The Importance of Divergent Thinking in Engineering Design

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Abstract

With the emergence of capstone and cornerstone engineering classes in recent years, design plays an increasingly prominent role in engineering education. This paper will focus on the importance of divergent thinking in the design process. (Divergent thinking is associated with creativity in that multiple unique solutions are generated for a single problem. In contrast, convergent thinking is a process that identifies a single “correct” answer.) Once divergent thinking is defined, the paper will examine how it is taught at universities, as well as the obstacles to teaching it. The paper will conclude with suggestions on how to encourage divergent thinking in the engineering design curriculum.

Introduction

Engineering: “The creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property.”

The above definition of engineering from the Encyclopedia Britannica originates from the American Engineers Council for Professional Development, which later became ABET. The word “creative” is the second word in the definition. Educators and business leaders recognize that creativity is a prerequisite to any innovative design. Unfortunately, engineering educators are doing a poor job of fostering the creativity necessary to fertilize innovative design. There is growing agreement that an engineering education can in fact discourage creativity, and that the schooling process in general squashes the creative potential of students. Teaching creativity in the design process is neither recognized clearly nor performed well in engineering curricula.

Terms and definitions

Design is a term widely mischaracterized and often vaguely defined. ABET defines engineering design as follows: the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.
Dick Buchanan, Carnegie Mellon University professor in the School of Design offers a simple definition: “Design is the human power to conceive, plan, and realize products that serve human beings in the accomplishment of any individual or collective purpose.”

Convergent thinking is a process of logical reasoning that converges on one “correct” answer. What is 2+2? Clearly it is four. There is only one right answer in this line of thinking. Convergent thinking is useful in the realm of analysis and any quantifiable engineering process. This method of thinking serves quite well in many of the “engineering science” classes taught to prepare an engineer.

Creativity may be simply defined as the ability to generate novel and innovative ideas in an effort to solve a stated issue, situation, or problem. Divergent thinking is closely associated with creativity in that multiple unique solutions are generated for a single question. For students of design, the key distinction between convergent/divergent thinking is that the convergent thought process operates in the knowledge domain – the domain where a distinct single answer will arise from our understanding of the topic – and divergent thinking operates in the concept domain.

For the purposes of this paper, divergent thinking is synonymous with creativity, and the two terms may be used interchangeably.

The Importance of Divergent Thinking

Divergent thinking is associated with the concept phase of design. This is the phase where students and professionals unfortunately spend the least amount of time. Winner and Penner in their 1988 paper identified the 70/30 rule. Their study concluded that 70% of cost is locked up in decisions that are made in the first 30% of a project life. It is important to tell students in design classes that thinking is extremely cheap. Students can imagine dozens, if not hundreds of possible problem solutions very quickly. They can also sketch or explore ideas on paper fairly rapidly. Prototyping and CAD drawing can become time intensive and expensive, and will necessarily commit a group to a smaller subset of design ideas. So it is essential in generating innovative solutions that designers spend a fair amount of time in the concept phase - the phase where divergent thinking dominates.

The Design Process

The design process has been codified by many educators, but the approaches are all fundamentally the same. The simplest expression of the design process is encapsulated in ETC, Express-Test-Cycle. This methodology may be explained as follows:

1. Express: This phase encompasses concept generation – brainstorming, ideation, sketching, defining the problem.
2. Test: In this phase ideas generated are tested and vetted against specific criteria.
3. Cycle: New issues inevitably arise that must be addressed, requiring a return to the Express phase.

Other approaches are equally valid, but ETC is useful to make the relationship between design and convergent/divergent thinking more transparent. In the Express phase, divergent thinking dominates. When a small group of solutions arise that are deemed preferable, design proceeds to the Test phase, where convergent thinking dominates.

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Engineers need to switch effortlessly between these two modes of thought as required. In Edward deBono’s 1999 book, *Six Thinking Hats*, he proposes an approach to looking at different aspects of a problem by “wearing” a different color hat – black for critical thinking, green for creativity, red for an emotional view etc. When a problem is clearly defined, a solution generated, and the path laid out, convergent thinking and applied engineering tools are the best choices. When an open-ended problem is encountered, divergent thinking serves best. Iteration between these two is recognized as an integral part of the design process, and a designer must readily switch between wearing the hats of convergent and divergent thinking.

