THE ROLE OF CREATIVITY IN ENGINEERING

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ABSTRACT

Creativity in engineering education is an ongoing critical issue for universities, in the sense that it helps meet the expectations for professional engineers, as well as complete the intellectual development of individuals. However, the importance of implementing creativity education in engineering education in the classroom has not been fully recognized. In this paper recent publications were reviewed in this regard, attempting to dissect what creativity means to engineers, and how they can overcome the stumbling blocks to creativity. Having explored the creative process, we suggested an operable tool based on Treffinger's creative learning model that can be implemented in a classroom setting to facilitate creativity.

Introduction

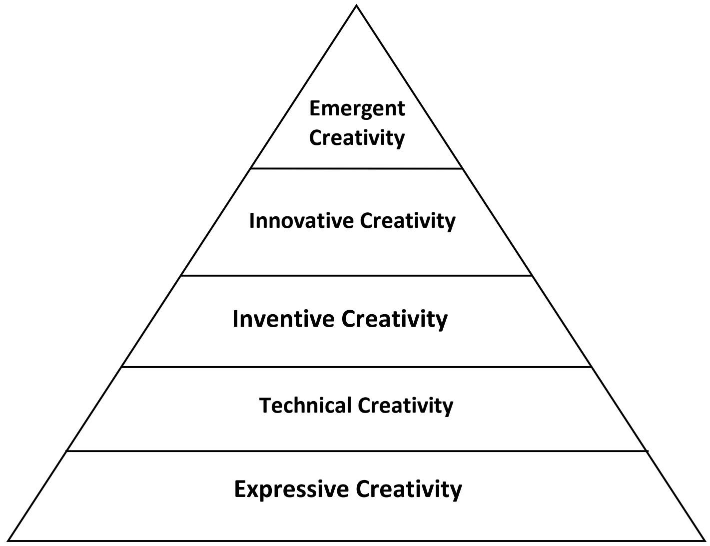
Universities are increasingly expected to provide more opportunities that foster and nurture creativity in engineering students (Baillie, 2002). The profession of engineering demands that engineers recognize validate and solve problems on their own or through a team work. More importantly, they should demonstrate original and critical thinking, and creativeness and innovativeness in their methodologies (Shaw, 2001). In short, engineers need a creative mind to meet the advancing goal of the engineering profession – to design new products or systems and improve existing ones for the benefit of humankind (Martin, 1991). Unfortunately, little has been done in many universities to place teaching emphasis on developing and facilitating creativity in their engineering students (Cropley and Cropley, 1999). This paper reviews the role of creativity in engineering.

What is Creativity?

It is difficult to give a simple and general definition of creativity. People often come up with their own definitions of creativity, such as "the ability to create" (Hardy, 2005). According to René (2003), creativity is the ability to challenge assumptions, break boundaries, recognize patterns, see in new ways, make new connections, take risks, and seize upon change when dealing with a problem. In other words, what you do is creative if it is new, different and helpful (René, 2003). According to Random House Webster's Unabridged Dictionary (v3.0), creativity is "the ability to transcend traditional ideas, rules, patterns, relationships, or the like, and to create meaningful new ideas, forms, methods, interpretations, etc." This definition stresses the creation of something innovative and useful from pre-existing knowledge and experience, which agrees with how most engineers see creativity (Christiano and Remires, 1993). In order words, creative engineers should be able to explore and scrutinize the available data or information and generate novel solutions to specific engineering problems or to the production of a unique product (Liu and Schönwetter, 2004).

Stages of Creativity

According to Taylor (1975), creativity is perceived as a hierarchy from a low to a progressively higher level (see fig. 1):



1. The first level is *expressive creativity*, the ability to develop a unique idea with no concern about its quality. This is illustrated by the engineering student who is asked, to for example, design a shelter using two square meters of cardboard, three meters of string, and thirty centimeters of duct tape, and invited to sleep in it for one night.
2. The second level is *technical creativity*, the proficiency to create products with consummate skills, but with little expressive spontaneity. For example, an engineering student emulates the exact behaviors in a laboratory assignment as modeled by the instructor, replicating the production of an existing structure, such as a bridge.
3. The third level is *inventive creativity*, the ability to develop a new use of old parts and new ways of seeing old things in an ingenious manner. Here the engineering student creates a prototype, the first of its kind based on the process of combining older ideas and synthesizing them into a new product.
4. The fourth level, *innovative creativity* is the ability to penetrate foundational principles or establish a school of thought, and formulate innovative departures. The engineering student is able to 'think outside the box', to move beyond the current thinking of engineering and develop a new way of creating and designing. For example, students are asked to design a motor driven by water as fuel.

