EARLY EDUCATION

Henry Petroski

Children's Engineering Convention

Williamsburg, Virginia

January 24, 2003

Children are born engineers. Everything they see, they want to change. They want to remake their world. They want to turn over, crawl, and walk. They want to make words out of sounds. They want to amplify and broadcast their voice. They want to rearrange their clothes. They want to hold their air, their water, their fire, and their earth. They want to swim and fly. They want their food, and they want to play with it too. They want to move dirt and pile sand. They want to build dams and make lakes. They want to launch ships of sticks. They want to stack blocks and cans and boxes. They want to build towers and bridges. They want to move cars and trucks over roads of their own design. They want to walk and ride on wheels. They want to draw and paint and write. They want to command armies and direct dolls. They want to make pictures out of pixels. They want to play games-computer games. They want to talk across distance and time. They want to control the universe. They want to make something of themselves.

Though children do engage in a naïve engineering of sorts, it can be the case that they do not hear the word engineer except in connection with railroad locomotives and do not know that their playful activity can be a lifelong profession. Grown-up engineering, which is as old as civilization, maintains the youth and vigor and imagination of a child. This is why, when presented to children on their own terms, the excitement of engineering is immediately apparent and fully comprehendible. There is no child too young to play and therefore to engage in engineering, albeit of a primitive kind. We have all done so as children ourselves. We have all devised, invented, and designed our own toys and games- and sometimes even imaginary friends to play with them with us. The idea of playfulness is embedded in engineering through the concepts of invention and design. This is not to say that engineering is frivolous, but rather to recognize that at its heart, the activity is one of giving the imagination its head, reining it in only to check impossible or dangerous dreams and to turn ideas into reality.

Although children experience the essence of engineering in their earliest activities, there is seldom any recognition that this is the case. Engineers themselves are understandably reluctant to equate their professional activity with mere child's play. After all, they studied long and hard to master their esoteric knowledge of atoms and molecules, stresses and strains, heat and power, currents and voltages, bits and bytes. They manipulate equations, not blocks. They use computers for serious modeling and calculation, not for fun and games. They design and build real towers and bridges that test the limits of reliability and safety, not the toy ones that totter and fall down with little consequence.

As important and serious as are the things that engineers learn in college and the things they do in practice, they are still not essential to comprehending the profession's fundamental activity, which is design. Design is rooted in imagination and choice-and play. Because this is so, the essential idea of engineering can be explained to children and can be understood by them.

There has been much said and written about the declining numbers and the disappointing lack of diversity among college students who are majoring in engineering. Among the factors to which this paucity is attributed are the lack of exposure of high school students to the very idea of engineering and to the fact that many do not take sufficient mathematics and science courses to be in a good position to gain entrance to engineering school, even if they do identify the profession as a possible career. These are both unfortunate occurrences, for the ideas of engineering should be integrated into the curricula not only of high schools but also of primary and middle schools. Indeed, our children are being done a disservice by not being exposed properly throughout their education to engineering activities identified as such. After all, even upon entering preschool and kindergarten, children have the prerequisites in their play for appreciating exactly what engineering is-design. Indeed, design is ubiquitous throughout their school day, even in their before-and after-school activities. It need only be pointed out to them that they are designing something, and therefore being engineers of sorts, in virtually everything that they do.

According to Nicholson Baker in his novel, *The Mezzanine,* "Shoes are the first adult machines we are given to master." As children, we learn to tie our shoes even before going to school. This is no mean accomplishment, as most of us may remember, and its execution is by no means as rigidly codified among classmates as the alphabet they are drilled in in school. There are different ways to tie a shoelace, as we readily learn when we help different children unknot theirs. This is a manifestation of the fact that the steps in tying a knot or bow can vary from family to family in ways that the order of the letters in the alphabet cannot. Most children learn from their parents how to tie a shoe, and in their teaching role the parents often have to relearn the process themselves from a different point of view. That there are different tying techniques is characteristic of the fact that tying a shoe is a design problem –and design problems seldom if ever have unique solutions. Each individual child may be taught to tie shoes in a prescribed way, but that is not to say that it is the only way or even the best way. The lessons that can come of such an observation are beneficial not only for introducing students to design but also for augmenting lessons in diversity.

