Advancing Engineering Education in P-12 Classrooms

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Abstract

Engineering as a profession faces the challenge of making the use of technology ubiquitous and transparent in society while at the same time raising young learners' interest and understanding of how technology works. Educational efforts in science, technology, engineering, and mathematics (i.e., STEM disciplines) continue to grow in pre-kindergarten through 12th grade (P-12) as part of addressing this challenge. This article explores how engineering education can support acquisition of a wide range of knowledge and skills associated with comprehending and using STEM knowledge to accomplish real world problem solving through design, troubleshooting, and analysis activities. We present several promising instructional models for teaching engineering in P-12 classrooms as examples of how engineering can be integrated into the curriculum. While the introduction of engineering education into P-12 classrooms presents a number of opportunities for STEM learning, it also raises issues regarding teacher knowledge and professional development, and institutional challenges such as curricular standards and high-stakes assessments. These issues are considered briefly with respect to providing direction for future research and development on engineering in P-12.

Keywords: design, problem solving, P-12 education

I. Introduction

Much of the impetus for expanding engineering education in pre-kindergarten through 12th grade (P-12) in the U.S. stems from concerns about the quantity, quality, and diversity of future engineering talent (American Society for Engineering Education, 1987; National Academy of Engineering, 2005; National Research Council, 1996; International Technology Education Association, 2002). Technology development and industrial growth are increasing at an exponential rate with expanding global application. Driven by the rapid development of enabling technologies, industries must become much more flexible and adaptive to remain competitive. Therefore, industry requires a workforce that is equally nimble at adapting to changing conditions so they can utilize newly available technologies and generate innovations of their own. This rapid evolution of technology suggests that students entering higher education must be prepared differently at P-12 if they are to be ready for the transition into undergraduate institutions working to provide a diverse STEM talent pool. However, enrollment in undergraduate engineering programs is declining and often lacks gender and ethnic diversity. Studies have indicated that interest in science, engineering, and mathematics as career options peaks during middle school years (Cummings and Taebel, 1980) for young women and minorities. New studies indicate that while young women are as competent as young men in the STEM disciplines they often tend to believe that science and technology are not relevant to their future career goals or they do not find the learning contexts inviting (Hsi, Linn, and Bell, 1997; Lent et al., 2005; Seymour and Hewitt, 1997; Linn, 2003). Women and minorities interested in STEM disciplines may find it difficult to identify their roles in technology-based activities. These learners may have fewer opportunities to develop the motor and spatial skills associated with the conceptual and constructive tasks involved in conceiving and crafting designs that they may imagine (Sadler, Coyle, and Schwartz, 2000).

Given the preceding concerns about the breadth and diversity of the talent pool, as well as the depth of knowledge needed by a twenty-first century workforce in areas related to STEM, it is critical to consider what is being done, and what might be done, in the educational system prior to college to improve outcomes of the P-12 educational process, especially regarding the engineering profession. This paper explores several critical issues and bodies of work that contribute to providing answers to those and related questions.

We begin by considering efforts of engineers and technologists to increase the engineering talent pool by implementing outreach programs in engineering, science, mathematics, and technology. Academic and professional bodies such as the American Society for Engineering Education (ASEE) have provided guidelines for K-12 engineering outreach that focus on hands-on, interdisciplinary, standards-based education emphasizing the social relevance of engineering as a discipline (Douglas, Iversen, and Kalyandurg, 2004). Similarly, the National Academy of Engineering (NAE) publication *Technically Speaking* (Pearson and Young, 2002) emphasizes the need for all people to obtain technological literacy to function in the modern world. The shared goal of such efforts is to transform the characteristics of the engineering pipeline for talented prospective engineers.

Not surprisingly, a number of efforts can be found that are consistent with the aforementioned policy documents. For example, Jeffers, Safferman, and Safferman (2004) provided an excellent summary of many engineering outreach programs including Web portals for learning resources, summer camps, after school and weekend programs, plus a number of teacher professional development efforts. Hunter (2006) has described engineering outreach efforts with links to mathematics and Hirsch and Kimmel have reviewed a number of programs focused on technology and science (Hirsch et al., 2003, 2005). The Building Engineering and Science Talent (BEST) (2004) initiative also evaluated a number of promising programs based on research results and their potential for impact on diversity for developing STEM talent.

Outreach programs focus on increasing engineering enrollment and technological literacy by providing educational opportunities and resources that make learning about engineering and technology relevant to young learners. Typically, this is done through engaging, hands-on, authentic activities (Carlson and Sullivan, 1999). An important pedagogical characteristic contributing to the success of outreach programs is reliance on opportunities for learners to generate ideas and act on them, followed by reflective discussions led by a knowledgeable person, a facilitator, who assists learners in noticing and explaining the scientific and engineering principles associated with the activity (Adams, Turns, and Atman, 2003; Cognition and Technology Group at Vanderbilt (CTGV), 1997; Schwartz, Brophy et al., 1999; Schwartz, Lin et al., 1999). In many successful outreach programs, learners often work in pairs or larger cooperative learning teams to develop skills related to working effectively with others. The activity aims to introduce appropriate formal vocabulary used by "experts" in the discipline and tools experts use to systematically analyze and solve problems (CTGV, 1997; Anning, 1994; Kolodner et al., 2003; Lehrer and Schauble, 2000; Linn, 2003). Many such outreach efforts are also designed and run by engineers and technology experts who can lead the discussions and respond to learners' questions. As we will discuss later, there is a need to identify ways to help P-12 teachers develop similar capabilities for guiding the inquiry process and in supporting interactions with and among their students as they tackle interesting problems.

Without doubt, outreach efforts are extremely important in increasing the potential pool of young learners interested in pursing a technical career like engineering or employment in a technical area requiring STEM knowledge (e.g., medical technology, technicians, mechanics, and industrial design). But it is questionable whether such outreach efforts are enough to attract the numbers of students needed in the field or if they can provide these learners with the experiences needed to succeed in the formal post-secondary engineering programs that they are being encouraged to pursue. With regard to the latter issue, research from engineering education and the learning sciences suggests that students need to develop a deep understanding of fundamental science, mathematics and technology principles across P-12 if they want to pursue a wide range of engineering and technical career opportunities. Fortunately, classroom-based initiatives have emerged that enable young learners to develop literacy, competency and interest in engineering thinking and technology proficiency (Raizen et al., 1995), several of which we discuss in subsequent sections of this paper. These initiatives are critical to the STEM education of all students and fundamental in supporting the growing demand for a work force who can *adapt to* and *innovate for* a rapidly changing world (Duderstadt, 2008).

Engineering education has outstanding potential to increase conceptual understanding of STEM disciplines for all P-12 learners while also increasing awareness of and interest in the role engineers play in supporting and advancing humanity, as many outreach efforts have demonstrated (see Table 1). We explore the opportunities for achieving important STEM learning outcomes through engineering education activities situated in P-12 formal learning environments. The next section is focused on ways in which engineering-related concepts and content are (and are not) finding their way into P-12 classrooms. This discussion ranges from national and state STEM content standards to research from the learning sciences illustrating the kinds of STEM learning outcomes that can be achieved through design-based instruction. In section III, we describe several examples of promising engineering curricula that have begun to have an impact in P-12 while simultaneously illustrating that there is limited empirical evidence about issues of program implementation and/or impact on student learning. Finally, in section IV we explore critical issues associated with bringing engineering into the P-12 learning and teaching environment and identify several research areas where knowledge is needed to achieve a wider impact of engineering education on STEM learning across the P-12 education continuum.

II. Engineering and Technology Education: Opportunities and Examples

A. STEM Learning Objectives for P-12 Learners: The Missing "E"

What gets taught in P-12 classrooms is often a function of what gets emphasized in national and state content standards, together with what is assessed on state-mandated achievement tests. Therefore, it is critical to ask what aspects of the "E" in STEM are currently found in major standards documents as well as what may be missing.

Although, specific engineering education content for elementary school has been left undefined by the ASEE and NAE, national standards in science and technology include standards for elementary schools pertaining to topics such as design and technology (National Academy of Engineering, 2005; National Research Council, 1996). Both documents call for young students to learn how to classify natural and human-made objects as well as practice and understand the steps of the design process. The National Science Education Standards (National Research Council, 1996) emphasize how design and understanding of technology inform students' understanding of science, while the National Technology Standards (Kelly and McAnear, 2002) and the Standards for Technological Literacy (STL) (International Technology Education Association (ITEA), 2000/2002) detail the design process and the critical thinking skills involved. At the state level, the Massachusetts engineering standards (Massachusetts Department of Education, 2001) contain many elements from the STL and provide a model for other states interested in having explicit standards for engineering. For example, at the elementary level (P-5), the focus is on materials, tools, machines, and engineering design. For grades K-2, the standards focus primarily on observing (which material is natural versus artificial), and categorizing and manipulating basic tools. For grades 3–5, the standards progress to learning more about simple and complex machines, classifying and categorizing with multiple properties, and understanding steps of the design process. Middle and high school learners progress toward more complex and abstract representations of systems. Science at these grade levels focuses more on the internal properties of matter and models of interdependent systems (e.g., ecosystems, bioengineering), and symbolic representation, inductive and deductive logic. These science and technology standards define one learning progression for P-12 learners that organizes important content knowledge and skills for processing information and comprehending how systems work.

