Teaching engineers to think creatively

Barriers and challenges in STEM disciplines

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Introduction

Creativity has long been portrayed as an elusive and ill-defined quality of people and things. Ford and Harris (1992) lamented the lack of attention paid to creativity in the social sciences, suggesting that it lacked a “universally accepted definition” (p. 186) and was undervalued as an academic ability. More recently, de Sousa (2008) suggested that creativity remains an elusive construct. While some might argue this was the case in the early days of the modern era of creativity research (e.g. in the decade immediately following Guilford (1950)) it seems increasingly unjustified to claim that the development of creativity in educational settings is being held back by a lack of clarity on what creativity is. This is not to say that the message is reaching the ears of the people who matter – in this case, teachers at all levels. Benson (2004) made this point very clearly – her anecdotal evidence suggests that primary school teachers, for example, express a concern about their own lack of understanding of the nature of creativity. Benson (2004) also highlights some common misconceptions – what her teachers did think they know about creativity is that it is simply a matter of letting children “do their own thing” (p. 138) and that creativity, at its core, is “developed mainly through art and music” (p. 138). In an earlier study of university students in the field of apparel design, Kawenski (1991) saw the same problem also among the students – “In the first place, their romantic notions led them to believe that creative thinking consisted of just letting their minds waft about dreamily, waiting for the muse to strike them.” (p. 263).

There seem to be at least two problems that beset attempts to build creativity into education, and not least, STEM education. First, many researchers active in the field of creativity encourage a view that creativity is a nebulous, elusive construct. Mishra and Henriksen (2013), for example, adopt a common pattern, and begin by propagating the myth that creativity is poorly defined, before offering their own definition. Second, that even as the construct has become clearly and concretely defined, this message has not filtered down to end-users – teachers and students. As a result, creative thinking continues to struggle to establish itself in engineering...
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education, even as key stakeholders (for example, the United Kingdom’s Royal Academy of Engineering) extol its value to the profession.

Four things need to happen to address these problems, so that engineers can be taught to think creatively. Benson (2004) makes it clear why: “unless misconceptions are identified and addressed, the development of creativity will almost certainly be hindered”. The first step is obvious, and involves communicating a clear understanding of the nature of creativity. It is also worth noting here that, while the definition may be complex in the sense of having a number of interconnected facets or dimensions, this does not mean that it must therefore be unclear or elusive. The second step requires a more detailed effort to explain the value of creativity in the context of STEM disciplines. Third is the need to identify the structural impediments in education that act as a barrier to creativity. Fourth is a clear set of guidelines for how our understanding of creativity can be translated into practical curriculum design, and learning outcomes in STEM. The following sections briefly address each of these steps.

What is creativity?

A significant factor that seems to be holding back the development of creativity in the STEM disciplines is the simple fact that, outside of what can be regarded as its “home” discipline (arguably, the field of psychology), creativity is often poorly understood. Baillie (2002), for example, writing about creativity in engineering education, asks (one can only hope rhetorically) “It is however not clear how creativity can be nurtured or fostered in students or how it can be assessed. What is creativity? What blocks it and what facilitates it?” What is not clear is why this should be the case. Each of the questions posed has been studied extensively, in most cases for 50+ years, and the results are accessible through a range of research journals and other reputable publications. It is simply not credible that engineering faculty, for example, can claim that these questions have not been answered adequately!

Even if we accept, as many do, that creativity has been tied too strongly to the arts (D. H. Cropley & Cropley, 2013) in the public eye (pp. 12–13), the fact remains that any teacher working in a STEM discipline, and interested in creativity, has already succeeded in “unhooking” creativity from the arts (McWilliam, Dawson, & Tan, 2011) and is primed to absorb the wealth of material that is available, for example by starting with the search-term “creativity” and Wikipedia.

As readily available as material on creativity is, there seems to remain some impediment that is blocking its wider acceptance in STEM disciplines. While this persists it is difficult to see any real progress in the task of teaching engineers to think creatively because new efforts seem to get stuck in a process of reinventing the wheel. STEM disciplines will make much more rapid, and meaningful, progress if they first recognise and adopt the foundation that has been provided by the 60 years of research that followed Guilford’s ground-breaking presidential address to the American Psychological Association in 1949. Guilford’s call to arms (published as Guilford, 1950), set in motion the modern creativity era (A. J. Cropley & Cropley, 2009, p. 8) that has resulted in a wealth of empirical research regarding what creativity is, where it is found, who engages in it, how it is achieved, how it can be taught, what hinders it, what promotes it, and many other questions of direct relevance to educators. Volumes such as the Cambridge Handbook of Creativity (Kaufman & Sternberg, 2010) and the Encyclopedia of Creativity (Runco & Pritzker, 2011) are excellent portals into the world of empirical creativity research, irrespective of discipline or goal.

