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Making The Strange Familiar: Creativity and the Future of Engineering Education

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Introduction

Why does the perception persist that engineers are uncreative, or worse, do not need to tap into creativity when most engineering projects demand creative or innovative approaches in the design of equipment, systems, and facilities? With the complexity surrounding every engineering project mounting as natural resources dwindle, the world population increases, and the global infrastructure and economy grow ever more intertwined, the creativity and innovation necessary to address the big issues facing civilization— maintaining the infrastructure; providing food, water, shelter, and power to the population; and growing sustainably and safely—will only increase in importance. But what is creativity and how can you teach it to engineering students? This paper examines these questions to make the case that fostering creativity knowledge, skills, and attitudes is vital for the future of engineering and engineering education. In so doing, the authors survey how creativity and innovation are approached (or not) in the classroom and offer strategies to make creativity a part of every engineering curriculum and course.

What is Creativity?

The late Dr. E. Paul Torrance, a pioneering creativity researcher for over 60 years, is widely considered the "Father of Creativity." He made it his life's work to study the nature of creativity and how it can be taught to students of all ages. Among his numerous contributions was groundbreaking research in educational psychology that led to a benchmark method for quantifying creativity. His "Torrance Tests of Creative Thinking" effectively debunked the common assumption that IQ alone determined creativity. It also led to the now accepted belief that creative levels can be increased through practice (Childs 2003).

Torrance defined creativity as "the process of sensing problems or gaps in information, forming ideas of hypotheses, testing, and modifying these hypotheses, and communicating the results. This process may lead to any one of many kinds of products—verbal and nonverbal, concrete and abstract" (Torrance 1963). This definition subsumes such creative "products" as works of art, but through the intentional use of scientific terminology (e.g., "hypotheses"), Torrance intended a more inclusive definition that included "inventions, medical discoveries, books, [and] monographs" (Torrance 1977). Clearly Torrance looked for creativity in science and engineering just as he did in theater and English departments.

Several other educators have offered definitions for creativity as it applies to engineering. It has been described as "the awareness, observation, imagination, conceptualization, and rearrangement of existing elements to generate new ideas" (Farid et al. 1993). Goldsmith described it as "The production and disclosure of a new fact, law, relationship, device or product, process, or system based generally on available knowledge but not following directly, easily, simply, or even by usual logical processes from the guiding information at hand" (Santamarina and Akhoundi 1991). Pereira (1999) defined creativity as "the capacity to perform mental work that leads to an outcome both novel and applicable."

The creative thought, then, is something that leads to the *creative act* or the creation of something new—an idea, theory, or physical product. When approaching technical matters, the term "innovation" is often used instead of creativity to describe the process that leads to insight or progress in a field, with a technique, or with a physical product. While innovation connotes a sense of inventing a thing as opposed to an idea or a theory, it is essentially a synonym for the creative process. Perhaps technical people prefer to be "innovative" rather than "creative." Regardless of what you call it, both innovation and creativity should lead one to the same end: to the exciting world of inventing and creating new knowledge, processes, and artifacts that push forward our science, technology, and art.

The Creative Process

The notion of a lone genius thinking up something brilliant and changing the world is a myth that has fortunately been debunked (Bogen 1991; Richards 1998; Weisberg 1986). Most people who study creativity now accept the notion that creativity is not something that happens in a vacuum. The definitions presented above articulate the notion that creativity is a *process* rooted in the real world. Every process has components, and the essential stages in the creative process include:

- Sensing, testing, modifying, and communicating (Torrance 1963);
- Orientation, preparation, analysis, ideation, incubation, synthesis, and evaluation (Osborn 1953); and
- Problem definition, preparation, incubation, illumination, and verification (Farid et al. 1993).

The creative process must go through a series of four stages, beginning with 1) a notion or need (sensing, problem definition, and orientation); 2) an investigation of that notion or need (testing, preparation, incubation, analysis, and ideation); 3) an articulation of a new idea or solution (modifying, illumination, and synthesis); and 4) a validation process of that idea or solution resulting in an idea, theory, process, or physical product (communicating, verification, and evaluation). These four stages should be familiar to engineers, as they more or less mirror the design process itself, which never forget is (or should be) a creative endeavor (Santamarina 2002). For example, 1) the client approaches the engineer with a need; 2) the engineering firm investigates the project parameters and potential solutions, often through a design team or charette approach; 3) the engineering firm presents its plan to the client; and 4) after numerous iterations, the final design is formalized. Countless variations of this simplified process exist, but hopefully it is apparent that, at its base, the engineering process is compatible with a creative process.