National Mathematics Standards can be seen as a complement to the science standards (National Council of Teachers of Mathematics, 2000). They aim to develop learners' fluent and flexible sense for numbers, mathematical operations and representations to perform quantitative analysis as part of solving problems (e.g., science investigation and design activities). Students need to estimate, or approximate, mathematical calculations through mental operations rather than always relying on procedural operations using paper and pencil. Young learners begin to quantify using whole numbers and represent different relationships of sets based on the size of the set. They develop a fluid sense for how to combine numbers (e.g., decomposing numbers into parts of a whole) and how to compare values. Their number sense advances in later years to include fractions, negative numbers and very small and large numbers. They learn to operate on these numbers and the relationships between these operations (e.g., division is the inverse of multiplication). Students are expected to express their ideas mathematically using equations, graphs, charts, and other visual representations. Like the science standards, the themes are constant across P-12 learners, but the level of complexity of the concepts increase as learners mature.

B. Engineering-Specific Learning Objectives for P-12 Learners

Engineers and technical professionals engage in tasks everyday that require applying STEM content knowledge and skills involving both forms of quantitative and qualitative reasoning as outlined by the national standards. It is useful to consider some of the specifics of this body of knowledge and skills and how they may relate to accomplishing major objectives of P-12 education. Reviewing definitions of engineering can provide some insights into this issue and with these definitions we can identify new opportunities to focus on the value added to STEM learning that comes from adopting an engineering perspective.

"What is engineering?" "What do engineers do?" Many developers of engineering learning materials answer these questions with statements like, "Engineers invent new innovations and processes and refine existing ones," or "Engineering applies math and science to define something new to address a human need." These statements focus on two major activities of engineers and some of the skills they use to accomplish their objectives. Other statements such as, "engineers are problem solvers" are also true, but too ambiguous to differentiate engineering activities from other disciplines that engage in problem solving. Such definitions provide little insight into *what* engineers do and *how* they accomplish their objectives. They also imply that engineers only take action when problems are posed to them.

A more thorough roadmap is needed to show how educators, learning scientists, and engineers are currently bringing engineering concepts and practices to P-12 learners and to identify the kinds of learning pathways students will experience during their formal education (Anning, 1994; Kimmel et al., 2006). This roadmap should begin with a more clear definition of engineering to identify what is unique about it relative to other technical domains. Also, this definition should detail goals and objectives for introducing engineering to young learners as part of the mainstream curriculum. As a means of making progress in describing the terrain more completely, and as a context for describing several P-12 instructional efforts enabling the learning of key engineering concepts and processes, we provide the following sketch of some key cognitive components of engineering.

Engineering requires applying content knowledge and cognitive processes to design, analyze, and troubleshoot complex systems in order to meet society's needs. These activities of design, analysis, and troubleshooting are what engineers do to develop new devices (e.g., cars, consumer electronics), processes (e.g., food processing, manufacturing, airport scheduling), and infrastructure (e.g., transportation, power distribution, and waste management) and change existing ones that shape our lives. Design and troubleshooting represent the types of ill-structured, or open-ended, problems on which engineers enjoy spending intellectual energy. They require trying to understand how a given system (natural, artificial, or social) functions and how the components of the system work together to achieve that function (i.e., the behavior of the system). Ill-structured problems are difficult to comprehend because of their complexity and the potential for multiple viable solutions. The complexity of problems can be attributed to the number of factors (variables) involved, as well as the fact that the interrelationships among these variables can be difficult to analyze and predict. Problem complexity is "concerned with how many, how clearly, and how reliably components are represented implicitly or explicitly in the problem" (Jonassen, 2000, p. 68). Solving a complex problem will tap into many of the cognitive processes associated with solving more constrained problem types such as logical, algorithmic, rule-use, decision making, diagnosis, strategic performance, case analysis and dilemma analysis [see (Jonassen, 2000) for a more detailed description of problem complexity and typology].

Cognitive processes are useless without content knowledge on which to operate (Zuga, 2004). The prior description of national standards illustrates the combination of both process and content related to the disciplines of science, mathematics, and technology. From an engineering perspective this would include constructing conceptual prototypes of a system using mathematical models (equation, diagrams, graphs) and generating data to predict performance. Therefore, in the early years P-12 engineering education may use many hands-on activities with technology to develop a qualitative sense for material properties, spatial reasoning, physics, mechanics, number sense, and general problem-solving strategies. More advanced lessons can build on the formalisms of mathematics and science to enhance students' ability to construct conceptual prototypes for their ideas. In addition, one could argue that these forms of knowledge and skills are fundamental to all technical professionals involved in the process of technical design, troubleshooting (diagnosing), and/or analyzing complex systems (e.g., devices, systems which could be biological, physiological, or social networks, and processes such as manufacturing or crowd control).

C. Engineering Content and Process in the P-12 Curriculum

Engineering activities and goals are not trivial and can be intrinsically motivating because they engage a natural desire to make something and they tap into the curiosity that comes from wanting to learn how things work. Educators, curriculum designers, and educational researchers have long known the benefits of design, troubleshooting, and reverse engineering activities to engage students in rich learning opportunities. Therefore, it is not surprising that learning through engineering design contexts serves as a popular instructional model used in science, mathematics, and technology education to meet many aspects of the standards. Design-based activities can develop deep conceptual understanding of the knowledge and principles of a domain and support the development of self-guided inquiry skills (Crismond, 2001; Fleer, 2000; Fleer and Williams-Kennedy, 2002; Johnsey, 1995; Kimmel et al., 2006; Kolodner et al., 2003; Lewis, 2005; Linn, 2003; Roth, 1995, 1996; Zubrowski, 2002; Johnsey, 1993; Sadler, Barab, and Scott, 2007).

In the discussion that follows we explore several research studies and programs that illustrate how design-based activities engage learners in complex problem-solving activities. Such activities require extended periods of inquiry to allow students to comprehend the problem, learn new information to define alternative solutions and formulate a solution to the problem. As learners conduct research for new information they will encounter formalisms (e.g., language, tools, and heuristics) experts use during the problem-solving process (Anning, 1994; Woods et al., 1997; CTGV, 1997); however, learning content and process at the same time may require novices to use a process unlike problem-solving strategies experts use to solve problems that have become routine through experience. Also, the situations often involve analysis of complex systems by breaking them down into functional components and explaining how the relationships among components achieve the overall system's functional objectives. Finally, such activities provide opportunities for learners to develop an interest in contexts that are familiar on a day-to-day basis (Jonassen, Strobel, and Lee, 2006), but unfamiliar from the standpoint of the formal knowledge shared by engineering professionals in the discipline.

D. Design-Based Learning and Engineering Design

Many educators organize learning experiences around a design model consisting of phases such as specifying, researching, making, testing, refining, and evaluating (Dillon and Howe, 2007). Johnsey (1995) reviews the history of design models to describe design expertise. Various design models have been used to organize learning experiences about technology, science, and mathematics around an engineering goal (often focused on designing a physical artifact). The instructional challenge is identifying engineering contexts that are accessible to the learners, difficult enough to be interesting and rich enough to provide links to the breadth of content knowledge to be learned. The first step is to identify the bounds of an engineering design challenge as a catalyst for learning.

Dym's definition articulates well additional details of engineering design:

> *Engineering design* is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints (Dym et al., 2005, p. 103).

General models of design by artists, scientists, and technicians share some of these aspects, but they may not engage in the same process or require the same analytical rigor to evaluate the feasibility of their designs or to meet implicit design constructs such as cost, manufacturability, safety, usability, and sustainability that make a design appropriate for many users and/or conditions. Engineering design establishes a set of additional constraints focused on satisfying other's needs (clients), not just the imagination of the designer. Determining these needs requires taking the perspective of the client and critically evaluating the context where there is a potential for optimizing. These cognitive skills are fundamental to innovation and may be underdeveloped in many instructional programs for the development of design, specifically engineering design. They can be developed in P-12 settings, but they should follow a progression of complexity that evolves as learners' technological, mathematical, and scientific literacy evolves. One challenge for designing instruction is to determine what model of design and what specific conceptual understanding is appropriate for the different grade bands.

Technology educators in the United Kingdom and Australia use engineering design activities to increase learners' technological literacy and appreciation of its importance to society. Many of these curriculum efforts leverage models of the design process as an organizing framework for structuring learning experiences (Dillon and Howe, 2007; Johnsey, 1995). With young learners, the activities are more craft based, working toward design goals the learners would like to achieve (Black, 1994; Jones, 1997). Therefore, the students act as their own client; they are encouraged to be premeditated in establishing criteria and evaluating whether or not their designs meet these criteria. Later, they advance to more complex goals that involve developing technologies and processes for others, increasing the potential to systematically approach their design activity and to develop solutions that are both novel and appropriate (Kimbell, 1986).

One example of design-based instruction is Fleer's pilot study with preschool children which used a simple design model of *planning, making* and *evaluating* (Fleer, 1999, 2000). In this study with children ages three to five the teacher told a fantastic story about a mythical creature living in her garden. The children were presented the open-design challenge to create a friend or home for the lonely creature. They began by *planning* their design with a drawing and a list of materials for the teacher to provide during the *making* of the "friend" and/or "house" for the mythical creature. Typically, the drawings were frontal views similar to artwork children generate to tell stories. Most were able to generate a list of materials they anticipated needing. These materials were made available to learners during the *making* portion of the design process. Many students used the requested materials to make their design, but no student referred to his or her drawings as a planning document. Several students switched materials from their original plan either to improve its structure or to copy ideas from other children's designs. *Evaluating* their designs was accomplished through interviews with the researcher. Some students were happy with their artifact and its structure, but no further explanations are reported. Based on other research this could occur because students take a more emergent design approach which begins with an ambiguous goal and they begin construction with whatever is available. At some point they declare the goal is met. This approach stems from free play activity during which learners' goals and direction are all their own (Brophy and Evangelou, 2007). In Fleer's study, many students could clearly articulate their expectations and could explain why their design did not meet their expectations. They could articulate their initial intentions and could explain the problem with their design and why it did not meet their criteria.

