Chapter 2
Grand Challenges for Engineering Education

Cary Sneider

In 2013 the National Research Council released *A Framework for K-12 Science Education: Practices, Core Ideas, and Crosscutting Concepts* (NRC, 2012), which laid the groundwork for revising state science standards. Unlike previous documents that presented long lists of concepts and skills, the *Framework* specified just thirteen core ideas that all students should learn at increasing levels of sophistication from kindergarten through twelfth grade.

What is even more remarkable than agreement on a coherent set of core ideas was the vision of practices of science and engineering that all students should learn. It was a vision both inspirational and practical:

> *We anticipate that the insights gained and interests provoked from studying and engaging in the practices of science and engineering during their K-12 schooling should help students see how science and engineering are instrumental in addressing major challenges that confront society today, such as generating sufficient energy, preventing and treating diseases, maintaining supplies of clean water and food, and solving the problems of global environmental change. In addition, although not all students will choose to pursue careers in science, engineering, or technology, we hope that a science education based on the framework will motivate and inspire a greater number of people—and a better representation of the broad diversity of the American population—to follow these paths than is the case today*. (NRC, 2012, p. 9)

The *Framework* included "engineering" alongside "science," and declared that students should study major global problems that require at least equal measures of engineering know-how and scientific knowledge. The document also included explicit instructions for presenting to students the engineering design process as both core ideas (what students should know) and practice (what students should be able to do.) Also included were important ideas about the two-way relationship between science and engineering (that science helps engineering advance, and

C. Sneider (✉)
Portland State University, Portland, OR, USA
e-mail: csneider@pdx.edu

L.A. Annetta, J. Minogue (eds.), *Connecting Science and Engineering Education Practices in Meaningful Ways*, Contemporary Trends and Issues in Science Education 44, DOI 10.1007/978-3-319-16399-4_2

engineering drives science forward), and the influence of science, technology, and engineering on society and the natural environment.

Development of the *Framework* was just the first step in the most recent effort to remake our nation's science education infrastructure. A coalition of 26 states, working with the independent organization Achieve, Inc., used the *Framework* as the blueprint for *Next Generation Science Standards* (NGSS Lead States, 2013), which spells out, grade by grade for K-5, and in grade bands for 6–8 and 9–12, statements that translate the major ideas from the *Framework* into specific learning targets, or "performance expectations." Together, the *Framework* and NGSS project an entirely new vision of science education to guide the development of new curricula, new assessments, new methods of teacher education, and new goals for our students.

These documents have launched what is likely to be a long campaign to integrate engineering and technology into our nation's educational infrastructure. Although a similar goal was put forward in *Science for All Americans* (AAAS, 1989), and the *National Science Education Standards* (NRC, 1996), the immense inertia of our educational system has so far resisted any significant integration of engineering and technology into science education, let alone social studies, mathematics, or language arts (although there are clear connections to all of those curriculum areas).

These global problems mentioned in the paragraph quoted above—such *as generating sufficient energy, preventing and treating diseases, maintaining supplies of clean water and food, and solving the problems of global environmental change*—are among the grand challenges that engineers will face with increasing urgency in the decades ahead as the human population continues to grow. The thesis of this chapter is that realizing this vision also poses grand challenges for science and engineering teachers at the K-12 level, as well as for school principals, district and state educational leaders, and those of us who work at universities charged with preparing tomorrow's teachers. This chapter will describe the sources of that resistance with the aim of alerting readers to the nature and depth of the challenge ahead, and suggest new pathways forward.

Grand Challenge #1 Explaining Technology

According to the *Framework* and the NGSS, science, engineering, and technology are interrelated but distinct terms:

> *In the K–12 context, "science" is generally taken to mean the traditional natural sciences: physics, chemistry, biology, and (more recently) earth, space, and environmental sciences … We use the term "engineering" in a very broad sense to mean any engagement in a systematic practice of design to achieve solutions to particular human problems. Likewise, we broadly use the term "technology" to include all types of human-made systems and processes—not in the limited sense often used in schools that equates technology with modern computational and communications devices. Technologies result when engineers apply their understanding of the natural world and of human behavior to design ways to satisfy human needs and wants.* (NRC, 2012, p. 11–12)

According to this definition the earliest uses of rock, bone, and wood to make implements for hunting and preparing food were *technologies*, as were the invention of fire, woven fabrics, and the earliest forms of agriculture. Although the nameless inventors who created these technologies did not have degrees in engineering, there is no doubt that they created what they did to solve very real problems in their environment.

Our early human ancestors carried technologies with them, but for the most part they lived in a natural environment. Today we are surrounded by technologies and we experience very little of the natural world. To appreciate the extent to which we depend on them, imagine what would happen if all of our technologies disappeared. First, this book would dissolve. Whether it's electronic or made of paper, it's a product of human invention. Next the lights would go out, as would everything that runs on electricity, oil or gas, since these all depend on technologies to utilize Earth's resources for energy and power. If you are indoors the furniture, rugs, and walls would disappear, and soon the entire building would be gone. Say goodbye to your glasses, cosmetics, and every stitch of clothing. Without the comfort and support of the technological world, you would be standing naked in a field or forest.

