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# Engineering Design Challenges in High School STEM Courses A Compilation of Invited Position Papers

Daniel L. Householder, Ed.  
2011



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## **Engineering Design Challenges in High School STEM Courses A Compilation of Invited Position Papers**

Edited by Daniel L. Householder, Co-PI  
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Since its initial funding by the National Science Foundation in 2004, the National Center for Engineering and Technology Education (NCETE) has worked to understand the infusion of engineering design experiences into the high school setting. Over the years, an increasing number of educators and professional groups have participated in the expanding initiative seeking to acquaint all students with engineering design. While there is strong support for providing students with engineering design experiences in their high school STEM courses, the lack of consensus on purposes and strategies has become increasingly apparent as the work continues. Among the unsettled issues are the degree to which engineering design challenges should be open-ended or well-structured, the extent to which engineering habits of thought and action are employed in resolving the challenges; the relationships between engineering design experiences and standards-based instruction in STEM courses; and effective sequencing of age-appropriate engineering design challenges.

This document began with a simple, straightforward question, “What are the requirements for a good engineering design challenge?” Matthew Lammi, then an NCETE fellow at Utah State University, addressed the question to Julia Ross, University of Maryland Baltimore County, who was telling a group of NCETE fellows about her success in engaging high school technology students and their teachers in authentic engineering design challenges. While her response was extemporaneous, the comments were obviously based upon rigorous analysis and reflection. In response to a subsequent request, she developed her suggestions about the selection of good engineering design challenges for high school students in more depth in personal correspondence. Her work provides the unique perspective of an experienced curriculum developer, teacher professional development provider, and successful implementer of educational change. She suggested these criteria for a good engineering design challenge for high school students:

- The challenge needs to be as wide-open as possible at first.
- It should be related to the real world. Framing the problem is very important; make the connection explicit.
- Pick challenges from areas that affect a teenager’s life.
- There has to be more than one way to do it, otherwise it’s too prescribed. It must be open-ended enough that there are several ways to do it successfully.
- Try really hard not to limit students to a “box of supplies” – giving students the “stuff” to work with is an artificial constraint.
- Use everyday stuff (materials) insofar as possible. Think of choices; walk around the house and the lab first before you go shopping.
- Try to get the students to sketch out possibilities.
- A good design challenge makes it possible to think about the math at several different levels. Help the students see that math is something that gets used – a tool at our disposal. Meet the kids where they are; the level of rigor needs to be within student capabilities. Help those with low levels of math skills to increase their confidence and help those who think they understand math to also understand its applications.

- There should be specific indicators of success in order to judge the quality of the solutions.
- More efficiency is better.
- Have costs been controlled? Is this the least expensive acceptable solution?
- Unnecessary instrumentation is resisted by students.
- Solutions should be functional, but “amenable to bragging rights.”
- Teachers need the opportunity to build prototypes as part of their professional development.
- Teachers have a difficult time relinquishing control as students work on design challenges.
- Fewer, broader, deeper design challenges are better than many, narrow, and shallow ones.
- INSPIRE originally developed challenges that could be completed in four weeks of daily 45-minute classes; that timeframe may need to be lengthened.
- Failure is important. Allow time to fail then recover and try again in order to build more success – may need another day in order to explore additional possibilities. Promote the attitude that failure isn’t failure. That doesn’t work in the real world. Failure is a mechanism for learning to do better.
- Establish clear minimum criteria for meeting the design challenge. Clear yes-no decisions based on clear-cut criteria – then quality-indicating criteria to minimize or maximize or optimize the design. (Personal communication, 2009).

In February, 2011, NCETE sought position statements from a small number of engineering educators, cognitive scientists, instructional designers, and professional development providers who have been engaged in long-term efforts to provide students with engineering design experiences in their high school STEM courses. Each of these experienced professionals was asked to provide brief descriptions of principles or guidelines that they consider to be most important in promoting effective infusion of authentic engineering design challenges into STEM courses for all high school students.

This compilation includes responses prepared by David Jonassen, University of Missouri-Columbia; Morgan Hynes and colleagues, Tufts University; Ronald Carr and Johannes Strobel, Purdue University; Christian Schunn, University of Pittsburgh; Arthur Eisenkraft, UMass Boston, and by Cary Sneider, Portland State University. The authors of the individual papers have not yet had an opportunity to review the work of the others. We anticipate that additional responses may arrive from other invitees and plan to include those papers as they become available. Those of us at NCETE are deeply appreciative of the careful analysis, clear exposition, and sound logic displayed by the authors in their respective papers.

The individual papers are being posted on the NCETE web site, <http://www.ncete.org/flash/research.php>. In addition, we anticipate that they will provide a basis for discussion, synthesis, and integration of points of view on engineering design challenges for high school students during the NCETE Invitational Caucus on Engineering Design in Grades 9-12 in August ,2011.

Comments are also welcome from readers; address them to [dan.householder@usu.edu](mailto:dan.householder@usu.edu).

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## Design Problems for Secondary Students

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### How do design problems vary?

Are there different kinds of design problems? According to Brown and Chandrasekaran (1989), Class 1 design problems are open-ended, non-routine creative activities where the goals are ill-structured, and there is no effective design plan specifying the sequence of actions to take in producing a design model. Class 2 problems use existing, well-developed design and decomposition plans (e.g. designing a new automobile). Class 3 designs are routine where design and decomposition plans are known as well as customary actions taken to deal with failures (e.g., writing a computer program).

Jonassen (2011) argued that problems vary in terms of structuredness, complexity, and context. On the structuredness and complexity continua, design problems tend to be the most ill-structured and complex. Brown and Chandrasekaran suggest that design problems may vary along a continuum from well-structured to ill-structured, depending upon the context in which they are solved. In formal, school contexts, design problems are often more constrained, allowing many fewer degrees of freedom in their representations, processes, or solutions and are therefore more well-structured.

McKenna and Hutchison (2008) reported a study in which undergraduate engineering students solved two design problems: one well-structured and one ill-structured. The well-structured problem was consistent with those typically presented to students in freshman design seminars and high school design assignments:

Develop a device that:

- Can cool six-12 ounce beverage to  $< 40^{\circ}\text{F}$  in under five minutes
- Is portable
- Able to cool 30 beverages
- Cost of building material is less than \$30

Although several solutions exist, this problem is fairly well-structured because of the pre-defined constraints which restrict the problem space and the range of allowable solutions. Such problems are conceptually classifiable (heat transfer), which constrains solutions and solution methods even more.

The ill-structured problem that they presented to engineering students was:

Design assistance for a Government Health Organization (GHO):

- GHO is working to combat mother-to-child HIV transmission
- HIV can be passed through breast milk
- Mothers insist on breastfeeding to avoid being labeled by disease

This problem is more ill-structured because the goals and constraints are not defined. The solution depends on psychological beliefs and personal opinions, making it less predictable. That is, there are a large number of solutions, and assessing the effectiveness of alternatives would rely on unstated and under-specified criteria.

Context also plays an important role in specifying the nature of design problems. In formal classrooms, it is important that problem solutions can be evaluated on stated criteria, because that is a cultural expectation in classroom instruction. Such expectations are not relevant when assessing everyday workplace problems. Workplace engineering problems, for example, tend to be ill-structured and complex because they possess conflicting goals, multiple solution methods, non-engineering success standards, non-engineering constraints, unanticipated problems, distributed knowledge, and collaborative activity systems, where the importance of experience and the use of multiple forms of representation are required (Jonassen, Strobel & Lee, 2006).

