Title: Nurturing Creative, Thinking Engineers

Author Name: Sanjay Goel,
Jaypee Institute of Information Technology, Noida, India

Publication date: September, 2011
Book: Engineering Education: Challenges, Changes, Champion Teachers,
Editor – Viney Kirpal,
Publisher: WIPRO, India

NURTURING CREATIVE, THINKING ENGINEERS

SANJAY GOEL

Computer Science and Engineering

goelsan@yahoo.com

Engineering involves conception, design, invention, development, application, improvement, and production with an emphasis on current and future needs of society. Engineers plan, design, test, integrate, maintain, improve, reverse engineer, re-engineer. They also evaluate components, products, applications, systems, services, standards, processes, and methodologies encompassing various artifacts. They investigate complex problems, identify and develop best practices, document and defend findings. They make decisions even under conditions of unreliable and misleading information and provide consultancy on multi-faceted complex problems. In the process, they are also required to criticize assumptions and inferences as well as face questions of ethics and sustainability. Trends of growing complexity and fast-paced innovation have further increased the importance of both creative and critical thinking in engineering. This paper describes an experiment with training student engineers in creativity and critical thinking.

Thomas Disch has defined **creativity** as the ability to see relationships where none exist. According to Albert Rothenberg, the creative process is a matter of continually separating and bringing together, bringing together and separating in many dimensions.

In the context of engineering, creativity is necessary for designing innovative artifacts, systems, processes, and underlying theories. The biggest hindrance to creativity is the misconception of "knowing it all." Even young students start giving too much importance to pessimistic views and impediments because of the pressure to succeed, the memory of past failures personal others,' the feeling of insecurity, self-doubt, lack of confidence, etc. The overall socio-economic eco-system in India also encourages the students to avoid even small risks and follow some proven paths.

According to John Dewey **critical thinking** involves active, persistent, and careful consideration of a belief or supposed form of knowledge in the light of supportive evidence and the conclusion to which it tends. Critical thinking is necessary for controlling reasoning errors in various stages of engineering activities.

Critical thinking is considered as left-brain activity whereas creativity is ascribed to the right-brain. Creative thinking helps engineers in restructuring the problem/decision task, generating alternatives, and selecting decision criteria and strategies. Critical thinking is essential for them to understand complex and fuzzy situations as well as to make good and apt decisions. Critical thinking enables them to evaluate their options with respect to completeness, consistency, performance, usability, cost, extensibility, scalability, and so on. Creativity and critical thinking are crucial for engineering professionals.

According to a 2010 Nasscom report [1,2] India's fast growing engineering R&D services industry has reached $10 billion. According to this report, **there are over 300 captive Engineering R&D facilities in India employing about 85,000 engineers. Further, the leading 20 independent service providers that serve multiple verticals, employ over 60,000 engineers.** Nasscom forecasts that this industry will reach $24 billion by 2015, and possibly $45 billion by 2020. During this period, India has the potential to capture a 40% share of global offshore revenues in 11 key verticals of engineering R&D services -Aerospace, Automation, Telecom, Semiconductor, Computing Systems, Consumer Electronics, Medical Devices, Energy, Infrastructure, Industrial Automation, and Construction/Heavy Machinery. *This new opportunity can only be leveraged by emphasizing creative and critical thinking as core learning outcomes in engineering education.*

Traditionally, the focus in engineering education has not been well-aligned with these goals. The community that is responsible for transforming the lifestyle of the world has not yet transformed its own educational process. In the 1980s, Felder [3] remarked, "We teach primarily mechanics, and not reasoning methods; memorization and routine application, and not analysis, synthesis and evaluation. We don't encourage creativity and independence of thought, and in fact often do our best to discourage them." Sadly, much has not changed over three decades. The typical pedagogical engagements of engineering students do not help in enhancing their creativity, critical thinking, and innovative problem solving [4,5].

In 2009, we had conducted a survey among working software engineers and asked them to rate different pedagogical engagements with respect to the effect on various competencies including creativity and critical thinking. A large majority (82%) of respondents felt that as compared to all other kind of academic engagements, their projects had contributed most to develop their creativity. About 50% had also felt that their projects were also the most effective in nurturing critical and reflective thinking in them. Thinking-oriented lectures, research literature surveys, and discussions with students and faculty were perceived to have added to the cultivation of these competencies. *Written examinations, knowledge transmission-oriented lectures, and routine homework were found to be least effective* [6]. Unfortunately often engineering education revolves around these three pedagogical engagements.