The idea of tying a shoe, and the related problem of lacing one up, can be turned into playful educational activities that expose students to the idea of design and thereby to engineering. A recent article in the *New York Times*' "Science Times" described how Burkard Polster, a mathematician at Monash University, calculated that there are over 40,000 distinct ways to lace up a shoe with two rows of six eyelets each. In true academic mathematic fashion, Dr. Polster extended his research by viewing the laced shoe as a pulley system to determine which lacing pattern was most effective in performing its function. He also determined the lacing that could be effected with the shortest lace. The combinatorial mathematics used by Polster make the problem as he approached it unsuitable for school children, of course, but that is not to say that the practical problem itself cannot be used to advantage in the elementary-school classroom. How much fun could children have redesigning the lacings of their shoes into imaginative patterns and learning by dong that there is more than one way to solve a problem? Being told by the teacher that a mathematician calculated that there were exactly 43,200 different ways they could have solved the problem can only add to the wonder of the lesson.

Elementary-school students might also be asked if they could imagine how Dr. Polster got the idea of counting how many ways there are to lace a shoe. Telling them that he did so after learning that two physicists from Cambridge University calculated how many ways there were to knot a necktie provides another problem in design. Whether or not the children are in uniform-or whether the teacher is dressed casually or more formally than the students-the tie-knotting problem is not only one the children might take home to tackle with their fathers but also it expands the vocabulary of the professions to which the children are exposed. To their knowledge that mathematicians can have fun counting shoe lacing patterns, the students can add the mental note that physicists can have fun counting tie knottings. To this knowledge can be added the observation that if mathematicians and physicists have such fun counting things, imagine how much fun engineers have in designing things that can be counted.

(As an aside to teachers and others, here I should like to note that "Science Times," like many other current uses of the word "science," is in fact a misnomer. Science, strictly speaking, does not include engineering, which is an activity distinguished by its domination by design. Engineers designs things, like patterns of shoe lacings; scientists, including mathematicians, analyze things, like counting how many lacings can be designed. These are distinctly different activities, even though the object of their attentions can be common. The use of the term "science" to include "engineering" is a convenient shorthand of journalists and others, but it verbally subsumes engineering into an activity whose fundamental objectives are of another kind altogether. This use of "science" essentially keeps "engineering" out of the vocabulary of children, who consequently do not learn about all the possible ways there are to have fun with shoelaces, neckties, and so much more – including real towers, bridges, automobiles, airplanes, power plants, computers, and everything designed and made.)

Lunch or an after-school snack provides further opportunities for children to learn that design means that there is not just one way to do something. Consider the problem of designing a method for eating an Oreo or other cream-sandwich cookie with a glass of milk. Different children (and adults) will employ different techniques. Those with big enough mouths might just pop the whole thing in. Most will eat the cookie in steps, some taking a bite at a time, as if it were a real sandwich. Others will proceed by first twisting or prying off one side of the cookie to expose the cream. Some will eat the separated top right away; others will put it aside and attack the cream first. Even this allows for variations, with some licking it off and others scraping it off with their teeth, some using their top and others using their bottom teeth. After finishing the cream, those who put the top aside still have choices to make: whether to eat the top or bottom next. All along, the glass of milk on the table has allowed for further variations on the process, for the cookie may be dunked or not before each bite. Countess everyday activities, in school or out, provide ample opportunities to introduce young children to design and therefore to engineering.

