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A Possible Pathway for High School Science in a STEM World

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Abstract

Today's high school science teachers find themselves in a period of transition. For the past decade there have been calls for replacing a narrow focus on science education—the traditional courses in physics, chemistry, biology, and Earth and space science—with a broader curriculum on STEM (that is, the four allied fields of science, technology, engineering, and mathematics). However, at present there are no guidelines on what that broader curriculum should include or how it should be designed, and the gulf that has separated science and mathematics seems as wide as ever, despite decades of efforts to bridge the two disciplines. *Next Generation National Standards for Science Education* are currently being written, but they will not be released until at least 2013. To meet the challenge this paper suggests that educators look to the *Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress (NAEP)* as a source of principles on which to start the process of remodeling the high school science curriculum to better prepare our students to enter the STEM world of the 21st century.

Initial Ideas

A group of professors and graduate fellows at the University of Connecticut's Neag School of Education and School of Engineering proposed an engineering framework for the high school science setting (Koehler et al., 2005). Although it was not the only such proposal put forward, it provides a good example of what such an integrative curriculum might include. The purpose of the framework was to “change the current paradigm of compartmentalized science content predominant in secondary schools throughout the nation” by promoting “the simultaneous teaching of multiple science disciplines in concert with mathematics while incorporating engineering concepts and designs” (Koehler, 2005, p. 4). The proposed framework consisted of 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 *Benchmarks for Science Literacy* (AAAS 1993) Chapter 8 The Designed World, whereas Part II is similar to Chapter 3 The Nature of Technology, from the same document. The outline is also similar to the Technology and Science standards from the *National Science Education Standards* (NRC, 1996).

In a second publication, the authors of the framework explained how they used it as a way to compare the content of standards in 49 states (Koehler et al., 2006). That study found that most states had already adapted some form of technology standards within their science framework, but most of those documents focused on standards related to technology and society. Only 18 states, mostly in Northeastern United States, had a deeper integration of engineering standards reflective of the framework outlined above.

For the next step in the development of ideas that could frame a STEM agenda we turn to a new framework for developing a national exam, which recommends an essential core of concepts and abilities that all students should know and be able to do in the realm of technology and engineering.

Does NAEP Offer a Potential Pathway?

The National Assessment of Educational Progress (NAEP), known as “The Nation’s Report Card,” has provided detailed information on student progress in science at grades 4, 8, and 12 since 1962. NAEP is not intended as a high stakes test, and in fact individual student grades are not reported. Its value lies in using the same test to compare student learning across all states and several urban areas so that educators can judge the relative merits of state-level tests, and follow-up with in-depth research to find out what works, and where the greatest problems lie. The results for NAEP 2009 were released in February, 2011, and as usual the findings were not encouraging. The test of more than 300,000 children found that only 34% of 4th graders, 30% of 8th graders, and 21% of 12th graders are performing at or above the Proficient level in science. Although percentages of students who are proficient grab headlines, NAEP provides a much more valuable service in that the framework documents on which the tests are based, along with released items, provides guidelines for what students who are proficient in science should know and be able to do.

In the past few years the National Assessment Governing Board (NAGB), which is the federal agency responsible for NAEP, has commissioned the development of new framework documents for mathematics, science, and engineering and technology. Each of these documents recommends what all students should know and be able to do. Appropriately, they typically begin with definitions of the field they will address. The combined framework for technology and engineering literacy provides extensive discussions about the similarities, differences, and connections between technology and engineering.

What is the Difference between Technology and Engineering?

The title of this section has kept me awake many nights. Since engineers improve and develop technologies, the two subjects are clearly intertwined, but there has been much

confusion about their definitions. The various standards documents have taken some care to define *technology* and *engineering* and to distinguish them from *science*, and excellent articles have been written to clarify how these terms are commonly used by educators (Custer and Erekson 2008) and why one term would be better than the other as an educational strategy (Wicklein, 2003). In my opinion both terms are important since they mean slightly different things. Following are the best definitions that I have so far been able to find:

Technological literacy is the ability to use, manage, understand, and assess technology. (ITEEA 2007, p. 9) Technology is any modification of the natural world done to fulfill human needs or desires, from the simplest artifacts, such as paper and pencil, to the most complex, including buildings and cities, the electric power grid, satellites, and the Internet. Furthermore, technology is not just the things that people create. It includes the entire infrastructure needed to design, manufacture, operate, and repair technological artifacts. Students should know how to use new technologies, understand how new technologies are developed, and have skills to analyze the ways that new technologies affect us, our nation, and the world (NAGB 2010, p. xi).

