

## **Creative Thinking, Creative Problem-Solving, and Inventive Design in the Engineering Curriculum: A Review**

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### Abstract

During the past decade, and especially over the last few years, engineering educators have been promoting, and implementing in their classrooms, an increased emphasis on student creativity, problem-solving ability, and inventiveness. At a growing number of universities, student engineers are studying the creative process, developing advanced thinking and problem-solving skills, and learning to design by experience. Successful programs, projects, and research at premier engineering schools around the country are equipping students with the advanced creative and cognitive abilities required to succeed as contemporary professionals. This paper is a review of the innovative, multi-disciplinary, educational methodology that is manifest in several types of new efforts, including: 1) Engineering design in a studio atmosphere; 2) Engineering courses for creative problem-solving; 3) Encouraging creativity and insight through journal writing; 4) The agenda for creativity at the UK Centre for Materials Education; and 5) A focus on the personal creative process. Research for this review inspired *The Creativity, Innovation, and Design Report*, a new national publication dedicated to fostering creativity and innovation in engineering and applied science education.

### I. Introduction

At the 2001 ASEE National Conference in Albuquerque, Penn State engineering professors Donald Horner and Jack Matson spoke of their experiences teaching the course *Creativity, Innovation, and Change* in a "leaderless classroom," where students design their own education and traditional teacher-student relationships are cast aside, replaced with a mentor-creator collaboration that fosters invention and facilitates the creative process. Intentionally, say Horner and Matson, both the educational methods and objectives are non-traditional: "...the process of teaching creativity, innovation, and change to engineering students in a university setting must itself be creative and innovative while concomitantly promoting change."<sup>1</sup> These are two of an emerging group of educators who are recognizing the need for, and are implementing, a focus on creative problem-solving, the creative process, and inventive design in the engineering curriculum.

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This new focus on student creativity and innovation is largely a response to an increasingly complex professional landscape. Contemporary engineers, who face difficult and often enigmatic problems on a daily basis, must possess excellent problem-solving skills, an intimate knowledge of modern design processes, and a proven ability to innovate. A 1997 Journal of Engineering Education article by Gary Klukken (et al.) reads: "A lack of creativity is clearly problematic in a rapidly changing, technologically oriented world where generating new ideas is essential to survival."<sup>2</sup> Joseph Bordogna, the Assistant Director of Engineering for the National Science Foundation, agrees: "The engineer must be able to work across many different disciplines and fields...and make the connections that will lead to deeper insights, more creative solutions, and getting things done."<sup>3</sup> In a Spring 2002 Issues in Science and Technology article, National Academy of Engineering (NAE) President William Wulf, and Chair of the NAE Council George M.C. Fisher call for "a major shift in engineering education's center of gravity," away from the traditional "engineering science" approach, which emphasizes the scientific and mathematical foundations of engineering, and towards a curriculum based on experience, practice, and empirical design. "Many of the students who make it to graduation," write Wulf and Fisher, "enter the workforce ill-equipped for the complex interactions, across many disciplines, of real-world engineered systems...Today's student-engineers need not only to acquire the skills of their predecessors but many more, and in broader areas."<sup>4</sup> The Accreditation Board for Engineering and Technology (ABET) seems to agree; the 2000 "a-k" criteria<sup>5</sup> call for a design rich curriculum and contemporary, real-world educational methodology.

Beginning in the early 1990's, but specifically during the last few years, engineering educators have been modifying the curriculum by initiating courses and projects that foster in their students advanced thinking skills and an understanding of creative and inventive processes. Once predictable engineering classrooms are experiencing a (perhaps overdue) transition to a more holistic, multi-disciplinary educational ethos that has traditionally been enjoyed by students of the arts and humanities. Student learning experiences vary dramatically from classroom to classroom and from university to university as professors draw inspiration from diverse, often non-traditional sources, including the humanities, social sciences, philosophy, architecture, and art. Following is a review of an emerging paradigm-shift in engineering education as it is manifested at universities across the country (and in the UK). Subsequent sections of this paper discuss a variety of new types of efforts, including: 1) Engineering design in a studio atmosphere; 2) Engineering courses for creative problem-solving; 3) Encouraging creativity and insight through journal writing; 4) The agenda for creativity at the UK Centre for Materials Education; and 5) A focus on the personal creative process.