Two things will help anyone entering the field of creativity to proceed with a minimum of duplication. These two things tackle the question of “what is creativity?” First is a well-founded definition that represents the general consensus that has emerged over decades of creativity
research, and is broad enough to satisfy the needs of any domain. Plucker, Beghetto and Dow (2004) have captured all the essential ingredients in the following: Creativity is “the interaction among aptitude, process and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context” (p. 90).

The second vital ingredient is to recognise that creativity, and the preceding definition, define the phenomenon in terms of 4Ps: Person, Product, Process and Press (environment). This conceptual framework was first described by Rhodes (1961) and provides a convenient way of understanding the who, what, when, where and how of creativity. It is beyond the scope of the present chapter to describe each of these in any detail, however a brief summary of the 4Ps is warranted.

The Person addresses the factors relating to the psychology of the individual actor involved in the creation of the perceptible product. Research has shown that personal properties (e.g. optimism, openness, self-confidence), motivation (both intrinsic and extrinsic) and feelings (e.g. excitement, hope, fear) are distinct dimensions of the Person that each have a bearing on creativity (D. H. Cropley & Cropley, 2013, p. 62). Furthermore, these dimensions of the Person interact with each other in a variety of ways such that different combinations have unique consequences for creativity.

The Product addresses the output of the creative endeavour. Although it is no surprise that psychologists are interested in the creative person, it is also widely accepted that an essential core of creativity, whether in music and poetry, or engineering and science, is the tangible artefact. In fact, this definition of Product can be extended – any product, process, system or service that is both novel and useful qualifies as a creative product. Mackinnon (1978) concluded that “analysis of creative products” is “the bedrock of all studies of creativity”, and indeed, Morgan (1953) came to a similar conclusion. While more recent definitions of the creative product debate the existence of higher order characteristics (e.g. D. H. Cropley and Cropley, 2005), the foundation of definitions as far back as Stein (1953) is a combination of novelty and usefulness. For some thing to be considered creative, it must be original and surprising, and, it must address a real problem or need.

The Process typically addresses the styles of thinking that result in creative products. Although more complex and nuanced than is suggested here, two main thinking styles are commonly associated with creativity. It was Guilford (1950) again who laid the groundwork for understanding the roles that convergent and divergent thinking play in the production of creativity. While divergent thinking is often exclusively associated with creativity, it is important to recognise that convergent thinking also plays a critical role, especially when creativity is considered in the context of problem solving, engineering and other STEM disciplines. Engineers will immediately recognise this as a feature of the design process. Horenstein (2002) explained the essence of design as follows: “if more than one solution exists, and if deciding upon a suitable path demands being creative, making choices, performing tests, iterating and evaluating, then the activity is most certainly design. Design can include analysis, but it must also involve at least one of these latter elements” (p. 23). The core of engineering design therefore involves two stages: a stage of creative synthesis (i.e. divergent thinking), followed by a stage of logical analysis (i.e. convergent thinking).

It may be tempting to see Process in terms of activities such as brainstorming, however that is simply a tool to help people recognise and tap into divergent and convergent thinking. In activities such as engineering it is also possible to think of Process in terms of the stages that an individual or team undertake as they solve problems and satisfy needs, creatively or otherwise. However, this should not detract from understanding Process as the core cognitive activities that underpin creativity: divergent thinking and convergent thinking (A. J. Cropley & Cropley, 2009).
Finally, the Press examines the role of environmental and social factors on creativity. More specifically, Press can be considered to address both: (a) how the “climate” can either facilitate or inhibit creativity, and; (b) how the “environment” reacts to the production of creativity. Press therefore touches on not only factors such as management support for creativity (e.g. rewarding creativity, encouraging risk-taking), and how the physical environment may foster creativity (e.g. through the provision of plants and adequate lighting in the workplace), but also on the way that society tolerates radical deviations from norms (are creative people ridiculed or hailed), and even the rules and standards that govern professional activities such as engineering.

What is the value of creativity?

Even if well-defined, creativity may still struggle to gain a foothold in STEM education because its inherent value is not recognised or understood. At a very general level Sternberg (2007) expresses a sentiment common in discussions of creativity and innovation, and the value that they bring to society: “The problems we confront, whether in our families, communities, or nations, are novel and difficult, and we need to think creatively and divergently to solve these problems” (p. 7). Creativity is of value because it tells us everything we need to know about generating the solutions to these novel and difficult problems – how to generate them; who can generate them; how to recognise them; how to stimulate them.

More specifically, Pilzer (1990) builds a compelling, albeit unwitting, explanation for the importance of creativity in the context of STEM disciplines. Writing on the subject of economics, he describes the relationship between a society’s wealth, its physical resources, and its technology. In simple terms, “technology determines what constitutes a physical resource” (p. 28) and “Technology determines . . . both the efficiency with which we use resources and our ability to find, obtain, distribute, and store them” (p. 32). Without technology, a society’s wealth is low because it is unable to make productive use of resources such as iron ore, oil, solar energy, fertile land and even information. Without technology it is unable to extract greater value from these raw materials, or to turn them into valuable, tradeable goods and services. The process of the efficient transformation of physical resources into wealth drives a constant stream of new problems that require new technological solutions. The novelty and effectiveness inherent in these problems and solutions encapsulates the importance of creativity, and their technological basis highlights the importance of STEM disciplines in realising the latent wealth of any society. It seems axiomatic, therefore, that teaching engineers (and other STEM disciplines) to think creatively is absolutely essential to a society’s ability to generate wealth, and as a result provide a stable, safe, healthy and productive environment for its citizens.

