CHAPTER 4

ENGINEERING IN ELEMENTARY SCHOOLS

Cathy P. Lachapelle and Christine M. Cunningham

Museum of Science, Boston

ABSTRACT

Engineering has not historically been considered an "elementary" topic. However, with the recognition that engineering's applied orientation may be particularly motivating to young children, that engineering can contribute to the meaningful integration of science and mathematics, and that children begin to have preferences about future careers before middle school, the push to include engineering experiences and practices in the elementary school curriculum has increased internationally. In this chapter we discuss the reasons engineering should be included at the elementary school level. We briefly review the history of the inclusion of technology and engineering in Europe, the United States, Australia, and New Zealand. Finally, we draw on a number of policy and standards documents from the United States, and our own experience developing and testing an engineering curriculum for elementary school, to propose a set of core concepts and practices for elementary engineering, as well as design parameters for the implementation of engineering curricula.

INTRODUCTION

People today are immersed in the designed world. Engineering touches all aspects of our lives and has shown its ability and potential to change our quality of life dramatically, for better and for worse. Because of this, it is more important than ever to educate a global citizenry that both understands the designed world—how technologies are designed, manufactured, and disposed of; the resources expended on their use; and their effects on people and societies—and is empowered to influence as well as affect technological change.
The elementary school level is key to accomplishing these very broad goals: to open children's minds to the diversity and ubiquity of technology and engineering, and to encourage the attitudes and habits of mind that will lead to their becoming agents of change for, not just consumers of, their developing world. In this chapter, we lay out the reasons for introducing engineering to elementary school students; the global history of engineering as a subject of study at the primary level; our own experience with the design, implementation, and evaluation of an engineering curriculum for elementary school; core concepts and skills for children to learn; and design parameters for engineering curricula and activities created for use in elementary classrooms.

WHY INCLUDE ENGINEERING AT THE ELEMENTARY LEVEL?

Just as it is important to begin science instruction in the elementary grades by building on children's curiosity about the natural world, it is equally important to begin engineering instruction in elementary school by building on children's natural inclination to design, build, and take things apart to see how they work (American Association for the Advancement of Science [AAAS], 1993). Children benefit from early exposure to engineering and technology concepts. In the following subsections, we elaborate on reasons to introduce children to engineering in elementary school.

Children are naturally inclined to tinker and create.

As Petroski (2003) pointed out, children are fascinated with building and with taking things apart to see how they work; many children engineer informally all the time. By encouraging such explorations in elementary school, we can keep these interests alive. By describing their activities as "engineering" when they are engaged in the natural design process, we can help children develop positive associations with engineering and increase their desire to pursue such activities in the future (Petroski, 2003).

Engineering and technological literacy are necessary for the 21st century.

As our society increasingly depends on engineering and technology, citizens need to understand these fields in order to make sensible decisions about benefits, costs, and the advisability of putting new technologies to use (Katehi, Pearson, & Feder, 2009; Pearson & Young, 2002; Raizen, Sellwood, Todd, & Vickers, 1995). Research indicates that engineering education may be able to increase the technological literacy of elementary school children and their teachers (Lachapelle & Cunningham, 2007; Thompson & Lyons, 2008; Macalalag et al., 2008).

Engineering in school holds the promise of improving math and science achievement by making math, science, and engineering relevant to children.

Engaging children in hands-on, real-world engineering experiences can open opportunities for children to make connections to and to practice skills in math, science, and other content areas. Engineering projects can motivate children to learn math and science concepts
by illustrating relevant applications (Engstrom, 2001; Katehi et al., 2009; Pearson, 2004; Wicklein, 2006). A small number of research studies have found that engagement in engineering design gives young (elementary and middle school) students opportunities to explore scientific ideas in context, which appears to improve their understanding (Fortus et al., 2004; Kolodner et al., 2003; Lachapelle et al., 2011; Penner et al., 1997; Sadler et al., 2000; Wendell et al., 2010). There is also limited evidence that elementary students engaged in the application of mathematics to engineering problems may show increased mathematics achievement (Diaz & King, 2007). More research in this area is desperately needed (Katehi et al., 2009).

Children are capable of developing sophisticated skills and understanding in engineering at an early age.

The National Research Council’s reviews of research (2000, 2007) show that experience is particularly important to this development, as is the intertwining of types of interaction with the learning domain. Process and content learning must proceed hand-in-hand. Limiting science instruction to the memorization of facts can impede children’s learning, as over time they need to be developing a rich knowledge structure that approximates and approaches the knowledge structure of an expert, through engagement with complex ideas in discussion, reflection, investigation, experimentation, and other disciplinary practices (National Research Council [NRC], 2000, 2007).

Engineering fosters problem-solving skills and dispositions.

In the modern world, problem solving can be a complex process, including problem formulation, iteration, testing of alternative solutions, and evaluation of data to guide decisions (Benenson, 2001). Problem solving requires persistence and confidence, character traits that can and should be fostered beginning with the youngest students. Instead of teaching children to absorb information and do as they are told, as in the traditional curriculum, good engineering instruction puts children in charge of their own progress and gives them the chance to take ownership of their work and their learning process.

Engineering, as a form of project-based learning, encompasses hands-on activity, inquiry, teamwork, and other instructional practices that are the best means for developing children’s “twenty-first century skills”: critical thinking, communication, collaboration, and creativity (Partnership for 21st Century Skills [P21], 2009). These skills are vital for all citizens to master so that our increasingly complex societies will prosper in the modern world (Miaoulis, 2001).

Engineering has the potential to increase student engagement, agency, and responsibility for learning.

Several well-designed curricular projects have found not only positive effects on student achievement, but also higher motivation and engagement in engineering design tasks than found in a more traditional curriculum (Barron et al., 1998). When children engage in engineering design tasks, they are more likely to take ownership of their designs and responsibility for their learning (Silk, Schunn, & Cary, 2009).
Learning about engineering will increase children’s access to scientific and technical careers. The number of Americans pursuing engineering has not kept pace with the demand for engineers (Stine & Matthews, 2009). There is evidence that many of today’s scientists and engineers developed interest in their careers during elementary school (Maltese & Tai, 2010). Furthermore, girls and minorities in particular tend to show declining interest in math and science beginning in middle school (Catsambis, 1995). Early introduction to engineering can encourage many capable children, especially girls and minorities, to consider it as a career and enroll in the necessary science and math courses in middle and high school (Katehi et al., 2009; Wicklein, 2006). Children who engage early with these subjects in high-quality ways are more likely to maintain interest.