Although the learners were given an open-ended challenge around a mythical client, they chose to design animals and structures from their prior experience.

Fleer's results suggest preschool children can plan a design and use their prior experience with materials to predict which materials they need to use. However, Hill and Anning's (2001) case studies were less optimistic, but the design task was around a craft construction and may have begun with different set of goals. In Fleer's study the drawings were simplistic and consisted of only one type of drawing, a two dimensional frontal view. Fleer suggests young learners need exposure to more types of drawings, such as architectural drawings. Welch and Lim (1999) found students who were taught how to make isomorphic drawings that show front, top and side views did not use sketching to develop their design plans. Young designers preferred creating a physical model when designing rather than sketching (Welch et al. 2000). Also, teachers could do more to model how to use drawings as planning tools. At this young age many learners altered their initial design plan once they had the materials. Several reasons explain this behavior to redesign. They revised their plan because their initial plan would not work (structural considerations), they were unable to work the technology (i.e., materials) to achieve their goals, or they learned a better way by observing others.

Another example from the United Kingdom (UK) comes from design and technology classrooms and projects. Johnsey (1995) conducted video tape analysis of four to ten year-old students engaged in design tasks. He found that students naturally engaged in a "Make-Evaluate-Make" design model and were not capable of planning ideas thoroughly before engaging with the materials. These results are difficult to interpret, however, since the numbers of participants in his study and their exposure to design curricula are not well described. Similarly, Roden (1999) looked at design process strategies longitudinally across five to seven year-olds in the UK (kindergarten to second grade in the US). His work focused on strategies at the dyad and group level rather than on the individual (hence he does not include his sample size). He used audio tape and field notes to look for specific problem-solving strategies. He found that older students were able to engage in more sophisticated strategies (i.e., Focusing on Tasks or Materials or Identifying Obstacles) and many of their strategies evolved (i.e., Practice and Planning) while other less sophisticated strategies diminished in use (i.e., Personalization and Talking to Self).

Wolff-Michael Roth observed a similar result to Fleer in his work with fourth and fifth graders working on a civil engineering unit on towers and bridges titled, "Engineering for Children: Structures" (EfCS) (Association for the Promotion and Advancement of Science Education (APASE), 1991). Like other engineering curricula, EfCS established an open-inquiry learning environment around realistic and complex problems. The intent of this curriculum summarized by Roth is to allow students to:

> (a) identify and test their own problem frames and solutions in ill-defined contexts, (b) design their own procedures and experiments, (c) formulate new problems based on previous claims and solutions, (d) link current experiences to prior activities and knowledge, and (e) share and discuss their procedures, products and solutions (Roth, 1996, p. 183).

The EfCS provides an authentic application of science that also "fosters positive attitudes towards science and technology" (APASE, 1991). Roth's research focused less on quantified student outcomes of engineering understanding and more on qualitative analyses of how students interacted and developed their ideas. He observed groups who could successfully articulate a design plan with drawings and execute the plan with some unanticipated problems. However, other groups used an emergent design such as Fleer observed in preschool children's design. These children continually faced small problems they needed to evaluate and reframed their problems based on their constraints of structural stability, aesthetics, and other personal goals. This problem solving ability demonstrated a willingness to reframe their thinking based on evidence that the structure did not meet the desired goal or a constraint a team member wanted to achieve. Roth (1996) found that students generated multiple types of problems while working on the tower design problem. Macro-problems dealt with overall design, meso-problems with implementation and micro-problems with actual construction. These problem levels were generated throughout the design process. The children were continually rearticulating their goals of form, methods of structural stability, function, use of specific materials and aesthetics. Further, the evolution of the groups' negotiation of values went through iterative states of evaluation, learning, and redesign.

Roth's work suggests how educators might work with students throughout the design process and documents the unpredictable nature of student design work in groups at the elementary level. Part of this unpredictability comes from the open endedness of the problem. Another reason could relate to variance in students' competency with the technology (material properties, support structures). Some students could anticipate how materials and structures would work during the construction process; therefore, for them, the construction process had become routine. Others faced many micro problems as they constructed because the materials or supports did not work as anticipated, or flaws were detected as two children tried to combine the components they had constructed (system integration task). Therefore, the natural cycle of iterative design places students in a continuous cycle of test and evaluation. This example also illustrates how learners may have more iterations through the design process as they learn about the content compared with expert designers who have more prior knowledge to support their articulation and selection of an appropriate plan of action (similar to Wineburg's observation of experts engaged in a process of discovery for new knowledge versus an expert drawing from his existing knowledge to define similar explanations for contradictions in historical documents (Wineburg, 1991)). For novices, learning occurs during all three levels of problem-solving activities (macro, meso, and micro) with each level targeting different learning objectives (e.g., critically evaluating needs, defining a problem, planning a design, identifying relevant content knowledge, and skills related to constructing prototypes, conducting tests, evaluating results and making decision about what to revise).

Gustafson (Gustafson and Rowell, 1998; Gustafson, Rowell, and Rose, 2001) conducted a three-year longitudinal study in Alberta, Canada, using a specific curriculum, Problem Solving Through Technology, and a written performance-based assessment. The researchers looked in depth at how students responded to two questions regarding structural stability and strength at one and three year marks. They found students were able to offer more useful suggestions about how to make a tower stronger at the year three mark, but the results were not remarkable. The group also presented a definition for "elegant" design suggestions (one single change that will improve the design) and found that older students were more likely to offer elegant solutions than younger students. Using a pre-, post- assessment design and lacking a control group, it is difficult to say if these results are related to the curriculum or to the children's normal cognitive development.

E. Supporting Science Learning Through Design Activities

The preceding studies of design illustrate children's incredible adeptness and creative ability to conceive, construct, test, and refine a product for a specific goal. Thus, it appears that children are natural engineers/technologists who can pursue a goal that meets constraints defined by others and their own personal interests. They can engage in iterative cycles of problem-solving situations to a solution that they evaluate for its appropriateness relative to a defined function. These evaluations are validated through tests using perceptual cues from concrete examples. This very simple model of engineering inquiry ends with the evaluation of a product and does not necessarily include systematically evaluating many alternatives and explaining why they work. A significant concern is whether a simple engineering model helps to reveal the scientific principles that explain how something works, or if it helps students to generalize what they have learned to future design situations. This might be possible if learners engage in additional design activities that require them to compare and contrast design decisions based on new goals (CTGV, 1997; Kolodner et al., 2003). Alternatively, a pedagogical approach which uses a design process could teach more of the physical science concepts explicitly during the particular phases of the design process. The following discussion describes several examples from science education that build from an engineering model of inquiry toward a scientific model of inquiry to achieve a broader set of STEM learning objectives.

The scientific model of inquiry provides a systematic way for children to evaluate various design alternatives and explanatory models. Schauble et al. (1991) used design challenges to engage students in a process of evaluating what factors most influence desired goals that students might have, such as the fastest car, a boat that can handle the most weight, or a windmill that can do the most work (i.e., lift the most weight). Through conversation with the teacher and peers, the learner discovers a method to systematically control specific parameters and run experiments. The learner can set up controls as a normative reference. In this case the product students generated was not a product for a customer as much as it was a simple test prototype of a specific feature of the design used as a stimulus for experimentation. Through scientific inquiry, learners develop important tools they can use to generate and evaluate potential design alternatives and develop experimental methods to reliably evaluate whether their model meets design criteria.

Sadler replicated similar experiences with middle school children by engaging them in cooperative design projects with challenges against nature (Sadler, Coyle, and Schwartz, 2000). Students repeated experiments to evaluate cause-and-effect relationships by constructing a prototype through empirical methods. For example, they were given the challenge of reducing the weight of a paper truss while maintaining maximum strength. Students needed to evaluate the structure to decide where material could be removed without decreasing the strength. Students conducted a series of experiments to evaluate their decisions. This process required teams to discuss *logical* deductions, between each step of the process. One unique result of this activity is the range of strategies students employed as they reviewed data from one experiment to the next iteration. Some students made very conservative steps while others took more aggressive steps, and then backed off. Sadler finds that these challenges engage both male and female students. An instructional principle he emphasizes is to present clear and explicit challenges that are accessible to learners (Schwartz, Brophy et al., 1999). Also, competition can be a good motivator, and competition against nature, rather than peers, can be more inclusive for girls and minorities. Design challenges conducted at this age level facilitate learners' noticing of scientific principles that govern structures like bridges and engage learners in a collaborative exercise that develops logical thinking and communication skills (Sadler, Coyle, and Schwartz, 2000).

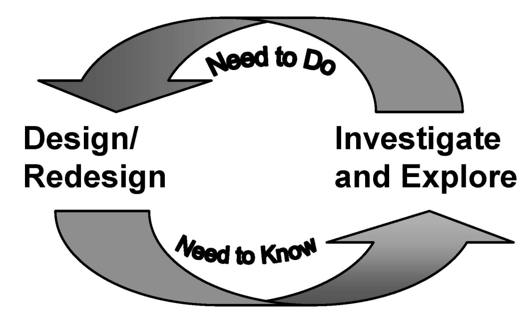

Figure 1. Learning by Design blending design and inquiry cycles.