When I was asked to write this paper, I decided to approach some of my former students and requested them to recall those educational experiences, instructions, interactions, interventions during their engineering education that contributed to enhance their creativity or critical thinking or both. Within a week, I received more than fifteen responses from some excellent professionals. Most of them had graduated in year 2005 or later. One of them had graduated in 1993. Some of them had pursued MS at universities like Stanford, CMU, Cornell, etc. Many of them had worked or are working with companies like Microsoft, Adobe, Bloomberg, etc. Some important excerpts from these responses lave been collated in the Appendix.

Curiosity is the most fundamental requirement for ‘learning.’ Incongruity, contradictions, novelty, surprise, complexity, and uncertainty can arouse curiosity. Cognitive Dissonance Theory [7] postulates that recognition of an inconsistency results in cognitive dissonance, and motivates an individual to resolve the dissonance. The traditional teacher-centric didactic education does not create much dissonance among learners. However, inductive instructional approaches like Inquiry teaching or *Problem Based Learning (PBL) succeed well in creating the required dissonance.* Alumni’s feedback given in the Appendix shows that inductive instructional approaches are very effective not only for learning the subject matter, but also for sharpening the creative and critical thinking skills. In my personal experience, using inductive instructional approaches is the strongest catalyst for enhancing students’ creative and critical thinking skills. Inductive instruction’s gains can be further enhanced with the help of many other supplementary ideas. Some such ideas have been successfully tried out by us in our courses offered by CSE and IT department of Jaypee Institute of Information Technology (JIIT). A few of these are listed below:

1. We ensure that students experience *sufficient academic rigor*. Full time PG students have a minimum of 50–60 hours of weekly engagement. It includes the time spent in lectures, tutorial, seminars, laboratories, project work, assignments, literature survey, field work, and self study, etc. As against the normal requirement for UG students of 20-30 contact hours per week, faculty members regularly design and monitor assignments and student-projects to ensure student engagement for an additional 30-40 hours per week. Unfortunately, a very large number of Indian engineering colleges and faculty members do not attempt to provide any such involvement and rigor. I believe that all faculty members should develop the habit of giving some challenging assignments after every class, even if it means more work for them and their students.

2. Students are frequently required to observe, analyze, create, and evaluate. The exams and assignments pose higher level challenge to the students. Exams that mainly engage the students in activities like asking them to calculate, explain, prove (studied theorem, studied method), define (studied definitions), write, solve, etc encourage rote learning only. First hand observation is necessary for both creative as well as critical thinking. The students are frequently engaged in collecting primary data by observing people, the environment, artifacts, systems, or processes. Subsequently, assignments are given that require them to conceive and propose some artifacts or theoretical constructs to enhance their creativity. The assignments that require them to evaluate artifacts, theoretical constructs, or proposals contribute towards sharpening their critical thinking ability.

3. Most of our engineering courses have a semester-long group project to engage students in engineering activities like planning, estimation, design, development, troubleshooting, debugging, testing etc. However, rather than viewing a project as

the culmination activity, we view it as the instrument of creating a richer context for learning the subject matter. Though it significantly increases the workload of students as well as the faculty, its benefits in terms of student learning are worth the effort.

In project-centric teaching, we reverse the traditional teaching methodology. In our scheme, at the beginning of the course, the teachers first help and guide the students to formulate the initial project problem. Examples and templates are used to complete this task. Since it is not possible for the faculty to discuss every project in the large class, they select one or two of these projects to define the initial and simplistic project scoping and specification of these projects through classroom discussion. Students follow a similar process to complete these tasks for their projects. Faculty guide the students to incrementally enhance their project scope later in the semester, essentially to create the context for the forthcoming concepts and topics of the subject matter. They refine the project scope before introducing any new topic.

The faculty brings in the concepts after setting the context. Conceptually, this model has some similarity to zero inventory manufacturing practice. The learners are not given a large inventory of unused concepts. The concepts are introduced only after creating the need for its use with reference to the students' semester-long project. We have developed the conceptual schema[8] for defining the main characteristics of student projects' evolution in project-centric evolutionary teaching of 'Object-Oriented Programming,' 'Software Engineering,' 'Database Management Systems,' 'Web Application Engineering,' 'Enterprise Software Development,' 'Information Systems,' and 'Object Oriented Systems and Programming.' All these schemas have also been tried in their courses by concerned faculty members at JIIT. The evolutionary stages of the defining characteristics of student projects in a course called 'Web Application Engineering' are given below as an example:

i. Single Thin Client Web Application
ii. Single Thick Client Web Application
iii. Multiple Thick Client Web Application
iv. Multiple Rich Client Web Application
v. Multiple Rich Client Web Application with automated database population
vi. Secure Multiple Rich Client Web Application with automated database population
vii. Mobile enabled Secure Multiple Rich Client Web Application with automated database population.