Engineering has the potential to transform instruction. To date, engineering at the elementary school level has been taught in a hands-on fashion—for the most part, in out-of-school settings. Well-designed engineering curricula meet the criteria for project-based learning: (1) each unit begins with a problem or question that drives the project; (2) children work on the project or question through guided inquiry; (3) children, teachers, and others work collaboratively; (4) the unit provides scaffolds to support children’s performance at a level higher than what they could accomplish alone; and (5) children create an artifact or set of artifacts as a result of their work (Krajcik & Blumenfeld, 2006). The best engineering curricula, by these criteria, are cross-disciplinary, engaging children in multiple related disciplines, including but not limited to science, technology, and mathematics. They immerse children in a learning environment that expects deep thinking, collaboration, and agency. They are based on a social constructivist theory of learning that posits that children learn best when engaged in the disciplinary practices and complex problems of the fields they are learning.

Inquiry science learning involves children in learning the content, skills, and practices of science through collaborative engagement in the investigation of important, relevant questions (Hmelo-Silver et al., 2007; Minner et al., 2010). While inquiry science methods are widely accepted as good pedagogy, they have not been widely implemented. This is due in part to teachers having so little experience with or training in inquiry science methodology, and in part to the ready availability of more didactic traditional instructional methods and materials, among other reasons. Engineering is largely a new subject for elementary school classrooms, and in the instances where it has been taught, it has always been implemented in a hands-on manner (though not always thoughtfully incorporating other important aspects of project-based learning, including guided inquiry). As teachers try to gain confidence with well-designed engineering activities and curricula and see clear impacts on students’ achievement and motivation, they are more likely to consider transforming their practice in other domains to a similar model.

HISTORY OF ELEMENTARY ENGINEERING AND DESIGN: AN INTERNATIONAL PERSPECTIVE

Elementary school children in a number of countries have engaged with curricula that introduce them to engineering or technological design. In most industrialized nations in the early 20th century, education included an introduction to manual arts, such as woodwork-
ing, sewing, cooking, and so forth, usually at the secondary school level. It was not until approximately 1970 that advocates in Europe, the United States, Australia, and New Zealand began calling for "technological literacy": for citizens to understand the basic concepts of technology, as well as its impacts on society (Cajas, 2001). By the 1990s, a number of industrialized nations had national efforts underway to transform the "industrial arts" into a more broadly defined "technology education" or "technology studies," expanding into the elementary grades and addressing technological concepts such as control, processes, and systems, as well as planning, producing, and evaluating technologies. As a secondary goal, these efforts aimed to engage minority and underrepresented students such as girls and aboriginal students (Cajas, 2001; Rasinen, 2003). As of this writing, at least four European countries—England, Cyprus, Denmark, and Estonia—specify technology education as a separate subject within the primary school curriculum; at least six others include technology education as a mandatory part of the primary science or environmental studies curriculum (Dow, 2006). In both New Zealand and Australia, technology education is included in the primary school curriculum (Jones & Compton, 2009; Middleton, 2009). China and India are working to expand technology education in primary schools (Ding, 2009; Natarajan & Chunawala, 2009), while some provinces in Canada (Hill, 2009) and a number of states in the United States have specified technology and, in some cases, engineering learning standards for elementary school children.

To understand the possibilities for engaging elementary school children in engineering, it is important to understand the history of such efforts internationally. In the following sections, we describe technology education (and, where considered as a separate movement, engineering education) in a small number of exemplar countries. For a more comprehensive review of global efforts in technology education, see Jones and de Vries (2009).

**England**

The United Kingdom was one of the first nations to specify the teaching of a design process in primary schools. England and Wales adopted a "design and technology" curriculum in the early 1990s for all grades. The new design and technology curriculum integrated industrial arts, business, and crafts (Harris & Wilson, 2003). Currently, England has its own design and technology curriculum, which is required for all students prior to secondary school and is optional in secondary school (Wales also now has its own separate curriculum). England's curriculum details what content should be taught and provides guidance as to how it should be taught. In England, design and technology is a core subject that can be taught as a stand-alone subject or integrated with the teaching of other subjects. Student performance is evaluated using national assessments (Benson, 2009; Rasinen, 2003).

Though the implementation of the design and technology curriculum suffered in early years from a lack of teacher preparation and curricular materials, subsequent revisions of national curriculum documents clarified the importance of identifying the user, purpose, and function of designed products and added evaluation guidance for teachers, resulting in improved instruction (Benson, 2009). Currently, there is a new push for engineering to be more prominently included in the national curriculum in England as part of a new national science,
technology, engineering, and mathematics (STEM) program; however, there is considerable confusion over how engineering relates to design and technology. Clark and Andrews (2010) contrast engineering with the existing curriculum, saying that engineering requires more critical thinking skills and application of science and mathematics than is included in design and technology, which is more closely related to craft. They note that currently only out-of-school clubs provide access to engineering, but there are fears that many children (especially girls) will be alienated by the elitist and male-centric nature of the competitions and design challenges featured in such clubs, and so become disinterested in engineering.

Australia

The situation in Australia has been most recently described in depth by Middleton (2009). In Australia, national guidelines set forth what and how content should be taught, but individual states determine the details of curriculum. For technology education, Australia’s national document on technology education, the Technology Key Learning Area, specifies that all students in primary school and junior high school are expected to learn technological skills, with the expectation of increasing the number of innovators and bolstering citizens’ abilities to evaluate technological challenges and policy decisions. Technology education in Australia is generally taught as a separate subject area, though it may be integrated with other disciplines, a practice that is particularly common at the primary school level. As in other countries, primary level implementation has suffered from a lack of professional development for teachers; however, where it is being implemented well, teachers are enthusiastic and student learning gains have been impressive. Currently, technology education is part of most primary teacher preparation programs.

Canada

In Canada, each province and territory has its own policy regarding technology education, reviewed in depth by Hill (2009). Most provinces and territories have technology as part of the curriculum for middle and secondary schools. Technology education is specified as part of the curriculum for elementary school in Ontario, the Northwest Territories, and New Brunswick. While both Ontario and the Northwest Territories have a science and technology curriculum for grades K–6, New Brunswick specifies only information technology (software application) for study in elementary school. Ontario currently uses a curriculum released in 2007 with more of a basis in the field of science, technology, and society (STS). The curriculum used by the Northwest Territories is based on Ontario’s earlier curriculum.