Learning by Design™ (Kolodner et al., 2003) blends design/redesign activities with investigate/explore activities (see Figure 1). As with the other models of design-based instruction, the problem begins with a design challenge. Students then begin "messing around" with materials and devices to facilitate their brainstorming of ideas and questions that they need to learn more about. This activity sets up investigations into concepts they "need to know" to articulate appropriate alternatives to what they "need to do" for the design. Through discussions led by the teacher and supported by common tools of problem-based learning, the class engages in a process of systematic investigation. The process of understanding the challenge generates a number of inquiry questions requiring systematic investigation. Thus, like Schauble (1991) and Sadler (2000), the Learning by Design instructional model begins with larger ill-structured design activities to set up experiences for students to learn through systematic design and inquiry. For example, middle school students learning about forces and motion can replicate the scientific process after conducting multiple iterations of building and testing various combinations of small vehicles and propulsion systems (Hmelo-Silver and Pfeffer, 2004; Kolodner et al., 2003).

The Learning by Design instructional model explicitly illustrates the interaction between a design cycle used to construct a product and an inquiry cycle used to systematically describe the scientific principles that explain why their product performs (behaves) for various configurations. This instructional model illustrates again an important developmental distinction between novice and expert. Experts with strong conceptual knowledge may navigate the design cycle differently than the novice who is learning simultaneously the design process, scientific process, and content knowledge. The expert has the necessary content knowledge either from direct experience solving similar problems (well defined schemas, e.g., Chi, Glaser, and Rees, 1982), or through computational methods (qualitative or quantitative) they can use to predict the outcome of their decisions. Novices do not have this prior background to anticipate how their design decisions will work without building and testing their ideas. Therefore, they learn the science, mathematics, and technology by conducting research on factors influencing the design, making thoughtful decisions about an alternative, generating a prototype and running experiments to evaluate the design. The interpretation of the results and generation of new alternatives are a critical component of the students' conceptual development of scientific and mathematical knowledge and skills. This process of testing and evaluating results requires learners to generate an explanatory model for how the system works. Now, like experts, learners can begin to use this working model of their product (functional prototype) to make decisions about how to refine their product for the next design iteration. These kinds of experiences generate practical models students can use in future situations that have similar problem characteristics because they now have a mental model (Gentner, 1983; Johnson-Laird, 1980) they can use to anticipate how the system will perform under specific conditions.

In science education at the elementary school level, design activities have been used to aid students in understanding science concepts and developing models. However, the design process is not always explicit nor is the connection to technology. In elementary science education, the work of Penner, Lehrer, and Schauble and their collaborators is most notable for connecting science and design through a focus on models and systems thinking (Penner, 2000, 2001; Penner et al., 1997; Penner, Lehrer, and Schauble, 1998). For example, they presented first and second graders, and third and fourth graders, with the challenge to design a model of the elbow using assorted building and craft materials (dowels, balloons etc). The learning goal was to understand how the muscles and bones in the elbow work as well as the qualities of an effective model.

In their findings, they note that younger children initially paid more attention to perceptual, or structural qualities (hands, veins) than to functional qualities. If they did pay attention to functional qualities, they focused on how the elbow flexed and did not constrain its motion. As the teacher directed their attention, however, they were able to work on functional qualities. Through class discussion and demonstration, the students revised their model to restrict its motion into hyperextension. Older children focused much more naturally on functional qualities. From students' discussions of how they were going to construct the model, researchers were able to gain insight into students' understanding of how muscles worked (or did not work). In their work with first and second graders, they engaged control groups (one of similar aged children and one of older children) to see which group of students was able to better evaluate the qualities of a good model of the elbow. The modeling group of first and second graders and the older children paid attention to functional qualities of a good model while the younger control group (who did not participate in modeling) focused on perceptual qualities (Did it look like an elbow?).

Finally, Hmelo-Silver illustrates how to use design and modeling to understand complex systems (Hmelo-Silver and Pfeffer, 2004). In these studies, design becomes a process of mimicking the function of another system, such as designing an artificial lung. This system involves a number of interdependent components defining its *structure* (e.g., lungs, diaphragm, brain), to achieve its function (e.g., bring in oxygen to the blood, remove waste from blood, move lungs to get air in and out, control rate of movement of lungs based on metabolic changes in body). Using the Learning by Design instructional model, students developed a model of a lung. This design challenge introduces the question, "How does a device achieve its function?" The next question is "How can the same function be achieved using a different mechanism?" Therefore, the "need to know" investigations revolve around understanding the components of a system and the interdependence of these components. Hmelo found that students who constructed the models could better explain the structure and function of the system and its components compared to those who studied the biological system through traditional instruction. The students who constructed the models were less apt to define the causal relationships (behavior) between the components. This structure, behavior, and function (SBF) framework for analyzing a system provides a useful method for assessing students' understanding of complex systems. What can be observed in all the studies is that the design process involves a complex network of interdependent components with individual properties that determine their structure and emergent properties that define the system behavior.

The design process as described above involves troubleshooting ones own "design" (object, systems and processes) when it does not work, but the process is not the same as trying to make sense of someone else's "design". Systems thinking can also be fostered through troubleshooting and reverse engineering (or dissection) (Sheppard, 1992) activities. Troubleshooting and reverse engineering require investigating someone else's design to either repair it, replicate it, or refine it. In this context, the learner does not know all the intentions of the original designer and must induce it by systematically evaluating the casual relationships that make a design achieve its function by observing its behavior. This process is not trivial and can involve very similar scientific inquiry skills used to understand natural systems. As a science activity, learners can systematically take apart everyday objects to explain and document how it works. As an engineering activity the process can include a more critical analysis of the original designer's decision making process to answer the question why it is a good design. This kind of analysis involves thinking about all the different constraints involved in achieving the function while maintaining additional constraints of cost, manufacturing, safety, or sustainability to name a few. This analysis also induces a logical thought process which could potentially transfer to other domains involving complex decision making, such as urban planning or political decisions (present day and historical). Little research has been conducted on this idea in P-12 learning environments, and warrants further investigation.

F. Summary

A design context provides learners with an opportunity to be generative, reflective, and adaptive in their thinking as they engage in activities of planning, making, and evaluating a device, system or process. The examples illustrate multiple ways to bring design activities into the curriculum for learners to develop literacy for STEM content knowledge and processes. Very young learners appear able to articulate, or demonstrate in their actions, their plans for constructing products (e.g., puppets, block buildings, towers, lego robots, windmills and playdough) with some level of intention. Some young learners can evaluate their designs. Older students learn to critically evaluate more complex systems like an elbow or lung requiring them to notice features of structure, function, and behavior. The hands-on learning associated with the "making" activities provides a first-hand experience of the properties of materials and principles of physics associated with technical fluency. In all cases, the design activity requires learners to notice and reflect on the structure, function, and behavior of a process (e.g., mechanics, human interactions, social studies), a device (artificial system) or natural phenomena (natural system) to ask the initial questions, "What should I make?," "How does it work?," "What factors in the design are critical to my goals?," and "What can I manipulate to achieve my goals?," to name a few. Novices will not have the content knowledge to answer these questions, but through intentional learning activities they can be taught what they need to know in order to progress toward an appropriate design solution. Briefly, the research studies presented in this section illustrate how inquiry based science and mathematics instruction using design contexts (or design-based instruction) can develop learners' competencies to:

- Evaluate and explain the structure, behavior, and function of complex systems (natural or artificial).
- Develop cognitive models (mental models, or schemas) of how "systems" work.
- Design and conduct experiments to inform decision making.
- Communicate and negotiate ideas with others.
- Apply geometric and spatial reasoning.
- Represent and manage complexity of a system using diagrams.
- Express ideas and results with mathematics (computations, tables, graphs charts).
- Synthesize ideas (own and others) toward an appropriate solution that meets goals.
- Conduct experiments to evaluate if a design meets criteria for success.

In these studies, engineering contexts are used to motivate a "need to know" by satisfying a "need to do" as an intrinsic desire of all young learners. In science instruction one of the major goals is to explain how things work by conducting controlled experiments and to observe important relationships between variables. These objectives are very important indeed; however, the critical evaluation of how well a design meets its intent is not always the focus of design activities used in science and mathematics inquiry.

An engineering model of inquiry can also include objectives to:

- Critically evaluate multiple perspectives (understand others needs, e.g., a client, or others design decisions).
- Generate questions about what more needs to be known about the problem context before taking action.
- Generate plans that balance multiple constraints (e.g., specific client needs, cost, safety, manufacturing, environmental awareness, culture, and global factors).
- Identify and evaluate multiple alternatives (e.g., decision matrix) to support decision making.

Also, these inquiry-based models of instruction are grounded in constructivists theories of knowing and guided by similar principles that consider the learner, the knowledge to be learned, assessment practices, and community in the classroom and in the profession (Bransford, Brown, and Cocking, 1999). Examples of such principles include:

- Define design challenges functionally.
- Define design challenges in authentic contexts.
- Define design challenges that are accessible to learners (i.e., they can comprehend the problem and generate initial ideas based on prior knowledge).
- Provide dynamic formative feedback.
- Allow time for multiple iterations toward a solution.
- Involve social interaction to support teaching and learning.

Instructional models such as Learning by Design and STAR.Legacy (discussed in the next section) illustrate the importance of including all of these principles in the process. Learning is not just the process of constructing products through hands-on activities; learning includes the precursor activities of reflecting on what you already know and generating learning goals for what more you "need to know" (establishing individual learning goals). Also, it requires the learners to build prototypes of their ideas, test their ideas, and refine them based on what they learned. Therefore, young learners who are still learning critical content knowledge will iterate through the problem more than an expert. The instructional process takes time to complete if novices are to achieve robust understanding of the content and inquiry skills. Hmelo stresses that the need to think "… about design as a system of activities and allowing time so that the full system can be carried out, allowing its full set of affordances to be realized" (Hmelo-Silver and Pfeffer, 2004, p. 248).