Actually, the above scenario is optimistic. Chances are without technology very few of us would survive long at all. In 1900 people could expect to live about 47 years. The vastly extended life expectancy that we enjoy today is only partly due to advances in medicine and improved child mortality rates. The technologies involved in processing fresh potable water is largely responsible for our increased lifespan, just as the technologies involved in growing and processing food have greatly increased the carrying capacity of our planet.

Despite the wide diversity of technologies that we encounter daily, and their importance for our very existence, most people don't even think about them. And when they do, they use the term "technology" in a very limited sense. According to a pair of Gallup polls, for the great majority of people the word *technology* is "tied more to the modern apparatus, machines, and gadgets people have developed" (Rose et al. 2004, p. 1). In 2001, most people who were asked: "When you hear the word 'technology' what is the first thought that comes to mind?" the majority responded "computers" (67 %), while a few responded "electronics" (4 %). Those numbers were virtually unchanged in 2004 (68 % and 5 % respectively).

For the most part teachers of all subjects and grade levels also use the term "technology" in a limited sense, although in a way that is somewhat different from the general population. When teachers claim that their students "don't have access to technology" they are not saying that their students have no pencils and paper. Instead they usually mean that their school does not have sufficient computers or tablets for their students to use. And a classroom "equipped with technology" usually means a Smart Board, which offers the functions of a computer and projector rolled into one.

If we expect our students to understand what engineers do, an important step is coming to understand the products of engineering—the technologies that engineers design and modify to meet people's needs and wants.

To gain some insight into the nature of technology, pick up an object within reach. If you're sitting at a desk a pen will do, as will a piece of paper or more complex technology such as a calendar or cell phone. If you're reading in bed pick up a tissue or alarm clock, and ask yourself these questions:

- What was this technology designed to do?
- What did this particular piece of technology replace?
- How does this technology function better than what was used in the past? How is it worse?
- Where did the materials used to make this technology come from?
- What technologies were required to produce it, and transport it here?
- What will happen to this technology when I'm done with it?
- Could this technology be improved? If so, how?

Helping people realize that the vast number of products around them are technologies would be a step in the right direction; but only a step. People who do understand that technologies are all of the ways that people change the world to meet human needs and wants tend to think of products. But technologies also include processes and systems. A bus schedule is a technology. A recipe for baking a cake is a technology. Life insurance is a technology. Our nation's system of government is a technology. All of these have been created by people, and modified and improved over time. While the people who shaped these technologies may not have been licensed engineers, they were nonetheless "doing engineering." That is they were solving problems in a way that is systematic and iterative.

Why is it important for everyone to learn about technology? Isn't it enough for the professionals to understand it, since most people seem to do just fine with their limited understanding? A thoughtful answer to that question was provided by the National Academy of Engineering and the National Research Council in a short report entitled *Technically Speaking: Why All Americans Need to Know More About Technology*.

> *As far into the future as our imaginations can take us, we will face challenges that depend on the development and application of technology. Better health, more abundant food, more humane living and working conditions, cleaner air and water, more effective education, and scores of other improvements in the human condition are within our grasp. But none of these improvements is guaranteed, and many problems will arise that we cannot predict. To take full advantage of the benefits and to recognize, address, or even avoid the pitfalls of technology, Americans must become better stewards of technological change.* (Pearson et al. 2002, p. 12)

Technically Speaking points out that it is not only our standard of living that is at stake. As the world's population grows, so does our impact on the environment. While developing nations mechanize agriculture, produce more energy, goods, and services, and turn more arable land into cities, the impact on the environment grows at an ever faster rate. To counter these trends we need to be both leaders and collaborators in finding new solutions to the unanticipated effects of yesterday's technologies, such as our changing atmosphere due to the burning of fossil fuels, the impact of pesticides on amphibians and other fragile species, and industrial wastes from thousands of sources. In other words, we need a strong, creative, and flexible technical workforce *and* a technologically literate populace to solve these global challenges. Given how little people's understanding of technology has changed in recent years, that is a grand challenge indeed.

A pathway forward proposed in *Technologically Speaking* consists of 11 recommendations that include incorporating technology into state standards, curriculum, and assessment, as well as the preparation of teachers. The recommendations call upon the National Science Foundation and other federal agencies to support research in how people learn about technology. Museums, private industry, and engineering societies are asked to educate the public, and especially journalists about the nature and importance of technology. The eleventh recommendation is for the White House to add a Presidential Award for Excellence in Technology Teaching to those it currently offers for mathematics and science teaching.

To some extent these recommendations foreshadowed the rise of STEM education as a new national goal, and the *Framework* and *Next Generation Science Standards*. Nonetheless, we have a long way to go before we begin to turn the tide, so that a majority of people have a broad and deep understanding of the "T" in STEM.