Are Engineers Creative?

Engineers are not commonly perceived as creative professionals. A recent Harris Poll sponsored by the American Association of Engineering Societies and IEEE-USA found that "only 2 percent of the public associate the word 'invents' with engineering; [and] only 3 percent associate the word 'creative' with engineering" (Bellinger 1998; Wulf 1998). The discrepancy between doing and being perceived as doing creative work is readily apparent with civil engineering.

The creative side of design, especially regarding civil engineering, is commonly thought to lie with civil engineering's sister discipline—architecture. "Star" architects such as I.M. Pei, Frank Gehry, Ceasar Pelli, and Santiago Calatrava are commonly celebrated in the media and in the common imagination as creative visionaries. The name Frank Lloyd Wright evokes the very essence of creativity. Whereas architects are the ones who approach the aesthetic and "soft" side of design, civil engineers are thought to approach the "hard" and technical sides. But common as it may be—even among the ranks of civil engineers—this is a gross misconception.

In his article "How Creative Engineers Think," Tom Peters explores the creative problem solving of leading engineers such as Gustave Eiffel (Peters 1998). Based on archival data, Peters determined that many groundbreaking design concepts stem from simple, often sublime reformulations of current thinking and practice, and that these creative breakthroughs are often fed by study and observation outside of engineering paradigms.

What "normal" civil engineers do is inherently creative, as comparisons between the creative process and the design process demonstrate. The same can be said for chemical, electrical, industrial, mechanical, and systems engineers. Yet while "creativity is an essential component in engineering design," focused interviews with leading creative engineers has found that "engineering schools do not adequately prepare students for creative endeavors or for the realities of modern industry" (Richards 1998). While the first part of this statement may not trouble or concern the average engineer overmuch, the second part should.

Should Engineers Strive To Be Creative?

The insight and understanding that civil engineers possess could immeasurably enhance the effort to solve the crucial issues facing the 21^{st} century such as maintaining the infrastructure, providing clean water and food, and protecting the environment. Creative solutions to these big issues are essential to the health, viability, and continuation of civil society in the 21^{st} century. Yet far from leading the effort to build more efficiently, with less waste, and in a safer manner, civil engineers very often follow the age-old project model and provide valuable technical services without creative input or leadership. The market for civil engineering design and consulting services is not likely to diminish in the 21^{st} century; the only questions are what role civil engineers will play in determining the scope of their contributions and the market value for these services. The issue quickly becomes can civil engineers afford *not* to be creative?

The problem of creativity in civil engineering begins at the base. Civil engineering as a profession (and engineering in general) has not been *intentional* about educating students to become creative in their application of their technical and professional skills. Said another way, the value of creativity is not explicitly communicated to students as a priority of their education. Yet even in the most technical of positions, civil engineers must find novel and unique ways to approach and solve design challenges, whether this means placing piping in unique formations or finding a way to stabilize soil in a nontraditional manner.

Consider for a moment a massive public works project that has taxed the abilities of the civil engineering profession and the construction industry. The Central Artery/Tunnel in Boston, known as the Big Dig, has been called "the biggest, most complex, and most expensive highway engineering job in U.S. history" (Vizard 2001), as well as "the largest publics works project ever undertaken in the history of the United States" (Bushouse 2002). Rerouting over 200,000 vehicles a day without ceasing traffic, gaining and keeping public approval, and acquiring the necessary environmental permits have been just a few of the many challenges requiring significant communication, leadership, systems thinking, and creative problem solving from many project participants. Keeping existing roads operational has necessitated innovative management techniques and construction methods, including the use of global positioning technology, laser measuring tools, and the use of slurry walls, ground freezing, and chemical stabilization of soil (Angelo 2001).

Yet for all its success—and when completed, the project will help revitalize and change a historic, economically important downtown—The Big Dig has gone way over budget and suffered from oversight, unforeseen consequences, and contractor bankruptcy. While the Big Dig may be an extreme example—clearly it is at the edge of the project spectrum—it can still serve as a touchstone and as a warning for civil engineering and engineering as a whole. In the 21st century, 20th-century solutions and thinking are not going to get the job done. How is the global community going to rebuild Iraq? How is the U.S. going to build less vulnerable and more secure facilities? How can we continue to update the aging infrastructure in our nation's cities without interrupting the flow of commuters and commerce? And how can we solve the as-yet-unheard-of problems that will inevitably arise as the world grows smaller and opportunity costs loom larger?