**Connections Between Engineering Design and Creativity**

Design is an increasingly more important part of the engineering curriculum. Senior capstone projects have been a part of that experience for decades, but recently cornerstone and Project-Based Learning (PBL) has become more ubiquitous. There are some distinct elements that are present in most project-based design courses that can be linked (either rightly or wrongly) to encouraging creativity. Those elements are teeming, brainstorming, open-ended projects, and design notebooks.

**Teaming**

There is an expectation that the words “teaming”, “design”, and “project” grouped together add up to creativity. Virtually every engineering student will work on a team project in a design course. At a 2003 workshop entitled “Advancing Inventive Creativity through Education” and sponsored by the Lemelson-MIT Program, Henry Petroski observed that students can go through their entire college career without ever doing a project all by themselves. Petroski, a professor of civil engineering and history at Duke University, argues that there is too much emphasis on teeming. He suggests that we might be losing two inventors out of every team of three. He observes that the vast majority of patents issued in the US are single author patents. A 1959 study published by Barnlund supports this suspicion that perhaps current engineering curriculum overemphasizes teeming at the expense of creativity. Barnlunds study concluded that high performing individuals do not benefit from working in groups – in fact their performance suffers. Although teeming provides a real world experience it can be a deterrent to creative thinking, and shouldn’t be the only skill taught in a design class.

**Brainstorming**

The concept of brainstorming was first introduced in the 1957 book “Applied Imagination : Principles and procedures of creative problem solving” by AF Osborn. Osborn identified many of the tenets that govern brainstorming today – deferring judgement, freewheeling, leapfrogging, and emphasizing quantity over quality. Brainstorming has become the signature tool for divergent thinking in the design process. Unfortunately, the understanding that brainstorming is only a tool not a replacement for divergent thinking is lost on educators as well as students. A study by Coskun supports this concept. His study showed that brainstorming was only marginally successful in generating creative ideas. By engaging participants in divergent thinking exercises before brainstorming the results improved significantly.
A paper by Ogot and Okudan is an example of how educators misconstrue brainstorming. They argue that “brainstorming calls upon the designer to look inward for inspiration on creative solutions to problems, by drawing upon past experiences and knowledge. This can be a daunting task that may or may not be fruitful. This is especially true for undergraduate students whose past engineering knowledge and experiences are quite limited.” Unfortunately Ogot and Okudan imply that the only good ideas are ones that may be realistically implemented - but this misses the point entirely! Too often engineers leap to the analysis of ideas generated in brainstorming. (One of the brainstorming rules: suspend judgement.) Unfortunately this misunderstanding is the norm rather than the exception in most engineering design courses.

Ogot and Ogudan also imply that innovative ideas must come from a base of knowledge. This is very much in line with accepted engineering pedagogy of teaching engineering science classes (math, mechanics of materials, etc) before introducing project-based learning. However, this belief is at odds with three economists who coined the term curse-of-knowledge in a 1989 paper. Their study finds that better informed agents are incapable of ignoring information even if it is in their best interest. Their conclusion: more knowledge is not always better. This is true in engineering as well. Experts are the least likely to be innovators in their field. This is consistent with the message of creativity professionals like Roger von Oech who preach that creative ideas come from looking at problems in a new light, or from a different angle. A 2007 article in Mechanical Engineering Design magazine about the design of a sewage treatment plant details just such a story. Sometimes the best innovators are those completely unburdened with a technical understanding of the problem at hand. This frees them up to ask the questions that no one else dares to ask — and to force experts to reevaluate the status quo.

There is far too much focus on the single act of brainstorming as divergent thinking. It is only one tool in the design process and can be ineffective if used improperly or in an inappropriate context. It is not a substitute for creating an environment where creative thinking is rewarded and encouraged.