Grand Challenge #2: Explaining What Engineers Do

You've checked into a hotel room only to find that the toilet does not flush. You call the front desk, and after apologizing for the inconvenience the clerk promises to notify "Engineering" right away. Does that sound familiar? Perhaps you've also noticed that many public buildings have a room where janitorial supplies are kept that is labeled "Engineering." A somewhat more elevated vision of engineering is portrayed in Star Trek, where unsung heroes in "Engineering" often save the day by fixing the warp drive just in time to fend off a Klingon attack.

The common conception of engineers as the people who repair and maintain modern conveniences is widespread, and presents one of the greatest challenges to implementing new educational standards related to engineering. Why, after all, would a parent want their child to spend valuable hours in school learning the skills needed for menial jobs? A reflection of this view has been a policy of the National Collegiate Athletic Association (NCAA) that established a Clearinghouse for reviewing every high school course in the country to ensure that college athletes were prepared to meet the academic rigors of college. When Massachusetts adopted engineering as a part of its science standards in 2001, a number of high schools developed rigorous engineering courses. The NCAA Clearinghouse rejected all of these courses as "vocational" subjects—that is, not a college preparatory course. A letter from the Commissioner of Education in Massachusetts to the President of the NCAA was required to reverse the policy—but only for schools in Massachusetts.

School guidance counselors, who presumably have their fingers on the pulse of the nation's job markets, have a more nuanced view of engineering. The Museum of Science in Boston investigated conceptions of engineering among school guidance counselor and found two prevailing viewpoints: One view was that engineering referred to trades such as plumbing, sanitation, or similar vocations. The other view was that engineers were brilliant people to whom science and mathematics came easily. Consequently, in some schools the only students who were counseled to consider engineering were those who struggled with academic work, while at other schools only the top students were counseled to apply to top engineering schools such as MIT. To counter these narrow views the Museum of Science developed a daylong program that brought guidance counselors together with engineers and engineering graduate students. Many of the guidance counselors were surprised at the wide variety of engineering specialties, and the number of educational institutions that offered various levels of engineering degrees.

Increasing the public's understanding of the engineering profession to the extent that they encourage their children to consider engineering as a career is grand challenge #2. To meet the challenge it will be important to enlist the help of museum educators, journalists, and other thought leaders to help public audiences understand the essential role of engineers in modern society.

Grand Challenge #3 Developing New Curriculum Materials

Since Massachusetts was one of the first states to include a very strong engineering thread in its science standards, the Museum of Science in Boston undertook a major project to develop curriculum materials that teachers could use to teach children and youth about the world of technology and engineering. The Museum developed curricula at the elementary, middle, and high school levels. The best known of these is an elementary program called *Engineering is Elementary* (Cunningham & Hester, 2007).

Engineering is Elementary introduces children to engineering through a series of stories about children who live in different countries. Each story features a technology that is important in that country. Career awareness is built by including a different type of professional engineer in each story—usually a parent, aunt, or uncle of the story's main character. The story sets the context for a design challenge that the children will do in class, using simple materials. All EiE units emphasize connections among science, language arts, and social studies, so teachers will not see this effort as "something else they have to add." Instead, the EiE units illustrate the connections among the different school subjects. For example:

Materials Engineering and the Great Wall of China tells the story of Yi Min. Students learn how materials engineers investigate the properties of earth materials like pebbles, soil, sand, and silt, and how different materials were combined to create the Great Wall of China. They then investigate on their own to determine which earth materials would make the strongest, sturdiest wall. For the design challenge, students construct their own "mini Wall of China."

Environmental Engineering and Drinking Water for India centers on the story of Salila, a girl in India whose family cannot just tap a faucet to get a drink of fresh water. In this book students learn about the human requirement for clean and safe drinking water and the consequential need for environmental engineers to ensure water quality. This unit addresses the increasingly important issue of water quality through lessons that teach students about water contamination and the ways that people ensure the quality of their drinking water. Students plan, construct, test, and improve their own water filters.

Mechanical Engineering and Denmark's Windmills explains how engineers design machines to capture wind energy as told by a young boy named Leif. The story includes the science concepts of air resistance, air pressure, and air as wind, and a description of Denmark's extensive wind turbines, which provide a renewable energy source. Students explore different materials and shapes conducive to catching the wind. For the design challenge, students create their own windmills that can lift a small weight.

These instructional materials aim to do much more than explain what technology is and what engineers do. The goal is to teach student to *think* like engineers. For students at the elementary level, that means identifying a situation that they want to change as a problem to be solved, and to approach the problem with a systematic design process involving five phases—asking pertinent questions, brainstorming ideas, planning, creating, and improving the design. A number of evaluation studies have shown the curriculum to be highly effective (Lachapelle, Phadnis, Jocz, & Cunningham, 2012).