Most of the available assessment for the efforts discussed in this review is qualitative. The relative effectiveness of these programs and courses is often determined

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by considering each participating student's cognitive advancement, project work, and personal feedback to the instructor. These informal methods of assessment are not surprising, considering the generally process-oriented, non-technical curricula. Additionally, because each effort is relatively new, longitudinal data is scarce and, when available, still usually qualitative. To fairly assess the real value of the following innovative programs, it is necessary to suspend our familiar reliance on quantitative data, relying instead the evidence imbedded in individual learning processes, student responses and evaluations, and moments of creative and cognitive discovery.

## II. Engineering Design in a Studio Atmosphere

"Learning Engineering as Art: the New Paradigm," reads the byline of the Illinois Institute of Technology (IIT) Invention Center web page ([www.iit.edu/~invention/](http://www.iit.edu/~invention/)). Directed by Francisco Ruiz, an associate professor in the Department of Mechanical, Materials, and Aerospace Engineering, the Invention Center became fully functional during the 2000-2001 academic year, as a result of continuous development since 1995 and an ongoing partnership between IIT and the National Collegiate Inventors and Innovators Alliance (NCIIA). The goal of the center is to emphasize "synthesis" (concept) over "analysis" (calculations) as a means of fostering creativity in student engineers. "When viewing engineering as an art," writes Ruiz, "a different paradigm of engineering education emerges. Instead of 'assembling' new engineers in a production line, where productivity is the goal, new engineers can rather be 'grown' in an organic way."<sup>6</sup> Modeled after an art studio, the Invention Center provides each student with personal workspace for ongoing design projects; the atmosphere becomes intensely creative, and master-apprentice learning relationships are developed among students and faculty. Classmates share computers, texts, and prototyping tools, meeting regularly to discuss their progress and share insight on individual and team projects. Because the studio is a fully equipped and self-contained space, it fosters an intensely creative atmosphere in which students learn to "turn-on" their creativity as they enter.<sup>7</sup> The artistic ethos at IIT is indicative of an emerging group of engineering schools that is initiating project-based, studio-centered design programs for students.

Just across the city from the IIT Invention Center, at Northwestern University, an 8000 square foot design studio is home to a practice-based two-quarter course called "Engineering Design and Communication" (EDC). Working in teams, first-year students confront real-world design problems submitted by entrepreneurs, non-profit organizations, and industry. The design studio is open 24 hours a day and perpetually full of students designing and building prototypes. Each team's academic quarter culminates in a final presentation for its clients, including an oral presentation, written proposal, and working prototype or visual mockup. A team of faculty from the Colleges of Engineering and Arts and Sciences, led by mechanical engineering professor Edward

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Colgate, developed EDC to teach engineering design and technical communication to first-year students through real-world problem solving in a project-based studio environment. “The project-oriented format is important for several reasons,” says Colgate; “the first is motivation. Because we seek out real clients with real problems that need solving, the students are highly motivated. The second is lack of structure. Understanding how to deal with ambiguity, even to the point of using this as an asset because it allows creativity, is an important part of the design process.” Because student projects originate with true clients, ambiguity is always present in some measure. “Our students also learn that clients tend to state problems in terms of solutions,” Colgate continues, “and that it is valuable to understand the underlying needs. A third advantage of the project-based format is that it reflects the way that engineers work in industry.”<sup>8</sup>