Both Ontario and the Northwest territories based their model of design on engineering—particularly on fields of engineering with connections to the physical sciences. A variety of models exist for how to conduct technology education. In early years of implementation many teachers in Ontario used curricula from England’s design and technology curriculum, but locally developed curricula are now more common. Because of a lack of resources, little has been invested in the professional development of primary school teachers, with the result that many Ontario teachers have implemented a design process that is too generic, structured, and context-free to be of interest or use to young children (Hill & Anning, 2001).
New Zealand

In New Zealand, the technology education curriculum for all pre-college students was designed and released from 1995 to 1999, and continues to be in effect. Its release was accompanied by significant efforts for professional development at all grade levels, later followed by pre-service teacher education. A 2001 national study of the technology education curriculum and its effectiveness in practice found that the curriculum was being nearly universally implemented through late secondary school. Primary school teachers expressed that they most needed help with finding and purchasing materials for children to work with, as well as guidance in implementing and assessing the technology education curriculum. Though they were concerned about having too many areas to cover across the curriculum, they were generally satisfied with the technology curriculum strands and confident in teaching them. The majority of teachers reported that they use problem solving, hands-on activities, and an approach tailored to the interests and abilities of children and classrooms (Jones, 2006; Jones & Compton, 2009).

In 2007 a new, reorganized curriculum based on constructivist and sociocultural learning theories and built with input from international researchers and local educators was released. The revised curriculum is organized into three strands: (1) nature of technology, (2) technological knowledge, and (3) technological practice (Jones & Compton, 2009). In this scheme, the technological practice strand most closely corresponds to engineering.

United States

In the United States, the push for technology education began in earnest with several efforts by national organizations to create guidelines or recommendations for what and how engineering and technology education should be taught at the pre-college level, including elementary school (ages 5–11). The Benchmarks for Science Literacy (BSL) (AAAS, 1993) include learning goals for understanding the nature of technology as well as the designed world. The National Science Education Standards (NSES) (NRC, 1996) describe how knowledge of technological design can help children understand science. The International Technology Educators Association (ITEA), now the International Technology and Engineering Educators Association (ITSE), with the support of the National Science Foundation and NASA, began work in 1994 to create the Standards for Technological Literacy (STL) (2000), which detail the most comprehensive standards of the three documents for the development of design skills as well as understanding of the concepts and processes of technology.

A couple more recent reports from the National Academy of Engineering examined in depth the possibilities for K–12 engineering education and standards. The report "Engineering in K–12 Education: Understanding the Status and Improving the Prospects" (EK12) by the Committee on K–12 Engineering Education under the auspices of the National Academy of Engineering and the National Research Council details recommendations for principles for implementing engineering education in K–12 settings (Kachet et al., 2009).

In 2010 a committee of the National Academy of Engineering (2010) reviewed the advisability of creating content standards for K–12 engineering education. It concluded that the field was not yet ready to develop engineering content standards for pre-college students.
Instead, it recommended that engineering educators and researchers focus on identifying a core set of engineering concepts and skills with learning progressions across age groups, and specify what good engineering curriculum and pedagogy should look like.

Engineering has appeared in the new Framework for K–12 Science Education (FSE) drafted by the National Research Council (NRC, 2012). The authors of this document called for engineering to assume a more prominent role than it had in previous science standards. The framework informed the development of national standards in science, called the Next Generation Science Standards (NGSS) (NGSS Lead States [NGSS], 2013). In addition to specifying core ideas in life, physical, and earth science fields, the standards also include core ideas, performance expectations, cross-cutting concepts, and practices related to engineering. As is the case with previous standards documents, the NGSS detail content and skills as learning objectives for students, but do not specify curriculum or represent official federal policy. K–12 educators in the United States are now working to integrate engineering into their science classes. This chapter is intended to help educators and curriculum developers identify core engineering concepts, skills, and practices that belong in elementary classes, as advocated by the 2010 NAE report.

LESSONS LEARNED FROM THE DESIGN AND IMPLEMENTATION OF “ENGINEERING IS ELEMENTARY”

Our own experience working with elementary school children and teachers has convinced us of the value of teaching young children to engineer. We began the Engineering is Elementary (EiE) curriculum development project in 2003. Since that time, we have developed, tested, revised, and released 20 engineering units. We estimate that, between sales and grant-funded implementation, more than four million students and 50,000 teachers have engaged with the materials to date.

EiE units are designed to supplement science instruction, not to replace it. Each unit targets one common elementary science topic (e.g., plants, ecosystems, rocks and minerals, solids and liquids) and one field of engineering (e.g., package, environmental, geotechnical, chemical engineering). Each unit prepares and guides children through a relevant design challenge, beginning with a storybook and including materials explorations and experiments. For more details about the design of the curriculum, see Cunningham and Hester (2007).

For example, in the Now You’re Cooking: Designing Solar Ovens unit, children first read the story “Lerato Cooks Up a Plan.” In this story, Lerato is a girl from Botswana who spends a lot of time collecting firewood. Her sister’s friend, who is studying to be an engineer, returns to her village from university for a visit and teaches Lerato about green engineering, energy, insulation, and the process of making a solar oven. Lerato experiments with the solar oven design until she is satisfied that she can use it for cooking and spend less time collecting firewood. After reading the story, children learn more about green engineering by completing a life-cycle assessment of paper, comparing re-use with recycling and waste, and examining their own use of paper in class. They learn more about heat energy and insulation when they conduct an experiment to see which materials (foam, paper, etc.) and forms (flat or shredded) work best to insulate a cup. They compare the impact of different materials
on the environment and discuss the implications of what they have learned for insulating a solar oven. Their final challenge is to improve a solar oven design by insulating it without creating too much waste.

All EiE units underwent extensive pilot and field testing before release to the public. In the first year of design, each unit was tested in 6-10 elementary classrooms with experienced EiE teachers. Developers and formative evaluators observed each lesson, making and testing ongoing improvements. At the same time, assessment questions were developed to align with the key engineering and science content of the unit, and then tested for validity and reliability. In the second year of development, each unit was tested by 12 teachers in each of five states. Feedback was collected from participating teachers, as well as pre- and post-assessments from children. For example, understanding how heat energy dissipates through different materials is key to the Designing Solar Ovens design challenge; summative evaluation showed that children participating in this unit in conjunction with their usual science unit on thermal energy and insulation performed better on the post-assessment of these science topics, as well as technology and engineering concepts, than a similar but not randomly assigned control group that participated only in their usual science unit. The effect size derived from our HLM model was moderate (Cohen's $d = 0.589$). Though causal inferences cannot be drawn from such evaluation data, we find the results promising, particularly when taken in conjunction with feedback from teachers implementing the unit. Results were consistent across units, both for student assessment outcomes and for teacher feedback, in an evaluation of 9 of the 20 units:

Results from teacher feedback forms indicate that teachers feel the EiE units provide opportunities for students to learn more about science and engineering. For all nine units, teachers reported that (1) their students practiced discussion, communication skills, and teamwork; (2) their students practiced problem solving and critical thinking skills; (3) students learned or had high-quality opportunities to learn or apply unit-specific science and engineering content; (4) students made connections with the real world, including recognizing engineering in everyday life; (5) students had fun, were motivated, and were engaged; (6) they valued students’ opportunities to engage in high-quality hands-on activities. (Lachapelle et al., 2011, p. 153)

Working in classrooms has provided our greatest source of conviction that elementary engineering is worth pursuing. The enthusiasm and effort children put into their design challenges and experiments, and their own expressions of what they are learning, have convinced us of the value of this endeavor.