**Design Notebooks**

Design notebooks are bound books in which designers keep their notes, thoughts, ideas, etc. Long an important tool in the design process leading to a patent, design notebooks are poorly utilized in the context of a design curriculum. An interesting paper by Eris suggests design notebooks as a tool for cultivating divergent thinking. The notebooks encourage documentation of a variety of ideas as well as various ways of expressing those ideas. This is an important tool that deserves better recognition in design coursework.

**Open-Ended Projects**

When instructors offer limited specific instruction on design projects, students gain real-world experience in solving open-ended problems. Any well-designed project should teach students how to deal with failure and overcome obstacles, but open-ended projects encourage students to learn how to learn on their own, and self-direct their work. An open-ended project gives students a much greater feeling of ownership and forces a divergent thinking phase to concretely
identify the problem and generate solutions. If projects are guided too closely by instructors, students will simply learn to follow instructions.

**Teachers and Students at Odds**

Kazerounian and Foley created 10 maxims of creativity and polled instructors and students on whether these were present in their coursework. Of the ten criteria they established, engineering students felt 9 of the 10 were missing, and the instructors felt only one was missing. Their study led them to conclude “the environment and factors that impede creativity in engineering are far more profound and dominant in the engineering education than they are in sciences education and naturally far more than those in liberal arts education.” The most important maxim, and one worth noting, is that designers must keep an open mind. It is easy to be blinded by current paradigms, and without an open mind it is difficult to see the next great idea.

One student approached the author of this paper after the class was chided for poorly formed design notebooks in a project-based class. (There was little to no evidence of concept generation in any of the class notebooks.) The student asked what the point was in generating any other ideas if the first one worked just fine. With this type of thinking, there would be no reason to ever develop a car - our feet work just fine. The philosopher Emile Chartier posited a salient warning when he said “There is nothing more dangerous than an idea when it’s the only one you have.”

**Obstacles to Teaching Divergent Thinking in Engineering**

Engineering education has been based largely on an “engineering science” model that predicates that engineering is taught only after a solid schooling in science and mathematics. A senior capstone project is frequently the only opportunity students are afforded to exercise their skills in a design environment. Engineering schools have recently recognized, with pressure from industry leaders, that we are turning out students with skills, but little understanding of how to apply them.

ABET describes the necessary components critical to a design pedagogy: The engineering design component of a curriculum must include most of the following features: development of student creativity, use of open-ended problems, development and use of modern design theory and methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations, production processes, concurrent engineering design, and detailed system descriptions. Further, it is essential to include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact.

Educators in engineering schools struggle constantly with assimilating creativity into the engineering curriculum. Our current engineering curriculum, in fact our entire schooling system, favors a convergent thinking approach. This bias is apparent early in the schooling process. Roger VonOech, in his book, *A Creative Whack on the Side of the Head : How You Can be Creative* tells a very poignant story. He says this: “When I was a sophomore in high school my English teacher put a small chalk dot on the black board. She asked the class what it was. A few seconds passed and then someone said, ‘a chalk dot on the blackboard’. The rest of the class
seem relieved that the obvious had been stated, and no one else had anything more to say. ‘I’m surprised at you,’ the teacher told the class. ‘I did the same thing yesterday with a group of kindergartners and they thought of fifty different things it could be: an owl’s eye, a cigar butt, the top of a telephone pole, a star, a pebble, a squashed bug, a rotten egg, and so on. They really had their imaginations in high gear.’ The point is that our education system promotes a highly convergent thought process at the expense of our ability to exercise divergent thinking.

Divergent thinking is so difficult to teach because it presents a lot of uncomfortable issues for engineers. It’s messy. It’s chaotic. It’s unstructured. It’s uncomfortable. These are attributes an engineer seeks to avoid and control. Obstacles to teaching creativity to engineers include the following:

- Attitude of educators towards creativity
- The fact creativity is difficult to grade and there’s not a single right answer
- The chaotic and messy nature of creativity
- The stigma of failure
- The time commitment involved

Design is also not static. Sometimes engineering faculty will create a stock class, much like statics or mechanics of materials, that can be handed off from teacher to teacher with little change. This must be done with careful consideration, as design and creativity are inherently living processes and do not lend themselves well to a static class structure.