The Business Case for Creativity

The world has grown interconnected and complex. In this new, interdependent era, local problems can quickly become regional or even international. Power disturbances cost the U.S. economy over $100 billion annually with loss of data and compromised safety just a few of the consequences (Doyle 2001; Lineweber and McNulty 2001). Global energy use, meanwhile, is increasing exponentially—faster even than population growth. The world population in 1940, at just over 2 billion, consumed 2.5 gigatons of oil equivalent of power (EPRI 1999). In 1999, a population of 6 billion consumed over 11 gigatons—an increase in power over population of almost 2 to 1. The U.S. Department of Energy (DOE) reports that over the next two decades "growth in U.S. energy consumption will increasingly outpace U.S. energy production" (NEPDG

2001). If this tend continues America will develop "increased dependency on foreign powers that do not always have America's interests at heart" (NEPDG 2001).

Traffic congestion costs the 75 largest urban areas almost $70 billion annually (TTI 2002). Since 1970, the number of registered vehicles in the United States has nearly doubled while road capacity has increased only 6 percent. If this trend continues, by 2020, our country will experience "trucks that can't make deliveries on time, people who can't get to or from work, air quality that continues to deteriorate as commerce suffers and our over-all geopolitical position weakens because we are forced to become ever more dependent on foreign oil" (Seabrook 2002). Meanwhile, the amount of arable land available worldwide is dwindling at a steady rate, as an estimated 3.7 billion acres of topsoil are eroded each year (ISR 2001). These concerns affect all Americans and arguably all citizens of the world—but who is going to address them and on what terms?

The recent outcome-based criteria developed by the Accreditation Board for Engineering and Technology (ABET) stipulate that graduates develop:

> e) An ability to identify, formulate, and solve engineering problems; and
> h) The broad education necessary to understand the impact of engineering solutions in a global and societal context (ABET 2003).

Nowhere in the eleven ABET outcomes criteria, however, is there reference to creativity or the need to teach creativity to students. What kind of engineering problems are future engineers going to solve? If they are to solve the critical issues surrounding the infrastructure, economic development, and the natural environment, then new and innovative solutions will be demanded:

> To meet the exigencies of our greatly changed world, we must rethink and reengineer infrastructure system life cycles to serve their original purposes under new conditions, such as globalization, deregulation, telecommunications intensity, and increased customer requirements (Heller 2001).

If students (and future engineers) are to understand the broad impact of engineering solutions in a global context—as called for by ABET—they will be forced to grapple with variables and contingencies that will continue to evolve. How will civil engineers of the future learn to approach and solve these problems? Creatively, of course.

You Can't Even Teach Creativity, Can You?

Without training in the fundamentals of creativity, it is little wonder that so few engineers are viewed as creative professionals and that only 3% of the population associate "creative" with engineering. As with leadership, it is a far too common a notion that creativity is an inherent gift that one either does or does not possess. Not only can creativity be taught, it *is* taught effectively at all levels of education, from kindergarten to graduate school. Some engineering professors make creativity an explicit component of their courses (Ghosh 1993; Masi 1989; Richards 1998). A select few programs such as Olin College and Worcester Polytechnic Institute even go to great lengths to cultivate creativity throughout their curricula (Sanoff 2003). On the whole, however, civil engineering programs are not intentional about developing creativity.

Most any process can be improved, and since creativity is essentially a process, it too can be studied, tracked, and improved. There are tests and metrics that can help measure and gauge creativity, but the experts agree that to develop creativity you must learn to flex and reflex your creativity muscles (Klein and Shragai 2001; Plucker and Runco 1998; Torrance 1977). This process is often enhanced though the use of creativity tools such as brainstorming and idea notebooks (Feldhusen and Treffinger 1986; Navin 1993). Brainstorming is a two-step process where ideas are first generated without constraint, and then critiqued using criteria such as practicality or applicability to the problem domain. Many variations exist, including using computer programs such as Ideafisher (Santamarina and Akhoundi 1991; www.ideafisher.com). But again, you must use it or lose it. If one does not consistently practice creativity techniques, like any machine or muscle, they will grow rusty and stiff. Yet like riding a bicycle, once you learn how to be creative, you will have a hard time not remembering—or taking advantage of—the basics.

Richards (1998) recommends a series of activities to incite creativity when faced with an engineering problem:

- Immerse yourself in a domain or problem;
- Be prolific—generate lots of ideas;
- Use tools for representations and thoughts (e.g., brainstorming, notebooks, and sketches);
- Play with ideas;
- Avoid premature closure;
- Don't be afraid to be different;
- Be open and receptive to new ideas;
- Do it—practice your craft;
- Maintain a product orientation;
- Relax—indulge your diversions;
- Reflect—review what you have done;
- Have fun!