Engineering literacy is the ability to solve problems and accomplish goals by applying the engineering design process—a systematic and often iterative approach to designing objects, processes, and systems to meet human needs and wants. Students who are able to apply the engineering design process to new situations know how to define a solvable problem, to generate and test potential solutions, and to modify the design by making tradeoffs among multiple considerations (e.g. functional, ethical, economic, aesthetic) in order to reach an optimal solution. Engineering literacy also involves recognition of the mutually supportive relationship between science and engineering. That is, engineers respond to the interests and needs of society and in turn affect society and the environment by bringing about technological change. (NAGB 2010, p. xi).

In brief, technological literacy is the ability to use, manage, understand, and assess technology, but does not include the ability to improve or create new technologies, while engineering literacy is the ability to solve problems and meet goals using the engineering design process. Both of these capabilities involve knowledge and skills—understanding *and* doing.

In the interests of full disclosure I should point out that I may be in the minority in separating these definitions. The *Standards for Technological Literacy* (ITEEA 2007) includes engineering design capabilities as a subset of technological literacy. And although the new NAEP framework defines technology and engineering separately, it defines *Technology and engineering literacy* together as “the capacity to use, understand, and evaluate technology as well as to understand technological principles and strategies needed to develop solutions and achieve goals.” (NAGB 2010, p. B3)

What Principles Can Guide Science Education in the Future?

The *Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress (NAEP)* lists a fairly large number of principles in three broad areas: Technology and Society, Engineering and Systems, and Information and Computer Technologies. It is not intended for all of these principles to be taught in science classes. For example, many of

the important ideas from Technology and Society might better be taught in the context of a social studies class, and principles of information and computer technologies should be an important component of all science classes. However, principles that lend themselves especially well to science classes of the future are the principles in the area of Engineering and Systems, which is broken down into four sub—areas: A. The Nature of Technology; B. Engineering Design; C. Systems Thinking; and D. Maintenance and Troubleshooting.

Principles in each of these four areas can be interpreted in many ways and may be introduced to students using a variety of different teaching methods. However, if we adopt Wiggins and McTighe’s (1998) concept of “backward design” identifying these principles as STEM educational goals provides the starting point for answering the question of what technology and engineering would look like when integrated into a high school science classroom.

My contribution to meeting our challenge is to annotate principles in response to the assigned questions, relying on my (admittedly distant) experience as a high school science teacher to offer an interpretation of what these principles mean for teaching. The annotated list can be found in the appendix to this paper. Below I draw from the appendix to offer a few responses to the four big questions included in the challenge. (Letters and numbers after each recommendation refer to specific cells in the appendix tables.)

1) To what degree should engineering design challenges be open-ended or well-structured?

A similar question is the extent to which science inquiry experiences should be open-ended or well-structured. Most instructional programs provide both—a mixture of structured experiences to help students learn specific inquiry skills, and open-ended experiences that enable students to bring together various skills and develop creative approach to the research question. Similarly, teachers should provide structured design challenges and guidance so that students can become familiar with the features of the engineering design process (B2). They should also encourage creativity by providing open-ended challenges and urge their students to think of several different solutions to a problem before developing and testing any single idea (B4).

2) To what extent should engineering habits of thought and action be employed in resolving the challenges?

The NAEP framework provides suggestions for what those “habits of thought and action” should be. For example, one principle states that “Engineering design is a systematic, creative, and iterative process for addressing challenges” (B1). This orientation toward problem solving is quite different from the tendency of high school age youth (and many adults) to attempt to solve problems by trying the first solution that comes to mind. Recognizing that it is important to take the time to define the problem, generate several solutions, and to test, evaluate, revise and test again is an important habit of mind that students can learn from participating in engineering design challenges. Habits of mind related to technology include three key ideas about maintenance and troubleshooting: tools and machines must undergo regular maintenance to ensure their proper functioning (D1); troubleshooting is a systematic approach to diagnosing a technological failure (D2); and the combined technology-engineering habit of mind—to take into account the entire life cycle of a product during the initial design (D3).

3) *What are the relationships between engineering design experiences and standards-based instruction in STEM courses?*

The movement for common state standards is gaining steam. A large majority of states currently share common educational standards in mathematics and language arts. Science is next, and a first step is being taken by the National Research Council (NRC) in cooperation with Project 2061 of the American Association for the Advancement of Science (AAAS) and the National Science Teachers Association (NSTA). The NRC released a preliminary version of what it is calling a *Framework for Next Generation Science Education Standards* in July, 2011. The draft includes a major portion on technology and engineering in parallel with sections on physical science, life science, and Earth and space science. Also, a chapter on science practices includes a discussion of the importance of engineering design as a companion to scientific inquiry. So, if this effort remains on track (and there is good reason to believe that it will) the question of the relationship between engineering design experiences and standards-based instruction will be moot. They will be one and the same.