5. The fifth and highest level is *emergent creativity*, the ability to incorporate the most abstract ideational principles or assumptions underlying a body of knowledge, as in the example of Einstein's work on general relativity.

For engineers, setting the highest goal at a level of 'innovative creativity' or 'effective novelty'(Cropley, 1999) may be more realistic and achievable, considering the fact that engineering is a profession where scientific principles or findings are applied to produce useful products and services (Shawn, 2001), and novelty is the single common element for numerous definitions of creativity (Morgan, 1953).

Divergent Thinking and Creativity

One major component of creativity is divergent thinking, which involves producing new and possibly multiple solutions or answers or ideas to a problem or question from the available information (Baillie, 2002). It is measured by four main characteristics.

1. The first one is *fluency*, the ability to generate many responses or ideas. To achieve high fluency requires much training in brainstorming, with emphasis on the quality of responses.
2. The second is *flexibility*, the ability to change the form, modify information, or shift perspectives. In other words, a flexible student is able to generate varied ideas from new perspectives.
3. The third is *originality* or the ability to generate unusual or novel responses. Here an engineering student should be encouraged to practice bold imagination, and take risks of identifying and rationalizing the novelty.
4. The fourth is *elaboration*, the ability to embellish an idea with details. To elaborate a novel idea and finally turn into an innovative product requires a solid and broad knowledge of science and engineering.

Team working should be encouraged here in order to bring a diversity of expertise together. In general, personalities such as the following are needed to motivate divergent thinking (Cropley and Cropley, 1999):

a. Openness
b. Flexibility
c. Nonconformity
d. Willingness to take risks
e. Tolerance of ambiguity
f. The courage of one's own convictions

Convergent Thinking and Creativity

Convergent thinking centers on deriving the single best solution or answer to a given problem or question from the available information (Cropley, 1999). Convergent thinking differs qualitatively from divergent thinking in that the latter leads to the variability whereas the former leads to the singularity of information production (Cropley, 1999). Although divergent thinking is believed to be the cognitive basis of creativity (Guilford, 1950), both schools of thinking are interactively involved in the development of creativity (Cropley, 1999 and Isaak & Just, 1995). Interesting, convergent thinking may play a more important role in the early stage of creativity development. According to a threshold model, a minimum level of conventional and factual knowledge (singularity) is needed to produce new ideas (variability) (Cropley, 1999). Whatsoever, creative engineers are usually skilled at both divergent and convergent thinking (Liu and, 2004).

The Creative Process

According to Liu and Schönwetter (2004), creativity involves the process of creating or creative activities. The creative process, starting from a problem or question, has been described in many ways and basically contains four phases: preparation, generation, incubation, and verification (Baillie, 2002).

The *preparation phase* includes defining, reformulating and redefining the problem or question. The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle, require creative imagination and marks real advance in science, claimed Einstein and Infeld (1938). The way a problem is framed, exclaimed Baillie (2002), often reflects the purpose which directs diverse means of mind towards creative ends.

The *phase of generation*, also described as brain-storming (Osborn, 2008), involves shaking out all associative ideas or concepts to the problem. Engineering students, after having defined, reformulated and redefined the problem or question, move towards generating solutions as many as possible. Oslapas (1993) opined that Many creative brainstorming techniques, including mind mapping, symbolic analogy, forced connections, and manipulative verbs can be used at this stage.

The *incubation phase* is a period of full relaxation or relaxed attention, which allows one's subconscious intelligence to suggest solutions. Reportedly, people often generate a potential idea after a certain time of incubation (Tomic and Brouwers, 1999). For example, many solutions to difficult challenges can often be resolved after a break away from active processing. The most renowned example may be that German chemist Friedrich August Kekule von Stadonitz cracked the ring structure of benzene after a schnapps, in which he dreamingly saw a whirling serpent that was swallowing its tail.

