Fostering Inventiveness in Engineering Education – an International Perspective

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Abstract

Who is an engineer? What set of creative and other capabilities should an engineer posses? What should be taught and what can be developed with experience? This paper describes some basic differences in views on substance of engineering knowledge and inventiveness, as well as pluses and minuses of some aspects of engineering education in North America, Europe and Eastern Asia. Views by industrial leaders and engineering professionals from different countries on weaknesses in preparation of mechanical engineering graduates for professional carrier and its challenges are also included. University role in preparation of professionals versus industry short-term and long-term demands for skills of a graduate is described from perspectives of engineering professors and engineering professionals advising applied engineering programs.
Engineers of the future: 'inventors' or 'improvers'? Should students be taught how to invent or how to improve first? Can inventiveness be taught? This paper attempts to show how the answers to the above questions differ among cultures and various models of engineering education.

1. Introduction

Significance accorded to engineering knowledge, engineering skills and inventiveness vary from country to country. Learning process starting in early childhood and teaching methods used reflect functioning of the society a person is raised in. The result is formation of a professional molded by the society to its cultural and ethical environment and largely to its self-perceived needs. Technological competition on the global market requires a deeper insight into a significance of various aspects of engineering knowledge and inventiveness. Different approaches to the education of engineers should be scrutinized and recognized for their strengths and weaknesses.

It is widely accepted in North American culture, that reasons a person is gifted intellectually or physically, is creative or inventive can be traced to person's inborn talent. Creativity and other talents cannot be acquired by learning; hence teaching them is fairly pointless. A champion sportsman is made of 80% of inborn talent and 20% of hard work. On the other hand, the hard work and focus on goals are among the cornerstones of North American culture. In contrast to the above perception of the origins of personal talents, cultures in East Asia and to some degree in Central Europe emphasize continuous hard work as the most important virtue of successful professional or sportsman (20% of inborn talent and 80% of hard work make a champion). Parts of these believes can be traced to social culture, living conditions and often religion of each region or country. Stemming from them are expectations and roadblocks faced by young people: promotion of novelty versus maintenance of old tradition, defiance of authority versus respect, submissiveness and patience, glorification of exploratory drive of youth versus status-quo and wisdom of elders, best is yet to come versus good old days, new improved ways versus good old ways, and so on.

2. Engineer == Creator =?= Inventor

2.1 Ingénieur

The origin of word 'engineer' has nothing to do with locomotives, engines or motors as commonly perceived in English speaking world. It traces its roots to French '*ingénieur*' which was derived from '*ingénier*' (to exert somebody's mind), '*ingéniosité*' (ingeniousness) and '*ingénieux*' (ingenious). The origins of '*ingénieux*' point mainly at 'ingenious' rather than just 'thought over' but do not point at 'inventive' (*inventif*). So, is engineering about inventing? Ideally yes. Famous phrase by Theodore von Karman "Scientists describe world that is, engineers create world that never was". Engineering is about creativity, and ideally about inventing too. But do we even know how a human mind comes up with an invention? A successful engineer has not only traits of a scientist, technician, and craftsman, but also of an artist, accountant and others.

2.2 Creativity and Inventiveness

There is no single understanding of words '*creativity*' and '*inventiveness*'. Creativity is often understood as creation of something new, but not necessarily ground breaking. Inventiveness is often understood as creation of something innovative, something totally new that never existed before. The dividing line between '*new*' and '*innovative*' is in most cases extremely elusive which is the reason for words creativity and inventiveness being used interchangeably as well. More insight into the various levels of creativity is presented by DeBono, who also articulates the "Six Creative Hats" taxonomy [1]. Analysis of over 2 million patents done by developers of Theory of Inventive Problem Solving (TRIZ) shows that only 1% of the patents were based on a major scientific discovery, 4% based on field of discovery external to the scientific field of patented application, 18% based on existing technical system, while the remaining 77% were minor inventions or repackaged existing solutions [2, 3].

Altshuller [4] cites inconclusive results of many psychological studies aiming at describing creativity and process of creation. He concludes that till these days, psychologists truly dodge the problem by studying creativity using only experiments with brain-teasers and chess-type challenges. In essence, since 1940's, no new results have been obtained in explanation of process of creativity and its psychology [4]. It should be noted however that there are substantial differences between inventiveness and creativity based on field of application. Artistic creativity does not require nearly as much basic knowledge as technical creativity does. Metrics for assessing creativity in artistic works are subjective at best and difficult to define ("tastes cannot be discussed" says one French proverb). Assessment of technical creativity is usually very strict, in most cases can be measured, and often expressed in numerical terms by comparing new solution to old ones by using a set of metrics.