Design pervades the lives of children and adults alike. There is virtually nothing that we do that is not touched by design. We design our own approaches to the everyday things of life, like lacing our shoes, knotting our ties, and eating our cookies. But we also design our own procedures for washing our hands, taking a shower, putting on our clothes. As I recall, there is an episode of *All in the Family* in which Archie Bunker's son-in-law, Mike, is watching Archie put on his shoes and socks. Mike goes into a conniption when Archie puts the sock and shoe completely on one foot first, tying a bow to complete the action, while the other foot remains bear. To Mike, if I am remembering correctly, the only right way to put on shoes and socks is first to put a sock on each foot and only then put the shoes on over them, and only in the same order as the socks. In an ironic development in his character, the politically liberal Mike shows himself to be intolerant of variations in how people do common little things their own way, unaccepting of the fact that there is more than one way to skin a cat or put on one's shoes.

There are times when we do proscribe how certain everyday things are done, even though there might be countless ways to vary the procedure. This is especially the case in more formal social situations, where doing things by individual design might detract from the formality or, in some instances, even prove to be repulsive to polite society. Thus, we have manners and social protocols. Arbitrary as they sometimes may seem, such things as table manners and restraint in creativity at the table obviate distractions that otherwise might make eating with others, especially strangers, a less than pleasant experience. Imagine what it would be like at a business lunch if the group of people around the table ate with the individuality that children eat cream-sandwich cookies. As many ways to eat a sandwich as their might be, there are also practical reasons beyond decorum for following a customary procedure. By keeping the sandwich intact and bringing it to the mouth in the conventional way, we demonstrate one of the sandwich's design features: The fingers are kept free of mustard and mayonnaise by the bread which in turn means that the outsides of the drink glasses remain relatively neat and clean throughout the meal and that after lunch the business associates can shake hands without feeling they are washing dishes.

We discover as children, sometimes with the guidance of an adult but often by our own devices, a lot of preferred ways to proceed with all sorts of social and recreational activities. There are many ways to design a ball game, and the plethora includes the supplemental use of bats, rackets, bases, baskets, goalposts, nets, and more. But when there are two or more participants in a ball or any other game, there must be agreement on which implements are allowed and which rules are to be followed. Otherwise what would transpire would hardly be a game as we know it. Imagine a player on a tennis court serving a football with a baseball bat across a volleyball net to an opponent with a lacrosse stick. As many ways as there might be to design a game using a ball, only an agreed-upon set of rules is likely to produce a recreational activity that is not chaotic. If the objective is to have a friendly, or even a fiercely competitive game, it must proceed according to rules of a rigid design. Even the game of solitaire is best played by sticking to the rules. Engineers must certainly stick to the rules of physics, chemistry, and the other sciences.

Putting together a jigsaw puzzle is an activity that can be done alone or in groups. Either way, it provides another fine example of how many ways there are to achieve a single objective, such as forming a single picture out of hundreds of pieces of color and shape. Theoretically, it is possible to solve the puzzle by starting with an arbitrarily chosen piece and then trying to fit each of the remaining pieces to it. Systematically trying each piece in each orientation on each side of the starter piece would lead eventually to a match, and the procedure could be followed to completion. I know of no one who works a jigsaw puzzle in this tedious and unimaginative way, because one of the implicit challenges is to finish the puzzle as efficiently as possible. Almost everyone looks for edge and corner pieces first, completing the periphery before tackling the more amorphous middle. If nothing else, this way there are fewer pieces to contend with. As many ways as there might be to complete a puzzle, the preferred way is the most efficient way.

So it is with engineering. There are many ways to build a water crossing, ranging from a set of stepping stones to a majestic bridge to a tunnel. What kind of bridge or tunnel might be best for a given crossing depends on many factors, including river bottom conditions, shipping requirements, and traffic capacity. The different ways in which a bridge alone could be designed and constructed are virtually countless, but since the added constraint of economy is usually imposed, only very few are viable. Experienced engineers will know which kind of bridge works best for what conditions, just as experienced game players will know effective strategies for winning and experienced puzzle solvers will know what pieces of the puzzle are best attacked first. Everyone benefits from experience, but we must often rely on the experience of others to get our start in a new endeavor. This is certainly true when students are looking ahead to career choices.