The *verification phase* includes, according to Baillie (2012), analyzing, clustering, and evaluating all the solutions or ideas, and planning and implementing actions. For example, an engineering student attempting to solve an engineering problem begins by collecting all possible reasons and solutions by brainstorming, and then analyzing, clustering and evaluating the solution based on his or her experience and knowledge. A few most possible solutions will then be chosen. Next, the student focuses on planning the action such as the design of experiments. Once planned,the student can move toward implementing the actions needed to solve the problem, starting with experimentation of the most possible solution.

Barriers to Creativity

Davis and Palladino (2000) posited that the development of creativity is affected by personal and situational factors. Situational factors (e.g. mood, reward, motivation and attention) may exert less adverse influence than personal factors (e.g. knowledge, skills, and attitude) which may eventuallyeradicate creativity. It is the instructor's responsibility to teach students how to recognize and remove blocks to creativity. According to Christiano and Remires (1999), some of the common blocks include:

1. *Fear of the unknown*. Avoiding unclear situations; overweighing the is known versus the known; and needing to know the future before going forward. *Solution*: teaching students efficient means of information gathering skills to clarify the situation.
2. *Fear of failure*. Drawing back; not taking risks; and settling for less in order to avoid possible pain or shame of failing. *Solution*: providing students with opportunities of failure with the intent of using these opportunities as teachable moments – times when students are usually most receptive to an explanation of why it did not work.
3. *Reluctance to exert influence*. Fearing of using aggressive or pushy behavior which may influence others; hesitating to stand up for what one believes; and failing to make oneself heard. *Solution*: incorporating stories of inventors who, because of their persistent belief in their innovations, even when faced with opposition, provided valuable products.
4. *Frustration avoidance*. Giving up too soon when faced with obstacles, in order to avoid the pain or discomfort that is often associated with change or novel solutions to problems. *Solution*: telling stories about great inventors, such as Edison who survived thousands of experimental failures.
5. *Resource myopia*. Failing to see one's own strengths; and depreciating the importance of resources (i.e. people and things) in one's environment. *Solution*: role-modeling integration of personal strengths with the resources available.
6. *Custom-bound*. Over-emphasizing traditional approaches or methods; and strongly revering for the past; and tending to conform even when unnecessary. *Solution*:

providing students with opportunities to brainstorm new ideas based on classic traditions.

7. *Reluctance to let go*. Trying too hard to push through solutions to problems, instead of letting things happen naturally; and distrusting of human capacities. *Solution*: providing students opportunities to make things as they wish and encouraging them to go ahead.
8. *Impoverished emotional life*. Depreciating the motivational power of emotion; attempting to hold back spontaneous expression; and neglecting the importance of feelings in achieving commitments. *Solution*: providing opportunities of celebrating student achievements. Some engineering schools achieve this through various national and international competitions, rewarding the creative efforts of students.
9. *Over – certainty*. Persisting in non – functional behavior; and failing to check out one's assumptions. *Solution*: providing students with opportunities to reflect and evaluate their methods of creative problems solving.

Christiano and Ramires (1993) observed that intelligence may also challenge creativity Many students with orthodox education tend to have their thinking confined in specifically structured patterns, and rarely show variation in their thoughts. Although these students are more likely to effectively accomplish short-term tasks (e.g. assignments in a course), they may be unable to deal with real-world problems, which are constantly in flux (Dacey, 2005). Solution for these students is to be part of team or group projects in which other team members role model thought process variation in solving problems.

Engineering Perspectives on Creativity

While Jackson (2014) observed that engineering is a discipline that seems to recognize and value creativity, US Engineers Council referred engineering as the creative application of scientific principles. The manifestations of engineering creativity are overwhelming in everything that surrounds us, and the nature of ingenuity and creativity remains elusive. Furthermore, Felder and Brent (2003) argued that today's education system neither promotes ingenuity nor provides all the necessary tools to sustain it. Engineering requires innovation, creativity and flair focused in a design process…. Design is at the heart of engineering and it is there that professional engineers demonstrate their creativity and innovations (Felder and Woods, 2000).