After every iteration, a short but *reflective report writing* and/or face-to face sessions multiply the learning benefits of the projects. I have personally found Borton's three questions for reflection – *What? So what? Now what?* --very effective for structuring such reports. The first of these questions is about observation, the second stimulates critical thinking, and the third engages students in creative thinking.

4. Most interesting ideas develop at the intersection of diversified disciplines. Hence, *Interdisciplinary projects* are encouraged. Students are motivated and guided in applying their engineering skills to the domains of their interest. Some of my students have done some very interesting projects in the area of computer music. Some others have been able to integrate their interest in painting and dance with their computing knowledge and skills to create some very unusual projects. There are many other such examples in other domains like sports, theatre, cartoon making, puppetry, etc.

5. Frequent opportunities are created for engaging the students in *brainstorming.* These brainstorming sessions engage them in (i) identifying the limitations of the existing systems, artifacts, and processes, and also (ii) proposing the specifications of newer systems, artifacts, and processes. Techniques like 'Six thinking hats' developed by De Bono [8] are very helpful in productive brainstorming. During different thinking modes of this technique, the participants are required to engage in creative as well as critical thinking.

6. Techniques like *Osborne's checklist (SCAMPER)* and *TRIZ* have been found to be very useful for inculcating creative thinking among students. All these techniques can be easily integrated in the context of any engineering course. SCAMPER is a very simple and easy-to-use creative thinking tool. SCAMPER is the acronym for Substitute, Combine, Adapt, Modify/Minify/Magnify, Put to other use, Eliminate, and Rearrange/Replace. I have often used this technique in the classroom to stimulate novel ideas generation by students. Forty TRIZ principles[9] for inventive problem solving have been identified after examining a huge number of patents. These principles have also been used to stimulate and nurture creativity in students in some of my courses. Since 1996, 'The TRIZ journal' is being published every month. Interested readers are encouraged to refer to this wonderful resource.

7. Use of *models and standards of critical thinking* is very useful for structuring critical analysis activities. Paul's model of critical thinking[10] has been found to be very effective in developing critical thinking. Critical thinking involves the processes of identifying, analyzing, synthesizing, evaluating, reviewing, and considering the subject in the light of multiple standards like clarity, specificity, relevance, logical, significance, consistence, breadth, depth, accuracy, precision, fairness, and completeness. I have often asked students to critique some engineering artifacts or theories with the help of Paul's model. In the specific context of developing engineering systems' oriented critical thinking, Paul's model can be further enriched with additional standards like performance, usability, cost, extensibility, scalability, modularity, maintainability, reliability, public health and safety, social concerns like privacy and equity, sustainability, etc.

8. We also engage our senior students to mentor the projects and other activities of junior students. This improves their critical and creative thinking of senior students. (Another paper in this book discusses the details of this approach).

A curriculum that overemphasizes established theories, processes, and best practices inhibits the development of creative and critical thinking [11]. Often science and engineering subjects give the impression that there is always a right answer and that the 'facts' will resolve disputes. They concentrate on mathematical analysis rather than creativity and critical analysis[12]. Li et al[13] have found that self-perceived gains of students' critical thinking skills most significantly depend upon the degree of their integration into the academic and social community of the university and the quality of the initial courses. The quality of teaching and the quality of curriculum were found to be the most significant factor in influencing their academic and social integration respectively.

Amoussou et al[14] have identified and collated the following activities for enhancing creativity and design in computing courses:

(i) reflecting on the sources of inspiration including brainstorming techniques,
(ii) reflecting on bias that may affect creativity and design,
(iii) identifying and defining the steps of the design process and providing design examples,
(iv) identifying and defining criteria and constraints,
(v) practicing methods of evaluating options,
(vi) reflecting on norms of communication, and
(vii) discussing ethics within the context of design.

Lassig [15] has proposed adopting a balanced view about six environmental conditions to inculcate creativity in computing students'. These are:

(i) a supportive and nurturing environment that also provides obstacles and challenges,
(ii) some constraints are helpful for novel/unfamiliar tasks that are to be performed with limited knowledge and skills,
(iii) evaluation generally inhibits creativity. When it must be done, the criteria should be clear. Self-evaluation can also facilitate creativity,
(iv) if the task is not too difficult, competition can stimulate a person who is initially not very motivated. However, if the task is difficult or the person is already motivated, competition can create anxiety and inhibit creativity,
(v) enthusiastic cooperation does not automatically lead to more creative ideas, and
(vi) role models are helpful in enhancing creativity, only when they encourage independent thinking.