The Museum of Science also developed a middle school mathematics curriculum called *Building Math*, in which students learn mathematics concepts and skills in the context of engineering design challenges, and a high school course entitled *Engineering the Future: Science, Technology, and the Design Process*. The latest curriculum, *Engineering Today*, provides enrichment units to complement existing science materials. Although these materials were developed before the *Framework* and NGSS, they can easily be adapted to align with the new standards.

At the high school level teachers need to decide if they will teach engineering design in a course that focuses on engineering and uses science to support the engineering concepts; or a course that primarily focuses on the science and uses engineering to help students better learn the science. Both approaches are valid. The science first perspective is that science concepts and processes are more fundamental than practical applications. The engineering first perspective is that students are likely to be more motivated by applying science in the real world.

An Investigation of the Impact of Strengthening the "T" and "E" Components of STEM in High School Biology and Chemistry Courses is an NSF project led by Debra Brockway at Stevens Institute of Technology in New Jersey, to develop and evaluate engineering units that would be integrated and taught in the context of high school chemistry and biology courses. The rationale for that project is that today, if engineering is taught at all, it is typically part of a physics course. However, only about a third of all high school students take physics. That's up from about 18 % in the 1970s and 1980s (Neuschatz, McFarling, & White, 2005; Tesfaye & White, 2010), but it means that most students would miss engineering entirely if it is just taught in the context of physics. However, most students take biology or chemistry, so if engineering is built into these courses most students will have an opportunity to learn what engineering is all about.

Luckily, there are a substantial number of curriculum materials that combine science and engineering. The *Go-To Guide for Engineering Curricula* is a three volume series that describes 40 curriculum programs, ranging from pre-school to high school seniors (Sneider, 2015). The curricula employ a wide variety of different methods. Although these materials are not fully "aligned" to the NGSS since they were developed before the standards were released, they have nonetheless been developed in the spirit of the new standards; and to some extent they helped to influence the standards since they provided an existence proof that curricula can be developed that blend science and engineering.

In summary, we do have some instructional materials that blend science and engineering; but none of these materials are a precise match for the NGSS. The grand challenge of developing instructional materials for teaching engineering in the context of science can be met—but as we show in subsequent sections, it's not an easy lift. Challenges include recognizing that designing and building things alone is not necessarily engineering, learning about the various dimensions of engineering design that students need to learn, and the common misconceptions and difficulties that students encounter. In the next section we drill deeper, into what it means to teach the design process.

Grand Challenge #4 Teaching the Design Process

Today many teachers claim that they already teach engineering because they occasionally have their students build newspaper towers or bridges from cardboard or popsicle sticks and test them to failure. Another popular "engineering" activity is designing a holder for a raw egg that will keep the egg from breaking when it is dropped. None of these are in fact engineering if students are not being taught design principles. They also do not belong in the science curriculum if students are not encouraged to apply scientific ideas and mathematics when doing these activities.

Curriculum developers need to base their work on research showing which instructional methods represent best practice. Unfortunately, the body of research literature on how to accurately and effectively teach the design process is quite limited, particularly in contrast to the science-education research base.

Crismond and Adams (2012) found a way around the problem of too few studies of engineering in K-12 schools by casting the net wider to include *any* studies on the teaching of engineering design, including such related fields as industrial design and teaching engineering at the college level, based on the reasonable assumption that engineering design is a transferrable skill and that people of various ages in many different fields encounter similar problems when engaged in designing a product, process, or system to solve a problem. Their work is based on an analysis of more than 400 papers from 170 peer-reviewed journals concerning the cognitive aspects of design. The results are organized in a table that summarizes expert and novice strategies. Table 2.1 is an abbreviated version of the table published in *The Science Teacher* (Crismond, 2013). The descriptions in the table of how beginners vs. informed designers meet design challenges provide insight into what it means to teach design principles to students.

In its extended form the table provides suggestions for how teachers can help their students progress from "beginning" to "informed" designers. Let's look at an example. The first pattern—Problem Solving vs. Problem Framing—poses the challenge of helping students move from treating a design task as a well-defined, straightforward problem posed by the teacher, to a situation that needs further exploration and definition in terms of criteria and constraints. Instructional strategies that are recommended include having the students state the problem in their own words, explain how they think a good solution would function, and to restate the problem in a way that would allow them to begin investigating possible solutions.

While Crismond and Adam's (2012) contribution to engineering design education is helpful, moving students from beginning to informed designers is complex and a grand challenge for engineering education.

Grand Challenge #5 Developing Assessments

Grand Challenge number 5 has two parts: (1) to develop ways to assess large numbers of students in ways that tap their creative abilities to engineer solutions to problems as called for in the NGSS; and (2) to develop assessments that teachers can use to find out what their students have learned (or not) and how they think about engineering and technology, so they can adjust instructional appropriately.

Starting with large-scale assessments, it's important to keep in mind that the NGSS is an assessment framework. That is, the performance expectations that make up the heart of the NGSS are intended to be endpoints in instruction. They illustrate what students are expected to be able to do to demonstrate their understanding after instruction. In contrast, prior sets of standards were statements of facts. Consider, for example what a fifth grader should be expected to know and be able to do about the sun, according to the *Next Generation Science Standards* (NGSS Lead States 2013) and the *National Science Education Standards* (NRC, 1996), the most recent comparable document.