The need to study creativity and understand its underlying mechanisms is now globally accepted by the scientific community (Sawyer, 2012). Many studies testify the importance of engineering to the community (Badran, 2007). Being frequently in a position where there is a need for innovation, engineers should be able to actively participate in the creative process. The development of creative skills as part of engineering training is therefore essential, crucial and indispensable as Morin, Robert and Gabora (2014) rightly observed.

Barriers to Creativity in Engineering Education

Jackson (2014) listed the following as barriers to creativity in engineering education:

1. Related to teaching – what the teacher does:
   i. Too much time is spent on teaching details which are either irrelevant in the education context or the knowledge would be picked up in practice.
   ii. Reluctance of teachers to try fresh teaching methods as they require more time and offer no real promotional benefits.
   iii. Formal evaluation of teaching performance which is good for ensuring standards are maintained or established but kills creativity as those in charge are more concerned with procedures and less about education
   iv. Having tutors or mentors who are not experts or who have not had sufficient real practical experiences.
   v. Interfering too intrusively in the student's practicing of the various processes involved.
   vi. Failing to give adequate importance/currency to the creative aspects of the activity (e.g. not giving an appropriate portion of the available marks to that part of the overall activity).

vii. Over loading the students (in the module, or in the wider curriculum).

2. Relating to assessment and motivation:
   i. The assessment/evaluation of the learning process being purely extrinsic (i.e. externally determined and allowing students no or little personal ownership or say in the process.
   ii. Overloading the student in the module or in the wider curriculum – which often invokes the adoption of intelligent coping strategies e.g. role memorization or surface processing of the learning material.
3. Relating to what the students' do:

   Activities that do not involve at least simulation of the real creative process, but which are too abstracted from it (e.g.) mere verbal or algebraic-numerical, linguistic representation of the process.

4. Relating to perceptions:
   i. Some engineers believe one has to 'produce a working model or device' before he/she is regarded as creative. This, in turn, prevents them from taking an idea further.
   ii. Lack of perception by the student of the relative importance and relevance of the activity.
   iii. Many students create new devices, approaches, etc in a non academic situation. For example the students in Singapore are very creative in coming up with solutions for non academic activity but see academic work as 'routine' and creativity is not welcome (Jackson, 2014).

Engaging, Activating and Encouraging Creativity in the Classroom

Shaw (2001) said that since creativity emanates from problems, it seems more natural for engineering students to gain creativity through practice of problem-solving, as they are inevitably expected to be effective and creative problem-solvers. Wright (1994) added that teaching the students systematic approaches to solving problems is very important, because understanding the routes of problem-solving may help illuminate how to activate creativity in the students. Hoover and Feldhusen (1994) proposed a theoretical model of the systematic problem-solving pathway, starting from sensing the existence of a problem and ending up with verified solutions (see fig. 2). Treffinger, Isaksen and Dorval (2007) reported a simpler version, which is based on four components: understanding the challenge, generating ideas, preparing for action, and planning approach. An effective teaching strategy would thus be to walk students through the pathways using several engineering problems, in order to demonstrate the usefulness and efficiency of following through the strategy.

Fig. 2: Problem – solving pathway (adapted from Hoover and Feldhausen, 1994).

Following the creative process and systematic pathways of problem-solving, the creative learning model proposed by Treffinger Isaksen and Dorval (2003) is a powerful tool for an instructor to stimulate and develop creativity in engineering students. The model consists of three hierarchical levels: learning and using basic thinking tools; learning and practicing a systematic process of problem solving; and working with real problems. Each of these is further detailed below.