A project-based, industry-linked design format has also been adopted by the University of Pittsburgh, whose School of Engineering opened the Swanson Center for Product Innovation in 1999. “We’re meeting a demand,” says the Swanson Center’s Educational Director and Assistant Professor of Industrial Engineering, Mary Besterfield-Sacre, “to get innovative products to industry and to get products from industry to market faster. We’re also adapting to new accreditation standards (ABET 2000 “a-k” criteria) and giving students an opportunity early on to experience a professional design atmosphere.”<sup>9</sup> Participating students are pursuing a minor in “Product Realization” as part of their undergraduate engineering curriculum. The creative educational practices at the Swanson Center are reminiscent of those at IIT’s Invention Center and Northwestern’s EDC program, featuring teams of students solving real-world design problems in a creativity-intense, technologically supportive atmosphere. “Generally,” says Besterfield-Sacre, “five groups participate per semester. We team each group with a corporate sponsor, a faculty advisor, and a graduate-student advisor. While we adhere to no specific educational or creative pedagogy, students are enabled and encouraged to develop innovative ideas and products.”<sup>10</sup> The Swanson Center provides guidance and “all the latest tools,” including design, multi-media, and reverse-engineering labs, as well as rapid prototyping and rapid manufacturing facilities. Besterfield-Sacre notes that the problem-based learning format has been working very well; several student teams have applied for patents and are in the process of marketing their products.

### III. Engineering Courses for Creative Problem-solving

During the past several years, some engineering educators have been developing creative problem-solving courses that radically depart from the established curriculum. In these classes, technical instruction is often secondary to the primary goal of developing student thinking skills and problem-solving ability. In 1995, the Mechanical Engineering (ME) Department at Rose-Hulman Institute of Technology introduced a new class that was intended to be a “one shot” comprehensive creativity primer. The class, titled

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“Creative Design,” has been taught by several members of the ME faculty. Professor Don Dekker emphasizes that his class focuses on stimulating the creative process, on overcoming conceptual blocks, and on teamwork and discussion in the classroom. Dekker requires his students read and respond to two texts that are both recognized as premier creativity-enhancing tools: Conceptual Blockbusting,<sup>11</sup> by James Adams, and Jump Start Your Brain,<sup>12</sup> by Douglas Hall. By allowing students to read, write, process, and discuss the material independently, Dekker encourages increased creativity and communication skills. Accordingly, he gives no lectures in class, but instead functions as a facilitator of discussion and a general source of information for the students.<sup>13</sup>

Dekker bases student evaluation on daily responses to the readings, as well as a more extensive book report. In addition, class participants take turns presenting creative projects drawn from the "Brain Programs" in Hall's book, which are techniques for overcoming preconceived ideas and stimulating creative thought.<sup>14</sup> Examples of these Brain Programs include the *Mind Dumpster*, a “brain purge program,” the *Stimuli Two-Step*, which stimulates ideas through analogy, and *Hitchhiking*, a method of traveling between and connecting ideas. Dekker's class has received overwhelmingly positive reviews; participants appreciate its informal and collaborative nature, as well as the applicability of the educational concepts to future problem solving tasks.

The Systems and Software Engineering curriculum at Penn State’s School for Graduate Professional Studies includes a creative problem-solving course titled “Creativity, Innovation and Change.” At the Great Valley campus, Dr. Kathryn Jablokow teaches this course; it is also offered at the State College campus, instructed by the team of Dr. Jack Matson and Dr. Donald Horner. By virtue of the creative nature of the course, these educators are able to apply diverse and innovative educational methods in their classrooms.

Jablokow perceives her classroom as a forum for “teaching students to think differently about their own thinking and to apply what they learn about their thinking as they solve problems in their profession.”<sup>15</sup> For cognitive inspiration, students are subjected to a participatory introduction to a set of psychological models: The Osbourne-Parnes Creative Problem Solving model and Rolf Smith’s Seven Levels of Change, as well as several models of cognitive diversity, including M. J. Kirton’s Adaptation-Innovation Theory, and Carl Jung’s personality types. With this new information, each student embarks on a personal “Thinking Expedition” that is designed to reveal thinking patterns and cultivate creative potential through discovery, risk taking, and collaboration.