**CORE ENGINEERING CONCEPTS AND SKILLS AT THE ELEMENTARY LEVEL**

All the major standards and benchmarks documents published in the United States address basic concepts about the designed world and technology as part of what elementary school children should know (AAAS, 1993; ITEA, 2000; NRC, 1996, 2012; NGSS,
The BSL and NSES focus primarily on the use of technology by scientists, while the STL and FSE address the designed world more generally. However, only the FSE and the most recent NGSS use the term *engineering* throughout to refer to the practices of technological design.

One ambiguity across most of these documents is the meaning of the word “technology.” The STL define technology as both the designed world and the processes for creating it. The newer FSE and NGSS define technology as “all types of human-made systems and processes,” and engineering as “any engagement in a systematic practice of design to achieve solutions to particular human problems” (NRC 2012, pp. 11–12; NGSS 2013, vol. 2, p. 103). From our own experience working with children and teachers, we find it more natural and less confusing to follow the FSE and NGSS and call the artifacts and products of the designed world “technology,” and to call the principled process for creating technology “engineering.”

There are other means for creating the designed world, including art. Design can include aesthetic considerations that are intertwined with, but can sometimes far outweigh, the practical side—for example a dance, as compared to a public library featuring classical architecture. While elementary school teachers often want to consider these subtleties, they need not be addressed with elementary school children.

Both teachers and children often think only of electrical or electronic items as technology (Lachapelle & Cunningham, 2007; Solomnidou & Tassios, 2007). Teachers, in particular, often think only of educational technology (computers and other technologies used to support children’s learning) or information technology as technology. It seems that “everyday” technologies, as well as their engineer creators, are invisible to children and adults alike as objects for critical consideration. Where do technologies come from? What is their impact on the world? How can they be improved? Possibly the most important reason to introduce engineering to elementary school children is to make the designed world—and its designers—visible to tomorrow’s citizens, so they can be informed decision makers and creators of the designed world of the future.

In the remainder of this section, we lay out the core engineering concepts and skills that we believe elementary school children should learn. All of these concepts and skills have been advocated, in one form or another, by the five U.S. standards and benchmarks documents or by researchers in technology education. Our intention here is to compile a list, informed by our own experience with elementary school teachers and students and by a growing consensus in the field, of those concepts and skills that are most relevant for the elementary level.

The designed world (and its relationship to the natural world)

*The designed world includes any modification of the natural environment created by humans to satisfy a human need or desire.* The designed world stands in contrast to the natural world. A technology is any object, process, or system that people create and use to solve a problem or fulfill a desire. People design, create, and use technologies for many reasons. Scientists, for example, use technologies to learn about the natural world. People use technolo-
Table 4.1. Core engineering concepts and skills at the elementary level.

The Designed World (and Its Relationship to the Natural World)
The designed world includes any modification of the natural environment created by humans to satisfy a human need or desire.

A system—whether natural or technological—is a collection of components that have their own independent properties, behaviors, and functions, and yet are interacting and interdependent.

Materials have properties that make them more or less suitable for a variety of applications.

Resources are needed to get things done; these can include energy, materials, tools and other technologies, people, time, information, skills, money, and so forth.

The designed world includes many different kinds of technologies.

Influences on and Effects of the Development of Technology
The form of technological development is influenced by the people developing it, the people wanting or needing it, and the environment (natural, economic, and cultural) in which it is developed.

Each technological product has a life cycle that begins with the natural materials and other resources used to create it, can include breakage and repair, and ends with waste, repurposing, or recycling.

Technologies have a developmental history that is intertwined with the histories of people and societies.

Engineering: Technological Design
People engineer: they use tools, materials, knowledge, mathematics, symbols, systems, and skills to solve problems by creating or improving technologies.

The engineering design process is a flexible but purposeful method that engineers use to support the development of technologies.

Engineering is an interdisciplinary field, with especially strong ties to science and mathematics.

Engineers often work collaboratively in teams with other engineers and scientists.

Goals are the intended outcomes of engineering a solution to a problem, while requirements are parameters defining limitations and expectations for the solution.

Engineers use models, including drawings, sketches, computer programs, and 3-D replicas, to brainstorm, plan, test, and communicate ideas and solutions.

Persistence, analysis, and the productive use of failure are essential aspects of design.
gies to satisfy survival needs such as food, shelter, and protection. Tools are technologies that help people get things done. The designed world touches all aspects of people's lives (AAAS, 1993; ITEA, 2000; NRC, 1996, 2012). In our own work, we have found that it is not difficult to support children in building a more principled and standards-congruent understanding of the nature of technology (Jocz & Lachapelle, 2012).

A system—whether natural or technological—is a collection of components that have their own independent properties, behaviors, and functions, and yet are interacting and interdependent. Most technologies are made up of pieces that fit together and work together as a system (AAAS, 1993; ITEA, 2000; NRC, 1996, 2012; NGSS, 2013). Systems thinking is an engineering “habit of mind” that is vital to children's development of technological literacy and can be cultivated beginning in elementary school (Katehi et al., 2009).

Materials have properties that make them more or less suitable for a variety of applications. Some materials are natural, others are designed. For both natural and designed materials and objects, their structures are related to their functions (NGSS, 2013). Materials can be processed to change their properties (AAAS, 1993; ITEA, 2000; NRC, 2012). In order to gain skill in engineering design, children need experience with and understanding of the properties of a variety of materials at a qualitative level, as well as practice manipulating materials (Brophy, Klein, Portsmore, & Rogers, 2008) and choosing materials for a technological design. For the youngest children, vocabulary development—both of material names and property descriptives—must be a primary focus. In our experience, young children also need practice identifying different materials that make up an object; manipulation of materials must also precede design work because children have so little experience working with different materials.