Playwright Rosoy's thoughts published in Questions of Philosophy in 1975 are cited by Altshuller [4] : "Everyone knows that the act of creativity is not arbitrary. … the starting point of the greatest achievements and discoveries in all spheres of culture, science, technology and art is the sudden moment of enlightenment which occurs unexpected and without evident cause. This is what creativity is." Russian engineer P.K. Engelmeier in his 1910 book "Theory of Creativity" writes that "…the general theory of creativity is the theory which embraces all phenomena of creativity, artistic creation, technical invention, scientific discovery and also a novel practical activity aimed at being used for anything at all. … it would appear that genius is not at all a divine and rare gift … but is the destiny of everyone who has not been born a complete idiot." Various methods for creative problem solving, some highly touted but controversial, were described by Fogler and Leblanc [16]. Paradoxically, in everyday life it is difficult to discern what an invention is and what is not, let alone to define a heuristic of how to make one. Nevertheless, expectations faced by engineers in the field of inventions are real.

2.3 Engineering Education

Since the very beginnings of engineering education in Ecole Nationale des Ponts et Chaussées established in 1747 in Paris, purely technical knowledge has been considered the core of engineering education. Accounts of teaching inventive problem solving to its élèves are limited to in-filed training/apprenticeship with an experienced military officer. Overall capability of a military officer was primarily judged by his ability to successfully solve problems on hand, whether using ingenious solutions or proven ones. The graduates were military men whose task was to outdo enemy forces by means of smart use of available knowledge, and even more importantly, to develop (create or invent) new equipment and work methods. Since early days of mankind, inventions were most tightly connected to warfare. With rapidly growing body of available knowledge, a uniform instruction of future engineers became necessary. L'Ecole Polytechnique established in 1794 in Paris, is considered to be the first engineering institution with a structured process of engineering knowledge transfer. The founders of that institution recognized that for future technological leaders (still primarily military, but increasingly civilian) knowledge and skills needed for a successful career, could no longer be provided by the centuries old education model of one master and few apprentices. Education of a goal-minded individual who uses technical knowledge as a principal tool and communicates effectively with non-technical personnel became the emphasis of the education in that institution. The principles of today's engineering work have remained virtually unchanged. Increasingly, functioning of an engineer is viewed in context of international scientific and economic environment. Many examples of approaches that evaluate value of creativity, efficiency and overall output of engineering work are available from academic and business point of view [6 - 11]. Experimentation was frequently an integral part of some inventive undertakings. Hands-on projects are believed to be one of the best avenues to teach the concepts of the above mentioned core knowledge and skills of present day engineers [12 - 14]. Some engineering programs have been almost totally revised to allow room for learning through doing, that is by creating educational environment that closer reflects real-world engineering practice [15]. Critical thinking and effective problem solving was described by numerous authors, among them Cloete who describes Eight Elements of Reasoning and problem solving heuristic [17].

3. Teaching Inventiveness

In technical inventions, the more difficult the task of invention (which in itself is very difficult to assess at the beginning of the process) the more numerous are the initial solutions which have to be analyzed in order to produce a set of feasible solutions. As described above, even if one believes that creativity cannot be taught, methods that promote creativity do exist and have proven their usefulness in at least the past 6 decades [1, 4, 14, 16, 27]. How to convince students that looking for simplest and robust solutions is better that optimizing existing ones? After all what is the use of all the knowledge they have acquired in various disciplines of science and engineering? Where is the room for continuous improvement?

Teaching of inventiveness is strongly related to the way engineers (also engineering students and in general students showing engineering aptitudes) think in action. How engineers think as compared to other professionals has been described by several authors, e.g. [14, 17, 18, 19]. These references do not explain though what makes engineers think creatively and how to build on it.

3.1 Search for the Best Solutions

One of the most daunting teaching tasks is to motivate students to prove that their solution has shortcomings, list them and look for a better (more robust) solution. It is like asking for development of lack of self-confidence and continuous self-doubting. That does not bring ‘feel good’ reward and is often taken personally. How to explain, and better yet convince, that one should not abandon seeking an ideal solution?

Best Solution = Ideal Solution

Example:

“The Ideal Machine is No Machine”.

