STIMULATING CREATIVITY : teaching engineers to be innovators

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Abstract - *Engineering is a creative profession; indeed that phrase appears in the title of a consistently popular introductory textbook [1]. Yet few courses in the standard engineering curriculum require or even encourage creativity. Students often feel that creative behavior is actively discouraged in their classes.*

Several engineers [2,3,4,5] have designed courses or programs to foster creativity, and the recently rekindled interest in engineering design in the curriculum has led to greater emphasis on innovative thinking. Although creativity is generally required for first and fourth year design projects, it is curiously absent in-between.

In this paper, we explore the nature of and conditions supporting creativity, how to foster it in engineering education, and describe several courses designed to teach engineering students to be innovators.

What is creativity ?

Is Creativity a mysterious gift? a unique talent? a trait? an ability? an attitude? Is it innate, or can it be learned and taught? Does it develop spontaneously? or is it always present in some individuals? Clearly, some people are more creative than others. Is this due to the way they think? how they see the world? or how they react to it? Are certain thought processes , attitudes or beliefs associated with creative production? If so, perhaps anyone can learn to be more creative.

We all have implicit theories of creativity and of many other psychological concepts. These ideas may agree with what cognitive science has discovered about such attributes, or may diverge in important ways.

Two recent studies have focused on how engineers view creativity - one involving students, the other practicing engineers from industry.

Richards [6] developed a survey to assess students' beliefs about both creativity and intelligence, and their views on who are creative or intelligent people and which professions require creativity or intelligence. Students were also asked to list the attributes or characteristics they associated with each of these traits.

The attributes students most frequently associated with creativity included novelty, fluency, open-mindedness, unconventionality, synthesis, insightfulness, and attitude.

People cited as creative included many writers, musicians, entertainment personalities, artists, political figures, cartoonists , and a few scientists, inventors, and engineers. However, Einstein was the person most frequently listed as creative, followed by Edison, daVinci, Jefferson, and Bill Gates.

Although most students feel that engineering is a creative profession, they rarely included the names of engineers on their lists of creative people. One problem seems to be that students don't know the names of many engineers. This may be because many of the major engineering achievements are the result of the efforts of large teams and organizations. Engineering advances are often incremental improvements on existing products, not the kinds of major breakthroughs which bring public recognition. And I fear most engineering faculty don't emphasize in their classes the names of individuals responsible our greatest technological achievements.

I now regularly use this survey in my classes - both to gather information and as a stimulus for discussion. After thinking about these issues and committing their opinions to paper, students are much more active participants in the class discussion.

Klukken, Parsons, and Columbus [7] interviewed eight professional engineers about their creative experiences in industry. Each had been identified by a peer as being a particularly creative individual. The interviews covered each person's views on creativity, their personal experiences with creative work, and their reflections on engineering education. The interviews were conducted jointly by an engineer and a psychologist, and were recorded for later review and analysis.

Based on their interview results, the authors identified four clusters of attributes which these engineers felt influenced creative performance; these were classified as personal motivation, environment and work conditions, tools, and mental processes. *Desire and fulfillment* summarizes the intrinsic motivation of creative individuals; they want to be creative, to go beyond mundane solutions, and produce something new and different. *Autonomy and support* describe the environment which facilitates creative contributions; an individual needs the freedom to experiment, and to fail, in order to take the risks necessary to pursue new ideas. *Openness and knowledge* are cognitive tools; one must be solidly grounded in a technical field to be able to contribute to it, while maintaining an openness to new ideas and information and a willingness to be influenced by outside sources. *Engrossment and connection* reflects the experience of total involvement with a problem. It includes focus and “flow”.

These engineers were asked to assess the state of engineering education and especially its role in promoting creative thinking. They felt that engineering schools do not adequately prepare students for creative endeavors or for the realities of modern industry.