Resources are needed to get things done; these can include energy, materials, tools and other technologies, people, time, information, skills, money, and so forth. People use resources when they create and use technologies (AAAS, 1993; ITEA, 2000; NRC, 2012; NGSS, 2013); they can conserve resources by being careful in their use (by reducing how much they use, reusing or recycling materials, and turning off devices that use energy when they are not needed) (AAAS, 1993; ITEA, 2000; NRC, 2012). In our work with elementary teachers, we have found that though they tend not to think of resource use when looking at products, they can readily be guided to do so; children, too, can learn to think about resources, with practice.

The designed world includes many different kinds of technologies. Children should become familiar with a wide range of technologies and the engineering fields that develop them. Technologies may include (but are not limited to) medical and related biotechnologies, agricultural and environmental technologies, energy and power technologies, information and communication technologies, transportation technologies, manufacturing technologies, and construction technologies (AAAS, 1993; ITEA, 2000). We have chosen to expose children to different technologies by setting each unit in the context of the development of a specific technology by a particular engineering field. This use of detail brings the unit to life for children, helping them to make connections between their problem solving and its relevance in the real world. It also is a way to introduce children to technologies they might not have otherwise considered to be technologies (Jocz & Lachapelle, 2012).
Influences on and effects of development of technology

The form of technological development is influenced by the people developing it, the people wanting or needing it, and the environment (natural, economic, and cultural) in which it is developed. Technologies can have good effects, bad effects, and unintended consequences for people, societies, and the natural world (AAAS, 1993; ITEA, 2000; NRC, 1996, 2012; NGSS, 2013). Technologies can produce waste and/or pollution, which is a problem (AAAS, 1993; ITEA, 2000). People (both engineers and consumers) need to take an active interest in the responsible development and consumption of technologies to ensure that the impact of technologies is as beneficial as possible (AAAS, 1993; ITEA, 2000; NRC, 2012). People also need to use technologies carefully and dispose of them properly (NRC, 2012). In our experience, children are capable of understanding how the form of a technology they are designing should fit its desired purpose. They find it much easier to reason about how many people need to be able to fit in their gondola than about raw scores. In designing activities for children, we find that activities work best when they include a context for children to reason about—and that this in-turn affects children’s understanding of the relationships among technology, people, and environment.

Each technological product has a life cycle that begins with the natural materials and other resources used to create it, can include breakage and repair, and ends with waste, repurposing, or recycling. All aspects of a product’s life cycle can affect the environment. People can extend the life of a product and reduce its impact on the environment by repairing it or reusing it. Recycling is a means of turning old products into the raw materials for new products. (NRC, 2012). Recycling is also an activity in which many classrooms, schools, and families are already involved.

Technologies have a developmental history that is intertwined with the histories of people and societies. People improve and develop technologies. This changes how they live and influences people to innovate further (AAAS, 1993; ITEA, 2000; NRC, 1996, 2012; NGSS, 2013). Since ancient times, people have used tools and invented technologies, and they continue to improve them and invent new ones (AAAS, 1993; NRC, 2012; NGSS, 2013).

Engineering technological design

People engineer: they use tools, materials, knowledge, mathematics, symbol systems, and skills to solve problems by creating or improving technologies. To solve a technological problem, it helps to look first at how others have solved similar problems. There are many different ways to solve a problem and many different kinds of technological solutions that will work to solve a given problem (ITEA, 2000; NRC, 2012; NGSS, 2013). Because there is no perfect solution for all contexts, engineering solutions must take into consideration the specific human and environmental context in which they will be used, as well as possible impacts and trade-offs for use (AAAS, 1993; ITEA, 2000; NRC, 2012). Children should develop skills in selecting, using, and manipulating tools, materials, mathematics, symbol systems, and knowledge as they create technologies. They should also practice evaluating potential solutions and examining trade-offs (ITEA, 2000). We find that many children want to engineer; they want to “play” at being engineers. Through repetition, they become more familiar with the possibilities of engineering practice.
The engineering design process is a flexible but purposeful method that engineers use to support the development of technologies. The engineering design process generally includes: defining a problem (including criteria and constraints), brainstorming, planning and creating a solution, testing and evaluating a solution, redesigning in order to improve a solution, and communicating findings. Children should develop skills in using these practices (ITEA, 2000; Katehi et al., 2009; NRC, 2012; NGSS, 2013). For young children, this means supporting them in becoming more purposeful about design. There are many aspects children can work on, including but not limited to how to ask and answer good questions, how to make clear and communicative drawings and other representations, how to record findings and questions, and how to analyze a design and use findings to work on improvements. As in learning to write, there are always new ways to grow.

Engineering is an interdisciplinary field, with especially strong ties to science and mathematics. Engineering solutions often rely on science and math (ITEA, 2000; NRC, 2012; NGSS, 2013). Children should practice developing mathematical skills and applying science concepts and practices in an engineering context (Katehi et al., 2009; NGSS, 2013). EiE teachers consistently report that their children understand science concepts better after applying them in an engineering context (Lachapelle et al., 2011).

Engineers often work collaboratively in teams with other engineers and scientists. Children need to learn to work collaboratively (NRC, 2012; NGSS, 2013). The teachers we work with consistently emphasize developing collaboration skills as a valued benefit of engineering education.

Goals are the intended outcomes of engineering a solution to a problem, while requirements are parameters defining limitations and expectations for the solution. Requirements include criteria (what is needed in the design) and constraints (limits on the design, including resource limits). It is important to have a clear understanding of the goals and requirements for engineering a technological solution to a given problem, so that the problem can be solved effectively (ITEA, 2000; NRC, 2012; NGSS, 2013). Engineers generally design products for other people (clients) to use (NRC, 2012). Children should develop skills for evaluating goals and requirements, optimizing for a given context, and taking the perspective of the client into consideration (Brophy et al., 2008).

Engineers use models, including drawings, sketches, computer programs, and 3-D replicas, to brainstorm, plan, test, and communicate ideas and solutions. Models can be used to show all of the parts of a design and how they fit together (ITEA, 2000; NRC, 2012). They can be used to analyze and test possible solutions for problems with or limitations on performance (NGSS, 2013). Models represent some but not all aspects of the real world; they can be used to learn about the real world (AAAS, 1993). Learning to make effective drawings and models is not an easy task for children; they tend to focus more on appearance or structure than on behavior or function (Penner et al., 1997). We have found that it helps to continually remind children to label parts and materials in drawings, and to have children give their drawings to peers to construct or to the teacher to evaluate.