The Ideal Machine is when an action is completed but there is no machine to do it. This way of reasoning is one of the fundamental directions of thought of the Theory of Inventive Problem Solving [5]. No room for optimization! Call for invention.

3.2 Methods of Activating a Creative Search

Brainstorming has been used by mankind for millennia (certainly longer than earliest forms of democracy). Modern, controlled form of brainstorming is credited to american A. Osborne who in 1940's structured its flow. He noticed that some people are more inclined to generate ideas, and some tend to be inclined towards critical analysis. In an unstructured discussion the above mentioned two groups vie for attention which produces very few useful results. In order to put some order and prevent obstruction of the creative process Osborne divided brainstorming into separate stages of generation of ideas and analysis of ideas. Sounds simple. Yet, let's ask ourselves how many successful and how many unsuccessful brainstorming sessions have we participated in our professional lives?

Synectics is considered one of the most powerful method of activating the search. It was proposed by american W. Gordon in 1960's. The synectic storm permits elements of instantaneous criticism and requires utilization of four special methods which are based on anlogy:

1. direct (how similar problems were solved)
2. symbolic (give in two words a model definition of the essence of the problem)
3. fantastic (how would figures in fairy tales solve the problem)
4. personal (try to put yourself into the object being worked on, and reason from that viewpoint)

While brainstorming can be taught in about one day, learning and practicing synectics is considered to require about one week.

3.3 Teaching Methods of Creative Search

From educational point of view there are many problems in teaching creativity using any method of idea generation, not only the two described above. The below two lists of problems are compiled based on surveys and personal thoughts.

From students' perspective (based on anonymous in-class surveys):
- an assignment for creative search is usually considered simple
- the search process is considered simplistic and fun
- documenting the brainstorming results is a waste of time
- students feel good about their accomplishments
- grades are almost always too low
- creative search methods are of little engineering value

From instructor's perspective (personal thoughts of the author of this paper):
- it is difficult to maintain order in multiple groups at the same time
- as a rule, students waste time on side thoughts
- students are very unwilling to sketch their ideas
- students (being aware of upcoming analysis stage) try at all cost to steer away from venturing into unknown physical effects and technologies
- no clear-cut answers make grading difficult
- students are almost always unhappy about the grades

3.4 Is designing 'new' educationally better than improving 'old'?

Teaching creativity (that is based on some systematic approaches) requires many exercises designed to spark innovative thinking. Many designers spend great deal of time rediscovering already existing solutions. Transposing proverb "Only fools learn from experience, smart peoples learn from history" into engineering ground, we can say that previously devised designs, both successful and unsuccessful, form a great base for learning inventiveness.

One of the important student activities that should be more often included in curricula are forensic case studies. These studies of failures can be used as lecture or lab example problems, homeworks and individual or group projects. A limited use of such case studies is already present, especially in civil engineering curricula. Other engineering disciplines, e.g. mechanical and electrical, offer equally good grounds for introducing study of failures. Such studies offer extensive possibilities of giving small to large size projects tailored to the level of students' knowledge, and as such could be used even during freshman year. The projects can easily blend theory and hands-on experiences. The forensic studies render themselves very well to use of various methods of creative search. In order to be an effective teaching tool, the forensic studies must be well prepared with known and proven answers in order to avoid students' dissatisfaction and stem any trend towards guessing, disorganized search for answers and 'anything goes' solutions. Many scholars assert that the forensic case studies teach historic perspective for the topic, spark students' interest about role of an engineer, professional ethics and expected practice standards in early stages of academic/professional education [20]. Is there a risk of frightening students with the consequences of poor engineering work? Certainly there is some, but Delatte argues that this risk is well worth taking [20].

4. Weaknesses of engineering graduates

Table 1 lists important Product Realization Skill (PRS) in which professionals form US industry perceive engineering students to have biggest deficiency gap in relation to industry expectations. It is noteworthy that these Product Realization Skills correspond very closely to the most important ones listed in Table 2. Is the American engineering education doing inadequate job in these areas and spend too much time in the less important ones? It is tempting to say yes, but one also needs to remember that mastering the skills listed in Table 1 requires experience and time to hone them. With the exception of teamwork and communication skills all other PRS must have a sound foundation of more basic engineering knowledge.

