of critical and creative thinking through progressively more demanding design and technology teamwork. In addition to team-building skills mentioned above, high school students should show evidence that they recognize the advantages of the combination of teamwork and individual effort, that they focus on the quality of work by the entire team, and that they are willing to engage and assist weaker members of their team.

9. Concern for the societal and environmental impacts of technology involves personal values as well as knowledge and skills.

Grades K-5: Elementary school students are capable of realizing that because of our ability to invent tools, materials, and processes, we humans have an enormous effect on the lives of other living things. Such new or improved technologies can have both positive and negative impacts. Consequently, decisions involving technology should be made with possible societal and environmental impacts in mind.

Grades 5-8: A**t** the middle school level students should show evidence of a more sophisticated understanding of the pros and cons of technological changes. On the positive side, transportation, communications, nutrition, sanitation, health care, entertainment, and other technologies give large numbers of people today the goods and services that once were luxuries enjoyed only by the wealthy. However, these benefits are not equally available to everyone. Furthermore, technological changes often have side effects that were not anticipated. For example, the first pioneering engineers who developed automobiles did not realize that this invention would cause tens of thousands of deaths per year as the speed of cars increased. Students' decision-making should show evidence that they are attempting to take possible societal and environmental impacts into account.

Grades 9-12: High school students should be able to conduct risk analyses of technological innovations. Risk analysis is used to minimize the likelihood of unwanted side effects of a new technology by considering such questions as: What alternative ways are there to achieve the same ends, and how do the alternatives compare to the plan being put forward? Who benefits and who suffers? What are the financial and social costs, do they change over time, and who bears them? What are the risks associated with using (or not using) the new technology, how serious are they, and who is in jeopardy? What human, material, and energy resources will be needed to build, install, operate, maintain, and replace the new technology, and where will they come from? How will the new technology and its waste products be disposed of and at what costs? Students should also be aware that risk can be reduced by a variety of means: overdesign, redundancy, fail-safe designs, more research ahead of time, more controls, etc. They should also come to recognize that the cost of such precautions may become prohibitive.