Level 1: *<u>Learning and using Basic Thinking Tools</u>*

The instructor begins with direct instruction in using thinking tools, and then incorporates the tools into course contents. Note that students need to know how to use the tools specifically and effectively, in order to facilitate the idea generation process in the creative process (Baillie, 2002). Sample thinking tools include:

1. Analogical thinking
2. Brainstorming
3. Mind mapping
4. Attribute listing
5. Morphological synthesis
6. Force relationships or connections
7. Idea checklists
8. Manipulative verbs

Analogical thinking is to transfer an idea from one context to a new one (Davis, 1992). He further said that, the invention of Pringles potato chips is a result of analogical thinking: the idea was inspired by the analogy of wet leaves, which stack compactly and do not destroy themselves. To implement this technique, students are encouraged to deliberately ask questions like 'What else is like this?', 'What have others done?', 'Where can I find an idea?' and 'What ideas can I modify to fit my problem?'

As the most frequently used tool to generate new ideas (Oslapas, 1993 and Davis & Palladino, 2000), *brainstorming* means bouncing ideas out about a subject, no matter how wild or ridiculous they may appear. In order to obtain high-quality results, the instructor and students need to observe some rules of thumb. According to Rossiter and Lilien (1994), the instructor should follow six principles of brainstorming:

i. Give instructions and emphasize the number not quality of ideas.
ii. Set a difficult goal for the number of ideas.
iii. Ask individuals, not groups to generate the initial ideas.
iv. Use groups to integrate and refine the ideas.
v. Ask individuals to provide the final ratings and to select the best ideas.

vi. Keep the time short for brainstorming.

In addition, the instructor should encourage originality and elaboration of any ideas, but not criticize and evaluate the ideas until all responses are collected.

Mind mapping is a variant of brainstorming. Oslapas (1993) said it involves tracking and recording our thoughts in pictures (or sketches) as well as words. This technique tends to reflect our thinking more accurately than brainstorming does, because we think in both words and pictures.

While brainstorming or mind mapping is a general procedure, *attribute listing* is a technique specifically oriented towards idea-finding. By this technique the students begin by identifying all characteristics or attributes of the subject (e.g. product or process) being studied, and then think up ways to change, modify or improve each attributes (Wright, 1994). *Morphological synthesis*, and *forced relationships or connections* are elaborations of the technique of attribute listing (Oslapas, 1993 and Davis, 1992). After the list of all attributes required for the subject is generated, the students are asked to create attribute sub-lists by putting as many alternatives under each attribute, and then to take one item from each sub-list and combine them into new forms.

The thinking tool of idea checklist means making a checklist that will encourage the user to examine various points, areas, and design possibilities of a subject (Wright, 1994). A sample checklist according to Wright (1994) for a device improvement may include ways to:

i. put the device to other uses;
ii. modify the device;
iii. rearrange the device;
iv. magnify the device;
v. reduce the device.

Similar to idea checklist, the technique of *manipulative verbs* utilizes a series of verbs to help seeing a subject from a fresh perspective (Oslapas, 1993 and Osborn, 2008). Chose the verbs that suggest the ways the subject can be manipulated (e.g. alter its shape, function, and size). Sample verbs include magnify, minify, rearrange, alter, modify, substitute, reverse, combine, etc. (Oslapas, 1993 and Osborn, 2008).

Learning and using basic thinking tools open up more channels for students to highly-efficient divergent thinking (with concurrent gains of fluency, flexibility, originality, and elaboration), and thus help students to engage in the initial stages of the creative process (i.e. preparation and generation). However, more is required for creativity to be fully activated. Students require exposure and adoption of a systematic process of problem solving.

Level 2: *Learning and Practicing Systematic Process of Problem Solving*

The instructor continues by providing opportunities for students to learn and practice systematic steps or processes for effective problem solving. Level 2 extends the use of the tools from Level 1, and provides a structural methodology for their applications in solving problems. It is critical for the instructor to ensure that the students understand the systematic problem-solving pathways, and promote the 'right' practice problems. Basically, individuals tend to work with the problems associated with their needs, values and interests, which are more likely to motivate them for problem construction and creative thinking (Mumford, Palmon and Redmond, 1994). In addition, the problems should not be too challenging for the students. Although many believe that more challenging problems lead to more creative ideas, an optimal level of challenge exists for effective problem solving – moderately challenged students normally show the best results (Deci, Vallerand, Pelletier and Ryan, 1991). Example teaching techniques include case studies, simulations, role playing, and group or team work (Woods, 1996).