An expedition metaphor permeates Jablokow’s course, and students are encouraged to perceive their evolving thinking as a journey. In preparation, “expedition vests,” “idea passports,” and journals are distributed on the first day of class. Students use a “mess-finding kit” to identify problems and “mind maps” for charting their ideas as

they progress toward the solution to a problem. Jablokow says that student engineers who participate in her course will leave with a new understanding of creative and cognitive theory, and with new skills that include “the ability to evaluate and change one’s own thinking based on heightened self-awareness, and an improved capacity for leveraging the cognitive preferences of one’s peers in group settings based on a new understanding of and appreciation for different creative styles.”<sup>16</sup> Feedback from students confirms this acquisition, as many have cited the course as a source of inspiration and personal cognitive evolution. Past student responses include: “This course has given me great insight into my personal behavior traits,” and; “The things you learn in this class are building blocks for your future.” Also, many students have applied their project work to professional ventures, including the development of new companies and patent-pending devices.

Seemingly the antithesis of Jablokow’s highly structured classroom, Horner and Matson’s approach to *Creativity, Innovation, and Change* involves a classroom with virtually no initial structure. The “leaderless classroom” relies on its own participants to initiate structure and develop course material. The students are, in fact, *entirely* responsible for their own learning experience. The professors assume roles as non-decision-making mentors, allowing the course to evolve according to the self-organization, leadership, and priorities of the students. Working from a rudimentary syllabus, students work both independently and in collaboration to identify problems, initiate and conduct projects, and discuss results. Horner and Matson confirm that the leaderless classroom is a radical educational method, and that its effectiveness is driven by its tripartite nature: “Students must take charge of the content studied and learning process employed while also experiencing what it is they’re trying to learn...As students are immersed in unfamiliar roles, the inevitable frustration and confusion provide a stimulus for discussion and creative thought.”<sup>17</sup>

#### IV. Encouraging Creativity and Insight through Student Journal Writing

At the University of Virginia (UVA), in lieu of a required composition course through the English Department, first-year engineering students complete a class in the Division of Technology, Culture, and Communication (a special unit of the College of Engineering) which emphasizes writing skills, leadership ability, and problem-solving techniques. The broad, multi-disciplinary nature of the course has inspired a variety of innovative methods of relaying fundamental thinking and communication skills. An integral element of Dr. W. Bernard Carlson’s class is a contemporary, industry-born, journal-writing program: the Idea Marathon System (IMS).<sup>18</sup>

Originally developed in 1984 by Takeo Higuchi, a technical manager at Mitsui & Company in Japan, IMS involves generating as many creative ideas as possible and

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keeping them in a notebook. This notebook is a personal forum for the expression of all types of ideas, including solutions to problems, plans for the future, insights, and ideas for new products and procedures. Carlson used IMS in the engineering classroom to facilitate the creative process. He hoped that by keeping the notebooks, students would gain a valuable tool for recording, relating, and developing new ideas. The students were encouraged to seek creative inspiration by examining their everyday lives and imagining alternatives and solutions. Carlson found that most students were more comfortable working on a computer and resistant to the “old-fashioned” pen and paper, although some realized the flexibility afforded them by bringing together words and sketches in a more personal, lasting space. The notebooks included passages from books, articles, and lectures, reactions to museum and gallery visits, illustrations, connections, and a wealth of original ideas.<sup>19</sup> Some students found inspiration in the architecture of Thomas Jefferson, who designed the UVA campus and also kept a detailed personal notebook throughout most of his life.