Persistence, analysis, and the productive use of failure are essential aspects of design. Even well-designed technologies sometimes fail (AAAS, 1993). Sometimes things do not work, and people do not know why. Troubleshooting is a purposeful way to find out. Experiments
can be used to test technologies, sometimes to failure, to generate more information about how and why they work. Asking questions, carrying out investigations, and making observations are also aids to problem solving, design, and troubleshooting (ITEA, 2000; NRC, 2012; NGSS, 2013). Reverse engineering is another method for figuring out how things work and why they are designed in a particular way (Brophy et al., 2008). Testing to failure can also be fun and is well worth building into an engineering unit. For example, children participating in the EiE unit Designing Walls use a “wrecking ball” to smash their walls until they break; they then examine the mortar for cracks, crumbling, and other signs of failure. This is often their favorite part of the unit: sitting as a class in a circle around the wrecking apparatus, waiting to see how each group’s wall performs.

**DESIGN PARAMETERS FOR WORKING WITH TEACHERS AND STUDENTS**

Engineering at the elementary school level will necessarily look different than engineering for older students. Concepts and skills must target what children are developmentally ready for; elementary school teachers have few preconceptions and little preparation for teaching engineering. Curriculum development and professional development need to support students and teachers in learning engineering practices, ways of seeing and thinking about the world, and habits of mind that prepare children to become capable, responsible, and informed decision makers and agents of change for the technological world of the future. Engineering curricula and activities for elementary school students and teachers should follow the principles set out below and summarized in Table 4.2.

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Standards Documents</th>
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<tr>
<td>Set ‘learning in diverse real-world contexts.</td>
<td>FSE, EK12</td>
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<tr>
<td>Engage students in concrete activities that involve the manipulation of materials and the use of tools.</td>
<td>FSE, NGSS</td>
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<tr>
<td>Encourage the purposeful application of science and mathematical skills and concepts.</td>
<td>EK12, NGSS</td>
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<td>Promote the flexible and iterative use of the engineering design process.</td>
<td>STL, EK12, NGSS</td>
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<td>Support children in developing confidence and strategies to solve ill-defined problems.</td>
<td>EK12</td>
</tr>
<tr>
<td>Have children collaborate with their peers and work in teams.</td>
<td>FSE, EK12, NGSS</td>
</tr>
<tr>
<td>Provide children with opportunities to communicate about their designs in a variety of ways, for a variety of purposes and audiences.</td>
<td>EK12, NGSS</td>
</tr>
<tr>
<td>Purposively reinforce the core concepts, and give children a chance to practice core skills.</td>
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<tr>
<td>Support teachers in learning engineering practices and successfully implementing engineering curricula and activities with their students.</td>
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Set learning in diverse real-world contexts. The engineering context needs to be meaningful, accessible, and real to children (Brophy et al., 2008; Lewis, 2005). When children can see that what they are learning is important in the real world and why, they are more likely to be motivated to engage in learning (Baker & Leary, 1995; Buxton, 2010; Klassen, 2007). This is especially true where the context is something that children care about, in particular a focus on the social and societal importance of what they are learning (Brotman & Moore, 2008). Children need to see that designs are generated for clients—for the people and contexts where they will be used—because these are fundamental features of engineering (Brophy et al., 2008; NRC, 2012). Without a real-world context, there is the risk that activities will be done merely for the sake of doing activities—making crafts—with no attention to the functional purpose of engineering and design. While craft activities have their own value, and engineering design activities share some valuable characteristics with crafting, children also need practice taking the perspectives of others, evaluating a product against requirements, and thinking about the societal and environmental impacts of technologies—features of engineering practice that come naturally with a meaningful and believable real-world context.

By setting different engineering activities in different engineering contexts—for example, by engaging children in a biology-related challenge, a structures design challenge, and a chemistry-related challenge—it is possible to expose children to diverse engineering fields. This has the potential to keep children’s interest high and to engage a variety of children with different personal interests. In particular, attention should be paid to developing engineering lessons and activities that attract underrepresented minorities (Katehi et al., 2009). An overreliance on engineering activities involving mostly structures and vehicles, which are of particular interest to boys, risks “turning off” girls, who are less likely to be interested in such things (Clark & Andrews, 2010; Miller, Blessing, & Schwartz, 2006).

Another advantage of setting engineering lessons in diverse contexts is that it affords integration across subject areas. Instead of simply doing “engineering,” children can engage in activities that help them practice their skills in reading, writing, mathematics, and science, and learn more about geography and other cultures as well. This not only allows teachers to flexibly use time designated for different subjects to work on engineering projects, but it also allows them to pursue multiple goals for their students with one integrated curriculum. EiE pursues this strategy by introducing each unit with a storybook that not only sets a specific context for children to think about and allows the teacher to use reading time for engineering, but also introduces key ideas in engineering and science, and introduces a new culture. The interdisciplinary nature of engineering also provides excellent opportunities for using science and mathematics in meaningful ways. When children see how and why science and mathematics are relevant, they are better able to understand how, why, and when they should be used. For example, students working on the EiE unit Designing Hand Pollinators conduct experiments comparing the effectiveness of different materials in picking up and dropping “pollen.” They collect data in small groups, and the teacher combines their data in a chart shared by the whole class. This leads to opportunities to talk about why different groups may obtain different results, what it means to conduct a “fair” test, and how to measure the “pollen” accurately.
Engage students in concrete activities that involve the manipulation of materials and the use of tools. Young children, in particular, have limited experience with materials and their properties, and the safe and proper use of tools. Experience with real materials and tools supports the generation of innovations and reasonable designs, and is a goal of both science and engineering education (NRC, 2012; NGSS, 2013). At the elementary level, tools commonly include rulers, scissors, tape, glue, and so on. Giving children the opportunity to explore a wide variety of natural and human-made materials allows them to make more informed design decisions and gain insights into the designed world around them.

By working with real materials and tools, children have the opportunity to acquire direct, physical feedback about the feasibility of their designs. They also can develop and test representations more easily. Manipulating representations mentally is demanding for novices, and mental models can be manipulated in ways that are impossible in the real world; by developing and testing physical prototypes, children have the opportunity to obtain some psychological distance from their ideas in order to work with them, to work with more complex ideas than they would otherwise, and to evaluate their ideas against reality (Roth, 2001).
Concrete testing of physical materials is most appropriate for elementary-age children, who have limited ability and skill to manipulate and make sense of more abstract representations. It is also helpful for children learning English and for those with less experience with and exposure to science. Engineering curricula and activities need to build in opportunities and methods for children to obtain real-time feedback (Brophy et al., 2008). Without the means to test their ideas, children are limited to imagining castles in the sky, instead of engaging in critical thinking as a vital aspect of engineering.

Young children also need to develop vocabulary for materials and their properties. Words such as shiny, transparent, stiff, sticky, and absorbent gain meaning when children handle and talk about a variety of materials and objects. Many EiE teachers, especially those of younger elementary students or English language learners, create flip charts with input from their whole class in order to use and discuss materials and properties. They tape material samples to the chart to help children connect the materials to vocabulary (see Figure 4.1).