There are other obstacles aside from the classroom issues. Senior faculty are uncomfortable with the chaotic and uncertain environment of creative design and are generally not involved in design classes. Junior faculty members are not assured tenure when their research focus is design, and seek to avoid these classes given the opportunity. The lack of faculty interest makes design education a lower priority for many universities.

**Attitude and grading**

Engineering educators are loathe to admit a purely subjective criteria into an objective field of curriculum. Students of art do not question teachers that award a C grade for their work based on ostensibly subjective criteria, but an engineering student expects a quantifiable process by which he or she may measure success or failure. Grading of creativity is frequently criticized as inappropriate for engineers, often delivered with an implication that engineering is somehow a more superior subject than pure art. (“Engineering is serious business”, “Artists don’t build bridges.”) The wall between engineering and art was not always intact. There are historical role models such as Leonardo daVinci, who could properly be called artist/engineers. The propagation of this attitude precludes the possibility of introducing a grading criteria for creative ideas, and essentially creativity goes unrewarded in engineering classes.

**Chaos**

There have been many attempts to systematize the creative process. Divergent thinking, by its very nature is not amenable to a systematic approach. In fact, many creativity adherents would argue that the very nature of systematizing is anti-creative. There have been attempts to develop a creativity IQ and engineering papers published that attempt to develop provable and
quantifiable techniques that return creative results. These are all attempts to organize and control the inherently messy and chaotic nature of creativity. Certainly there are techniques for encouraging creative thinking, but these are no guarantee that the most creative ideas will surface.

Failure

The fear of failure is often stated as another barrier to encouraging divergent thinking in the classroom. Failure carries a much heavier stigma in engineering than other disciplines. We often learn more from our failures than our successes, yet current grading practices do not provide a safe environment for students to take design risks.

How to Encourage Divergent Thinking in the Engineering Design Curriculum

It is clear that to become comfortable with divergent thinking within an engineering framework certain pedagogical changes must transpire.

1. Students and faculty must tolerate a certain amount of subjective grading on design projects, much as an aspiring graphic artist accepts the instructor’s opinion as part of the grading process. Creativity must be rewarded.

2. Projects in design classes must have open-ended solutions. This requires students to define problems and go through a divergent thinking phase to develop solution concepts. (A litmus test of good open-ended projects is whether or not student solutions come as a surprise to the faculty. If the faculty can arrive at every possible solution, the project was likely too narrowly defined.)

3. Exercises should constantly be introduced to encourage students to take different viewpoints when engaging in problem solving.23

4. Faculty must be as engaged in the process as the students. Roth and Faste of Stanford University suggest that projects should be developed for students using the same process through which the students are expected to engage.18 This requires faculty to actively engage in divergent thinking as well.

5. Curriculum must be developed in a way that creates an environment that tolerates, fosters, even encourages risk and failure. Grading criteria clearly must be reevaluated to gauge involvement in the process as opposed to merely the outcome.

6. Teaching must encourage students to use multiple modes of expression. Good designers can write, sketch, use math, express solutions kinesthetically, etc. Innovative ideas are not always immediately expressible in scientific language.24

7. Finally, students should be encouraged to explore their own learning styles, strengths, weaknesses, etc. In essence, students should learn about themselves. Good motivation is a powerful force in creative expression. This can be achieved in many ways, starting with standard Meyers –Briggs and other personality tests. It is a common story to hear of unmotivated and disillusioned workers in professions and positions that are simply bad fits for their personality. People who are comfortable and confident are those most likely to take risks, innovate, and challenge current paradigms.
Conclusions

There are many obstacles to teaching creativity and divergent thinking in an engineering curriculum. Educators all agree that creativity is important, especially in the context of design, but execution and encouragement of divergent thinking is not common. This paper has discussed why divergent thinking is important and where in the design cycle it is relevant. Creativity is addressed in current engineering curriculum in a variety of ways - some of these are appropriate and others are improperly implemented. But on the whole, not enough attention is given to foster good creativity skills. This paper concludes with a list of suggestions for how university engineering programs might better address and encourage divergent thinking.

Bibliography


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