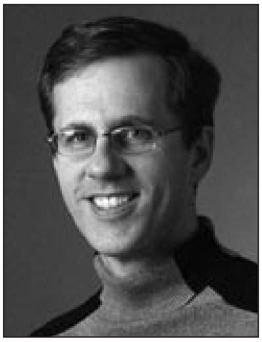
Researchers are investigating how and when children can learn engineering concepts and skills.

How Kids Learn Engineering
The Cognitive Science Perspective



Christian D. Schunn is an associate professor of psychology and research scientist at the Learning Research and Development Center, University of Pittsburgh.

Christian D. Schunn

The number of U.S. students who enter engineering programs in college is projected to drop, a trend that many believe will have a negative impact on the U.S. workforce (NAS et al., 2007; NAE and NRC, 2009). In addition, students who do pursue engineering degrees do not reflect the diversity of students in the United States, a pattern of enrollment that is likely to have a number of negative consequences, both for the successful practice of engineering and for the resolution of broader societal issues (NAE and NRC, 2009).

Although a relatively small number of children go on to become engineers, citizens in our technology-based society need to understand engineering issues, perhaps even be prepared to work collaboratively with engineers (NAE, 2002; NAE and NRC, 2009), which requires an understanding of what engineering is and what engineers do. The number of engineering exposure programs in formal (e.g., schools) and informal settings (e.g., museums, competitions, after-school programs, summer programs) is growing, but we have a long way to go before a majority of U.S. children have significant exposure to engineering (NAE and NRC, 2009). A dramatic increase in exposures to engineering could ultimately lead to an increase in the number and diversity of engineers.

Concerns about the lack of exposure to engineering for all children and ensuring a larger, more reliable supply of future engineers have been accompanied by the realization that we have not yet determined the best way to expose children to engineering skills and concepts. We are still investigating which aspects of engineering are developmentally appropriate for children of different ages and what kinds of experience are most effective. Because engineering has not generally been emphasized in pre-college settings, the body of literature on how children learn engineering is small. However, a few of the critical findings that have emerged are synthesized in this article.[1]

Defining Engineering for Instruction

A general principle for designing good educational environments is to begin with a specification of the end state, in this case, a definition of engineering (Wiggins and McTighe, 2005) and what we hope to accomplish through engineering education. On the most general level, I assume that engineering involves using analytical and empirical processes to design complex systems that meet stated objectives and take into account specific scientific and societal constraints.

There is some debate about whether the focus of pre-college instruction should be on preparing kids to learn engineering in college (e.g., focusing on math and science and stimulating interest in engineering) or on trying to develop engineering skills and thinking per se. Clearly skills in math and science are a requirement for filling the pipeline of future engineers.

Complex activities like engineering are usually divided into skills and concepts (Table 1). Although engineering overlaps and is symbiotic with science and math, some skills and concepts are much more specific to engineering. Thus providing all children with a broad exposure to engineering requires moving beyond basic skills in math and science. Stimulating interest in engineering as a career will require exposure to the practices of engineering.

Developmentally Appropriate Engineering Material for Kids

Many college engineering students struggle to meet the rigorous standards demanded in their college courses, especially when they are asked to apply science and math principles to complex design problems. Consequently, many universities continue to have serious retention problems among engineering majors. When engineering faculty look at things from this perspective, they may wonder if teaching engineering concepts and skills is developmentally appropriate for pre-college age children.

TABLE 1 Examples of Focal Engineering Skills and Concepts

Skills	Concepts
Design	Systems
Optimization	Subsystems
Modeling	Structure-behavior-function
Experimentation	Constraints
Teamwork	Trade-offs
	Requirements
	Side effects

A number of existence proofs have shown that teaching engineering is developmentally appropriate for kids, if it is done with the proper support. At the high school level, for example, thousands of kids engage in robotics competitions that require large teams of students to collaborate on meeting mechanical and electrical engineering design challenges.

I run a regional high school design competition in which the top teams from participating high school science classes bring in the results of eight-week-long innovative design projects (Reynolds et al., 2009). Teams are judged on how well they integrate science into innovative design solutions. Surprisingly, 9th graders (from biology classrooms) sometimes outperform much older children (from chemistry, physics, or environmental sciences classrooms), suggesting that innovative engineering design skills can be learned before the late teenage years (Figure 1).

A number of engineering-based curricula, even at the early elementary school level,[2] are being used to teach thousands of U.S. children from diverse backgrounds. The success of these curricula suggests that some aspects of engineering are generally accessible to a broad range of children at many different age levels.

However, working with pre-college-aged children is not the same as working with college-aged young adults. Clearly, there are differences in how quickly children

---

[1] For overviews of what we know about teaching complex skills and knowledge in general, see *How People Learn* (NRC, 1999) and *Taking Science to School* (NRC, 2007).