National Science Education Standards (p. 43)	*Next Generation Science Standards* (p. 49)
The sun, and average size star, is the central and largest body in the solar system	Support an argument that differences in the apparent brightness of the sun compared to other stars is due to their relative distances from Earth

Table 2.1 Characteristics of Beginning vs. Informed Designers

Design strategies	**Beginning vs. informed designer patterns**	
	What beginning designers do	What informed designers do
Understand the design challenge	**Pattern A. Problem solving vs. problem framing**	
	Treat design task as a well-defined, straightforward problem that they prematurely attempt to solve	Delay making design decisions in order to explore, comprehend and frame the problem better
Build knowledge, do research	**Pattern B. Skipping vs. doing research**	
	Skip doing research and instead pose or build solutions immediately	Do investigations and research to learn about the problem, and how the system works
Generate ideas	**Pattern C. Idea scarcity vs. idea fluency**	
	Work with few or just one idea, which they can get fixated or stuck on, and may not want to	Practice idea fluency in order to work with lots of ideas by doing divergent thinking, brainstorming, etc
Sketch and represent ideas	**Pattern D. Surface vs. deep drawing and modeling**	
	Propose superficial ideas that do not support deep inquiry of a system, and that would not work if built	Use multiple representations to explore and investigate design ideas and support deeper inquiry into how a system works
Weigh options and make decisions	**Pattern E. Ignore vs. balance benefits and tradeoffs**	
	Make design decisions without articulating reasoning, or attend only to pros of favored ideas and cons of lesser approaches	Use words and graphics to display and weigh both benefits and tradeoffs of all ideas before making a decision
Conduct tests and experiments	**Pattern F. Confounded vs. valid tests and experiments**	
	Do few or no tests on prototypes, or may run confounded experiments that cannot provide useful information	Conduct valid experiments to learn about materials, key design variables and how the system works
Troubleshoot prototypes	**Pattern G. Unfocused vs. diagnostic troubleshooting**	
	Use an unfocused, non-analytical way to view prototypes during testing and troubleshooting ideas	Focus attention on problematic areas and subsystems when troubleshooting devices and proposing ways to fix them
Revise and iterate	**Pattern H. Haphazard or linear vs. managed & iterative designing**	
	Design in haphazard ways, or do design steps once in linear order	Do design in a managed way, where ideas are improved iteratively via feedback, and strategies are used ultiple times as needed, in any order
Reflect on process	**Pattern I. Tacit vs. reflective design thinking**	
	Do tacit designing with little self-reflective or monitoring of actions taken	Practice reflective thinking by keeping tabs on design strategies and thinking while working and after finished

Table from Crismond and Adams (2012), with permission from the authors

Both of these statements include the idea that the sun is a star. However, they are vastly different from an assessment point of view. To assess the older statement all that is needed is a multiple-choice question or two, to find out if students know about the sun's position in the solar system, and how big it is compared with the planets. To assess whether or not a student meets the performance expectation from the NGSS, the student needs to have an opportunity to construct and articulate an argument (verbally or in writing) about why he or she believes the sun to be a star, even though it is much, much, brighter than the stars that can be seen in the sky.

The National Assessment of Educational Progress (NAEP), also known as "The Nation's Report Card" is not a high stakes test. Students do not receive individual scores. Instead, assessments are given to large samples of students to gauge the effectiveness of our nation's educational system, and to compare how well different states and 21 major cities prepare students in reading, writing, mathematics, social studies, science, and most recently, technology and engineering literacy. Many of the items ask students to perform challenging tasks like the one from the NGSS in which students are asked to support an argument. Students' papers are scanned and sent to hundreds of scorers across the country (many of whom are retired teachers) to score at home, using a rubric. The fact that hundreds of thousands of tests that involve constructed responses can be scored within a reasonable time demonstrates that it is possible to assess individual students' achievement of these new standards.

The second part of challenge number five concerns "formative" assessments—what teachers do every day to find out what their students have learned so that can better shape the learning experience. Some educators think of formative assessment only in terms of instruments or quizzes, while others think of formative assessment as a process that enables perceptive teachers to gain insight into student thinking. In fact, both are important, as illustrated in a recent series of studies to develop a new physics course (Osowiecki & Southwick, in press) that used several different methods of formative assessment keyed to traditional summative mid-term and final exams (Sneider & Wojnowski, 2013).

Assessment has received a bad reputation in recent years because of high stakes testing. Certainly we need to change the punishing tactics built into law concerning high stakes tests. However, when those laws are reformed we don't want to throw out the baby with the bathwater. Assessment is essential for teachers and students to measure progress and to plan instructional moves. We just need to replace the "sticks" with "carrots" and integrate assessment smoothly into our instructional programs. Without assessment there is no way to determine if our students are achieving the standards; and if we don't know what they know (or don't know) there is no way we can help them.