In case studies, the instructor poses specific situations or cases, and asks students to generate potential solutions and evaluate them (Woods, 1996). Although the selection of cases depends on a specific curriculum, Felder and Brent (2003) suggested the involvement of current global issues relevant to engineering, such as environmental/economic tradeoffs, problems related to globalization (e.g. moving of production facilities to other countries), and pros and cons of government regulations of private industry. Higher-level challenges can be further raised by occasionally introducing case studies of real-life industrial or problems from current research projects problems. The students are asked to identify what they would need to know to solve the problems and how they would go about obtaining the needed information (Felder and Brent, 2003).

Students can also learn problem-solving skills through computer simulations. Here the students are required to solve problems through using computer software. In fact, Felder and Brent (2003) affirmed that computer simulations have been used to conduct extensive parametric studies and process optimization (Felder and Brent, 2003). For mechanical engineering students, such simulation could be analyzing the mechanical behavior of a steel-constructed bridge with a constant load of traffic, using a finite element analysis software package (e.g. ABAQUS). The key in computer simulations is not to simulate the product itself (e.g. the bridge), but to test, evaluate or validate the situations (e.g. the constant heavy traffic) where the product is supposed to function (Christensen, 2002). Extensive drilling engineering students in computer simulations is more necessary than ever, because the simulations are often more cost-effective than physical experimentations, and have been used in almost all areas of engineering.

Role-playing is to have students, acting as identified key factors of a problem, interacting with one another, and asking them to conclude what combinations of the factors would eventually solve the problem. For example, getting students to role-play molecules in a reactive gas would teach them more about the dynamic behavior of a given system than would a standard lecture (Oslapas, 1993).

Even though an engineering problem could be resolved independently, more than ever it would involve interactive collaboration through group or team work. Actually, case studies, role-playing, and practice problems could be implemented in a form of team-work. Members in a group or team can provide one another with feedback, and challenge one another’s conclusions and reasoning. More importantly, they can teach and encourage one another through team-work (Treffinger et al., 2003) while gaining interpersonal and team-player skills which are also very important to a professional engineer (AEAC, 2004).

Training in both divergent and convergent thinking (e.g. deriving solutions by computer simulation) is involved at this level. Having been exposed to the full stages of the creative process through solving practice problems, students should have a creative mind, which will further mature through working with real problems in Level 3.

Level 3: Working with Real Problems

The objective of this level is to improve students' capabilities of and effectiveness in handling real-life problems and challenges. Working with others at this level, the instructor serves as a facilitator. Unlike Level 2, where the students learn the methodologies others have used to solve problems (e.g. by means of case studies), students must experience first-hand through hands-on unsolved problems at Level 3. In fact, students are expected to act as professional engineers, using the skills learned in Levels 1 and 2 to generate ideas, to identify the key issues, and finally, to solve realistic problems within certain restrictions (e.g. time-frame, cost and materials).

Example of real problems include personal or group concerns, community needs or issues, new product (programs or actions), individual/organizational needs or opportunities, and special projects (e.g. the instructor's own research projects). The success of gathering real problems or cases requires the instructor to maintain current contacts with industries and keep abreast of contemporary developments of the related area. Sending students to an environment where they would be going to after graduation would empower them with confidence and challenge them with the real responsibilities and pressures of a professional engineer.

Conclusion

Understanding creativity and the creative process in the context of engineering is essential for an instructor to be able to foster creativity in engineering students. In addition to teaching students to identify and remove the blocks to creativity, the instructor can use the creative learning model to further facilitate and nurture students' creativity through teaching strategies oriented towards problem-solving. Success of the CASE (Creativity in Arts, Science and Engineering) project (DeWulf, and Baillie, 2008) may suggest that creativity potential often lies dormant in most students and it is the instructor's responsibility to unblock the barriers and unlock or ignite creativity.

Teaching creativity in a university setting does not mean that every graduate will become an Edison or Einstein. It does, however, suggest that students might become creativity productive in meaningful ways. Teaching with a purpose of facilitating creativity would also help students learn more about their own creative abilities, and attain greater personal and professional success and satisfaction through creative efforts (Treffinger et al., 2007).

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