### **What Kinds of Problems Should Students Solve?**

Students in high school and university are inured to assignments with convergent answers and established evaluation criteria. Because of that, their learning strategies tend to focus on finding the right answer. When well-structured problems are presented to engineering students, McKenna and Hutchison (2008) found that students conducted deeper searches for information related to the problem, made increased use of connections to prior learning, and were more directed in their learning. However, with ill-structured problems, students made fewer attempts to learn about problem, made fewer connections to prior learning, and made more ambiguous searches for information related to the problem. In short, they were uncertain about how to approach the problem.

Jonassen, Khanna, and Winholtz (2011) implemented a problem-based version of a materials science course in the mechanical engineering curriculum. In the course, students expressed considerable confusion about the way the course was structured around problems rather than topics, so they perceived the course as lacking structure. Although most of the students described their experiences with team members as positive, they collaborated ineffectively. Perhaps the most significant difficulty among the students related to the expectations of the course. While the students understood the relevance of the problems, they remained committed to the content-based exams. There was a significant disconnect between the methods that students used to study for the problems and those used to study for the exams, so traditional exams were eliminated in the second implementation. The course instructors found it difficult to provide timely feedback to students on their performance on the problems. These studies would suggest that high school and university students are ill-prepared for solving ill-structured problems.

However, contradictory evidence is provided by a series of studies by Kapur (2008, 2010, in press). He presented groups of students with well-structured problems and others with ill-structured problems in mathematics and physics. The students solving more complex and ill-structured problems without assistance experienced frustration while other groups received teacher-directed facilitation. Despite appearing to fail in their problem-solving efforts, the unsupported students solving the ill-structured problems significantly outperformed their counterparts on both the well-structured and higher-order transfer problems. Although frustrating, it appears that the productive failure approach engaged deeper level learning and problem solving in students.

To what degree are high school students able to conceptualize and resolve design challenges that include a number of complex variables or choices? That issue has not been informed by a lot of research. Clearly, motivation will play a significant role in student efforts to solve more complex and ill-structured problems. High school and college students have learned that most problems have correct answers, which becomes their exclusive goal preventing them from approaching ill-structured problems successfully. Our experiences in several studies in physics and engineering suggest that the correct answer is much more important than understanding the problem or transferring the skills required to solve it. Those expectations will need to be changed and the required efforts need to be scaffolded.

## **How to Teach Design Problem Solving**

Research in problem solving has most often sought the one best method for solving all kinds of problems. If we accept that different kinds of problems exist (Jonassen, 2000), then such an assumption is untenable. Design problem solving is addressed primarily in engineering design, product design, and instructional design. Most researchers have posited normative models for learning to solve design problems. For example, Dym and Little (2004) assert that solving engineering design problems involves the following processes:

1. *Problem definition*: from the client statement, clarify objectives, establish user requirements, identify constraints, and establish functions of product by providing a list of attributes
2. In *conceptual design* phase, establish design specifications and generate alternatives
3. In the *preliminary design*, create model of design and test and evaluate the conceptual design by creating morphological charts or decision matrices (See Chapter 3)
4. During the *detailed design*, refine and optimize the chosen design
5. For the *final design*, document and communicate the fabrication specifications and the justifications for the final design

If we accept that this or any model of design problem solving adequately captures the process for solving even a category of design problems, then these processes may be modeled or scaffolded for students during learning.

For purposes of learning how to design, Jonassen (2011) has argued that design problem solving can be represented as a series of decisions (see Figure 1). Those design decisions are based on multiple constraints and constraint operations in the design space. At the beginning of the design process, functional specifications and initial constraints are specified by some sort of needs analysis process. Designers then begin to refine the problem space by making decisions. The solution to each decision depends on what kind of decision it is, additional constraints that have been introduced into the problem, and whatever beliefs are held by the designer.

Most designers and problem solvers have preferred solutions to problems. In order to counteract those beliefs and biases, each design decision should be articulated by learners, who should be required to construct an argument in support of their decisions. With each cycle of decision making, the problem space narrows (decreasing spiral in Figure 1). That is, degrees of freedom in related decisions decrease and the solution becomes better defined. So, design problem solving should require learners to conduct some needs analysis in order to specify initial constraints and goal, followed by cycles of decision making where learners identify alternative

solutions to each decision and construct an argument to support their decisions. The quality of the argument should be judged by the quality of the evidence used to support the decisions as well as counterarguments rebutting alternative solutions (Jonassen & Kim, 2010).

The design problem space is usually represented as a model. That is, design is also a process of model building as well as decision making. As design decisions are made, designers begin to construct sketches that morph into models that morph into prototypes (see Figure 1). Engineers and architects most often begin by creating a drawing. As decisions are made about the design, the design model expands as the decision-making contracts (see Figure 1). The initial drawing

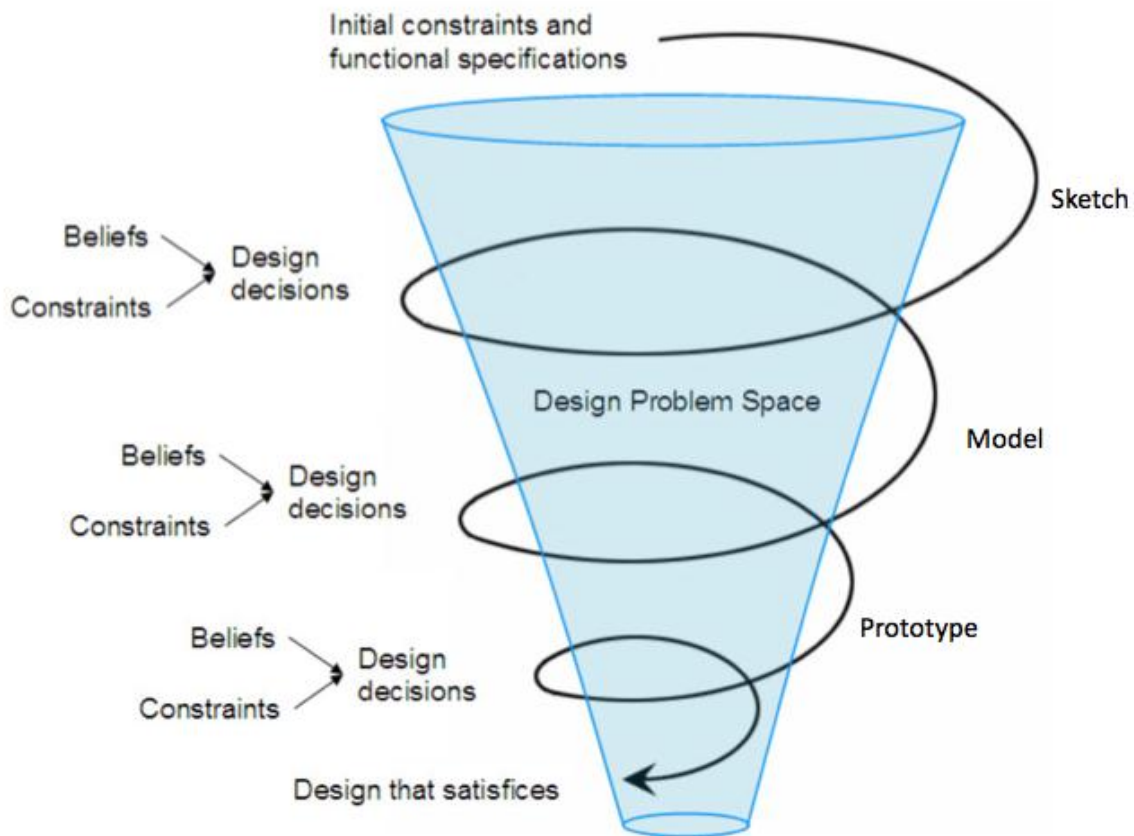


Figure1. Iterative design process.

may be converted to a CAD drawing, a computational model, or a 3-dimensional model. Instructional designers may begin by producing a storyboard and later converting that into a prototype of the learning environments. These models should reflect the functional requirements of the design as elaborated during the cycles of decisions.