As curriculum developers and teachers begin using the NGSS both types of assessments should improve, since the NGSS clearly specifies not just what students should know, but also how they should demonstrate their abilities to use the knowledge. While that may not be easy to assess with multiple-choice tests, assessments like NAEP are demonstrating that it can be done, even with large numbers of students.

Grand Challenge #6 Teaching the Teachers

The greatest challenge is likely to be experienced by teachers. Preparing elementary teachers to teach science has always been difficult; adding engineering just increases the burden. At the high school level it will be challenging to figure out how to fit five subjects into 3 years. Why five subjects? First, physical science includes both physics and chemistry. That's two. Then there's Earth and space science, which includes more at the high school level than physics and chemistry combined. Life science also includes a lot of really big ideas that take some time to teach; so that cannot be done in less than two semesters. And finally there's engineering. That's five subjects!

A report from the National Research Council (2015) recommends that educators at all levels take some time to figure out how to implement the new standards, and not rush to buy new curriculum materials that say "NGSS Aligned" on the cover. Teachers at all levels will need experience, practice, and opportunities to collaborate in developing new skills including, but not limited to:

- Integrating engineering design into science in ways that help their students develop engineering design skills alongside science inquiry skills;
- Engaging their students in all eight practices of science and engineering and helping them become more skilled at using the practices;
- Helping their students see the deep connections among the different fields of science and engineering through crosscutting concepts;
- Using formative assessment to monitor student progress, and enabling their students to gauge their own progress;
- Teaching fewer topics in greater depth;
- Teaching their students not only to use new technologies, but also how to acquire new technical skills on their own; and
- Communicating not only the enjoyment of science and engineering as interesting and challenging activities in themselves, but also the importance of all four STEM fields in developing sustainable practices that will allow society to thrive while maintaining healthy natural environments.

There is an especially bright ray of hope from informal educators, including afterschool and summer programs as well as museums and science centers. For example, 4-H is a huge informal education program in this country, with clubs and summer camps and afterschool programs for six million children. In recent years 4-H has greatly expanded their science and technology offerings such as robotics (Baker, Nugent, & Hampton, 2008). Science centers have also taken leadership in engineering education, both through exhibits and programs on site, as well as outreach (Alpert, Isaacs, Barry, Miller, & Busmaina, 2005).

There is no silver bullet, no single approach to helping teachers acquire these skills. Many approaches will be needed, and they will certainly need help from their fellow teachers of all subject areas, principals and other administrators, parents, local businesses and industries. In short they will need the support of their entire communities to meet these formidable challenges.

Grand Challenge #7 Balancing Technical and Academic Subjects

The U.S. and Great Britain have had a long history of establishing educational programs aimed at teaching technical skills, then eliminating them in favor of more "academic" pursuits (Firth, 2005; Donnelly, 1989; Christiansen, 1975). For example, at one time Boston Technical High School was a leading institution for preparing students to enter technical fields. As late as the 1950s graduates would be admitted to MIT if they maintained all A's. However, during the 1960s many of the "shop" teachers retired and were not replaced, and the space that had been occupied by those shops were reallocated (Sneider & Moss, 2004). That story is being repeated today in most states, as technology programs are closed and teachers laid off. According to the California Industrial and Technology Education Association and Foundation (2007) in the 1980s, nearly every public high school in California had a technology education program. After years of budget shortfalls, today only 20 % of California schools have such programs.

The grand challenge is to reconcile two conflicting educational philosophies. One that values learning how to solve a problem and actually produce something that meets a societal need, and the other that values learning for its own sake, and disdains the time spent in "getting one's hands dirty."

In "A Turn to Engineering: The Continuing Struggle of Technology Education for Legitimization as a School Subject," Theodore Lewis presents his view that the new emphasis on "engineering" rather than "technology" is a strategy to paint the technical arts with a high status brush, making it more acceptable in the eyes of society. He acknowledges the success that this approach seems to be enjoying, but cautions that "we may take ourselves too seriously, throwing out those aspects of engineering that remind us of our humble practical traditions, and keeping only those aspects that resonate with the dominant academic ideology of schools" (Lewis, 2004).

Grand Challenge #8 Engaging Technology and CTE Teachers

Grand challenge #8 is to persuade the nation's technology teachers and CTE teachers to join with science teachers to provide the kind of education that all students need to meet the global challenges that will surely increase in their lifetimes. In order for that to happen it will be important for school administrators and community leaders to recognize the special skills of these educators and the value that they bring to the school overall.

Support for technical education in secondary schools dates from the 1917 Smith-Hughes Act, which provided funds for vocational education in agriculture and home economics, and had the effect of isolating vocational education from the other high school subjects, a legacy which is evident even today. Federal support of vocational education continued throughout the twentieth century and into the twenty-first, primarily as a result of legislation beginning with the 1973 Perkins-Morse bill, most recently revised as the Perkins Act of 2006, which provides approximately $1 billion per year for Career and Technology Education (CTE) in the United States (Bennett, 2009).