Children used to see possibilities for their lives in the familiar roles of cowboy, nurse, or teacher. Now they might more readily think in terms of astronaut, athlete, or rock star. Everyone sees a doctor now and then, which also provides exposure to a common career goal. Many students learn about other options through family and friends, who often serve as role models. A good number of students must rely on what they are exposed to in school, relying on the experience of teachers to set forth the broader possibilities of what might be studied in high school and college. Engineering may or may not be presented as a possibility. It often depends upon how the idea of design is perceived and presented by teachers and parents alike.

Older children, such as those in middle or high school are often introduced to design in the context of "science projects" that are really "engineering projects." Among the most common is the bridge-building contest, in which students are asked to make a model bridge out of balsa wood, popsicle sticks, spaghetti, or some such fragile material. Even though the "contest" is often associated with a science course, the students are seldom given any substantive guidance about how to visualize, let alone calculate the structural forces involved. Most necessarily proceed by imitation of bridges they have seen in pictures or across highways. Increasingly, student-friendly computer programs have become available, most notably the West Point Bridge Designer (see **http://bridgecontest.usma.edu**), in which students can design virtual bridges and test them on the screen. Seldom in the classroom, however, the contests presented as exercises in engineering as opposed to, say, applied physics.

Before the collapse of the World Trade Center twin towers, live on television and replayed over and over on videotapes, the most widely known failure of a large engineering structure was that of the Tacoma Narrows Bridge. This 1940 disaster was captured on the contemporary medium of film, but it was subsequently transferred to videodisk, videotape, streaming video, and other media as they become available. Regardless of the medium, the collapse of the bridge was shown to generations of high-school students, usually in their physics class as an example of resonant vibration caused by the wind. In fact, the collapse mechanism is much more complicated (see "Engineering," *American Scientist*, September-October 1991, pp. 398-401), and represents an example of wind-structure interaction. Such sophisticated distinctions are understandably absent from most high-school physics courses, but the opportunity to say a bit about the bridge as an artifact of engineering design need not be. Instead of focusing exclusively on the bridge's final dramatic writhing as an illustration of a physical principle, the presentation of some background on the design of the bridge as an engineering achievement, albeit flawed, might give students an introduction to a profession that they might find appealing for the opportunities that it presents to change the world for the better.

It is also a familiar middle- or high-school assignment for students to build small vehicles that are powered solely by the energy stored in a rubber band or a mousetrap spring. These too are really engineering design problems, but they are seldom presented as such. Rather, at best they are presented as applications of physics, and at worst as mere competitions to devise the machine that travels fastest or farthest. There is certainly nothing wrong with allowing the students to enjoy the race, but it is unfortunate indeed if the pedagogical opportunity is missed to introduce the joys of design and to inform students that they are engaging in engineering, something that they might spend their lives enjoying-if only they take enough math and science courses to satisfy admission requirements for engineering school.

Teachers of physics and other subjects cannot be faulted for not promoting engineering if they have not been exposed to it themselves. Engineering is not a subject taught in every teacher’s college, and it is not a required field of study even in most fullservice universities. It is certainly possible to get a bachelor of arts or science-and a teaching certificate-without appreciating that engineering is a profession every bit as noble, rewarding, and satisfying as medicine and law. The absence of even the playful rudiments of engineering in the curriculum is unfortunate, as I have learned from doctors and lawyers who have expressed a disappointment that they were not exposed more to engineering while in school themselves.

Comparing engineering design to making sand castles or lacing up shoes or eating sandwich cookies or designing toys is not to trivialize it but to humanize it. The conventional wisdom, among the general population, as well as, among many teachers of children, is that engineering is a cold, dehumanizing, and unsatisfying career. Those who hold such a view are not likely to have met or spoken with engineers who enjoy what they do. They are no longer children playing with blocks or building castles on the beach, of course, but many of them retain a certain childlike fascination with the elemental structure of the world and with what can be done with timber and concrete and steel-or with atoms and molecules and microbes. They know that what they have fun designing and building and overseeing is essential to the smooth working of civilization. We should all learn this as children.