Despite the putative goal of optimization, most workplace design processes usually end when a satisfactory solution is defined. That is, the goal of design is satisficing (Simon, 1955), not optimization. Simon coined the term to describe decisions in which satisfactory solutions that suffice rather than optimize are acceptable. Although designers talk about optimization, design solutions are seldom, if ever, the best solutions (Marston & Mistree, 1997). In everyday,



workplace problems, designers are usually unable to articulate what an optimal solution is. The most commonly cited solution criteria noted by practicing engineers was “under budget and on time” (Jonassen et al., 2006).

So my recommendation for supporting engineering design problem solving among high school and university students is to present initial specifications and goals, and then require learners to analyze the problem in order to identify additional constraints. Learners then begin to make design decisions and to construct a model that reflects those decisions. For each decision, students construct arguments supporting their solutions. With each set of design decisions, the mode becomes more elaborate as the problem space becomes more circumscribed. The final decision is when does the design satisfy?

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## **Infusing Engineering Design into High School STEM Courses**

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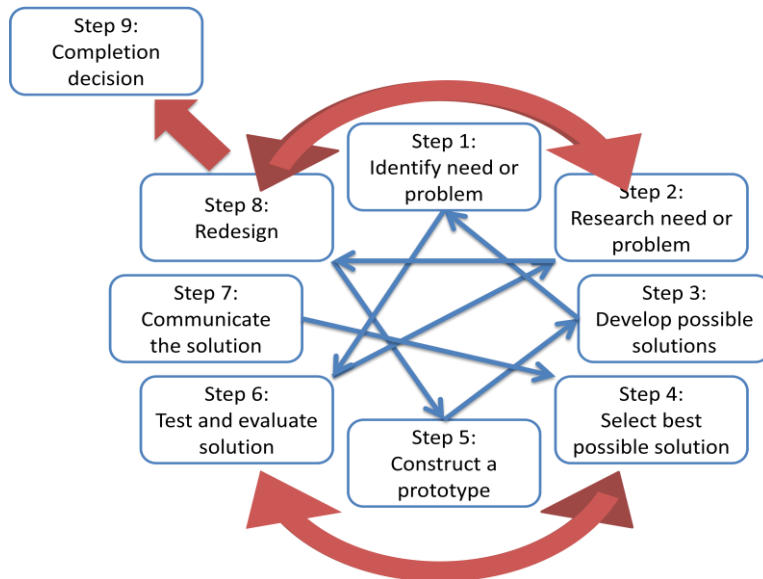
Society is recognizing the need to improve STEM education and introduce engineering design concepts before college. In the recent National Academy of Engineers report, *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*, the authors suggest that the STEM disciplines not be treated as “silos” and that engineering might serve as a motivating context to integrate the four STEM disciplines (Katehi, Pearson, & Feder, 2009). Recent research has suggested that integrated technology and engineering design curriculum can serve as a positive model for mathematics and science learning and retention (Ortiz, 2010; Wendell, 2011).

The Tufts University Center for Engineering Education and Outreach (CEEEO) strives to improve STEM education through engineering and believes every student should have the chance to engineer. Situated in Massachusetts, the first state to adopt engineering education at all levels in public schools (Massachusetts DOE, 2001), the CEEEO supports the belief that engineering education starts in kindergarten and continues to develop throughout their K-12 schooling. We also believe that at the core of K-12 engineering is the Engineering Design Process (EDP). The purpose of introducing students to the EDP is not to have them “build things”, a common misconception. The EDP is meant to teach students that engineering is about organizing thoughts to improve decision making for the purpose of developing high quality solutions and/or products to problems. The knowledge and skills associated with the EDP are independent of the engineering discipline (e.g., mechanical, electrical, civil, etc.) and engineering science (e.g., thermodynamics, statics, or mechanics) knowledge that a particular engineering challenge may call upon. Design tasks therefore entail developing the kinds of critical thinking skills commonly associated with engineering and technology literacy. Three key concepts in successful implementation of the EDP are: students are engineers; teachers need to listen to their students; and classroom environments need to change to properly enable learning through the EDP.

Recently, we worked with the Massachusetts State Department of Education to produce a revised engineering design document that describes a learning progression for the EDP from kindergarten through high school. This white paper describes the high school portion of that document geared toward the activities or skills we associate with the EDP as defined by the current Massachusetts curriculum frameworks. This depiction of the EDP implies a cyclical, stepwise process that is rarely the case in solving real-world engineering problems. Oftentimes the task requires some jumping around from step to step, as shown in the figure below.

By adopting this slightly adjusted paradigm, students will recognize that the EDP does not rely upon rigid thinking, but provokes creative and outside-the-box thinking. The purpose of learning engineering design is to encourage students to interact with engineering in hands-on activities as a practical application of math and science knowledge. Through actual practice of engineering, high school students learn that it is not simply building things. Instead, it is a process through which structures are designed, through which clear identification and definition

of the need or problem, research, planning and brainstorming, testing and evaluation, and communication are necessary.



**Figure 1 Engineering Design Process**

Programs that succeed in improving student learning through design or project-based learning include the University of Colorado at Boulder’s First Year Engineering Project, Purdue’s Engineering Projects in Community Service (EPICS), Armstrong Atlantic State University’s Talented Researcher in Engineering (TRIE) (Goeser et al., 2009), and the US For Inspiration and Recognition of Science and Technology (FIRST), to name a few. While these programs are not specifically created for high school curriculum, they provide positive evidence of students learning through design. Engineering design challenges across the country, such as those sponsored by NASA, are also aimed at interesting students in engineering.

All of the programs listed above, though they differ in their approach in instigating students’ involvement in engineering, center around engineering learning through hands-on activities. This approach has been advocated by many, altering the way students learn engineering (e.g. Committee on Engineering Education in K-12, 2009; Crismond, unpublished manuscript; Koehler, Faraclas, Sanchez, Latif, & Kazerounian, 2005). The EDP that we describe below is an integration of all of these concepts and does not necessarily need to be reserved for engineering-specific classes. In fact, courses that focus on design-based experiences, as reported by the Committee on Engineering Education in K-12 (2009) have reported, have shown to “improve student learning and achievement in mathematics and science, as well as enhance interest in STEM subjects” (Crismond, unpublished manuscript).