Table 3 shows list of weaknesses of engineering graduates and senior students in fields of mechanical, manufacturing and industrial engineering through author's international industrial experience. The list contains inputs from practicing engineers, engineering managers, owners of engineering businesses, technicians and customers (product end users who have technical education and expertise). The inputs cover the period of mid 80's till present and come from several European countries (Poland, France, Austria, Germany, Italy, Switzerland, Finland and

UK) and from Canada and the USA. Engineers in these countries are formed in three models of engineering education that historically were the most influential on global scale: German model of engineering education (prevalent in Central and Northern Europe), French (l'education polytechnique) and Anglo-American. Due to economical and social changes (especially in European Community) some differences between these models become less visible. Some generic aspects of engineering education that are common to Central and Northern Europe were described by King [21]. It is also important to point out that depending on social culture and professional expectations, some weaknesses are found to be more or less significant in different countries. Furthermore, some weaknesses are considered to be somewhat normal part of development of young engineering professional. Despite stressing Technical Rationality (scientific and engineering knowledge) throughout engineering curricula, certain aspects of knowledge constituting the core of the Technical Rationality are not taught to the satisfaction of industry (listed in Table 3 under numbers 1, 4, 5, 6, 7 and 9). As noted before, with growth of practical experience some weaknesses (mainly these numbered 1, 4, 5 and 6 in Table 3) tend to become less apparent. Although other engineering disciplines were not included in the process of compilation of this list, there are many reasons to believe that their graduates have similar weaknesses.

It is interesting (though somewhat expected) that list of engineering weaknesses as seen by the US industry [22] coincides with substantial portion of the list in Table 3. Some important additional items listed by Todd et al. are:

- technical arrogance
- poor perception of the overall engineering process
- lack of appreciation for variation
- consideration of manufacturing as boring

Table 1. Product Realization Skills listed in order of highest deficiency gap between industry expectations and students' proficiency level [8].

Deficiency rank	PRS
1	Problem solving
2	Design for manufacture
3	Systems approach to design
4	Written reports and presentations
5	Teamwork
6	CAD skills

Also worth noticing is that the list by Todd et al. does not contain some of the weaknesses listed in Table 3 (numbers 5, 7, 16, 17 and 19) because they were seldom considered important in the US education, economy or social culture in general. Nevertheless, the two lists show more commonalities than differences in the practitioners' perception of engineering education outcomes regardless of country.

Table 2. Most important Product Realization Skills as viewed by industry and academia. Numbers in % column show percentage of respondents who selected a particular skill or area of knowledge among twenty most important for a BS level mechanical engineer. Based on [6].

		INDUSTRY				ACADEMIA	
Rank by industry	Rank by academia	PRS	%	Rank by academia	Rank by industry	PRS	%
1	1	Teamwork	94	1	1	Teamwork	92
2	2	Communication	89	2	2	Communication	92
3	11	Design for manufacture	88	3	6	Creative thinking	87
4	5	CAD systems	86	4	17	Design reviews	86
5	7	Professional ethics	85	5	4	CAD systems	86
6	3	Creative thinking	85	6	11	Sketching/drawing	83
7	8	Design for performance	85	7	5	Professional ethics	82
8	14	Design for reliability	82	8	7	Design for performance	82
9	9	Design for safety	80	9	9	Design for safety	80
10	--	Concurrent engineering	74	10	18	Manufacturing processes	79
11	6	Sketching/drawing	74	11	3	Design for manufacture	74
12	12	Design to cost	74	12	12	Design to cost	74
13	19	Application of statistics	73	13	--	FEA	71
14	--	Reliability	73	14	8	Design for reliability	70
15	--	Geometric tolerancing	71	15	--	Physical testing	70
16	--	Value engineering	70	16	--	Design of experiments	69
17	4	Design reviews	68	17	--	Test equipment	68
18	10	Manufacturing processes	68	18	19	Systems perspective	67
19	18	Systems perspective	67	19	13	Application of statistics	67
20	20	Design for assembly	67	20	20	Design for assembly	65