4) *What is an effective sequencing of age-appropriate engineering design challenges?*

The *Technology and Engineering Literacy Framework for the 2014 NAEP* provides assessment targets for grades 4, 8, and 12. So, each of the principles listed in the appendix is spelled out in the body of the *Framework* at successive levels. For example, consider principle B3. “Requirements for a design challenge include the criteria for success, or goals to be achieved, and the constraints or limits that cannot be violated in a solution. The *Framework* specifies what this looks like at three levels as follows:

Grade 4: Requirements for a design include the desired features of a product or system as well as the limits placed on the design, such as which materials are available.

Grade 8: Requirements for a design are made up of the criteria for success and the constraints, or limits, which may include time, money, and materials. Designing often involves making trade-offs between competing requirements and desired design features.

Grade 12: Specifications involve criteria, which may be weighted in various ways, and constraints, which can include natural laws and available technologies. Evaluation is a process for determining how well a solution meets the requirements.

Although the sequences specified in the *Framework* seem reasonable, they are not yet based on research. Over time it is expected that researchers will test these statements to see if they are indeed appropriate for students of the given grade levels, and if changes are needed. The *Next Generation Science Education Standards* are expected to provide an even clearer picture of how knowledge and skills build over the grades, with grade-by-grade standards likely.

In conclusion, documents that provide general principles and guidelines already exist for including engineering and technology in science courses; and there are good reasons to believe that these subjects will finally find a home in the science curriculum for all students. Today’s principles and guidelines (and tomorrow’s standards) are essential for helping teachers prepare their students to become the knowledgeable and skilled citizens, workers, and consumers of the 21st Century.

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Appendix

Text on this page is from the *Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress (NAEP)*, pages 2-18 and 2-19.

Because students live in a complex technological world, they face decisions every day that involve technology. Some of these are simple choices, such as deciding whether to use paper, plastic, or re-usable bags for groceries or choosing which form of entertainment to enjoy, while others are more far-reaching and complex, such as which type of job to choose or what sort of medical treatment to select. How well students are prepared to make those choices depends in part on their understanding of technology. Essential knowledge and skills in this area of technology and engineering literacy are divided into four sub-areas:

A. Understanding the Nature of Technology requires that one take a broad view. Simply put, technology satisfies the basic human needs for food and water, protection from the elements, health, energy, improved transportation, better and cheaper products, and improved communication. Students are expected to understand that the laws of nature provide limits on the types of technologies that can be developed. No one can create a perpetual motion machine, for example, since machines always require more energy input than they provide as useful output. Students are also expected to distinguish between science, technology, and engineering, and to recognize that science enables improvements in technology, while technological improvements created by engineers often lead to advances in science. Students should also recognize that some problems can be solved through behavioral rather than physical changes, for example, by encouraging the use of carpools to relieve traffic congestion rather than constructing additional highway lanes.

B. Engineering Design is an iterative and systematic approach to creating solutions to a broad variety of problems in order to meet people's needs and desires. The process of design includes defining problems in terms of criteria and constraints; researching and generating ideas; selecting between alternatives; making drawings, models, and prototypes; optimizing, testing, evaluating the design, and redesigning if needed; and, eventually, communicating the results.

C. Systems Thinking concerns the capability to identify the components, goals, and processes of systems. It also entails an understanding of such systems principles as feedback and control and also the ability to use simulations or other tools to predict the behavior of systems.

D. Maintenance and Troubleshooting are how most people encounter technology on a daily basis— by troubleshooting technologies that malfunction and by maintaining tools and systems so that they do not break down. The better a person understands the way that something works, the easier it is to maintain it and to track down problems when they arise.

A. The Nature of Technology

Key Principles*	Teaching Suggestions
A1. Technology is constrained by laws of nature, such as gravity.	Design challenges that require students to apply concepts they learned in science class to solve a problem present good opportunities for students to learn the concept of “constraint.”
A2. Scientists are concerned with what exists in nature; engineers modify natural materials to meet human needs and wants.	In order to learn the difference between the work of scientists and engineers it will be important for students to engage in both fields and reflect on differences in purpose, process, and product.
A3. Technological development involves creative thinking.	Students should be given design challenges at the right level of difficulty so they can come up with very different designs.
A4. Technologies developed for one purpose are sometimes adapted to serve other purposes.	In addition to providing real-world examples it is also important for students to have opportunities to think of new uses for current technologies.
A5. Science, technology, engineering, mathematics, and other disciplines are mutually supportive.	The obvious example of instrument technologies used by scientists should be enriched with stories of inventions that spurred scientific advancement, and new theories that led to new technologies.
A6. The pace of technological change has been increasing.	Students can reflect on the technological changes they have observed, including not only changes in computers and networking, but also changes in electric lighting, fabrics, foods, toys—all of the ways that people change the natural world to meet their needs and achieve goals.
A7. Tools help people do things efficiently, accurately, and safely.	Teachers can broaden students’ definition of “tool” to range from simple communication tools such as pencils and paper to complex scientific instruments.