Provided that students are exposed to the EDP prior to high school, as is now standard in the state of Massachusetts, the proposed CEEO learning progression addresses key aspects of how high school students should approach and solve engineering problems. Once mastered, this progression will enable students to tackle ill-defined problems and lead them to direct their own research on a problem that ends with a successful solution. This progression from beginning designer to informed designer endorses an engineering education progression throughout K-12

(Crismond, unpublished manuscript). While the process challenges students in a different way from their typical school subjects, it has been shown that students eagerly welcome the challenge (Goesser et al., 2009). Instead of sitting in a classroom scribbling down equations and memorizing facts that will be forgotten as soon as the bell rings, engineering design provides students with a vehicle to use all of the science and math material they have been taught throughout their education. By incorporating engineering into the traditional math and science frameworks, the paradigm would shift from “rigid, content driven, discipline-specific course work to a more problem-based engineering decision making model.” (Koehler et al., 2005, p. 1)

We were able to construct the following description of the skills and abilities associated with engineering design for high school students using research in the area of K-12 design education where possible, combined with our experience working in K-College engineering education. The following should not be read as a rigid set of guidelines that must be followed, but rather as a set of guiding principles to consider in curriculum design and instruction in high school engineering.

**Identify and define problems:** High school students are capable of identifying a need or problem in a given situation and should be provided the opportunity to do so. The goal should be for students to deal with ill-defined problems, identify the necessary constraints imposed on the problem, and acknowledge the clients’ desired specifications. Classroom challenges should emulate real-world engineering challenges as much as possible. When a teacher asks students to find a problem to solve, s/he is providing students with the opportunity to decompose a given situation in order to frame a problem in their own words (Koehler et al., 2005, Lemons et al., 2010). It is important that the problem is open-ended with many possible solutions (i.e. no one “right answer”). We believe that this approach not only provides students an opportunity to practice important critical thinking skills, but it also increases the likelihood of the students to take ownership of the project because it was not simply given to them by their teacher.

**Research the need or problem:** Once a problem has been identified, instead of rushing to solve the problem with the first solution that comes to mind, students must conduct some background research. Students should understand that there are many things to consider when solving an issue and recognize that they need to fully explore the challenge in order to be well-informed as to how to solve it (Crismond, unpublished manuscript). As such, engineering challenges and associated curriculum must make the need for and benefit of research clear to the students. It should not appear as something to rush through to satisfy the teacher’s request. This student-driven research allows students to comprehend that research is integral to the process of engineering (Ennis & Greszly, 1991), and that it will improve the quality and efficiency of their work. Note that it is highly likely that as students research the need or problem and discover new constraints or ideas that they will be redefining and clarifying the problem.

**Develop possible solution(s):** Recording multiple ideas for the task takes into consideration the need for planning and teamwork. Students should actively brainstorm in groups to help foster individual learning and creativity (Crismond, unpublished manuscript). Through this process, students work on their communication skills with others and grasp the understanding of tradeoffs (Crismond, unpublished manuscript) while forming their ideas within the problem criteria and constraints (Mullins, Atman, & Shuman, 1999; Radcliffe & Lee, 1989). By using words,

drawings, and prototypes, students can explore and develop ideas with clearly defined specifications (Crismond, unpublished manuscript; Gassert et al., 2005; Gentilli et al., 1999).

**Select the Best Possible Solution(s):** The ultimate purpose of design is eventually to create an end product that solves the problem at hand. At the elementary level, this usually implies one finished product selected by the teacher. At the high school level, students need to be able to justify and reason their own solution to pursue. This requires that a best possible solution be selected for the individual or group project. What may seem the best for one person may not always seem to be best for another person. This supports the notion that a perfect solution is rarely available to practicing engineers. This step necessitates that students will be able to back-up their ideas with proper consideration of evidence and issues that were discovered through problem definition and research (Dym et al., 2005). This also assures that students use their knowledge of math and science to make informed decisions, constantly assessing each one along the way.

**Construct a prototype:** Building is often the only concept students have about engineering prior to any engineering design exposure. This is clearly not the case, as the previous four activities describe the need for sufficient planning before construction can begin. The prototype is a representation or model (physical, virtual, or mathematical) of the final solution (Maki & Thompson, 2006). Iterative prototyping until an acceptable product is reached is a key component of this stage (Koehler et al., 2005), allowing students to physically construct a model of the solution (Carberry, Lemons, Swan, Jarvin, & Rogers, 2009). It is important to allow students to fail and learn from those failures as they iterate on their solution. It is not always important that the prototype perform like the intended final solution. Instead, it should demonstrate some functionality or look of the proposed final solution. Note that there may be a number of models developed throughout the challenge that build upon each other or represent different characteristics of the final solution (e.g., size, function, appearance, and feel).

**Test and Evaluate the Solution(s):** Students must create fair tests based on the constraints and requirements of the problem to judge whether or not their prototype is successful. Elementary students require a fair amount of guidance from their teacher on how to test and evaluate their solution, but high school students are capable of developing their own experimental tests to evaluate their solutions (Trevisan et al., 1998). Determining appropriate testing procedures may cause students to reengage in the research step (2) as they determine what methods and tools will help determine how well their prototypes meet the requirements (Gentilli et al., 1999). At this juncture, students have the ability to recognize that a finished *prototype* does not necessarily mean a finished *product*.

**Communicate the Solution(s):** Part of engineering is sharing your ideas and findings with others for feedback and marketing purposes. By the time students reach high school they are fully capable of documenting their solution through written documents, presentations, and constructions. The ability to organize information for understanding and clarity is necessary to present ideas to others (i.e. teammates, teachers, and clients): high school students are well aware of how to accomplish this (Gentilli et al., 1999). These presentations should include specifications, performances, issues, limitations, and constraints (Gassert & Milkowski, 2005). By giving an oral presentation, students will communicate their solutions in a language and style

that is understandable by a target audience, which could be their classroom, the entire school, or actual practicing engineers (Dym, et al., 2005). These presentations require that students accurately and completely document information pertaining to their solution.

**Redesign:** While elementary counterparts at this stage attempt to answer the question of why their design failed or succeeded, high school students focus their attention on redesigning the key problems with the intent to optimize their design (Koehler et al., 2005). Students at this level are able to troubleshoot their problems (Crismond, unpublished manuscript). Each decision they make aims to improve the prototype until a final product has been produced that meets all of the requirements and criteria, as well as passing all of the tests and evaluations.

**Completion (leaves the cycle):** The very last step of the EDP results in the determination that a final product has been achieved. This product is not simply the result of passing a set of predefined tests, but is based on whether or not students believe they have sufficiently optimized their product to the selected constraints. In this step, students make a decision that they have sufficiently met the design requirements and are ready to implement their prototype as a final product (Gentili et al., 1999).

Though the description above seems to imply a set path or stepwise approach to the EDP, it is important to remember that throughout this process, students are constantly evaluating and testing their ideas, repeating steps as necessary and sometimes even restarting from the beginning. Occasionally the original idea will have some initial overlooked flaw or a different approach may become apparent through work on the challenge. By integrating this process into already standard STEM courses, students will gain an improved attitude toward and understanding of engineering. Through the act of presenting their work to such groups as teachers, peers, and family members, students can obtain an appreciative attitude towards engineering. We believe that it is critical that engineering design challenges and curricula be intentional in the development of students' process skills and mindful of this in the design of the activities for students.