[2] See for example City Technology (*http://www.citytechnology.ccny.cuny.edu*) and Engineering is Elementary (*http://www.mos.org/eie*) and p. 11 in this issue.

FIGURE 1 Two winning high school engineering design teams.

reason, how well they integrate complex information, and how much relevant science and mathematics knowledge they have mastered.

Even though a college-level curriculum is not developmentally appropriate for younger kids, the concept of "developmentally appropriate" material has relatively little to do with age per se (i.e., a time-locked biological progression) and much to do with how far the child has moved along relevant developmental progressions, for which there is huge variability, depending largely on environmental conditions (NRC, 2007). Under the right conditions, young students can engage in relatively sophisticated engineering design activities long before they reach young adulthood.

Helping Kids Learn Engineering

Once we know kids can learn important aspects of engineering, the natural question becomes: What are useful environmental supports? The four principles described below have been found to be useful in supporting early engineering learners.

1. Engage children in solving significant design problems from the beginning.

An important part of learning complex skills and concepts is engaging in versions of the main end-state performance task, in this case engineering design. Skills and concepts are acquired through systematic practice, not through magic bullets (Anderson and Schunn, 2000). Unfortunately, in educational environments, complex activities are sometimes so oversimplified that critical aspects are completely lost, and thus key skills are not learned (Chinn and Malhotra, 2002).

It may seem logical to teach the foundational concepts for a design problem first (e.g., the background engineering science or background mathematics) and only then introduce the design task. In many ways, the traditional engineering curriculum follows this model, often leaving significant design challenges until the last year. However, the "basics-first" approach is a poor instructional strategy for a number of reasons.

First, students find design engaging, and thus it can be a motivator for learning the precursors or foundational skills and concepts that must be in place before higher level engineering skills can be learned. For example, design problems can create a powerful motivation for learning relevant science (Hmelo et al., 2000; Schauble et al., 1991), and presenting design problems after the science has been learned eliminates this motivator. In the United States, poor performance in basic math and science (in contrast to reading) is considered socially acceptable, and many students are not motivated to do well in those subjects. To address this problem, new motivators are urgently needed, and engineering design activities is one of them.

Second, design can be integrated closely with science instruction to the point that it becomes the vehicle through which relevant science is learned (Hmelo et al., 2000; Mehalik et al., 2008). For example, a number of researchers have created instructional models in which science-learning activities are naturally integrated into design cycles. Students begin a design challenge; the early design fails, creating a need for scientific knowledge; the knowledge is acquired through experimentation and reading; and the design task is resumed, with new scientific knowledge in hand (see Figure 2).

Third, if students are involved in design only at the end of a unit, they spend relatively little time actually engaged in engineering design and thus learn relatively little about it. In many settings, the tail end of a sequence of activities receives short shrift, that is, the last activities are either skipped entirely or are done very rapidly in whatever time happens to be left. As a rule of thumb, if an activity is important, it should not be the last one.

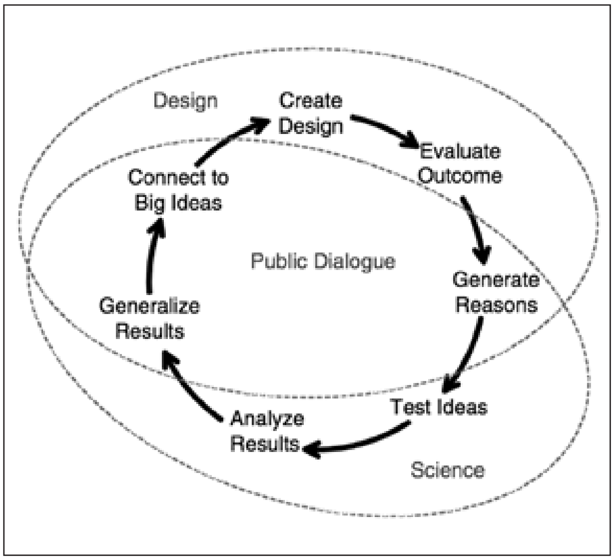


FIGURE 2 The design-science learning cycle. Source: Adapted from Apedoe et al., 2009.

Fourth, when science is learned as abstract formalisms with no connections or context, students often have trouble using that knowledge later to solve problems (NRC, 2007). Engineering design problems create a natural context for connecting to science concepts, just as engineering and science create a natural context for connecting to math concepts.

Finally, engaging in solving significant design problems appears to change students' career interests in engineering (Reynolds et al., 2009). The impact on children's career goals can be strongest in the early and middle school years, before they have been given an opportunity to make significant choices about elective courses and informal learning opportunities when they may choose to opt out of science and engineering-relevant activities.