III. P-12 Engineering Programs

In addition to the work on design-based teaching and learning that is ongoing in P-12, there have been a number of attempts to create engineering-based curricular materials and programs and support their dissemination and implementation in P-12 classrooms. In this section we provide examples of such curricula. Those chosen are highlighted because they have either initiated research on learning and professional development, demonstrated methods for blending STEM and language literacy learning objectives, and/or have established strong foundations for future impact. Many other fine examples of research based curriculum exist; some of which are included in Table 1. In presenting each of the examples, we have divided them into those focused at the elementary grade levels versus those focused at the middle school and high school grade levels. For each program, we provide some information about the program's history, its design and content, how it has been or is being implemented, and any available assessment outcomes and research findings. Noticeable in this work is the limited amount of data that are available on the efficacy and impact of these programs on key STEM learning outcomes. This, along with research about teacher knowledge and classroom implementation, remains an issue for the future to which we return subsequently.

A. Elementary Engineering Curricula and Activities

1) Engineering is Elementary

Program History and Overview: Engineering is Elementary (EiE) is one of the largest elementary engineering curriculum development projects. EiE focuses on integrating engineering with reading literacy and existing science topics in the elementary grades (Cunningham and Hester, 2007; Cunningham, Lachapelle, and Lindgren-Streicher, 2005). The project is primarily funded by the National Science Foundation (NSF) with matching funding from industry. It was originally developed at the Boston Museum of Science (MoS) to meet new engineering standards like those defined for Massachusetts (Driscoll, 2003).

Program Design/Content: EiE is aligned with national and many state standards and integrated with science, language arts, mathematics, and social studies. The 20 planned units (13 are currently available) (Museum of Science, 2007) include storybooks and lesson plans to guide educators through lessons that focus on a specific type of engineering using required science content and processes in a cultural context. Instruction begins with reading a story about a child who has a problem that could be solved with knowledge from a particular discipline of engineering. Students then engage in a related engineering design project. Each book may be used independently and does not require previous knowledge of engineering or the design process. For example, the curriculum "Leif Catches the Wind" focuses on wind and weather content as part of an investigation of renewable energy. The unit links to mechanical engineering through capturing the energy of the wind and controlled experiments contrasting specific design alternatives. Science content is linked with standards on simple machines and energy transfer. All units identify a goal and use hands-on activities to guide learners' inquiry toward that goal by explicitly referencing a simplified engineering design process. The steps of this design process include *ask, imagine, plan, create*, and *improve*. The books also stress material properties and how to determine which material is best for a given challenge.

Program Implementation: Preservice teacher education programs are beginning to use these materials in their courses; currently over 20 programs have been infused with the materials. EiE also provides in-service professional development for educators who want to implement the curriculum. EiE workshops range from two hours to two weeks. The program has created the "Engineering is Elementary Professional Development Guide," which outlines the program's structures and philosophies underlying professional development. EiE also offers a series of two-day Teacher Educator Institutes for professional developers who want to run workshops about EiE.

Assessment and Research Findings: From its inception, EiE has developed student assessments and collected extensive data to measure the impact of the curriculum. EiE assessments measure changes in students' understanding of engineering, technology, and the engineering design process. The unit-specific assessments probe students' understandings of the featured engineering field. EiE is currently collecting data to determine students' increased understanding of science when studied in conjunction with engineering (Cunningham, Lachapelle, and Lindgren-Streicher, 2005; Lachapelle and Cunningham, 2007). A study of children's attitudes toward, confidence in and career aspirations regarding science and engineering is also underway. Currently a controlled, pre-post study of children in states across the country is underway; this study will help to measure the impact of the curriculum and will be analyzed with respect to demographic data such as sex, race/ethnicity, free-reduced lunch, and mother tongue.

Findings of research studies show that children who use EiE make statistically significant gains on their understanding of engineering and technology concepts when their post-tests are compared to pre-tests. Not surprisingly, comparisons to control students who did not use EiE are quite favorable.

2) LEGO Engineering

Program History and Overview: The core purpose of the Tufts Center for Engineering Educational Outreach (CEEO) is to improve education through engineering. To this end, the CEEO works in the areas of outreach, research, and tool development to make engineering and design accessible and feasible in P-12 classrooms. The Center's most prominent project over the last ten years has been LEGO Engineering. The LEGO Engineering project centers around the ten-year collaboration between Tufts University and the LEGO Group to provide tools and resources to educators based on LEGO Education products, most notably the Mindstorms line. The Center initially selected the LEGO materials to implement the majority of its engineering efforts at the P-12 levels as well as the college level because of their ease of use as well as their power to enable students to engage in hands-on engineering design projects (Capozzoli and Rogers, 1996; Erwin, Cyr, and Rogers, 2000; Osborne et al., 1998). The success of the CEEO's initial LEGO-based engineering activities yielded a partnership with LEGO that generated the ROBOLAB software for LEGO Mindstorms, used by over ten million students around the world in 15 languages. From the proliferation of ROBOLAB and the Mindstorms products, a demand emerged for resources for educators to use these materials in their teaching of STEM content. This initiative has yielded the development of several books authored by educators (Bratzel, 2007; Green, 2007; Wang, 2007) as well as the development of a Web site (LEGOengineering.com 2008) specifically focused on using the LEGO materials to teach engineering as well as teach STEM content through engineering. The CEEO's outreach and tool development activities have been influential in shaping the development of the next generation of the LEGO Mindstorms product line (Seybold, 2006), which extends the power of the microprocessor and its potential for learning.

Program Design/Content: LEGO Engineering is the overarching project that encompasses a number of resources that have been developed over the past ten years in association with Tufts CEEO. The core principle that ties all of these efforts together is the ease of construction of the LEGO materials. The LEGO toolkit gives students the opportunity to design solutions to various problems while still allowing them to easily make changes (tinker) with their design. In addition, the LEGO constructions can create a working product of significant complexity while still remaining open ended. Hence, LEGO materials are quite different from other types of design materials. In contrast to low-end materials, like paper and tape, they provide higher reliability and therefore more concrete feedback to students as to why their design isn't working. They are easier and less expensive for the average teacher to implement than the traditional machine shop or electronic design projects. They are also more open-ended than many of the technology kits that allow for only a single solution (a balloon car). The LEGO material's flexibility allow multiple uses in a classroom from designing a robot to follow a line, to measuring the temperature decay of a coffee cup, to creating an electronic musical instrument.

The LEGO Engineering inspired books and activities help to give educators at the elementary, middle, and high school/college level basic activities for bring engineering into their classroom and teaching content through engineering. The Engineering by Design unit (Green et al., 2002) developed at Tufts CEEO introduces first grade school students to the engineering design process through simple lessons that build their understanding of construction and the design process. The unit starts with lessons on simple design tasks (like building a sturdy wall); these lessons define the problem and culminate in a more open-ended transportation design projects.

Terry Green's book *Primary Engineering* (2007) expands on the Engineering by Design concept with activities that integrate science and engineering for K-2 students. For instance, when learning about gearing, students are asked to build a snow plow that can push cotton balls. Although most vehicles can plow the dry cotton balls, only those with proper gearing can move the wet ones. At the middle school level, Barbara Bratzel's *Physics by Design* (2007) uses design and the LEGO materials to teach science. She combines highly scaffolded lessons (such as: how does blowing impact cooling?) with open-ended design projects (design a device to cool hot chocolate as quickly as possible). Finally, at the high school/college level, Eric Wang's book *Engineering with LEGO Bricks and ROBOLAB* (2007) aids educators in using the LEGO tools to teach computer programming, teamwork skills, and basic control theory.

Program Implementation: There are a number of ways that teachers and students become involved with LEGO Engineering. The LEGO Group offers a number of after-school programs through their LEGO Education Centers (LEGO, 2008). More than 120 centers around the world teach children fundamental design, programming, and construction skills. Many of these centers provide teacher and parent training programs. The LEGO Group and the CEEO have started a series of LEGO Engineering Conferences that serve two purposes: (1) to provide teacher training and (2) to build a community of teacher users (Tufts Center for Engineering Educational Outreach). Approximately 15 conferences are offered every year, primarily in the U.S., Asia, and Europe. Finally, the CEEO offers a week long summer workshop for local teachers.

Assessment and Research Findings: While LEGO Engineering has become quite popular, research on how it impacts student learning is still in its infancy. Several pending projects at Tufts Center for Engineering Educational Outreach focus on student outcomes including looking at how children learn engineering design with LEGO materials (Portsmore, Bers, and Rogers, 2007) as well as how an engineering approach in science impacts science knowledge (Bethke et al., 2008). Research has been conducted on how teachers learn and on how teachers report student learning. For example, Cejka (2005) conducted a preliminary investigation into how educators approach learning to bring LEGO-based engineering design into their classroom in a professional development setting. Her work found that the differing strengths of educators (e.g., building and programming engineering problem solutions) impacted their perception of what students might have difficulty with in the classroom. She also found general results about educators' need to know the "right" answer and uncertainty in how to address students' unanticipated questions that highlight their apprehension of bringing engineering into the classroom. Evaluation of a systemic LEGO engineering initiative (bringing LEGO materials to every grade level), which echoes this apprehension regarding implementation by educators (Cejka, Rogers, and Portsmore, 2006; Hynes, 2008), has been exploring how teachers use subject matter knowledge and pedagogical content matter knowledge in teaching LEGO-based engineering lessons. Cejka's qualitative work reports a variety of approaches and very different subject matter knowledge among teachers. This is a challenge that will need to be addressed in effective professional development programs.