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# **Integrating Engineering Design Challenges into Secondary STEM Education**

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## **Introduction**

Engineering is being currently taught in the full spectrum of the P-12 system, with an emphasis on design-oriented teaching (Brophy, Klein, Portsmore, & Rogers, 2008). Due to only a small amount of research on the learning of engineering design in elementary and middle school settings, the community of practice lacks the necessary knowledge of the trajectory of students' learning progressions towards design mastery and expertise and the appropriateness of otherwise established design pedagogies. The issue is even more pressing since many states are embedding engineering into their standards without a clear notion of how engineering (often conceptualized as design) works within existing standards (Strobel, Carr, Martinez-Lopez & Bravo, 2011). This paper synthesizes existing literature, which might provide us with insights on how to further investigate the issue of appropriate design pedagogies. At first, the paper contextualizes existing PBL research into engineering design. Second, the paper synthesizes the literature on inductive teaching and expert-novice differences as an additional literature base to conceptualize the role of design and engineering in the schooling system. Third, the paper contextualizes the questions on problem-appropriateness in engineering design into the current debate on engineering standards and their role in the P-12 education system.

## **The PBL Argument**

Engineering design challenges in the classroom expand on the traditional role of Problem-Based Learning (PBL), which is one of the best-researched instructional innovations. Across all age levels, PBL has been found to increase student motivation, performance on transfer tasks, deeper understanding of content particularly in the form of long-term retention (Strobel & van Barneveld, 2009), in addition to aiding in building mental models of difficult science and math concepts (Linn, diSessa, Pea, & Songer, 1994, Oliver & Hannafin, 2001). PBL particularly emphasizes problems characterized as *ill-structured* (Jonassen, 1997), *open-ended* (Prince & Felder, 2006) or *wicked* (Stoltermann, 2008).

Ill-structured problems are real-world problems, where multiple solutions and paths are possible, information might exist or may not be provided (Jonassen, 1997), and in which the learner must identify the goals, variables and strategies to solve them (Ertmer et al., 2009). Ill-structured problem solving resembles design problems and both can be multidisciplinary, requiring skills from multiple content areas or content specializations such as combining math and science or using skills from algebra and geometry. Well-structured problems, at the other end of the spectrum, are often used to practice information covered in a specific lesson or in assessing specific skills that are not context-dependent (Jonassen, 1997). Ill-structured and well-structured problems both have their places in education and "...they are not dichotomous. Rather they represent points on a continuum...." (Jonassen, 1997, p. 87). Research on professional engineers as they solved problems indicated that authentic problems are best understood as compound groups of intertwined well- and ill-structured problems (Strobel & Pan, in press).



Open-ended or ill-structured problems help to promote intellectual growth, which is needed by students entering into college-level engineering studies. College engineering students may have had less intellectual development than students from other majors, who may be more dependent on authority and unwilling to challenge what is accepted to move into higher levels of intellectual development as may be expected of scientists and engineers (Felder & Brent, 2004a). "Open-ended problems that do not have unique well-defined solutions pose serious challenges to students' low-level beliefs in the certainty of knowledge and the role of instructors as providers of knowledge. Such challenges serve as precursors to intellectual growth" (Prince & Felder, 2006, p. 7). Our position in this paper is that the dichotomy of well- and ill-structured design may be resolved by looking at the intertwinedness of different and necessary competencies to solve complex problems.

### **Inductive learning providing insight for the pedagogical support**

Theoretical constructs on inductive and deductive instruction or learning provide additional support for a more ill-structured problem solving approach in P-12 engineering. Deductive teaching, stating a principle and then moving to applications is the traditional way of teaching engineering (Prince & Felder, 2006). In inductive teaching, problems or applications are presented and students learn the theories as needed to find the solutions (Prince & Felder, 2006). Inquiry learning, problem-based learning, project-based learning and case-based teaching are examples of inductive teaching that are proposed for application in engineering education (Prince & Felder, 2006). Deductive learning not only fails to motivate students but also fails to build on existing knowledge (Felder & Brent, 2004a). Providing a problem to be solved that sets up the need for information or skills provides instant relevance to the learners. Inductive learning, active learning and cooperative learning increase motivation, knowledge retention and deeper understanding (Felder & Brent, 2004b).

While advocating inductive teaching, Prince and Felder (2006) promote the use of a cycle of inductive to deductive to inductive teaching that provides motivating applications or problems that lead students to need information and skills, which adds instant relevancy. While the instructor in student-centered learning takes on the role of challenger and knowledge facilitator, some traditional instruction can be used to provide the needed information. Further applications or problems can be posed which incorporate even new concepts with the new information in a blend of inductive and deductive teaching. Constructivist in nature, the careful sequencing allows students to stay within Vygotsky's "zone of proximal development" while taking advantage of Bruner's conceptualization of the spiral curriculum (Prince & Felder, 2006). The "zone of proximal development" refers to the difference between individual problem solving ability and the approach used when receiving guided instruction (Vygotsky & Cole, 1978). Bruner's spiral curriculum allows a student to revisit previously learned concepts in order to support higher level or more sophisticated information (Bruner, 1977). "Material should not be presented in a manner that requires students to alter their cognitive models abruptly and drastically... students should not be forced outside their "zone of proximal development (Prince & Felder, 2006, p. 4)."

## **Expert-Novice Literature**

Engineering design problems provide familiar and real-world contexts in which learners (Tate, Chandler, Fontenot, & Talkmitt, 2010) can apply science and math concepts and develop mastery or expertise in new competencies: The Five-Stage Model of Dreyfus and Dreyfus (1980) outlined a path from novice to expert built on the premise that concrete experiences, rather than abstract principles, are the key to reaching the expert stage. Dreyfus and Dreyfus did not discount the need for abstract principles or conceptual content knowledge, but note the dramatic increase in performance once meaningful contexts are applied. "We argue that skill in its minimal form is produced by following abstract formal rules, but that only experience with concrete cases can account for higher levels of performance (p. 5)." As something becomes familiar, it becomes automatic and performance continues to improve naturally while new information or skill levels are added (Schneider & Shiffrin, 1977). Open-ended learning environments, which include ill-structured design challenges, allow students the opportunities to move from immature or incorrect mental models towards those of experts (Oliver & Hannafin, 2001).

Ertmer et al., (2009) compared novices to experts in ill-structured instructional design problems, noting that novices do not recognize the ill-structured problem for what they are, and spend little time analyzing the problem or considering multiple solutions. Experts, on the other hand, analyze the problems in depth and apply information from past experiences and knowledge while finding greater depth in the problem (Ertmer et al., 2009). "Experts possess more highly developed problem schemas because they represent problems physically in terms of real world mechanisms" (Jonassen, 1997, p.79).

Not only is cognitive load reduced and expertise fostered, providing real-life relevance in problem solving is the most effective way to encourage intellectual development (Felder & Brent, 2004). Tasks which are appropriate for any level of engineering education should include: predicting outcomes, interpreting and modeling physical phenomena, generating ideas and brainstorming, identifying problems and troubleshooting, formulating procedures for solving complex problems, formulating problems, as well as making judgments and decisions and justifying them (Felder & Brent, 2004a, p. 5).