The profession of technology teachers has evolved along with changes in national educational goals and sources of funding. Happily, not all states have eliminated their CTE programs, and in many states CTE is thriving. According to the Association of Career and Technical Education (ACTE), the broad field of career and technical education prepares youth and adults for a wide range of high-wage, high-skill, high-demand careers, and 94 % of all high school students take advantage of some CTE courses, which prepare students for hundreds of jobs organized in 16 career clusters.

Some consider technology education (TE) to be a specialty within CTE. However, others advocate technology education as a core subject for all students, not just those who are focusing on course work for specific careers (Wright, Washer, Watkins, & Scott, 2008). With the rise in support of STEM for all students, and especially the inclusion of engineering in the NGSS, the argument today is clearly in favor of engineering and technology for all students.

The educators who are most knowledgeable and capable of providing technology and engineering education are today's technology teachers, many of whom belong to the International Technology and Engineering Education Association (ITEEA). The initial response of the ITEEA to the Framework's inclusion of engineering as a core subject for all students was negative. A letter from the ITEEA to the NRC committee that drafted the framework argued that "science teachers might not have sufficient background to teach the new material and, moreover, that there is currently no agreement in the field about what the core ideas in engineering and technology should be. The letter also pointed out that a corps of technology teachers at the secondary level already exists" (NRC, 2012, p. 337).

In Beverly, Massachusetts, where *Engineering the Future* was being piloted as a ninth grade course, a science teacher was not confident that she would be able to help her students build prototypes. So she talked with the technology teacher who had a fully-equipped wood shop. He was more than pleased to work with her since he liked to include relevant science content in his courses, and often had students design and build projects such as hovercraft. The two planned the curriculum together and worked out schedules that allowed the students to build their prototypes in the wood shop, where they were able to receive training in how to use power tools. The technology teacher was also actively involved in developing educational uses of a large photovoltaic array adjacent to the school, which would make an excellent enrichment to the course. Unfortunately, a year later the technology teacher's position was eliminated and a new school was planned and built without wood shop facilities.

The point of this story is to emphasize the importance of supporting technology teachers and CTE teachers as co-leaders with science, mathematics, and other "core subject" teachers in order to realize the tremendous potential of engineering education for all students. Given the emphasis in the NGSS on both engineering and science, such collaboration would appear to be a winning strategy.

Grand Challenge #9 Teaching the Teacher Educators

Perhaps the greatest challenge is engaging university professors who prepare tomorrow's teachers in supporting the NGSS. A colleague interviewed a number of college and university professors in engineering to see what they thought of the new plan for including engineering within the high school science curriculum. He was dismayed to find that the few who knew about it were unenthusiastic, preferring instead for their incoming students to have a rigorous background in traditional science and mathematics. While there are legitimate concerns about infusing engineering into the K-12 science curriculum, and a need for conversations about issues such as reducing attention to subjects long included in the curriculum to make room for engineering, it makes little sense to consider only the knowledge and skills needed to succeed in college engineering courses. Most students will not major in engineering. The purpose of K-12 engineering education is to educate all students about the designed world, and to help them develop broad skills, such as defining and solving problems, that will serve them well in whatever career they pursue.

The recognition that effective K-12 engineering education can be of service to college engineering departments is recognized at a few universities, such as Tufts and Olin College, in which professors place a high value on motivation, and engage incoming students in interesting engineering activities from the start. Even more important are the universities, such as Purdue, Texas A&M, and Virginia Tech, that have departments of engineering *education*, where PhD candidates are learning what it takes to develop curricula and assessments in support of the NGSS, and to lead STEM education reform at the district and state level.

Grand challenge #9 is to find ways to engage an increasing number of university professors responsible for educating teachers at the elementary, middle, and high school levels to learn about the NGSS, recognize and support its purpose and goals, and figure out what it means for their own practice. The pathway forward must be led by college professors who understand the importance of engaging students in interesting engineering activities early, and are willing to reach out to provide assistance and encouragement to their colleagues who teach at the K-12 level.

Conclusion

Education is a conservative endeavor. It has tremendous momentum, in part because it is deeply embedded in society. The first two challenges, helping our entire population understand technology and what engineers do, is vast in scope. Until these challenges are at least partially met, it is difficult to see how teachers will receive support from their students' parents and community stakeholders. The next set of challenges, involving curriculum, instruction, assessment, and professional development of teachers, involves transformation of a profession. The history of educational reform that has swung back and forth between the scholarly and practical arts suggest it may be difficult to find a balance. The last two challenges are equally daunting, engaging technology educators who may be threatened by science teachers "taking over" their profession, and college professors who may have a narrow focus on the preparation of their incoming students. These grand challenges involve everyone in our society—not just the science educators.