Japan, economic and engineering powerhouse of past four decades, has relied mostly on adaptation of foreign ideas to its own cultural base for educating professionals for its economy. But Japanese education with its well-defined and rigid structures, heavy emphasis on quantifiable, testable knowledge, its lack of fostering unbiased thinking and creativity, faces even greater problems in effective preparation of future engineers [23 - 26]. Famous Japanese system "koza" which accords near absolute authority and power to a senior professor does in effect stem any intellectual descent, challenging approaches, creative and innovative thinking. The "koza" system by default puts in charge people who are least interested in changing status-quo [26]. The ramifications of this system so entrenched in society culture are visible throughout this country academic hierarchy, all the way down to graduate researches. Even undergraduate statistics show that 2 years ago women comprised for only 10.4% of all engineering freshmen [26]. From the perspective of my experience in senior level design course at CCSU, where I have often observed women coming up with ideas that no men has come up with, this is an important number. It suggests very low inclusion, which promotes low diversity of opinions and a uniform thinking. Although Japanese pre-college students fare exceptionally well in math and sciences, they score poorly on problem solving and creativity measures. The cornerstones of educating today's Japanese engineers are primary education and continuous on-the-job training. Industry vies for best graduates of best universities (considering them the most teachable and capable), and trains them within their own techno-economic culture. It should not be a big surprise that most Japanese inventions do not take place in university labs but in corporate labs, which by competitive business nature are more result than structure oriented [23, 25]. Present Japanese model of engineering education, in vast majority of its outcomes, is not considered a valuable example to follow [24, 25].

Table 3. Weaknesses of engineering graduates and senior students in fields of mechanical, manufacturing and industrial engineering as seen in Central and Western Europe and North America.

1. Little knowledge and marginal understanding of manufacturing processes.
2. No knowledge of value engineering and little appreciation for it.
3. Glorification of Hi-Tech, complicated solutions.
4. Disrespect for effective Low-Tech solutions.
5. Belief that creation of something new is always better than improvement of an existing one.
6. Lack of design capability.
7. Avoidance of contradictions in problem solving - drive to optimize existing solutions or add Hi-Tech patches.
8. Adoration for analysis and no understanding of synthesis.
9. Unskilled in defining core of a problem and deciding that a solution is 'good enough'.
10. Weak communication skills through means other than equations and calculations.
11. Weak communication skills through sketches/pictures/drawings.
12. No understanding of quality process beyond SPC.
13. Prefer working as individuals (no desire to work in teams).
14. Little project planning skills.
15. Little hands-on skills.
16. Overreliance on computer modeling and little understanding of field-testing.
17. No respect for ergonomics.
18. Always blaming the customer.
19. Low environmental awareness.
20. Lack of business skills.

5. Engineers as '*Inventors*' or '*Improvers*'

The discussion between educational psychologists whether to teach previous solutions to build a knowledge base or not to teach for not killing inventiveness of yet uninfluenced young mind is, among all countries, most visible in the USA. It is widely believed in the USA and in hard science circles that a human has its creativity peak before age of 30, hence creativity is mostly a gift. Herrmann argues that creativity is totally individual, hence it is impossible to formulate a general definition and apply it to everyone [28]. Other cultures and educational approaches (European and especially East Asian) accord bigger importance to the knowledge base and experience as the drivers for innovation. There is a huge number of technologies and designs developed in America that domestic business failed to capitalize on. One must seriously think whether we do not teach how to improve or there just is not a cultural or financial desire to pursue such activities. Looking at successes of these Japanese and German manufacturing sectors that are not driven primarily by ground-breaking inventions, the American week interest in continuous improvement seems to be rather cultural. Very high mobility of American workforce is also a huge detriment to devising and implementing improvements. It is however a plus in out-of-the-box thinking and conceiving novel solutions. Depending on which sector of industrial activity is taken into account, each has its specific technical, organizational and financial challenges which are very dependent on global place of the action, competition, openness of markets etc. Therefore a complete analysis of 'inventor' versus 'improver' cannot be done through the prism of education only, but rather through realities of each society.

It is an undisputable fact that a successful engineer always needed, and still will need, to have a blend of both 'inventor' and 'improver' in order to thrive in environments demanding ground-breaking inventions and those demanding improvements through systematic and proven approaches. Undoubtedly, improvement processes and techniques must be given greater importance in American engineering education especially through small design projects and forensic studies. Both activities require interdisciplinary analysis and synthesis, involve solving of open ended and ill-defined problems, and may require creative information search that is not confined solely to the library computers.

6. Conclusion

If inventiveness indeed cannot be taught, methods of activating creative search can. By nature, humans are inventive, therefore exposing students to variety of problems, scientific, technical and logical, allows for practicing methods of seeding creativity. Requiring 'the simpler the better' solutions and discounting optimization as the ultimate improvement method (or worst yet, an ultimate goal) has proven in one of my classes to foster drive for creative solutions. Teaching methods of activating creative search and in-class practices can provide engineering graduates with tools for proficient use of true of out-of-the-box thinking, both individual thinking and group thinking, which are increasingly valued by many employers.

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