Interest in engineering as a career is influenced not only by role models, but also by perceptions of the career itself. For example, introducing engineers to children as people who solve everyday problems has been correlated with interest in engineering careers, and experience using engineering design to solve everyday problems appears to reinforce that perception and increase interest in engineering careers (Reynolds et al., 2009).

2. Make visible models to support the design task.

Engineering design is often based on multi-layered abstract concepts, both of which can be barriers to learning. For example, design requires reasoning about trade-offs, which inherently means reasoning about many factors at once. We know that, compared to adults, children specifically have problems in dealing with multiple factors at once (Kuhn, 1991; Sweller, 1988).

Even engineering experts can have some cognitive limitations, that is, they can only consider so many variables at once. Most engineering problems are much too complicated to be addressed mentally. Therefore, engineers use models in various forms to offload the cognitive strain to a larger, partially externalized, computational system (Hutchins, 1995). In the early days of engineering, offloading was to paper and slide rules; today engineers make heavy use of analysis and design software.

Children can address the problem of cognitive overload in the same way. Just as external models help engineers solve design problems, they can also help children understand and define a problem by presenting requirements and constraints in a form that can be inspected externally (Penner, 2001; Resnick and Wilensky, 1998). However, although models are often transparent and directly meaningful to an expert, they can be confusing and laborious to translate for a novice (Berthold and Renkl, 2009; Hegarty et al, 2003). For each kind of model (e.g., data table, line graph, force diagram, or mathematical equation), children need time to understand what the model represents and how to interpret it.

More concrete models (e.g., diagrams, physical prototypes) can be subjects of discussion for groups of children, giving them an opportunity to build on each other's ideas (Roth, 2001). But mathematical models can also be helpful because they help children focus attention on critical information, stripping away irrelevant or superficial details. Although younger students clearly have much weaker mathematical skills than college students, even third graders can learn to use mathematical relationships to support design thinking (Lehrer et al., 2000).

3. Iterative design and redesign are better than single design cycles.

Actual engineering design is a complex, iterative process by which a design slowly moves toward better, more effective solutions. For students, this iterative process not only improves the solution, but also provides important learning opportunities for developing a better understanding of engineering concepts and skills. When students actually experience more than one design cycle for a given problem, they begin to appreciate that design is an iterative process.

Unfortunately, students are often only given time for one design cycle. As a result, the design is sometimes very poor, although the outcome might be improved with heavy-handed hints from the teacher. In either case, the child is left wondering how engineers manage to solve multifaceted problems.

Multiple design cycles enable children to develop a more complex, more complete understanding of relevant engineering concepts. Early in a design task, students tend to focus on superficial aspects of models, often misunderstanding the functional aspects of the design and making poor conceptual connections between models and engineering design. For example, children may create a prototype of an elbow that is the color of a human elbow but is otherwise dissimilar to the elbow joint and thus not a useful artificial limb. The initial model tends to become more functional and complex through design iterations and evaluation cycles (Penner et al., 1997), which not only lead to better designs but also to a richer understanding of the functional role of models in design. With each iteration, students can take into consideration more of the functional requirements of the design and more tradeoffs (Sadler et al., 2000).

Designing a model from scratch, however, tends to take so long that children often run out of time before they get to critical iterations (Hmelo et al., 2000). When time is short, a redesign task may be an effective way to "create" time for additional design cycles.

4. Provide sufficient time for exposure to engineering material.

Sometimes, engineering material is inserted into a curriculum, but only for a very short time, five hours or less, perhaps (e.g., a single museum visit, a single weekend workshop, or a few classroom periods at the end of a unit). These short-duration exposures are not long enough to involve significant, iterative design problems; therefore visible models are not likely to lead to meaningful learning about engineering. However, they might be effective as supplements to other engineering instruction.

Unfortunately, short-duration opportunities are the easiest for teachers to plan and implement, especially considering the typical teacher's investment in early engineering education. Typically teachers only spend a few hours or days in designing engineering activities for their students, a level of effort that can only support the design of a few hours of instruction.

In addition, for most teachers the K–12 curriculum is already packed, and pressure to cover more core content has increased with the advent of high-stakes testing. Thus engineering may be considered merely an enrichment activity, which means the teacher has very small windows of instructional opportunity.

I am not arguing here that enough instructional time should be provided in every experience to teach children the broad range of engineering skills, concepts, and dispositions for literate 21st century citizens or to prepare them for engineering college pathways. Either of those outcomes will certainly require a multiyear engineering curriculum. The point here is that children must have a minimal amount of time for each exposure to engineering content or design for it to have a real impact on student learning. It takes time for children to grasp big ideas about engineering.

Successful early engineering design experiences may last a total of only 20 to 30 hours (e.g., a week of summer camp, a month of Saturday museum workshops, a semester of Monday after-school sessions, or six weeks of everyday science class). Within that time frame, however, children can decompose a design task into subsystems, iterate on each subsystem, acquire relevant science concepts along the way, and come to understand a critical engineering concept or two.