What Psychologists (and others) know about creativity

Psychologists have studied creativity for more than a century; as have mathematicians, artists, and scientists. Different investigators have focused on either the people, processes, or products and performance involved in creative activity. The results of many studies provide a relatively consistent picture of the attributes of creative people and the conditions which foster innovative thinking, and support the findings of the two surveys cited above.

In his Systematic Introduction to the Psychology of Thinking, Johnson [8] reviewed a large number of studies on creativity and provided a framework for understanding them. He summarized the main dimensions of creative achievement as *intellectual leadership; sensitivity to problems; originality, ingenuity, unusualness; usefulness, appropriateness; and breadth.*

According to Amabile [9], there are three basic ingredients to creativity: *domain skills*, *creative thinking skills*, and *intrinsic motivation*. Domain skills are those acquired by becoming an expert in a field. Creative thinking skills include seeking novelty and diversity, being independent, being persistent, and having high standards. Intrinsic motivation indicates that the reasons for doing things come from within - from passion and pleasure, not as a result of external demands or pressures.

Much of the published research has been case studies or life histories based on interviews of creative individuals - from Wertheimer’s study of Einstein [10] to Csikszentmihalyi’s investigation of over 100 creative individuals of our time [11] and Shekerjian’s study of 40 winners of the MacArthur Award [12]. The key message of these studies is that creativity is usually manifested by a lifetime of achievement and continues to develop throughout a career. Creativity is attributed to certain individuals because they produce novel and important ideas or products - often repeatedly over the course of their lives.

Gardner’s studies of multiple intelligences [13] have found creative abilities in several domains: language, math and logic, spatial reasoning, music, movement and inter- and intra- personal skills. Indeed, creative expression seems to be a fundamental aspect of intelligence in all these domains.

Sternberg [14] has extended his work on intelligence to the realms of creative and practical intelligence. Our usual notions of intelligence relate to standardized test scores and academic performance. However, such IQ measures are not strongly related to creative achievement or to practical success. Many bright individuals fail to achieve original contributions, while some with less apparent talent excel in their fields and have a major impact.

Weisberg [15] asserts that creativity is not at all mysterious, but is readily understandable in terms of familiar psychological processes. He proposes that creative activity proceeds incrementally in small steps based on past experience and efforts through the exercise of conscious mental processes. Weisberg rejects both the “muse” (external forces) and “genius” (internal forces) views of creativity. Bogen [16] shares Weisberg’s view that creativity is a product of standard cognitive processes and psychological mechanisms.

Consistent Recommendations

The literature provides many lists of strategies and techniques for enhancing personal creativity [17 - 20]. The list below is somewhat different in emphasis from those found in most books, but it does share many common ideas. These guidelines for personal creativity are the basis for class discussion, demonstrations, and exercises. Using them, we try to convey those attitudes and beliefs, thought patterns, and habits and behaviors characteristic of creative people and teams.

Immerse yourself in a domain or problem. Learn everything you can about the topic. Become an expert. This requires time, effort and commitment- usually a decade or longer. But you must know the state-of -the-art in an area in order to transcend it.

Be Prolific ! Generate lots of ideas -

initially without evaluation or criticism. Include the unusual, the bizarre, the unreasonable. Don't be afraid of dumb ideas.

Use tools for representation and thought. Don't rely on memory. You might lose your best ideas. Keep a notebook. Write things down, sketch, draw and diagram, model using computers, construct physical prototypes. Visualization is an especially effective way of representing information. Pictures, models and prototypes can lead to understanding and insight.

Play with ideas. Experiment with multiple ways of thinking. Represent your ideas in several modes. Allow your thinking to become more abstract: think at a higher level; then more concrete: explore physical objects and events. Look for associations and links, similarities and differences, convergences and discrepancies. Reframe the problem or situation.

Avoid premature closure. Move beyond the obvious solution. If you know one way to solve a problem, look for others. Resist the pressure to achieve a quick solution. Don't stop with the first workable idea you find. The obvious solution is rarely the best one.