This list can be viewed as steps in an on-going process, as individual milestones in creative development, or as inspiration for a professor or team leader.

There is no right way to approach creativity, but an atmosphere encouraging divergent thinking (what people in creativity studies call innovative thinking) and uncensored thought generation is conducive to deriving novel solutions. This period of free play, no matter how long or short, must eventually be constrained in order to derive tangible, practical solutions (Pereira 1999). However, if one concentrates on practicality at the outset, it is likely that ordinary, tried-and-true solutions will result. And in the world confronting the profession, the same-old will make engineers has-beens.

The Opportunity for Creativity: Making the Strange Familiar

Creativity helps you see the world in a new way. Creativity helps you consider multiple angles instead of just one, and it helps create bridges between different fields of knowledge and between innovation and the tried-and-true. Quite literally, creativity can make the strange familiar, and the familiar strange.

Choosing to embrace creativity is never a zero-sum commitment that will make technical concerns secondary. Rather, creativity can be a powerful tool to enhance technical efforts to solve engineering problems of all kinds. As one professor has stated: "As educators, we are responsible for stimulating creative thinking among our students . . . . Our ultimate goal is to require original creative work as part of every engineering course" (Richards 1998). Taking a creative look at engineering education does not mean ignoring or choosing to disregard the normal project parameters or technical constraints that must be imparted to the next generation of professionals. Instead, using creativity can mean generating excitement in students as they approach engineering problems in original ways (Raskin 2003).

Classroom Strategies for Creativity

There are many ways to design classroom assignments or teamwork activities to develop creativity. Torrance (1977) recommends several guidelines to promote creativity:

Before a Lesson

1. Confrontation with ambiguities and uncertainties
2. Heightened anticipation and expectation
3. Familiar made strange and strange made familiar
4. Looking at something from several different psychological, sociological, physical, or emotional points of view
5. Provocative questions to establish set for examining information in new ways
6. Predictions from limited information required
7. Tasks structured only enough to give clues and direction
8. Encouragement to take next step beyond what is known.

After a Lesson

1. Ambiguities and uncertainties played with
2. Constructive responses encouraged
3. Going beyond the obvious encouraged
4. Elaborating some element through drawings, dramatics, imaginative stories, etc.
5. Search for elegant (better) solutions
6. Experimentation and testing of ideas encouraged
7. Future projection encouraged
8. Improbabilities encouraged
9. Multiple hypotheses encouraged
10. Reorganization or reconceptualization of the information that is required.

In addition, Torrance encourages instructors to develop *constructive*—as opposed to *critical*—attitudes in themselves and in their classrooms. In a series of experiments "students who assumed a constructive rather than a critical attitude toward available information were able to produce a larger number of creative solutions as well as more original ones" (Torrance 1977). Torrance's guidelines, as well as the process guidelines presented earlier in the paper, should drive the planning of any (every?) classroom assignment, with the goal of imparting creative mindsets to students. Engineering students must learn to approach problems with an open mind, unconstrained—though certainly influenced—by textbook solutions. They must learn to see the familiar as strange, and the strange as familiar on a regular basis, and not rush to spit back a single "correct" solution.

If the next generation of engineers is going to tackle the challenges that will inevitably face them on the job and in the field, they must learn to accept multiplicity (*looking at something from several different points of view, improbabilities encouraged, multiple hypotheses encouraged*, etc.) as they address engineering problems in their courses and, eventually, in their practice. Inculcating just such a mindset is the foundational goal of the new, innovative engineering programs being offered at Olin College where students must have "the creativity to envision new solutions to the world's problems and the entrepreneurial skills to bring their visions into reality" (Sanoff 2003). But how does Olin College or any other program foster creativity in particular courses and throughout the curriculum?

Encouraging creativity can be as simple as allowing small groups of students to brainstorm solutions to a problem set, refine their idea lists, and present their solutions to the larger class. Teamwork and creativity go hand in hand. In fact, one of the tenants of creativity is collaboration and brainstorming. With practice, students and teams of students will learn to set their imaginations free during the creative act to generate multiple, original ideas and solutions. They will also learn to curtail those lists at an appropriate time as project parameters and constraints naturally come into play. Merely giving students the freedom to explore by setting aside time in the curriculum for guided brainstorming and other creative acts to occur can produce surprising results. But to develop creativity, many programs are going further. Consider these outstanding examples:

- In the University of Iowa graduate course "Introduction to Literature Review and Proposal Writing" young graduate students are taught brainstorming and critical reading skills "to help them begin generating research ideas" and to learn to criticize research—both theirs and others (Jessop 2002).
- Freshman mechanical engineering students at the University of Nevada-Reno work in teams to design and build LEGO machines and structures in classroom exercises that simulate the industrial design process. This team-based, hands-on approach not only encourages creativity and helps in recruitment of students, it also gives them "an overview of engineering practice and exposure to the environment that engineers generally work in" (Wang 2001).
- For advanced systems engineering students, the U.S. Naval Academy has used similar strategies to enhance creative problem solving abilities. In a two-course capstone sequence, student teams can choose to design remotely operated vehicles to compete in a

"combative version of basketball" called Systems Ball. For over a decade the course and the competition tie-in have been "an effective and fun way to guide multiple students teams through the design process while stimulating their creativity." Success is "evident by instructors' evaluations and by the ingenuity and creativeness demonstrated by the students that enter the Systems Ball competition" (Dwan et al. 2001).

Problem-Based Learning

Santamarina (2002) warns that "teaching creativity has limited impact if it is not immersed in problem solving exercises." He recommends assigning daily time in the classroom for creative thinking and the "simple, yet far reaching modification" of incorporating additional, open-ended questions to every assignment. These questions should challenge students to make connections and move beyond the technical aspects of a given problem. Examples could include defining alternative solutions, critiquing other students' solutions, or changing the project parameters for a third-world nation or even for lunar colonization.

Project-based learning (PBL) forces students to creatively grapple with real-world-style projects. PBL can force engineering students to make connections between courses and also "to seek out and solve problems at the boundaries of the engineering disciplines" (Ghosh 1993). Used regularly, PBL can also result in:

- Increased critical thinking
- Increased self direction
- Higher comprehension and better skill development
- Self-motivated attitudes
- Enhanced awareness of the benefits of teamwork
- A more active and enjoyable learning process (Johnson 1999).

Evaluations of courses designed around PBL at Purdue indicate that "students are very positively motivated by projects which put what they have learned in a course into as real a perspective as possible." In addition, many faculty members will be pleased to learn that "students spend more time on these projects than they do for exams and other work but do not complain" (Sener 1998).

Case studies are a particular form of PBL, and modeling classroom lessons and assignments around actual, real-world projects can be an effective bridge to industry. Case study problems are the perfect vehicles to invite project participants into the classroom to engage students, as well as to address current or even cutting-edge practice and techniques. Case studies can also be an ideal venue to encourage creativity. Through case study assignments students can begin to see that there can be multiple solutions to a problem—even one that was completed in the real world. Case-study-based learning has been shown to encourage:

- Creativity
- Interaction among students
- Feedback from students to instructor
- Instructor's learning opportunity from students

- Connection of education to “real-life” problems
- Student’s understanding and retention of knowledge (Angelides et al. 2000).

Conclusions

If the next generation of engineers are to be “more than technical functionaries in the next millennium, there is a need to provide young engineers with an understanding of the social context within which they will work, together with skills in critical analysis and ethical judgment and an ability to assess the long-term consequences of their work” (Beder 1999). To solve the big problems facing the U.S. and world, the next generation of engineers will need a set of knowledge, skills, and attitudes that is sufficiently strong technically and broad enough regarding non-technical understanding of social, economic, and political systems. Creativity, or the ability to see the world anew, making the strange familiar and the familiar strange, can help infuse a sense of purpose in education and help students learn to appreciate and work within the Big Picture.

To remain competitive with international institutions and engineers, U.S. colleges and universities must foster creativity in their faculty and students. The next generation of engineers will require a creative outlook to approach technical problems in new ways. Incorporating creativity into student assignments promotes teamwork, communication, knowledge retention, ability to synthesize and make connections between courses and fields, and a smooth transition from formal education to practice. Fostering creativity in the engineering classroom also leads to student retention and better student-professor interactions. Incorporating creativity does not take a degree in rocket science. In fact, even an aerospace (and chemical and civil) engineer can find ways to infuse creativity into her students and classroom assignments.

Making the strange familiar—accepting creativity as a desirable mindset and attribute of engineers—is a tangible and realizable goal that can be readily and actively included in any engineering course and program. Designing and building the future will take more than technical know-how. It will take trial and error, effort, and even failure. If the next generation of engineers learns to approach challenges and assignments creatively, arriving at a safe, sustainable future will become more and more familiar, while the notion of the engineer as a pocket-protected technician will become stranger and stranger. Let’s work together to make the uncreative engineer a thing of the past as we usher in a new generation of adaptable, flexible, well-rounded, and innovative professionals.

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