B. Middle School and High School Projects

1) Project Lead The Way

Program History and Overview: Project Lead the Way (PLTW) is currently among the best known middle and high school engineering programs (PLTW, 2007). The Project is designed to add rigor to traditional technical programs and to traditional academic programs through project- and problem-based learning. It began in the 1997–1998 academic year, affiliated with the High Schools That Work (HSTW) project in 1999, and now serves over 1,300 schools in 45 states.

Program Design/Content: The high school curriculum is a four year sequence of courses including three foundation courses: Introduction to Engineering Design, Principles of Engineering, and Digital Electronics. Specialization courses include aerospace engineering, biotechnical engineering, civil engineering and architecture, and computer integrated manufacturing. The course sequence culminates in the capstone Engineering Design and Development course, in which students work in teams with a community mentor to design a solution to an open-ended engineering problem (Hughes, 2006).

The middle school curriculum Gateway to Technology consists of five nine-week units including Design and Modeling, Magic of Electronics, Science of Technology, Automation and Robotics, and Flight and Space. PLTW courses are designed to provide students with opportunities to understand the scientific process, engineering problem-solving, and the application of technology; understand how technological systems work with other systems; use mathematics knowledge and skills in solving problems; communicate effectively through reading, writing, listening and speaking; and work effectively with others (Newberry et al., 2006).

Program Implementation: Once a teacher has been selected by the school to teach PLTW courses and is accepted by PLTW, he or she must complete Assessment and Readiness Training that has a focus in mathematics and Core Training. Teachers then attend two-week professional development Summer Training Institutes at their state's Affiliated Training Center for each course they will teach. These courses are taught by master teachers and affiliate university professors. This training focuses on how to engage students in projects and problems requiring rigorous mathematics and science knowledge and skills and how to assess students' mastery of materials in addition to basic course content. During the academic year, the teachers have access to the PLTW Virtual Academy where they can access streaming video lessons via the Internet. PLTW's research indicates that their teachers are relatively happy with the training that they receive, with 71.4 percent stating that they mostly or completely agreed that the training prepared them to teach their new course (Bottoms and Anthony, 2005; Ncube, 2006). PLTW also offers counselor conferences for its member schools.

PLTW aims its programs for the top 80 percent of students. Students enrolled in the PLTW program are required to be enrolled in a college preparatory math sequence as well. They are also required to take end-of-course examinations in all but the capstone course. Several affiliated universities offer college credit for adequate end-of-course examination scores and cumulative averages.

Research Findings: When PLTW compared its students to those enrolled in the HSTW schools with similar career/technical fields, PLTW students fared very well. They completed more science and math classes and scored higher on NAEP tests. PLTW has just begun to assess the success of its programs by hiring TrueOutcomes of Fairfax, Virginia, to complete a multi-year study to see how well PLTW is meeting its missions and goals. This study will include an annual analysis of enrollment trends, student satisfaction questionnaires, and a long-term study of college success by PLTW high school students. Initial results show that 80 percent of PLTW graduates plan to attend college or community college the year after graduation. Sixty-eight percent plan to enroll in an engineering or engineering technology program.

2) The Infinity Project

Program History and Overview: The Infinity Project continues the theme of engineering design and technology literacy into middle and high school through applications that teach students how engineers design the technology around them. The curriculum focuses on advanced topics in digital signal processors (DSPs), including the Internet, cell phones, digital video and movie special effects, and electronic music. The authors identify the goals of the project: "In today's digital world, we believe students should be exposed to fundamental elements of technology so they will become competent, functioning, well-rounded citizens of the information age. This program helps all students realize, through hands-on experiments and general coursework, that the math and science they have been learning is applicable to real-world problems and a wide variety of occupations" (Infinity Project, 2007) .

The Infinity Project was developed in 1999 by The Institute for Engineering Education at Southern Methodist University and Texas Instruments, working in partnership with the U.S. Department of Education, the National Science Foundation and others. In 2003, the Texas Instruments Foundation contributed a three-year, $1 million gift to increase the reach and impact of the program (Rey, 2007).

Program Design/Content: Course materials are available in a textbook called *Engineering Our Digital Future* (Orsak et al., 2004), published by Prentice Hall. The textbook contains over 350 possible projects that can be conducted in a hands-on laboratory. Two students typically work together with materials provided in the Infinity Technology Kit. The total one-time cost of the program is reported to be the same as three to four classroom computers.

Program Implementation: Teachers in the Infinity Project must meet four criteria. They must be certified in math, science, or technology. They must be comfortable working with computer programs and be motivated to participate. Their school must have a demonstrated commitment to the program as well. Teachers must then participate in a 35-hour Professional Development Institute taught by master teachers. Teachers are supported through the year via an electronic discussion board on the Infinity Project Web site.

The curriculum is used by 230 high schools and colleges in 34 states and has impacted over 7,100 students. Schools range from comprehensive public schools with both inner-city and suburban campuses to magnet private, and parochial schools. The number of schools increased to over 285 in the 2007–2008 academic years. The program is also expanding internationally with schools in Australia, Ireland, Israel, Lebanon, and Portugal. The course can be taught as a stand-alone class or used as supplementary materials to a math or science class. Participating students must have completed Algebra II and at least one lab science class (Rey, 2007).

Research Findings: In 2004, the Infinity Project prepared a study for the Texas Education Agency as a part of the Innovative Course Renewal. A qualitative assessment was completed by the firm Decision Analyst, Inc. (Arlington, Texas). Twenty-minute phone interviews with ten Infinity Instructors were conducted. Eighty-five students participated in a student questionnaire. Instructors reported that students obtained a deeper understanding of math and science and improved their performance in other math and science classes. Additionally, they reported that students had an increased willingness to take other math and science classes and an increased desire to pursue engineering and/or technology degrees in college. Of the student participants, 94 percent would recommend the course to a friend, 83 percent of the students were considering engineering as a career, and 95 percent learned a new math concept (Douglas, 2006).

3) The Vanderbilt Instruction in Biomedical Engineering for Secondary Science

Program History and Overview: The Vanderbilt Instruction in Biomedical Engineering for Secondary Science (VIBES, 2008) consists of learning modules to teach either a high school level engineering course, a physics course, or portions of an anatomy or physiology course. Begun in 1999, the project was funded through the National Science Foundation's Vanderbilt-Northwestern-Texas-Harvard/ MIT Engineering Research Center (VaNTH ERC), dedicated to research and enhancing bioengineering education with technology. Two of the initial modules were adapted from curriculum units (or learning modules) originally designed for undergraduates in biomedical engineering. Additional modules continue to be developed to address science and mathematics standards. More information can be found at (VaNTH Engineering Research Center, 2008).

Program Design/Content: Each curriculum unit is based on a STAR.Legacy Cycle (where STAR stands for Software Technology for Action and Reflection), which engages learners in a process that develops their ability to generate and communicate new knowledge (Bransford, Brown, and Cocking, 1999; Schwartz, Brophy et al., 1999). The learning cycle shown in Figure 2 begins with students *Generating Ideas* around a contextually based *Challenge*. Next they compare their initial thoughts to *Multiple Perspectives* provided by experts who focus on different aspects of the challenge but do not offer a direct solution. This primes students to learn through extended *Research and Revise* activities during which data and information are gathered to help the students address the challenge. As part of this investigation they complete *Test your Mettle* activities to receive feedback on their progress. Finally they

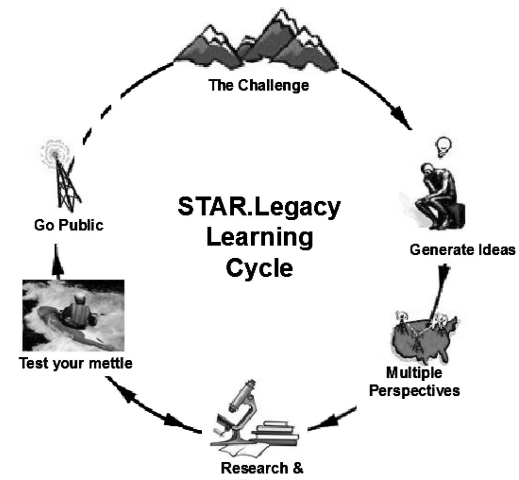

Figure 2. Learning cycle.

must synthesize what they have learned and share their solutions with their peers and others as part of *Going Public*.

VIBES has been recognized by the National Science Teachers Association (NSTA, 2008) as an exemplary program in meeting the National Science Education Standards (National Research Council, 1996). In addition to alignment with the NSES, each unit has been matched to the national math standards, AAAS Project 2061 standards (American Association for the Advancement of Science, 1993), ABET standards (ABET, August 1, 2007), and local and state level standards. VIBES is now being used in twenty-one states.

Program Implementation: Teachers participating in VIBES must be teaching a relevant course and have approval from their home school to participate in a VIBES workshop. Workshop training is an average of two days per unit and costs $250 per unit plus housing and/or food expenses. Teachers remain in contact with the VIBES developers via phone and e-mail in case they have questions or concerns about the materials as they teach them. Teachers are also encouraged to have their students take the pre- and post-tests used in the field testing so that their students can be statistically compared to the original field testers' results.