Encourage the purposeful application of science and mathematical skills and concepts. A strong conceptual understanding of science and mathematics can support effective designing by children (Lewis, 2005; NGSS, 2013). At the same time, the integrated use of science and math in engineering has the potential to strengthen understanding in all three subjects (Brophy et al., 2008; Katehi et al., 2009; Lachapelle et al., 2011; Roth, 2001; Zubrowski, 2002).

Engineering is based on knowledge of the natural world—science knowledge and skills are foundational in all areas of engineering—just as science relies on the designed world to further scientific discovery. Children are well positioned to understand and make use of this relationship when (with the guidance of teachers) they can flexibly but explicitly pass back and forth between the worlds of science and engineering. There are challenges to introducing or reinforcing science concepts through engineering design: students may use trial-and-error methods to solve challenges instead of science; teachers may have insufficient science content knowledge to be able to guide students to think about the science concepts afforded by their designs; or a class simply may have insufficient time to work on both engineering and science concepts and skills (Wendell et al., this volume). However, we have shown that it is possible to do both, with EiE students showing significantly increased science and engineering scores as compared to control groups (Lachapelle et al., 2011).

Mathematics is the foundational tool for the analysis and application of data. Children need to collect data and analyze them if they are to evaluate and improve a design, whether qualitatively or quantitatively. Well-designed engineering activities provide abundant opportunities for children to practice mathematical skills in context (Barron et al., 1998). Both the motivation for learning mathematics and the power of mathematics become evident.

In the EiE unit Designing Plant Packages, children read about Fadil and Bashira, who make a flowering plant sick when they wrap it in a box as a wedding present for their elder sister. They learn from their Aunt Rashe, a package engineer, about how to design packages to meet the needs of both the product (a living plant) and the intended recipient. Children draw on the lessons from the story when they create a rubric to evaluate plant health, discuss materials available for designing their own plant packages, and create, test, and improve their own designs, using the rubric they created to evaluate the health of the plants they packaged.
**Promote the flexible and iterative use of the engineering design process.** The flexible but purposeful use of an engineering design process can aid creativity and help produce solutions that are well tailored to the requirements of a situation, both for children and in the workplace (ITEA, 2000; Lewis, 2005). The "steps" need not be followed in order (NGSS, 2013). The engineering design process is a sound means for the practice of 21st-century "learning and innovation" skills: critical thinking, collaboration, communication, and creativity (P21, 2009), and for engaging with science and engineering (NRC, 2012; NGSS, 2013). Unfortunately, there is a tendency (often driven by misunderstanding on the part of teachers and curriculum designers) to rigidly define and separate the steps of the process, especially the designing and making phases. This is not only a misrepresentation of engineering as practiced in the real world, but also a cause of frustration for children, who are learning both concepts and design skills at the same time and need to be able to switch between more abstract planning and reflecting and more concrete manipulating, making, and testing activities (Brophy et al., 2008; Hill & Anning, 2001).

As part of the process, children need time to brainstorm freely, without competition or analysis, so they can think creatively (Webster, Campbell, & Jane, 2006). Creativity is an important aspect of engineering design and should be promoted with all children (Katehi et al., 2009). Children who are given a chance to generate their own ideas are more likely to feel ownership of the product and be invested in the process of their work. Many EiE teachers have reported that their students are eager to spend free time working on their design projects or to do further research at home. Children decorate their projects and show pride in them; when we observe EiE in classrooms, children frequently ask us to take pictures of them holding their finished designs and to show them or send them the pictures.

In addition, children need opportunities to test their ideas to failure. They need to see the failure of a design (in whole or part) as an opportunity for analysis, learning, and redesign. Engineering can provide children with the chance to analyze and learn from failure, or to practice coping with failure (Diefes-Dux, this volume). Persistence is also valued in all aspects of life; engineering design activities can provide excellent opportunities to practice it and reap its rewards, so long as children are given the time and flexibility to reflect, learn, and apply.

And, finally, iteration, reflection, representation, and communication are vital aspects of the design process. Children are capable of solving a variety of accessible and age-appropriate problems with iterative cycles of build/test/evaluate, but they need sufficient time for multiple iterations (Brophy et al., 2008; Katehi et al., 2009). They need opportunities to reflect on and improve their designs, to try out and test their ideas in the real world, and to communicate their findings to others, because it is through revisiting their ideas that much of learning happens (Sawyer, 2006b). Teachers can purposefully support and encourage reflection, multiple modes of representation, and communication by moderating whole-class discussions, asking children to justify their ideas, giving feedback on children's engineering representations, and asking children to refer to and rely on their written engineering work. Some teachers we have worked with have their students keep all their work in engineering journals, carry the journals to all small-group and whole-class discussions, and refer to them for evidence when making responses. We encourage teachers to use engineering
journals because we find that children are encouraged to become invested in their work and show more progress over time. Wendell and colleagues (this volume) have also worked with teachers who believe that prompting students to reflect in, create multiple representations in, and refer to their work in engineering journals acts as scaffolding for organizing the unit as well as for children’s development in the practices of modeling in multiple modalities and engaging in scientific inquiry.

Support children in developing confidence and strategies to solve ill-defined problems. The essence of problem solving is to learn iteratively from failure and redefine the problem (Duncker, 1945 as cited in Lewis, 2005). An attitude of optimism that technological problems can be solved is a “habit of mind” essential to engineering and worth cultivating in children (Katehi et al., 2009). The development of general strategies for problem solving—especially of ill-defined problems—is a foundational skill for engineering (Brophy et al., 2008), as well as for other fields. When children solve ill-defined problems and learn a variety of strategies for doing so, opportunities arise for the development of all four 21st-century “learning and innovation” skills, but perhaps especially critical thinking (P21, 2009).

Have children collaborate with their peers and work in teams. Innovation is a social activity, and creativity is spurred by collaboration (NRC, 2012; Sawyer, 2006a). Collaboration is a valued skill in engineering and in other fields; the most pressing problems to be solved today almost always require a team of people with a diversity of viewpoints and expertise (Katehi et al., 2009; Sawyer, 2006a). Collaboration is also one of the 21st-century “learning and innovation” skills (P21, 2009) and is part of the engineering design performance expectations specified by the NGSS (2013). When children interact and work collaboratively, they are capable of producing higher-quality designs than if they work alone (Solomon & Hall, 1996). Collaborative learning environments also encourage student engagement, particularly with minority children and girls (Burke, 2007).