Creating the NGSS with a strong engineering component and getting states to adopt it is just the first step. We will not succeed in transforming our educational enterprise so that our students will have the tools they will need to meet the global challenges of the future, if we don't meet the grand challenges of engineering education today.

References

AAAS. (1989). Science for all Americans. American Association for the Advancement of Science. New York: Oxford University Press.

Alpert, C. L., Isaacs, J. A., Barry, C. M. F., Miller, G. P., & Busmaina, A. A. (2005). Nano's big bang: Transforming engineering education and outreach. In Proceedings of the 2005 American Society for engineering education annual conference & exposition, Portland, Oregon.

Baker, B. S., Nugent, G., & Hampton, A. (2008). Examining 4-H robotics in the learning of science, engineering, and technology topics and the related student attitudes. *Journal of Youth Development: Bridging Research and Practice, 2*(3), 7–18, Spring 2008. Article: 0803FA001.

Bennett, W. (2009). *Vocational education philosophy and historical development*. Online instructional material for EVOC 637: Foundations of Career & Technical Education, California State University, San Bernardino. Retrieved from: http://cis.msjc.edu/courses/evoc/637/Assignments/DL6-8.pdf

California Industrial and Technology Education Association and Foundation. (2007). *Career and technical education: Problems and solutions*. Position Paper. Fresno, CA: CITEA.

Christiansen, P. (1975). *Theory and practice in the formative years of American mechanical engineering education: A cultural and historical analysis*. Doctoral dissertation. City College of New York.

Crismond, D. (2013). Design practices and misconceptions: Helping beginners in engineering design. *The Science Teacher, 80*(1), 50–54.

Crismond, D., & Adams, R. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education, 101*(4), 738–797.

Cunningham, C. M., & Hester, K. (2007). *Engineering is elementary: An engineering and technology curriculum for children*. In American Society for engineering education annual conference & exposition. Honolulu.

Donnelly, J. F. (1989). The origins of the technical curriculum in England during the nineteenth and early twentieth centuries. *Studies in Science Education, 16*, 123–161.

Firth, A. (2005). Culture and wealth creation: Mechanics' Institutes and the emergence of political economy in early nineteenth-century Britain. *History of Intellectual Culture, 5*(1). Retrieved from: http://www.ucalgary.ca/hic/issues/vol5/3

Lachapelle, C. P., Phadnis, P., Jocz, J., & Cunningham, C. M. (2012). *The impact of engineering curriculum units on students' interest in engineering and science*. Presented at the NARST annual international conference, Indianapolis, IN.

Lewis, T. (2004). A turn to engineering: The continuing struggle of technology education for legitimization as a school subject. *Journal of Technology Education, 16*(1), 21–39.

Neuschatz, M., McFarling, M., & White, S. (2005). Highlights from the 2005 high school physics teachers survey. *American Institute of Physics*. Retrieved from: http://www.aip.org/statistics/trends/highlite/hs2/hshigh.pdf

NGSS Lead States. (2013). *Next generation science standards: For states, by states* (Volume 1 the standards. Volume 2 appendices). Washington, DC: The National Academies Press.

NRC. (1996). National Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education. National Research Council (NRC). Washington, DC: The National Academies Press.

NRC. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas* (Committee on a Conceptual Framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education, National Research Council (NRC)). Washington, DC: The National Academies Press.

NRC. (2015). *Guide to implementing the next generation science standards*. Board on Science Education, Division of Behavioral and Social Sciences and Education, National Research Council. Washington, DC: The National Academies Press.

Osowiecki, A., & Southwick, J. (in press). *Energizing physics.* New York: Freeman. The course is also described at energizingphysics.com.

Pearson, G., & Young, T. A. (Eds.). (2002). *Technically speaking: Why all Americans need to know more about technology*. Washington, DC: The National Academies.

Rose, L. C., Gallup, A. M., Dugger, W. E., & Starkweather, K. N. (2004). The second installment of the ITEA/Gallup Poll and what it reveals as to how Americans think about technology. International Technology Education Association. *The Technology Teacher, 64*(1), 1–12.

Sneider, C. (Ed.). (2015). *The go-to guide for engineering curricula* (Three volumes: K-5, 6–8, and 9–12). Thousand Oaks: Corwin Press.

Sneider, C., & Moss, M. (2004). *John D. O'Bryant School for Mathematics and Science situation report*. Unpublished internal report to the Headmaster.

Sneider, C., & Wojnowski, B. (Eds.). (2013). *Opening the door to physics through formative assessment* [monograph]. Portland: Portland State University. Retrieved from National Science Education Leadership website: www.nsela.org/publications

Tesfaye, C. L., & White, S. (2010). High school physics courses and enrollments. *AIP Focus On,* August 1–6, 2010. Retrieved from: http://www.aip.org/statistics/trends/reports/highschool3.pdf

Wright, M. D., Washer, B. A., Watkins, L., & Scott, D. G. (2008). Have we made progress? Stakeholder perceptions of technology education in public secondary education in the United States. *Journal of Technology Education, 20*(1), 76–93.