Included in the curriculum are biomedical physics units that span nearly the entire physics curriculum. Unit topics include the long jump (kinematics), balance (Newton's laws), iron cross (torque), skin elasticity (stress and strain), medical imaging (waves and nuclear physics), electrocardiograms (electric fields and basic circuits), LASIK (optics), and hemodynamics (fluid dynamics). A new unit called Volleyball was in field testing in 2007–2008 and will cover conservation of momentum and energy with a focus in biomechanics. Each unit also includes some aspects of biomedical engineering. An additional unit with a focus on anatomy and physiology features swimming and covers the topics of glycolysis and the Krebs Cycle. This swimming unit requires students to design and build a way of non-invasively measuring oxygen ventilation. Finally, a new unit on toothpaste composition debuts this year for chemistry classes and focuses on balancing chemical equations, acids, bases, and neutralization.

Research Findings: Each of the VIBES modules has been field-tested and has proven to be effective in both teaching the basic science concepts as well as creating learners who are more successful in transferring their knowledge to new related problems (near-transfer) (Klein and Geist, 2006; Klein and Sherwood, 2005). In each case, the module was tested using control classrooms and experimental classrooms with the same pre- and post-tests. Pre-tests consisted of 8–12 short questions to measure understanding of the underlying concepts of the curriculum unit. The post-test repeated the pre-test questions and then asked traditional test-like application questions. The post-test also included one to two near-transfer questions. Statistical results indicate medium to large effect sizes for the experimental groups over the control groups. These modules have also been shown to be effective in urban, suburban, and rural classroom settings (Klein and Geist, 2006).

C. Summary and Next Steps

These examples represent some of the multiple curricular programs designed to introduce engineering content and abilities into U.S. P-12 classrooms. Projects involving engineering curricula, outreach, and professional development have published their methods; however, assessment and evaluation results that examine important research questions about teacher implementation and student learning have not often appeared in peer-reviewed journals. One of the underlying conjectures is that engineering education enriches teaching and learning for all learners' in P-12 environments and impacts outcomes across multiple areas of STEM content and process. The general claim is that engineering contexts naturally engage learners to participate in an active learning process and that learners achieve multiple learning objectives associated with managing ill-structured contexts like engineering design, troubleshooting and reverse engineering. As mentioned earlier, these contexts require abilities to comprehend complex situations, define problems within specific constraints (function, cost, build, safety etc.), define and evaluate alternatives and justify decision making with mathematical analysis, plus construct physical and conceptual prototypes to evaluate a design. However, very little research has been done to describe how particular engineering education experiences differ from regular science and mathematics instruction as well as how learning is assessed and/or how programs are evaluated. We cannot state with certainty that engineering contexts provide the conditions of applicability that lead to advanced abilities for applying STEM knowledge to novel situations, or that if they do, what are the necessary conditions and design features that lead to such outcomes. We also have yet to learn what prerequisite knowledge is necessary for learners to be successful in their pursuit of a STEM profession? Finally, we also need to know whether there are other models of instruction that can achieve similar results.

One major challenge in conducting research on the impact of engineering education programs and curricula involves assessment. Assessments of learning often only focus on retrieving factual knowledge or applying procedures. Traditional instructional methods can successfully develop these forms of knowledge and standardized tests are effective and reliable at measuring such knowledge. However, no research has been done to illustrate that such assessment measures are sensitive indicators of valued learning outcomes associated with successfully transforming ideas into innovations. Alternative forms of assessment are needed so that students can demonstrate their ability to generate new knowledge from what they know, seek new knowledge when they do not know, and identify multiple perspectives on a problem, along with generating and evaluating alternatives. For example, can students generate external representations to make sense of a complex problem, can they creatively generate a number of viable ideas and explain the pros and cons of each, or can they generate questions to identify needed information? Or given a failing system, can they systematically evaluate potential causes and generate appropriate plans for how to approach the problem? Assessing these skills requires new instruments beyond typical standardized test items and tasks. New assessment methods are also needed to provide formative feedback to learners and their teachers as an integral part of the teaching and learning process, as well as to provide reliable summative data illustrating students' achievement over time.

With regard to issues of efficacy and impact, P-12 engineering education programs need to conduct research on the extent to which they are reaching all students with respect to acquiring content and skills for problem solving, and in developing a sense of self as a learner and as a potential STEM professional. Are these programs truly developing new and diverse talent interested in pursuing engineering? Or are these programs simply capturing the hearts and minds of students already interested in pursuing STEM learning tied to other influencing factors (role models, parents, enrichment programs, hobbies)? More needs to be understood about how such programs provide for the inclusion of all students with participation in genuine engineering experiences that create opportunities and support for development of an interest in STEM related careers.

It seems clear that engineering can provide an anchoring context for learning about the other STEM disciplines. But more research needs to be conducted to better articulate these connections. In addition, engineering can provide an anchoring context for other disciplines as well such as social studies, art and history. For example, civilizations were planned and built with intention and have failed for a number of reasons. Exploring questions about how other civilizations worked and what decisions they made can follow similar strategies of design, troubleshooting and reverse engineering seen in developing "systems, devices and processes." Also, the arts can study technical drawing used by architects and engineers as a planning and communication document. This can help learners see multiple forms of artistic expression which also serve important roles in constructing our world. These documents are important for supporting the development of a designer's ideas and communicating these ideas to others.

While there is a paucity of "hard evidence" to address many of the concerns expressed above, there is promising work in the pipeline. For example, Engineering is Elementary has some very interesting research in conference proceedings about the significant, positive impact of their curriculum on students' technological knowledge with a new instrument for measuring technology literacy (Lachapelle and Cunningham, 2007). The VIBES project has itemized assessments of specific areas of knowledge which are focused at various cognitive levels. A new institute researching P-6 engineering at Purdue University, called INSPIRE, is conducting research on children's learning of critical content related to engineering as well as the development of the pedagogical content knowledge necessary for teachers to effectively support the engineering education process. With the unique focus that engineering education has in the U.S., understanding how learners—both K-12 students and their teachers—come to comprehend engineering and technology systems is definitely a field of research that needs expansion and further development.

IV. Challenges for P-12 Engineering Education

Numerous efforts around the world are bringing engineering into P-12 classrooms. In addition to those already mentioned, Table 1 outlines a number of other projects that have published results in a variety of engineering/technology education outlets. The list in Table 1 is not exhaustive, and more comprehensive reviews of programs are available (Hunter, 2006; Jeffers, Safferman, and Safferman, 2004). As discussed earlier, these initiatives range from simple books (e.g., EiE) and discovery design experiences to comprehensive, expensive programs (e.g., PLTW). They utilize diverse approaches such as classroom activities (e.g., NYC program, Adventure Engineering, Partnerships Implementing Engineering Education) or after-school robotic competitions (e.g., FIRST). These programs are led by teachers, university faculty, parents, and employees of local industries. Many are a direct response to industry concerns regarding the decreasing pool of engineering students, and a few are geared toward systemic change (e.g., Robotic@CEEO, DTEACh) to prepare all learners for a rapidly changing world. The latter is the most difficult goal to accomplish and is the only way we can count on increasing the engineering literacy of every high school graduate. These projects show great potential for achieving multiple STEM learning outcomes, but as with all change there are some significant challenges if further progress is to be made. In this section we outline two such challenges. The first relates to teacher readiness and professional development with respect to engineering education content. This is a significant human capital issue that needs systematic attention in the form of research and development. The second challenge relates to the nature and focus of curricular content standards and high-stakes assessments. This is a significant educational policy issue that impacts what is perceived as having instructional value by parents, teachers, and administrators, and thus students.

A. Teacher Readiness and Professional Development

Teachers are typically uncomfortable teaching content they do not understand well and thus they will often shy away from such content for fear of being unable to answer students' questions. This may be a particularly significant problem for K-8 teachers who are attempting to deal with engineering content and the processes of design and inquiry accompanying the learning of such content. For example, when a teacher approaches teaching engineering design and what engineers do, the "answer is in the book" system breaks down. She has no list of correct answers (i.e., a design solution) because ill-structured and open-ended problems are designed to have multiple "correct" answers. Teachers must become comfortable and proficient with the engineering process and learn to quickly recognize where learners are in the process. More important to student learning is a teacher's willingness to go beyond simply evaluating whether a product meets a level of "correctness". The appropriateness of a student's answer is linked to how their final design meets its function, the process they used to research their design and how well they can justify their decisions. Therefore, the teacher must learn a level of engineering *analysis* to determine the quality of a student's solution and the reasoning the child uses to validate his or her design, the explanation for how something works, or why something is not working. Many teachers lack the content knowledge and experience to make such an evaluation.