## **Integration of Engineering to Strengthen Academic Standards**

Pre-collegiate engineering education, whether it be stand-alone or infused into other content, aids development of engineering "habits of mind," which include "1) systems thinking, 2) creativity, 3) optimism, 4) collaboration, 5) communication, and 6) ethical considerations," (Katehi, Pearson, & Feder, 2009, p.7) and are linked to essential 21<sup>st</sup> Century Skills that are related to all subject areas. Engineering design challenges work to meet expectations for instruction in 21<sup>st</sup> Century Skills by teaching students adaptability, complex communication, social skills, non-routine problem-solving, self management, and systems knowledge (Bybee 2009; Dym, Agogino, Eris, Frey, & Leifer, 2006). Engineering design promotes questioning and inquiry, which develop the ability to reason, particularly with math and science content (Dym et al., 2009). The first step in any design project involves asking questions to reveal the problem. Engineering promotes systems knowledge, which requires greater complexity from emerging

engineers who need to deal with the dynamics of ever-expanding systems (Dym et al., 2009). Systematic thinking, reasoning, estimating and experimentation are beneficial habits of mind that will facilitate systems-focused engineers (Dym et al., 2009). Not only is problem-solving improved, but decision making is an important part of engineering education and engineering design (Dym et al., 2009). Collaborative teamwork in engineering helps learners to improve their decision making because they must learn to negotiate with group members, a process that requires internal sense making and decision making (Dym et al., 2009).

The importance of teaching engineering prior to the time students reach college is magnified by a 2008 study (Harris and Rogers) that examined competencies students should have before entering firstyear engineering courses. While “other-related competencies” were overall rated higher than some specific engineering, science, and math competencies, it is easy to see how integrated engineering instruction is important. Other-related competencies for incoming firstyear engineering students of importance are: 1) effective communication through writing; 2) reading comprehension; 3) honesty; 4) willingness to learn; 5) openness to new ideas; 6) problem solving skills; and 7) ability to follow directions (Harris & Rogers, 2008).

The habits of mind and 21<sup>st</sup> Century Skills that engineering can foster are reflected, for the most part, in those competencies (Bybee 2009; Dym, et al., 2005; Katehi et al., 2009). Important engineering/technology competencies for incoming first year engineering students include: 1) ability to sketch designs; 2) ability to operate fabrication equipment; 3) basic knowledge of engineering and the fields of engineering; and 4) ability to apply the engineering/technology design process. Mathematics competencies include: 1) competency in algebra; 2) competency in trigonometry; and 3) computation skills. Science competencies include: 1) ability to read meters, scales and other instruments; 2) relating science to math concepts; and 3) applying physics skills (Harris & Rogers, 2008). These findings highlight the importance of sequencing integrated engineering instruction in order to start building engineering capacity from an early age. Currently, there are states that have established engineering standards that allow for a sequential implementation of engineering knowledge and skills from first through twelfth grades that hopefully will help to prepare students to enter college with the competencies and intellect needed to become creative and expert engineers.

Existing state content standards and national technology standards help provide a model that is useful in building a logical sequence for learning engineering content (Strobel, Carr, Martinez-Lopez, & Bravo, 2011; Committee on Conceptual Framework for New Science Education Standards, 2010) that facilitates student preparedness for collegiate engineering education (Harris & Rogers, 2008) and learning progressions through different age and grade levels.

Integrating engineering at the secondary level (and all of P-12) is important because it meets the needs of schools that are looking for problem-based, hands-on and inquiry-related activities to integrate math and science content in a meaningful way (Carr & Strobel, 2011). Engineering, the “missing E,” of STEM (science, technology, engineering and mathematics) allows for integration of design activities into curricula (Brophy et al., 2008). Engineering provides a meaningful context for applying math and science principles (Chae, Purzer, & Cardella, 2010) and leads to improvements in math, science and technological literacy (Chandler, Fontenot, & Tate, 2011).

Engineering design goes beyond the normal problem-solving process, as testing and improving are traditional mainstays of the engineering design process (Strobel, Carr, Martinez-Lopez, & Bravo, 2011). A derivation of engineering design challenges called model-eliciting activities (MEAs) also contribute to the framework. MEAs are a form of open-ended problems based in real-world engineering contexts where a process that can be generalized, or a model, is the end product (Diefes-Dux, Moore, Zawojewski, Imbrie, & Follman, 2005). The engineering design process is applied in a mathematical context where the solution is tested with new data and improvements are made (Diefes-Dux, et al., 2005). Both engineering design and MEAs are being taught at various levels, from elementary school to university (Chamberlin & Moon, 2005; Carr & Strobel, 2011), and provide an underutilized connection of engineering to existing academic standards, which are often exclusively science oriented (Brophy et al., 2008).

## Conclusion

It is not just rhetoric to state that more research is needed in early design and engineering/design progressions in the P-12 system. Without the necessary research, appropriate needs assessment for building a model for the trajectory of engineering education throughout the grades is not possible and ultimately engineering in high school does not receive the appropriate foundation. From existing literature in a variety of contexts, a case can certainly be made that ill-structured problems have the greatest promise not only for the development of complex competency and transfer, but for the learning of the basics as well. This paper argues for resolving the dichotomy of ill-structured vs. well-structured problems by focusing on the intertwinedness of ill- and well-structured problems in authentic real world contexts; utilizing models of deductive teaching and expertise development as support for competency development; and integrating engineering into the existing standards, particularly where less integration appears, as in the case of mathematics.

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## Design Principles for High School Engineering Design Challenges: Experiences from High School Science Classrooms

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At the University of Pittsburgh, we have been exploring a range of approaches to design challenges for implementation in high school science classrooms (Apedoe, Reynolds, Ellefson, & Schunn, 2008; Ellefson, Brinker, Vernacchio, & Schunn, 2008; Schunn, Silk, & Apedoe, in press). In general, our approach has always involved students working during class time over the course of many weeks. So, our understanding of what works must be contextualized to that situation (i.e., without significant home support, by students enrolled in traditional classrooms, involving content that is connected to traditional science classrooms). However, our approach has been implemented with thousands of students in over 80 classrooms ranging from 9<sup>th</sup> grade biology or general science to 11<sup>th</sup> grade physics, from traditional mainstream science classrooms to elective Biology II or Honors Chemistry, and from high needs urban classrooms to affluent suburban classrooms. In other words, there is some important generality to these experiences. We have also conducted a number of studies on students in these settings, to understand a range of factors that influence student learning and affect outcomes (Apedoe & Schunn, 2009; Doppelt & Schunn, 2008; Reynolds, Mehalik, Lovell, & Schunn, 2009; Silk, Schunn, & Strand-Cary, 2009). This white paper provides a brief summary of principles that appear to guide successful experiences for students.