Don't be afraid to be different. Be an independent thinker. Evaluate information critically. Question assumptions. Overcome tradition, conventional practice, barriers, mental and perceptual blocks, and things as they are. Take risks. Resist group pressure.

Be open and receptive to new ideas. Assume multiple perspectives, different roles or points of view. Valuable insights may come from other disciplines. Creative individuals have often contributed to several fields.

Do It ! Practice your craft. Solve problems. Design things. And show your results to others. Build a solid base of experience, and develop skills in communicating your ideas.

Maintain a product orientation. Persist, carry your ideas through to completion. Finish your projects.

Relax. Take your time. Indulge your diversions. They provide time to think and often new things to think about. Insights sometimes come during relaxed situations - away from the work environment. Incubation is often necessary for original ideas to develop, or divergent strands of thought to come together.

Reflect. Step back; review what you have done and think about how you did it, and consider how to improve on it next time. Rethink, restructure, learn. Psychologists call this *metacognition.*

Have fun ! The long term motivation for accomplishment must come from within. Enjoy the process and the products. As Peter Lissiman says "The first rule of innovation is pleasure."

Courses designed to stimulate creativity

Can we teach creativity? Can these insights be incorporated into the Engineering Curriculum? Creativity is an essential component in engineering design. Different types of design problems require varying degrees of creativity, but innovation is a fundamental aspect of engineering practice.

At the University of Virginia, we offer several courses aimed at fostering creative and entrepreneurial thinking - ranging from the first year to the graduate level. The first two are required of all incoming engineering students; the others are elective courses.

Engineering Concepts and Design

In the first year, we offer two courses which introduce engineering design, the fields of engineering and applied science, and the major tools for representation and problem solving. *Engineering Concepts* covers the fundamental approaches to representing technical information and introduces a variety of computer tools (including spreadsheets, programming, computer aided design, and communications) and basic engineering concepts. *Engineering Design* is a project based course with multiple instructors from several fields of engineering and applied science. Each instructor assigns up to five design projects during a semester. Most are done in groups. Individual instructors have considerable freedom to select topics of interest to them [17]. For many students, these courses represent their first experience with both design and cooperative project-based learning.

Invention and Design is a unique course open to students from any school at the University. We strive to attract students from Arts and Sciences, Commerce, and Architecture, as well as various disciplines of engineering. This course is cross-listed with the Department of Psychology, and is taught by a team of faculty from three different departments. We require readings on psychological topics, design theory and methods, and the history of invention and design. Several classes are devoted to creativity.

In this class, teams of students invent and design in each of three domains selected to span the range of innovation activities[18,19]. They learn to prepare patent applications; and midway through the semester, we visit the patent office. Our students conduct their own searches (both on-line and manual) with help from a team of experts. They also become aware of a unique subculture focused entirely on innovation -- inventors, patent lawyers and search specialists, venture capitalists and financial analysts.

An essential component of this class is keeping individual and team notebooks - detailed accounts of the activities, processes, products, reflections and reactions to the projects. Of course, the necessity for such documentation is emphasized in our discussions of patents and protecting intellectual property. But even more important is the role of these tools in thinking and reflection. [24,25]

The Technology and Product Development Life Cycle focuses on technology and product development from the perspective of the corporation, and explores the roles and mechanisms for decision-making within the firm. In addition to the technical aspects of product development, the business and market concerns for product success are also addressed, as are the issues of industrial ecology and environmental impacts. This course is taught by faculty from both Commerce and Engineering. Several team - based projects stimulate creative thinking.

Creativity and New Product Development attracts advanced undergraduate and graduate students from engineering and commerce. Its key feature is its entrepreneurial focus. From the first day of class, the students are involved in finding design problems with real financial potential. Students are required to generate a patent application and a business plan, as well as a product design, a physical prototype, and a production plan. They must establish the financial viability of their product , and map out their plan for marketing it. Their final presentation is an executive briefing to an audience of potential investors. In this course, we emphasize the role of innovation in the commercial sector, and try to help our students make their ideas profitable.