The success of these or some other ideas mainly depends upon the faculty's epistemological belief about the importance of providing opportunities to nurture creative and critical thinking through their courses. Such efforts are not likely to succeed if course coverage continues to be considered as the single most important goal of teaching. Nurturing the mental habits of critical and creative thinking cannot be sacrificed or deferred for the sake of course coverage. Faculty members working at institutes with the status of universities, deemed university, or autonomous colleges have an advantage in being able to try out many of these ideas. However, I am sure that creative faculty members in other colleges can also find suitable ways of starting on this enjoyable and fulfilling journey.

References

1. Nasscom and Booz & Company, Global ER&D: Accelerating Innovation with Indian Engineering, 2010, http://www.booz.com/media/uploads/NASSCOM_Booz_ESR_Report_2010.pdf
2. InformationWeek News Network, India to capture USD 45 billion in ER&D services by 2020: Nasscom, May 21 2010, http://www.businessweek.com/technology/content/dec2010/tc2010128_116888.htm
3. Felder R. M., "Does Engineering Education Have Anything to do with Either One: Toward a Systems Approach to Training Engineers". R.J. Reynolds Industries Award Distinguished Lecture Series, North Carolina State University, 1982, retrieved from http://www.ncsu.edu/felder-public/Papers/RJR%20Monograph.pdf, pp 5-10, last accessed on October 16, 2005

4. Sanjay Goel, ''What is High about Higher Education: Examining Engineering Education through Bloom's Taxonomy'', *The National Teaching & Learning Forum,* Vol. 13, pp 1-5, Number 4, 2004.

5. Sanjay Goel and Nalin Sharda, ''What do Engineers Want? Examining Engineering Education through Bloom's Taxonomy'', Proceedings of 15th Annual AAEE Conference, pp173-185, 2004.

6. Sanjay Goel, ''Design of Interventions for Instructional Reform in Software Development Education for Competency Enhancement'', PhD Thesis, Jaypee Institute of Information Technology, 2010.

7. L. Festinger, *A Theory of Cognitive Dissonance*, Stanford University Press, Stanford, USA, 1957.

8. Edward de Bono, *How to have a Beautiful Mind*, Vermillion, London: 2004. Pp. 89-105. 'Six Thinking Hats' is a brainstorming technique developed by de Bono. According to this technique, at any time during brainstorming, all the participants collaboratively think in the same mode. The whole group simultaneously and consciously switches the same mode of thinking at the same time. He has identified six different thinking modes each represented by a different colour of the hat.

9. Kalevi Rantanen and Ellen Domb, *Simplified TRIZ: New Problem Solving Applications for Engineers and Manufacturing Professionals*, CRC Press, pp 129-210, 2002.

10. Richard Paul, Robert Niewoehner, Linda Elder, “The Thinker's Guide to Engineering Reasoning,” *The Foundation for Critical Thinking*, pp 4-24, 2006.

11. Luís Moniz Pereira & Ludwig Krippahl, ‘‘On Teaching Critical Thinking to Engineering Students’’, The 13th International Conference on Thinking, Norrkoping, Sweden, 2006, http://centrial,fct.unl.pt/~lmp/publications/papers/Critical Thinking07.pdf

12. Sharon Beder, ”Valuable Skills Learned from “basket-weaving “, Engineers Australia, pp 46, March 2000, http://www.herinst.org/sbeder/engineers/columns/probe3.html

13. Guihua Li, Shawna Long, and Mary Ellen Simpson, “Self Perceived Gains in Critical Thinking and Communication Skills: Are there Disciplinary Differences’?” *Research in Higher Education*, Vol. 40, No. 1, Springer, pp 43-60, February 1999.

14. Guy-Alain Amoussou, Eileen Cashman, Steve Steinberg, “Ways to Learn and Teach Creativity and Design in Computing Science,” Proceedings of Science of Design Symposium, Humboldt State University, ACM, pp 12-13, March 2007.

15. Carly J. Lassig, ‘’Promoting Creativity in Education -- From Policy to Practice: An Australian Perspective’, Proceedings of the seventh ACM conference on Creativity and cognition, ACM, USA, pp-229-238, October 2009.