- 1) *Design challenges (in science classes) should involve particular systems that naturally emphasize key science learning goals from those classes.* In order to have a rich design experience in which students experience deep connections between science and design as well as allow for the time to seriously engage in iterative design, the time spent on the design challenge must also do science instructional work (i.e., students must learn some science, and preferably traditional focal science content rather than ‘bonus’ concepts). But engineering design naturally involves some creativity / multiple solution paths. How does one insure that the design challenge stays on target toward the goal involving conceptual learning targets? We have found that a systems design approach helps to achieve this goal while at the same time teaching key engineering processes (subsystems decomposition) and concepts (systems concepts). For example, to teach key thermodynamic concepts in chemistry class (i.e., the relationships between chemical structure, chemical transformations, and energy) we had students design chemically-based heating or cooling systems. In order to make progress on such systems, students needed to learn key big ideas in chemistry, regardless of which kind of system they wanted to design (e.g., a headband that cools them on the dance floor, or a therapeutic blanket that heats athletes, or a heated toilet seat). To teach biology students about the central dogma in biology, we had students create expression systems involving genetically modified bacteria that expressed key features under certain environment situations (e.g., turn blue when the loofa is too old, or turn blue when too many people peed in the pool). To teach environmental science students about ecosystems, we had students design a natural filtration system to address pollution problems (e.g., a water filter system for drinking water while climbing).

- 2) *Design challenges should allow for some flexibility in choice of target goals.* Many design challenges involve very fixed targets, such as the FIRST robotics competitions. This approach requires that all students ‘buy in’ to the same design, whereas student interests vary and the same challenge is not equally motivating to all. In addition, having a fixed challenge creates performance goals (do better than others) rather than mastery goals (improve ones own skills and knowledge), whereas mastery goals tend to produce better learning outcomes in the long run and are motivating to students across a wide range of skills (Elliot, 2006). Allowing students to pick their own goals (within some reasonable range) increases situational interest, creates more mental connections between engineering and personal interests, and allows students to maintain mastery rather than performance goals.
- 3) *Design challenges should involve helping others.* When students pick their own design challenge, they can pick from a very internal perspective (e.g., locker alarms, touchdown detectors) or they can choose to help others (e.g., grandmother’s pill reminder, modified hairbrush for physically disabled adults). While some students will quickly consider the needs of others, many students require a prompt to go there (e.g., some reading materials about particular special needs populations, or field trips to particular settings such as nursing homes). When students focus on the needs of others, it is more natural to conduct research to quantify the engineering requirements, and the gratification of a job well done is even greater. Further, when students see that engineers solve real problems in the world, they become more interested in engineering careers (Reynolds, et al., 2009).
- 4) *Larger design challenges should be divided into subsystems.* Just as the early airplane designers struggled with the high cost of failure of whole airplane designs and the Wright brothers succeeded by breaking the difficult problem set into much more doable subsystems, students also benefit in many ways by being pushed to tackle individual subsystems in isolation and in sequence. This approach models some systematicity to the design processes and allows for more successful final products given limited design time. Incremental successes are more motivating than failed designs. Further, they provide support for students without overly scripting exactly what solutions are tried or exactly what process steps must be completed.
- 5) *Requirements documents set high expectations.* Students naturally get tired or bored with an extended design challenge at various points during its resolution. It is easy to consider the first or second solution ‘good enough’ and not seek to consider any further revisions, although those revisions are needed to push their design and science thinking. By starting with the creation of a requirements document with high ‘real world’ expectations, students are motivated to keep at the design challenge to meet the goals they set themselves, in addition to seeing the importance of design processes in solving real problems.
- 6) *Design challenges should require reflective presentations rather than just the construction of prototypes or demonstrations of prototype functionality.* Many students can get conceptually lost in the current design if the design itself is the only deliverable, forgetting to consider what design path was followed, what strategies were more successful, or why certain designs were less successful. The reflective designer learns more from the design process about the design process and about the factors underlying the successful design. Document requests along the way can be easily ignored as superfluous during an authentic design challenge. But when the documentation is a natural requirement of the final deliverable, then students are more likely to engage in real reflection. In one form, we have design symposia, in which students make and present posters that describe what the solution is, how it works, and the



process by which it was produced. In another form, students turn in mock patent applications, which require descriptions of the design, how it works, and evidence of systematic testing to show that it works. In a related fashion, we have found it useful for reflection to require intermediate presentations at natural design points (e.g., of requirements documents, of decision matrices, of early prototypes).

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## Engineering Design Challenges in a Science Curriculum

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Create a light and sound show to entertain your friends. Design an improved safety device for a car. Develop a 2-3 minute voice-over for a sports clip explaining the physics involved in the sport. Modify the design of a roller coaster to meet the needs of a specific group of riders. Design an appliance package for a family limited by the power and energy of wind generator. Develop a museum exhibit to acquaint visitors with the atom and nucleus and create a product that can be sold at the museum store after visitors leave your exhibit.

All of these challenges are part of *Active Physics* (2005), a high school curriculum developed with support from NSF, field tested with thousands of students and presently used across the country. The challenges (mentioned above) serve as a framing structure for the required science content. Each chapter (approximately five weeks of instruction) is introduced by way of a chapter challenge. The students upon hearing the challenge at first react with silence. We originally thought that the students' silence indicated interest – a rapt awe. Upon interviewing, we found out that the students were in shock. How can they possibly succeed at such a challenge? The sports voice-over or light show or museum exhibit interested them, but their lack of knowledge surrounding the science content suppressed any enthusiasm that they might have for the topic. After the first months of school, with some success at the chapter challenges, the students approached the next challenge with cautious confidence that they would be able to learn the science content and could then use their creativity to complete the challenge.

In this brief paper, I will outline the ways in which the chapter challenge is introduced, revisited and then completed. Included in the discussion will be how the chapter challenges are chosen, how we scaffold students' learning so that they can be successful and the benefits of the chapter challenge. *Active Physics* is neither an engineering course nor a technology course. It uses engineering design as a way in which students can approach their chapter challenge, but engineering design must remain in the background of the physics content and curriculum.

After being introduced to the chapter challenge on day one, students are then asked to imagine what a successful project will include. This requires them to set criteria for excellence that not only includes "correct physics content" but may also include creativity, adherence to the time limits, safety considerations, presentation skills and involvement of all members of the group. Students generate this list and the teacher helps students decide on an initial weighting of these different factors for a final grade. Since the students have not yet learned the required physics content, they are assured that they will revisit their grading rubric once the chapter is completed and prior to beginning work on their challenge. After completing their grading rubric, students can then compare their rubric

with the one presented in the book. Having them complete the rubric on their own leads to a much more productive reading of the book's suggested rubric. Students feel a sense of pride when they match most of the factors that are presented in the text. They also are able to read the text's criteria with a better understanding having given the criteria some initial thought.

At this point, they are also introduced to an "Engineering Design Cycle." The elements of the cycle are described to the students:

- Goal
  - Define the problem
  - Identify available resources
  - Draft potential solutions
  - List constraints to possible actions
- Inputs
  - Complete the investigations in each section
  - Learn new physics concepts and vocabulary
- Process
  - Evaluate work to date
  - Compare and contrast methods and ideas
  - Examine possible trade-offs to help reach goals and maximize efforts
  - Create a model from your information
  - Design experiments to test ideas and the suitability of the model
- Outputs
  - Present *Mini-Challenge* and intermediary steps or products
  - Present *Chapter Challenge* based on feedback from the *Mini-Challenge*
- *Feedback*
  - Obtain response from target audience leading to modification of the goal
  - Identify additional constraints, requiring restarting the input and process stages

After students complete each section (approximately three days of instruction), they are asked to "Reflect on the Section and the Challenge." This helps remind them of why they are learning this physics content (i.e. "I need this content to complete the challenge.") It also provides a formative assessment in which they get to transfer the knowledge from their investigations to a new domain – the chapter challenge.