Conclusion

Much remains to be learned about which aspects of engineering concepts, skills, and dispositions are difficult for children to master and the best ways to help them overcome those difficulties (NAE and NRC, 2009). However, the principles described above can provide some guidance for introducing children to engineering.

References

Anderson, J.R., and C.D. Schunn. 2000. Implications of the Act-R Learning Theory: No Magic Bullets. Pp. 1–33 in Advances in Instructional Psychology, Vol. 5, edited by R. Glaser. Mahwah, N.J.: Lawrence Erlbaum Associates.

Apedoe, X., B. Reynolds, M.R. Ellefson, and C.D. Schunn. 2009. Bringing engineering design into high school science classrooms: the heating/cooling unit. Journal of Science Education and Technology 17(5): 454–465.

Berthold, K., and A. Renkl. 2009. Instructional aids to support a conceptual understanding of multiple representations. Journal of Educational Psychology 101(1): 70–78.

Chinn, C.A., and B.A. Malhotra. 2002. Epistemologically authentic inquiry in schools: a theoretical framework for evaluating inquiry tasks. Science Education 86(2): 175–218.

Hegarty, M., S. Kriz, and C. Cate. 2003. The roles of mental animations and external animations in understanding mechanical systems. Cognition and Instruction 21(4): 325–360.

Hmelo, C.E., D.L. Holton, and J.L. Kolodner. 2000. Designing to learn about complex systems. Journal of the Learning Sciences 9(3): 247–298.

Hutchins, E. 1995. Cognition in the Wild. Cambridge, Mass.: MIT Press.

Kuhn, D. 1991. The Skills of Argument. Cambridge, Mass.: Cambridge Press.

Lehrer, R., L. Schauble, S. Carpenter, and D.E. Penner. 2000. The Interrelated Development of Inscriptions and Conceptual Understanding. Pp. 325–360 in Symbolizing and Communicating in Mathematics Classrooms: Perspectives on Discourse, Tools, and Instructional Design, edited by P. Cobb. Mahwah, N.J.: Lawrence Erlbaum Associates.

Mehalik, M.M., Y. Doppelt, and C.D. Schunn. 2008. Middle-school science through design-based learning versus scripted inquiry: better overall science concept learning and equity gap reduction. Journal of Engineering Education 97(1): 71–85.

NAE (National Academy of Engineering). 2002. Technically Speaking. Washington, D.C.: The National Academies Press.

NAE and NRC (National Academy of Engineering and National Research Council). 2009. Engineering in K–12 Education: Understanding the Status and Improving the Prospects. Washington, D.C.: The National Academies Press.

NAS/NAE/IOM (National Academy of Sciences/National Academy of Engineering/Institute of Medicine). 2007. Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. Washington, D.C.: The National Academies Press.

NRC (National Research Council). 1999. How People Learn: Brain, Mind, Experience, and School. Washington, D.C.: National Academy Press.

NRC. 2007. Taking Science to School: Learning and Teaching Science in Grades K–8. Washington, D.C.: The National Academies Press.

Penner, D.E. 2001. Complexity, Emergence, and Synthetic Models in Science Education. Pp. 177–208 in Designing for Science: Implications from Everyday, Classroom, and Professional Settings, edited by K. Crowley, C.D. Schunn, and T. Okada. Mahwah, N.J.: Lawrence Erlbaum Associates.

Penner, D.E., N.D. Giles, R. Lehrer, and L. Schauble. 1997. Building functional models: designing an elbow. Journal of Research in Science Teaching 34(2): 125–143.

Resnick, M., and U. Wilensky. 1998. Diving into complexity: developing probabilistic decentralized thinking through role-playing activities. Journal of the Learning Sciences 7(2): 153–172.

Reynolds, B., M.M. Mehalik, M.R. Lovell, and C.D. Schunn. 2009. Increasing student awareness of and interest in engineering as a career option through design-based learning. International Journal of Engineering Education. Forthcoming.

Roth, W.-M. 2001. Learning science through technological design. Journal of Research in Science Teaching 38(7): 768–790.

Sadler, P.M., H.P. Coyle, and M. Schwartz. 2000. Engineering competitions in the middle school classroom: key elements in developing effective design challenges. Journal of the Learning Sciences 9(3): 299–327.

Schauble, L., L.E. Klopfer, and K. Raghavan. 1991. Students' transition from an engineering model to a science model of experimentation. Journal of Research in Science Teaching 28(9): 859–882.

Sweller, J. 1988. Cognitive load during problem solving: effects on learning. Cognitive Science 12: 257–285.

Wiggins, G.P., and J. McTighe. 2005. Understanding by Design, 2nd ed. Alexandria, Va.: Association for Supervision and Curriculum Development.