Engineering students at the University of Texas at Austin are also achieving creative inspiration through journal writing. In the January 2002 Journal of Engineering Education article “Nurturing Faculty-Student Dialogue, Deep Learning and Creativity through Journal Writing Exercises,” Chemical Engineering (ChE) Professor Brian Korgel explains the effectiveness of student journaling as a means of encouraging creativity and the exploration of concepts that challenge traditional teaching techniques. “The student journal,” he writes, “promotes deep learning and stresses that students create conceptual links between course concepts and experiences in their own lives; thus, helping students access self-knowledge.”<sup>20</sup> As an assigned element of ChE 363 (Unit Operations II: Separations), the journal consists of a non-graded personal section, non-graded feedback to the instructor about the course, and graded descriptions or analogies of pre-assigned, class-related topics. Once per week, students are required to produce an analogy or creative exploration of current class material. Students are encouraged to respond thoughtfully and creatively, and extra credit is awarded through a class vote for “best analogy.” During their journal-writing assignments, students experience a rare opportunity to explore their ideas and make unique connections in a low-stress, open-ended, creative environment. One student responded: “The journal forced me to sit back and conceptualize relations so that I can better picture them applied to everyday life and thus understand them better...I think this is very important for my future, not only for applying concepts in the field, but also for communicating with people.”<sup>21</sup> Certainly, as witnessed by many noted inventors and thinkers, a notebook of one’s own creative ideas can be an unparalleled source of inspiration.

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## V. The Agenda for Creativity at the UK Centre for Materials Education

Based at the University of Liverpool, the UK Centre for Materials Education “aims to support and promote good and innovative learning and teaching practices, as informed by research, in the disciplines related to, and using, materials.”<sup>22</sup> For the engineering field, the Centre is a premier source of educational research; and under the direction of Deputy Director Dr. Caroline Baillie, it maintains a pioneering role in fostering creative thinking in student engineers. In May of 2002, the Centre hosted a symposium at Armorer’s Hall in London titled: “Enhancing Creative Thinking in Science and Engineering.”<sup>23</sup> Topics included the necessity of preparing students to solve complex industrial problems, the nature of creative design, scientific methods for generating ideas, and the importance of drawing. Baillie, who is also a senior lecturer of materials at the University of London, gave a presentation that addressed the components of the creative process, including problem definition, overcoming preconceived ideas, and generating and evaluating new concepts. These symposium topics are indicative of the growing body of creativity research conducted by Baillie and her colleagues at the Centre over the past several years.

In 1999, after managing a nationally sponsored project entitled, “Fostering Creativity Within Engineering,” Baillie, with Materials Scientist Simon Dewulf, wrote the book CASE: Creativity in Art, Science, and Engineering.<sup>24</sup> The text, forwarded to all engineering schools in the UK, suggests that the process of fostering creativity in students should be performed in three phases: The *preparation phase*, during which problems are defined and students learn to use new knowledge; the *generation phase*, during which left and right brain approaches to creativity are combined and students achieve awareness through experimental making; and the *verification phase*, during which ideas are shared and critiqued. The book is currently in preparation for re-release. Baillie has provided additional insight into the nature of teaching and learning in Learning to Learn, a guide for science undergrads, and Professional Engineering: Teaching for Better Learning (with P. McHugh and W. Davies). Currently, with Dewulf as co-moderator, Baillie is soliciting the input of fellow educators through an ongoing online creativity forum ([www.ijee.dit.ie/forum/forum1home](http://www.ijee.dit.ie/forum/forum1home)), sponsored by the International Journal of Engineering Education. This open discussion addresses questions such as: How can we implement creativity in an engineering educational context? and, how can we address creative thinking, creative problem solving, and creative design? The enthusiastic international response and subsequent debate has provided crucial groundwork for establishing a global network of engineering educators who study and teach creativity.

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## VI. A Focus on the Personal Creative Process

In 1996, following a request from the Virginia Tech University Honors Program, Dr. Eric Pappas developed a class that brings together a variety of creativity skills: "Creative Process, Creative Writing, and Engineering Design." The class focuses on "the inspiration, motivation, discipline, and the original expression of ideas as methods of exploring the creative process in the humanities and its applications to creative design in engineering."<sup>25</sup> Students in the class focus on experimenting with creativity skills in the community, normally with individuals with whom they interact on a day-to-day basis. Students keep a journal on all their assignments and discuss their reactions with others in the class.