Computer aided engineering and design

Initially this graduate level course simply provided an overview of CAD/CAM and introduced a variety of CAE concepts and software tools. Now students are required to include an original design as part of their work. Since they learn to use computer tools intended to facilitate engineering innovation, it seemed appropriate to require them to actually design something.

Educating for creativity: lessons learned

All of these courses are non-traditional and somewhat subversive. They undermine the idea that there is one right answer to every problem and it can be found only through analysis. Such courses may be threatening to both students and faculty. After several years of teaching about creativity, invention, design, and innovation, I have learned a few things that work,… and many things that don't.

We must help students to broaden their perspectives. Typically professional education becomes more specialized and focused, and therefore increasingly narrow and limited, as students advance in their curriculum. As they become experts in their fields, they often develop the attitude that they know the answers to all interesting problems. Indeed part of expertise is having a corpus of solutions to known problems. However to be creative, experts need to be receptive to new ideas and exposed to many, varied influences. They must learn to transcend their expertise.

All of the courses described above employ interdisciplinary teams to solve open ended problems. Most encourage the participation of non-engineers. By working in diverse teams, our students learn to understand multiple points of view and varieties of expertise. In addition, we should encourage our students should take as many courses as possible outside of Engineering, especially Psychology, Human Factors, Statistics, and Studio Art (drawing, painting, sculpting, and computer graphics). **We must require innovation**. If creativity is expected from them, students will exhibit it. As they experience being creative, they will seek further opportunities to be so. This requires that we expand the types of problems we assign, and the types of solutions we accept and encourage. By now, everyone is familiar with open-ended design problems and they are regularly given to freshmen and seniors. How many of us, given a good solution from a student team, send them back to find a better one?,….or a different one?…or an unusual one? One of the engineers interviewed by Klukken et al [7] proposed giving problems for which the professor knows of no solution.

We must promote a product orientation. Our students should focus on results. Persistence and follow-through matter in life and work. People are judged creative because they have produced novel ideas or products that have made a difference. We encourage our students to enter the annual national competitions for design, innovation and invention, especially the B.F. Goodrich, Padnos and Lemelson. This process requires well - documented proposals and action plans. Several of our project teams have won external support to continue their efforts beyond the course.

We must make students aware of the nature of and conditions for creativity. We can enhance creativity in our students by helping them understand the social and psychological processes involved. In our classes, we explicitly discuss both the theory and practice of creativity. To realize their creative potential, students must develop certain attitudes, behaviors and habits, as well as domain knowledge and thinking skills. They should study what is known about creativity, design, invention, innovation, and especially entrepreneurship. By understanding the conditions which foster innovation and the patterns of creative thought, they are better equipped to realize them in their own lives and careers. Two feature articles [26,27] in a recent issue of ASEE Prism were devoted to fostering creativity in engineering.

Case studies, histories, anecdotes and stories can provide both content and motivation, and may help shape attitudes and beliefs. Business successes, and failures, may be used to illustrate creative, and mundane, solutions to problems, and the relevance of multiple perspectives.

We must provide tools for creativity - both physical and cognitive. Our students must learn how to capture and manipulate ideas. The design notebook, a reflective journal , and a sketchbook are valuable tools. Computer programs for solid (3D) modeling, analysis, simulation, and visualization can be used to capture, manipulate, and communicate our ideas. Equally important, we must encourage ways of thinking, perceiving and evaluating information which support creativity and innovation. Many of these were reviewed above and in Panitz [26] and Gibney [27]. Finally, we must help develop our students' presentation, communication, and negotiation skills.

Our ultimate goal is to require original creative work as part of every engineering course. Every academic discipline requires innovation from its participants. We must convey to our students the opportunities for discovery, invention and design in every field. We must also convey the fun and excitement of working in our fields. Our enthusiasm is necessary to develop the passion and commitment we expect in practicing engineers. As educators, we are responsible for stimulating creative thinking among our students.

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