However, teachers report that they need to plan and attend to group dynamics in order for children to successfully engage in and learn from their work with peer groups (Wendell et al., this volume). Our observations of children using ElE and our work with teachers similarly show that student group work must not be taken for granted. Children need support in learning to work effectively with group members, particularly with managing competing ideas for how to proceed. Teachers can provide support and make success more likely by attending to the composition of groups, being willing to reconstitute groups that are not working, presenting models of effective group interactions, and having children reflect on their own contributions to the group (Wendell et al., this volume). We have also seen teachers assign roles or allow children to self-assign roles within the group, and establish routines for common group processes like brainstorming. Our rule of thumb is that there should be no more children in a group than their grade level, with less-experienced children in smaller groups regardless of grade; so, for example, second-grade students can effectively work in pairs and fourth-graders in groups of four.

Provide children with opportunities to communicate about their designs in a variety of ways, for a variety of purposes and audiences. Communication is another of the 21st-century “learning and innovation” skills (P21, 2009) and a “habit of mind” essential to engineering
(Katehi et al., 2009). In engineering, children need to communicate their ideas with peers in their teams. They need to represent their plans and communicate to the teacher what materials they will need. As a team, children explain their designs to the class or other audience.

Communication can take the form of speech, gesture, sketching, formal plans or symbols, posters, and other public presentations (NGSS, 2013). Young children who have not yet developed the scientific and technical vocabulary to talk about their work can rely on real, physical objects and gestures to support their learning of more formal language. Similarly, they can rely on sketches and drawings to scaffold the development of formal symbol systems and representational practices (Roth, 2001). Scale models and representational drawings are difficult for the youngest children to work with; this becomes less of a problem as children grow older (Hill & Anning, 2001). With adult guidance, children can learn to make 3-D representations on paper, taking into account spatial relationships and point of view (Solomon & Hall, 1996). Figure 4.2 shows examples of engineering drawings made by two second-grade children participating in the Designing Windmills EiE unit. The children are not yet drawing the details of how parts go together, but they are beginning to label important parts and materials. They are also able, at this early age, to produce rudimentary front and side views.

![Figure 4.2. Engineering drawings by grade 2 students (girl, left; boy, right).](image)

*Purposively reinforce the core concepts and give children a chance to practice core skills.* Every engineering activity, lesson, and curriculum needs to be organized around objectives for learning one or more core concepts and skills. Without careful attention to how an
activity and lesson introduce, reinforce, and encourage reflection on core concepts and skills, there is serious risk that engineering will devolve into doing activities for the sake of activity (Barron et al., 1998). Even with a curriculum that is designed to be focused on core concepts and skills, learning opportunities can be lost if teachers do not keep abreast of the activity: pointing out connections, helping children recognize their learning, and especially reserving adequate time at the completion of an activity for children to reflect on and communicate what they have learned. Teachers and their students have a tendency to get caught up in activity right up until the end of time allotted—and lose time available for reflection, which is key to learning (Sawyer, 2006b; Schauble et al., 1995).

Teachers of EiE, like others, often get caught up in construction activities and lose time for reflection. We use a number of strategies to help teachers avoid this problem. First, teachers are encouraged to post the “guiding question” for each lesson at the start of the activity, to discuss it, and to tell students that they will revisit it at the end of the activity. EiE provides reflection questions to be discussed or written on worksheets or in engineering journals. Teachers are encouraged to plan to end early to allow sufficient time for reflection. Students are given prompts to write down what they are learning from the activity as it progresses, which can be reviewed if necessary on a following day, so that reflection time can be taken later. In our experience, however, teachers who are best at allotting time for reflection and redesign are those with experience—those who have done one or more EiE units already.

Support teachers in learning engineering practices and successfully implementing engineering curricula and activities with their students. Examples and models of excellent engineering teaching at the elementary school level are not widely available, making it difficult for teachers to know how to implement such lessons and activities (Solomon & Hall, 1996). A certain amount of content knowledge is necessary in order for teachers to implement engineering activities that are reasonably true to engineering practice and to call out and reinforce key engineering concepts as they are relevant in children's activity. Teachers need to practice engineering for a client within a context (which can be simulated), so that they understand that engineers design to meet the requirements of others, not simply build to suit themselves, as so many context-free “engineering” activities seem to suggest (Diefes-Dux, this volume). Teachers must learn enough about engineering analysis to evaluate children's designs against criteria and constraints (Brophy et al., 2008). Teachers also need hands-on experiences in professional development where they can “try out” the lessons with peers, then work with their students, and finally return to reflect on the experience with their peers. While elementary teachers implementing engineering for the first time tend to focus on logistics, in subsequent years teachers are more prepared to focus on engineering content and skills, as well as cross-subject integration (Diefes-Dux, this volume).

Teacher guidebooks can also be a venue for improving practice, when they are designed not simply to deliver instruction directly to children, but to aid teachers in adapting their enactment of curriculum to their own students, class environment, and community context (Ball & Cohen, 1996). For example, teacher guidebooks can scaffold teachers’ learning by providing “novice” teachers with step-by-step instructions; notes for what to look for in terms of student learning, responses, and behavior; and in-depth information about engi-
neering content, while "advanced" teachers could benefit from tips about how to improve implementation, discussion of how to deepen children's understanding of engineering and technology concepts and skills over time, and discussion of the rationale for different pedagogical choices (see, e.g., Ball & Cohen, 1996; Davis & Krajcik, 2005). The provision of curricular materials that are educative for teachers, particularly focusing on teachers' development of pedagogical content knowledge, can improve implementation in classrooms (Schneider & Krajcik, 2002).

RECOMMENDATIONS

We recommend that elementary school engineering continue to focus on exposing both teachers and children to the core practices of engineering through design challenges that span diverse engineering fields and contexts. Engineering at the elementary level should not focus on communicating to children facts that they memorize and regurgitate. Rather, as just suggested, we believe that elementary engineering needs to concentrate on helping children develop skills, processes, understandings of overarching concepts, and engineering habits of mind. With supportive materials and professional development, teachers can implement engineering in a way that encourages children's efficacy and motivation and increases skills in teamwork, critical thinking, and problem solving. By engaging in hands-on challenges, children can practice flexible use of the design process, have experience with the manipulation of materials, collaborate with peers, communicate their designs, learn to see failure as a tool for continual improvement, and come to see themselves as capable and creative innovators, analysts, and problem solvers. Repeated exposure to a diverse range of engineering fields and contexts provides children an opportunity to see breadth and depth in the human-made world; to experience basic engineering concepts such as resources, constraints, materials, processes, and systems; to see the relevance of engineering to their own lives; and to apprehend a wide range of opportunities and career paths for their own futures.

REFERENCES