* Key Principles are from the *Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress*, page X.

B. Engineering Design

Key Principles*	Teaching Suggestions
B1. Engineering design is a systematic, creative, and iterative process for addressing challenges.	Providing guidance to students engaged in projects can help them see the systematic and iterative nature of the design process.
B2. Designing includes identifying and stating the problem, need, or desire; generating ideas; evaluating ideas; selecting a solution; making and testing models or prototypes; redesigning; and communicating results.	While it is valuable for students to have an overview of the engineering design process, even more important is the opportunity to go through the process several times to get to know its features.
B3. Requirements for a design challenge include the criteria for success, or goals to be achieved, and the constraints or limits that cannot be violated in a solution. Types of criteria and constraints include materials, cost, safety, reliability, performance, maintenance, ease of use, aesthetic considerations, and policies.	Students can work backwards from a given product to infer the criteria and constraints that the product was designed to meet. They can also work forwards, and specify criteria and constraints to meet new program challenges.
B4. There are several possible ways of addressing a design challenge.	Students should be encouraged to think of several solutions to a problem before developing and testing any single idea.
B5. Evaluation means determining how well a solution meets requirements.	Testing designs in engineering is similar to testing hypotheses in science.
B6. Optimization involves finding the best possible solution when some criterion or constraint is identified as the most important and other constraints are minimized.	At least some engineering projects need to include two or more iterations where students prioritize criteria or constraints and modify the design to achieve the best possible design.
B7. Engineering design usually requires one to develop and manipulate representations and models (e.g., prototypes, drawings, charts, and graphs).	The ability to develop and manipulate models cuts across many science and engineering fields, so it is important for students to have many occasions to develop this skill.

* Key Principles are from the *Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress*, page X.

C. Systems Thinking

Key Principles*	Teaching Suggestions
C1. Systems may include subsystems and may interact with other systems. Systems may also be embedded within larger systems.	The ability to define a model for a given purpose is important in both science and engineering. Students should have many opportunities to apply this skill in the context of studying a system to better understand how it functions (science) and to determine how the system might be modified to solve a problem or accomplish a goal (engineering).
C2. Dynamic technological systems require energy with more complicated systems tending to require more energy and to be more vulnerable to error and failure.	Tracing the flow of energy and energy transformations within a system is equally useful in science (e.g. tracing flow of energy in an ecosystem from the Sun to top-level predators) as in engineering (e.g. tracing the flow of energy in a vehicle from fuel to forward motion). Students should have opportunities to apply the same systems concepts to natural and designed systems.
C3. Technological systems are designed for specific purposes. They incorporate various processes that transform inputs into outputs. Two important features of technological systems are feedback and control.	Reverse engineering existing systems provides good opportunities to for students to identify the purpose of a system, its boundaries, inputs, outputs and internal processes, positive and negative feedback effects, and systems control. After students have reverse engineered several systems they should have opportunities to design new systems.
C4. Various methods can be used to increase the reliability of technological systems.	A good approach to reliability is to engage students in thinking about products or systems of personal interest that typically fail, and to think of ways to improve the reliability of those products or systems.

* Key Principles are from the *Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress*, page X.

. Maintenance and Troubleshooting

Key Principles*	Teaching Suggestions
D1. Tools and machines must undergo regular maintenance to ensure their proper functioning.	From automobiles to ovens, maintenance is an essential service that we need to keep our various technologies working as we want them to. Students might begin with simple systems, such as oiling of hand tools to keep them functioning. They could then compare these simple maintenance processes with the more complex maintenance that occurs “behind the scenes” in typical schools, such as inspecting the building’s furnace, air conditioning, water, ventilation, and waste water system, and to finding out from local experts how these systems are maintained.
D2. Troubleshooting is a systematic approach to diagnosing a technological failure.	One of the most common ways that we interact with technology is when it doesn’t work. People do not have to be experts to troubleshoot even complex systems using such methods as making sure it has a source of power, isolating each element of the system to see if it works independent of the others, identifying all of the ways the system might fail and ruling them out one at a time.
D3. Taking into account the entire life cycle of a product is an important part of designing.	It follows from all of the above principles that an ideal product or system will require little maintenance, is reliable and easy to troubleshoot on the rare occasions that it does break down. In addition to designing a product for longer life, it is important to reduce impact on the environment by taking into account extraction of raw materials and transportation needs, as well as final disposition of the product when it no longer functions.

* Key Principles are from the *Technology and Engineering Literacy Framework for the 2014 National Assessment of Educational Progress*, page X.