Preparing teachers to blend engineering education into the curriculum requires identifying and understanding better the unique interaction of pedagogical knowledge, domain knowledge, and the combination of the two, often referred to as pedagogical content knowledge (Shulman, 1986; vanDriel, Verloop, and de Vos, 1998), as it applies to engineering content and skills. Teachers often have experience with advanced methods for engaging their learners in classroom activities that enhance learning and maintain manageable classroom behaviors. Their training helps them establish an encouraging and supportive learning environment that supports collaboration and peer learning. However, many teachers do not have experience with engineering or science contexts nor do they have the teaching experience to anticipate the kinds of difficulties learners might demonstrate. Further they have no background to know how to converse with their students about who designs these technologies and how they do it. Therefore, this combination of insufficient domain knowledge and how to effectively manage its learning can become a very strong barrier for elementary teachers to contribute

Program	Grades	Project Links and/or Publishers
Adventure Engineering	6-12	control.mines.edu/ae/
ASEE	K-12	K12engineering.org
Center for Technology Education	K-16	www.hofstra.edu/Academics/SOEAHS/TEC/
Center for Mathematics, Science, Technology, and Pre-engineering	3-5	mst-center.intrasun.tcnj.edu/index.htm
Children Designing and Engineering	K-6	www.childrendesigning.org/home.html
DTEACh	K-6	www.engr.utexas.edu/dteach/
Engineering by Design	K-5	www.epcnh.org/Engineering By Design.htm
Engineering is Elementary	3-5	www.mos.org/eie/
Engineering our Future NJ	K-12	www.ciese.org/eofnj/index.html
FIRST robotics	8-12	www.usfirst.org/
Infinity Project	6-12	www.infinity-project.org
INSPIRE – research and teacher professional development	P-5	engineering.purdue.edu/INSPIRE/
International Technology Education Association - Engineering by Design	5-6	www.iteaconnect.org/
MWM - Materials World Modules	6-12	www.materialsworldmodules.org/
NASA - for Educators	K-12	www.nasa.gov/audience/foreducators/
Partnerships Implementing Engineering Education (PIEE – WPI)	3-5	www.wpi.edu/Academics/PIEE/Publications/
PreK – 12 Engineering	K-12	www.prek-12engineering.org/
Primary Engineer	P-11	www.primaryengineer.com/
Principles of Technology	9-12	CORD communications www.cordcommunications.com
Project Based Inquiry Science (developed by Researchers of Learning By Design instructional approach)	6-12	It's about time publishing – www.its-about-time.com/
Robolab@CEEO	K-12	www.ceeo.tufts.edu/robolabatceeo/
TEACHEngineering	3-5	TEACHEngineering.org
TeachersDomain	3-5	www.teachersdomain.org/
Technnically Speaking - National Academy of Engineering	K-12	www.nae.edu/nae/techlithome.nsf/
Technology, Science and Mathematics Integration Activities	K-12	teched.vt.edu/TE/html/ResTSMintg.html
TE-MAT	3-5	www.te-mat.org/

Table 1. Sample of engineering education projects for P–12 learning.

to the development of technical talent (e.g., nature of science) (Akerson and Hanuscin, 2007). We are optimistic, however, that well designed and supportive ongoing professional development can encourage teachers to use and develop curriculum materials and modules that blend engineering, mathematics and science in the early years.

Another issue is that teachers often do not perceive engineering as an accessible career for the majority of their students (Cummings and Taebel, 1980). For example, engineering is often perceived as intellectually difficult and requiring a love of mathematics and science. Such stereotypes of engineering are common perceptions held by the general public and mirrored by teachers. For various reasons, teachers see only a small portion of their students meeting these criteria. As a consequence, they may interpret the inclusion of engineering education as an additional curriculum area serving only a few students. Therefore, they will focus their attention instead on teaching content they perceive as helping all their students achieve outcomes defined by national or state STEM content standards and assessed through state-mandated standardized tests. They therefore look to outreach and enrichment programs as the opportunity for the engineering bound students to learn the specific content for engineering and technology careers, but this is not enough.

Teachers could have the largest impact on developing students' abilities and interest in engineering and technology related careers as a profession. Outreach efforts for engineering education continue to target the readiness of teachers to adopt and adapt engineering curriculum for their classrooms. Some programs provide kits of materials, manuals and face-to-face professional development. One time workshops help orient teachers to the new instructional methods and content. Therefore, they are typically prepared to implement a specific sequence of activities in their classroom. However, they also require methods to learn how to blend these activities with existing instructional materials. Sustaining change requires building a cohort of teachers successfully implementing such changes with measurable results. This requires developing a community of teachers with a vested interest in sustaining change in their own practice and profession. They will require a sense for how the materials meet their instructional goals in the classroom and their professional goals as teachers. Therefore, with the support of community, universities, administration and parents, teachers can begin to take on the challenge to adapt. For example, the Engineering Our Future New Jersey (EOFNJ) project is a state-wide initiative to introduce pre-engineering curriculum as part of its core. The scale of this effort establishes a need and desire for teachers to become part of a community of practice dedicated to the goal of integrating engineering thinking into the curriculum.

Educating in-service teachers to become comfortable and competent with teaching engineering education takes time. The engineering programs we mentioned earlier (Project Lead the Way, VIBES, Infinity Project) require teachers to be certified in a STEM related discipline as part of their eligibility for the professional development. This prerequisite content knowledge is critical to efficiently training teachers to bring engineering back to their high school classrooms. Many assumptions can be made about what they already know and their understanding of inquiry. Many P-8 teachers' backgrounds do not include these prerequisites which suggests they may need more training time to learn the content and pedagogical content knowledge necessary to teach engineering. A one week training session may get them started, but they will need more sustained efforts to support their ongoing development. Several studies are underway with the INSPIRE institute to explore the thresholds for when teachers become competent at adopting and designing engineering curriculum in their classrooms.

While much work is needed in areas of teacher professional development and in-service education, pre-service teacher education also needs to become a focus of attention. Part of that focus should be on the inclusion of course experiences and course content that can support teaching in multidisciplinary domains like engineering. Such course experiences could provide the foundations for all elementary teachers to teach and adapt engineering curricula and instructional materials to the needs of their students. The goal should be to help teachers develop their abilities to notice how STEM disciplines work together at a conceptual level, and learn to notice where engineering occurs in the world. This could be an excellent complement to current science and mathematics methods courses, and include methods to notice the engineering involved in accomplishing the products and processes that shape our daily lives (Brophy and Mann, 2008). Such courses could be co-taught by faculty in schools, colleges, and departments representing engineering education, STEM education, and engineering and technology.

B. Redefining Standards and Assessments

The standards in mathematics, science and technology play a critical role in improving science, math and technology education, but at least two major questions remain: "do the standards provide adequate preparation for engineering and technology? And, do the standards generate enough interest in engineering and technology?" (Fadali and Robinson, 2000). In a review of current standards, Fadali and Roberson, argue that good implementation of the National Science and Technology Standards could adequately prepare learners for careers in engineering and technology. However, the standards do not focus enough on engineering contexts, engineering problem types (design, troubleshooting/reverse engineering and analysis) and methods to develop interest and awareness in what is engineering and what engineers do. In addition, a stronger focus on having students work with the "doing" of the engineering process can engage an important component of problem comprehension, identification and problem definition/framing. The process of synthesizing ideas and testing these ideas is critical to displaying innovative qualities for creating novel and appropriate solution. Without emphasizing this part of the engineering process in the standards teachers may be inclined to over structure this process to accelerate entry into activities focusing more on scientific inquiry.

One solution may be to institute separate engineering standards to complement the science, mathematics and technology standards. These standards would make engineering specific objectives more visible to teachers. Establishing such standards is an ongoing activity and states like Massachusetts have defined standards to meet such objectives. Other states may emulate these actions as policy and other institutional considerations related to implementation are addressed. Additional work needs to be done to determine the appropriateness and efficacy of advocating for separate engineering standards and how having such standards will impact institutional change across P-12 levels of the educational system.

As discussed at the end of section III, research and development on methods and models of assessment tied to meaningful content and achievement standards is much needed if systemic change is to occur in P-12 education. Realistically, change at the level of national and state standards and assessments will doubtless take considerable time. Therefore, it seems clear that outreach and curricular programs of the type discussed earlier in this paper must continue the challenge of making engineering a more visible goal of teaching and learning for the future. These programs must move beyond the stage of rhetoric about their value and generate credible research results that demonstrate students' achievement of important STEM learning objectives. Such research studies need to demonstrate how engineering contexts efficiently achieve learning with understanding of engineering concepts, how they contribute to the development of important processing skills and capacities, and finally that they have a significant influence on the numbers of students' interested in STEM careers, particularly careers in engineering.

C. Final Thoughts

Learning engineering requires identifying opportunities to conceive of something new, comprehending how something works, and researching and applying knowledge to construct something novel and appropriate for others. Young children can engage in these activities and appear to be quite motivated and adept at doing so. Also, middle school age children are in formative years when they start making choices to pursue technical disciplines. Those opting out of STEM-related careers are those who do not see themselves in such roles or dislike the STEM disciplines; therefore, they choose a pathway that may be difficult to redirect later in their academic careers. Teachers, curriculum, instruction methods and other academic experiences can have a huge influence on such decisions, especially for women and minorities. Therefore, not cultivating qualities of engineering problem solving and design, and not modeling inquiry processes in young learners does us all a great disservice as we prepare for the future.

Engineering education can focus on broadening the pipeline of talent capable of leading innovation in the U.S. On a larger front, engineering education also has the potential for taking the lead in developing an adaptive society for a rapidly changing world. Achieving these goals is linked to an engineering model of inquiry focused around design, troubleshooting and analysis as a precursor to becoming competent in a STEM related professions. Learning to effectively apply content knowledge will occur by linking this model with a scientific model of experimentation to explain how systems work (natural or artificial) and systematic methods to diagnose problems. In this paper we have identified many examples of how this can be done to achieve science, mathematics and technology learning objectives. Additional research is needed to better understand issues of curricular change and teacher and student development of engineering thinking and technology to demonstrate the importance of engineering education in P-12 (Lawless and Pellegrino, 2007). The research needs to address questions such as when, where, and how are children's abilities and perceptions of engineering and technology changing? What level of teacher preparation is necessary for teachers to adopt and adapt existing engineering curriculum materials? What level of preparation is necessary for teachers to develop their own materials? What resources could facilitate teachers' ability to design their own learning materials? What institutional factors need to be addressed to support the integration of engineering and technology curriculum into mainstream educational curricula? What specific content is appropriate for each age of learners? Also, what are appropriate assessments that measure engineering related outcomes? These are some of the many ongoing research and development questions that need to be considered as part of a vision for broadening engineering education and its impact in P-12 learning environments.

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