APPENDIX

What Contributes to Creative and Critical Thinking: Excerpts from Alumni’s Reflections

Following are some excerpts from the responses of the alumni:

- *Open inventive atmosphere*…no 'stick to book only' approach. No copy book assignments/ Open book examinations
- *Problem Based Learning*..Starting from a problem and building towards a solution. In-class activities especially group based ones. In the next few minutes as the entire class scrambled to solve this group problem, we realized that our mental models of learning were about to be shaken up during this course. … till then, I had never attended creative classes like this where we participated in some class activity to develop some complex algorithm. …told us to think out of box and told us to come up with any new idea which we would like to see in the computer in the next few years...I remember everyone in class was jumping and thinking about something new. A step away from traditional methods of teaching and guiding us to look at life’s simple processes that we had taken for granted, providing a different perspective. Professor used to give a problem first, allow us to think and solve it for a couple of minutes and then introduce the algorithm to solve it. This approach piqued my interest in what was going to be taught and helped me get a better grasp of the

application of what and why we were studying. Professor always used problems, to explain a concept rather than starting with the theory. In one of the classes, professor even let us choose our own problem. We all decided on the problem of a scientific calculator. And with professor's help, guidance and prompting on all of us on our own designed the solution right from the functional requirements, data structure to the algorithm. When professor presented us with a problem, he would always prompt us or question us till we would start figuring out how to do it. In effect we were not only just developing solutions, but were helped to develop a line of thinking towards tackling any problem. And not only that, we would later even revise [evaluate] how effective our solution was, or if it was in fact the best solution to the problem that we had taken up. Professor showed us a presentation and asked each of one us turn by turn, to tell him what we saw, or what problem we could model around the object featured in the slide. Professor used to do the brainstorming during the lecture sessions.

- Writing a concept of future real systems in the form of *fantasy stories* as part of 'Data Structures' assignment was very innovative and some of our batch mates wrote about systems which are now becoming a reality…Many of these systems were discussed in a lecture class of 200 students and new ideas were generated.
- Theoretical courses didn't really help that much in enhancing creativity. Courses that focus more on *implementation* are my personal favorites and provide a window for enhancing your creativity significantly. When we entered the 'Data Structures' class on the very first day professor told us to select a project for the end of the semester and the whole semester we worked on that project and the end of that semester we were able deliver a project which was complete and made us understand what a software system looks like. That perspective was necessary and mandatory for engineering students as I find most people lacking that. Assignment to develop a new Game. …create an educational game that I first enjoyed any kind of programming in college. If necessity is the mother of all invention then pleasure in work is the source of creativity.
- Students saw Professor as 'ambitious' and not laid back. Some like me were inspired to be ambitious 'Forcing' us to work on tough problems made me dig deeper and go beyond my comfort zone and this is what results in true experience… I do remember thinking about this problem back and forth… taught me to critique my own solution and come up with counter examples that broke my algorithms thereby helping me come up with a solution which I would be fairly confident upon.
- *Active involvement of Professor* with the students and probing at the right time with right intent. …having a professor available at odd hours did boost student's morale and 'go-getting' attitude.
- Professor's passion for applying computer science to problems in other domains/ We toured art galleries to broaden our horizon. Allowed me to think at systems level, without boundaries and unconventionally. I was encouraged to work in the area of Computer Music and center most of my course activities like Projects and programing exercises around Music. This helped me get more interested in applying Computing Science principles and knowledge to areas "outside" the realm**.** we were trained in. looking at the larger picture**,** think about important design issues, learn to focus on one domain and excel in it.

- Students were free to choose their projects/goals, team size and team members, Assignments for reading, summarizing, validating, or extending research paper
- Major contributors for nurturing these traits were books, documentaries, tons of movies, and meeting very smart people. Professor emphasized much on reading a range of good books on our course as well as our subjects. I realized the significance of this much later.
- I remember somehow hearing "*a quick solution is a dirty solution"* in my head if something seemed too simple. Always made me to reevaluate… The most important thing I learned from 'Data Structures' classes is to dig out the problem completely before acting on it.
- Use of existing models helped structure the otherwise abstract task of critical thinking.
- Sincere conversation: …that was also the longest conversation, I have had with anyone regarding my general outlook towards life…In that single conversation I learned more about myself than I had in about 20 years … Sometimes *it's just about asking the right question.*
- Professor provided many opportunities to present our work and let people know about it. Recognition led to additional pleasure and encouragement/prizes were always great for positive reinforcement.