The most important objective of this class is to bring together creativity skills by practicing the discipline and motivation required to understand the nature of personal change. By employing intentional growth strategies, students create a creative process that is versatile and effective in their academic, professional, and personal lives.

At the beginning of the semester, students are assigned two out-of-class reflective exercises that focus on the thinking process and are a central component of the class. "Reflection: An Hour of Silence," and "Intentional Change: Three Day Assignment," help students learn introspection skills and discover the negative effects that the barrage of outside stimulation (radio, stereo, television, surfing the net) have on their thinking skills. In addition, students learn "writing and drawing as thinking skills," structured and unstructured brainstorming methods, and listening and speaking skills through assignments that relate to their professional and personal lives.

Students also explore the barriers to creativity created by their attitudes towards diversity, including sex, race, ethnicity, gender, lifestyle, personal philosophy, and geographic origin. As a tools for overcoming such barriers, students practice non-argumentative conversation skills as a means of exchanging information and opinion without feeling the need to "win" arguments or convince others of their points of view.

Class time focuses on discussing the results of the out-of-class activities and applying newly developed creativity skills to composing original poetry and short stories. Students are required to submit at least two well-revised poems and two short stories (in addition to their journals). The skills students use to develop an individual creative process and creative writing skills are used to further develop a creative process that can be applied to engineering design. In addition to the skills they learn in the first half of the semester, practicing and employing visualization and drawing skills are central to students' early efforts to conceive of and apply a personal creative design process to a specific engineering design project.

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Having developed some thinking skills and knowledge of the creative process, students complete individual and group engineering design and redesign projects using these new skills, while documenting in writing the thinking processes that led to their designs. The final project is an invention, for which they must track and document the thinking processes that inspire their ideas and lead them to through each stage of design.

The assessment for the class takes the form of a final written evaluation (in addition to the standard University student evaluation form: the average for 11 classes taught was 3.82/4.0). Typical comments include: "This class helped me define creative process and taught me the skills I need to apply it to academic and personal tasks," "I understand more completely how creative skills apply in the arts and sciences and how to use them," and "I increased my practical creativity and design skills."

## VII. Conclusion

Bound for an industrial environment marked by rapid advancement and complex problem-solving demands, it is critically important that student engineers are comprehensively prepared to become professionals. Professional success is increasingly dependent on problem-solving acuity and the ability to think creatively. Students who graduate with an understanding of the creative process and who possess a proven ability to innovate are highly recruitable and immediately advantaged in the workplace. The preceding programs, along with new academic efforts initiated each year, are establishing creative problem-solving, advanced thinking skills, and inventive design experience as integral components of engineering education. While most new programs are enjoying remarkable success at specific universities, there is presently no visible unification of these efforts on a national (or international) level. Increasing involvement and interest in this trend have presented an opportunity for the creation of a regular publication dedicated to the assimilation, circulation, and exchange of current information about the innovative creativity- and design-oriented pedagogy that is emerging at many universities.

In the interest of perpetuating creative and inventive thought in engineering, science, and technology classrooms, faculty members at Virginia Tech and James Madison University have initiated *The Creativity, Innovation, and Design Report* (CID Report). Premiering in January 2002, and written primarily by and for engineering, science, and technology educators, the CID Report showcases individuals, classes, projects, and research from both academia and industry that foster creativity, thinking and problem-solving skills, and innovative design practices. The CID Report is distributed once per academic semester to all accredited engineering departments in the U.S., as well as to selected corporations, individuals, and international programs. The CID Report maintains a methodology-based, interactive format; each article and feature includes,

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whenever possible, contact information for the involved educator/student/professional, as well as links to more expansive discussions of the topic (i.e. other publications or online information). The ongoing objective of this project is to establish a dynamic network of engineering educators, students, and professionals who are researching, developing course material, and publishing information on creativity, thinking, problem-solving, and inventive design. For more information on *The Creativity, Innovation, and Design Report*, e-mail Jesse Pappas (editor) at: [jpappas@vt.edu](mailto:jpappas@vt.edu).

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