Midway through the chapter, the students complete a Mini-Challenge. The students are re-introduced to the Engineering Design Cycle. They are better able to understand this cycle at this point because they have now completed half the sections of the chapter and are well aware of the "inputs" that can be used in the "process" and "outputs" phases. They are reminded of the goals for the chapter challenge and asked to review the criteria that they set for success. They are reminded that they have more to learn in this chapter which will help them with the chapter challenge, but that this is a good time to give the Chapter Challenge a first try. This first try gives the students a good sense of what the challenge entails and how they and their teams may approach completion of the challenge. They are

then reminded of the sections (and physics concepts) that they have completed. They are also given specific instructions as to how to bridge the physics concepts to the completion of this mini-challenge. This is the process stage that they undertake for one class period. Each team presents their work to the entire class as the “outputs” phase of the mini-challenge. Finally, the teams receive “feedback” from the other teams and the teacher. The “feedback” from the mini-challenge will become additional “input” for the final design in the Chapter Challenge.

The Mini-Challenge serves a number of distinct purposes. As mentioned, it gives the students a sense of what the challenge entails. The presentation of their Mini-Challenge makes students aware of what is working well and what should be altered in their approach. The presentations also allow teams to see what other teams are doing. This provides them with new ideas for their chapter challenge. It also provides peer pressure for some teams to ratchet up their effort to match the efforts of other teams.

After the Mini-Challenge, the students complete the remaining sections in the chapter. Once again, each section concludes with an opportunity for students to “reflect on the section and the challenge.” Each section continues to broaden the knowledge that they can bring to the chapter challenge.

The chapter concludes with the final exposure to the Engineering Design Cycle. In a two-page spread, students are once again led through the cycle and given some hints and suggestions for how to navigate the “process” and “outputs” phase and reminded of the feedback that they will both give and receive.

The presentations of the chapter challenge have a number of distinct benefits. In preparing for the chapter challenge, students must transfer their knowledge of physics concepts to the task at hand. Research has shown that transfer is an important component of learning. Learning takes place during the transfer. The students must apply what they have learned to a new domain. It also serves as purposeful learning. A student may want to describe the path of a football and may only then realize that her knowledge about the physics of the motion is tenuous. Now is the opportunity for this student and the team to review that section with the specific goal of using this information in their chapter challenge.

The chapter challenge also provides motivation. It has been well documented that student motivation positively impacts learning. We may expect that students will display pride in knowing the equations for the conservation of momentum, but the real pride comes from each student team finding creative ways in which to communicate momentum conservation. In the execution of the chapter challenges, students have the opportunity to choose something that interests them. In the sports voice-overdub, student teams decide which sport will be theirs. Many teachers expand the definition of sport to any physical activity so that a student team can include ballet or break-dancing. One teacher suggested that a team of girls who were consumed by the fashion world may want to explain the physics of runway strutting. The point is that different teams have a choice of what interests them in their choice of how to complete the chapter challenge.

The students also gain a level of “expertness.” In a sports voice-over challenge, all students in the class will understand and be able to solve problems using Newton’s 2<sup>nd</sup> Law. One student team will become “expert” at applications of Newton’s 2<sup>nd</sup> Law to baseball while other teams will become “expert” at applications of Newton’s 2<sup>nd</sup> Law to lacrosse, soccer, swimming or volleyball. Being an expert also contributes to engaging students intellectually.

The chapter challenges also provide an opportunity for students to promote their culture and their interests in the classroom. We live in a wonderfully diverse nation. In some schools and classrooms, students speak more than twenty languages. Teachers are often told that it will be beneficial to bring a student’s culture into the classroom. How is this possible? When a new student comes into class from Nicaragua, is a science teacher supposed to read a book about Nicaragua and pretend to be an expert? In one challenge, students are required to create a light and sound show. This light and sound show will certainly reflect the interests and cultures of the students. One student group may use Latino music, while another may use rap, a third may use African folk tunes, and another may use hip-hop. The student groups are able to bring to the chapter challenge their interests and their cultures. We can then respect, celebrate, and honor those cultures.

Finally, the presentation of the chapter challenge provides a meaningful review of the physics concepts of that chapter. The review is not conducted by the teacher, but rather by each team during the presentation. Since each team chooses their own sport or creates their own museum display or presents their own light and sound show, the entire class learns about the physics concepts in several different contexts. Each team contributes a new context in which to view the physics concepts.

The criteria for choosing the chapter challenges include student interest, breadth of physics concepts, ability to grade, and opportunity for original, unique outputs. Ideas for chapter challenges that would engage high school students were generated by a group of physicists and physics educators that fell within certain large topic areas – sports, medicine, transportation, communications, energy and home. (Some of these coincide with broad technology fields.) Each chapter challenge had to be rich enough in physics concepts to require approximately one month of instruction. Displaying mastery of the physics content had to be a requirement for completion of the challenge. After we converged on the first challenge, we realized that we needed to find a way in which to grade the challenge. This led us to the idea of creating a grading rubric which then led us to the idea of having the students create the grading rubric. Since this work was done in 1993, grading rubrics had not yet emerged as an important consideration in school instruction.

In imagining what students may create for their design, we insisted that all teams would not have identical outputs. For example, in many physics courses the analysis of a roller coaster is the vehicle for introducing, explaining and then testing for an understanding of energy conservation. Designing a roller coaster was an obvious choice for a chapter challenge. In creating a chapter challenge regarding the design of a roller coaster, we were surprised that real roller coasters are not entertaining because of energy conservation but

because of forces. The chapter had to straddle the content of energy conservation and forces for it to include important physics concepts and to be relevant. We also realized that in many classes, all students analyze the same roller coaster and all get identical answers. We wanted to engage students and have them design unique roller coasters. We therefore added the additional constraint that students have to design their roller coaster for a specific population – thrill seeking daredevils, elderly people, young children, or physically challenged people. This additional constraint adds to student engagement (i.e. they choose the riders) and allows for radically different designs of roller coasters. Finally, high school students were surveyed about their interest in these challenges. These surveys forced us to table some of our ideas and led to challenges which had inherent interest for our target population.

In using engineering design challenges in *Active Physics* as well as in *Active Chemistry*, we have promoted an engineering perspective, introduced the engineering design cycle and used engineering vocabulary in high school science classes. We review the engineering design at multiple times in each chapter – at the introduction, at the mini-challenge and at the chapter challenge. We also remind students of the need to connect their new physics concepts to the chapter challenge after each of the ten sections per chapter. These are physics and chemistry courses. Most state frameworks in science do not mention any of these engineering design principles nor do any of the state exams in science ask students to demonstrate their knowledge of these principles. We have found that these chapter challenges are a motivating addition to the science curriculum and can be effectively added to the curriculum. We view these as a necessary component of our programs and recognize that learning will be diminished without them.

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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 21<sup>st</sup> 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 4<sup>th</sup> graders, 30% of 8<sup>th</sup> graders, and 21% of 12<sup>th</sup> 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 Erikson 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 21<sup>st</sup> 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

<b>Key Principles*</b>	<b>Teaching Suggestions</b>
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.