Gertner (2012) further illustrates the value of creativity in STEM, describing the driving force behind the activities of the famous Bell Labs: “that the growth of the system [the US telephone system run by AT&T] produced an unceasing stream of operational problems meant it had an unceasing need for inventive solutions” (p. 45). The impetus for creativity, moreover, was not simply technological in nature: “the engineers weren’t merely trying to improve the system functionally; their agreements with state and federal governments obliged them to improve it economically, too” (p. 45).

The value of creativity can also be considered at the level of the individual. For example, D. H. Cropley and Cropley (2000) drew attention to the benefits of creativity in education: “modern research has demonstrated that although students with high IQs usually obtain good grades both at school and university, they are consistently outstripped by those with not only a high IQ but also high creativity” (p. 207). Cropley and Urban (2000) expand further on this point. Facaoaru (1985), studying professional engineers, determined that those rated by their
peers as the best engineers were not only technically or conventionally better, but had more characteristics typical of creative people. Cropley (1994) suggests “creativity is indispensable for ‘true’ giftedness”. In other words, the value of creativity to the individual is that it can be taught and developed (Torrance, 1972).

Fasko (2001) describes other examples of the benefits of creativity in an individual and educational setting, citing earlier work by Parnes and Noller (1972) who reported data on a study into the benefits of creativity courses. Fasko (2001) notes that “Parnes and Noller found that students who completed the sequence of creativity courses significantly outperformed comparable control students” (p. 324) across a range of idea generation, evaluation and problem-solving measures, and that their performance in other courses improved as well. A study by Mohan (1973) found a similar result for teacher training, while Mack (1987) discussed the perceived need for creativity training among teachers, and the perception of teachers of the importance of creativity training for children.

Although only touching on the available evidence, it seems reasonable to assert that creativity is beneficial for society, necessary for effective, technological problem solving and adds value to the individual engineer. It remains, however, under-represented in engineering curricula.

Barriers to creativity in STEM education?

The “Sputnik Shock” of 1957 was perhaps the first occasion where creativity, science and engineering were linked together in the context of education. The success of the Soviet Union’s space program gave rise to a “wave of self-criticism that centred mainly on the argument that the Western world’s engineers had failed” (D. H. Cropley & Cropley, 2005) (p. 169) and creativity was, perhaps for the first time, seen as a core part of engineering. Indeed one of the first legislative reactions to the Sputnik Shock was the US National Defense Education Act of 1958, which provided significant funding to stimulate and support STEM education. The Act recognised that “The defense of this Nation . . . depends as well upon the discovery and development of new principles, new techniques, and new knowledge” [emphasis added] (National Defense Education Act, 1958).

Despite such compelling pressure, it is by no means clear that creativity succeeded in permeating engineering education. Kazerounian and Foley (2007) encapsulate the problem as follows: “If creativity is so central to engineering, why is it not an obvious part of the engineering curriculum at every university?” The reasons for this failure to translate theory into practice are many and varied. Walther, Kellam, Sochacka and Radcliffe (2011) suggest that the problem may lie in “persisting difficulties of the construct of outcomes-based education as the current paradigm of formal engineering education” (p. 704). Walther and Radcliffe (2007) earlier expressed this as a mismatch between different kinds of learning outcomes and predominant teaching approaches. In simple terms, a learning outcome framed around the development of declarative knowledge of, say, engineering mechanics, may be amenable to a “traditional” teaching approach in a way that a more diffuse graduate quality such as “the ability to think creatively” is not. A fundamental dilemma faced by engineering educators, in preparing students for the “diversity of competency demands” (Walther & Radcliffe, 2007, p. 44) is “whether to equip students with a broad (and arguably shallow) knowledge base in many domains, or prepare them for specific job tasks and a contribution to a narrow subject area (technical depth)”. Creativity is, by its nature, a broad, generic competency. If poorly understood, and perceived as the antithesis of the “serious business” of engineering (Kazerounian & Foley, 2007), it is little wonder that it is not only undervalued, but absent in most curricula.
How can creativity be embedded in STEM education?

If it is true that creativity is failing to make a mark in STEM, and especially engineering, education, then what can be done to change this? Like Kazerounian and Foley (2007) I believe that this is because it is “not valued in contemporary engineering education” (p. 762). However, I believe that it is undervalued not so much because of issues of outcomes-based learning, or the debate over broad/shallow versus narrow/deep knowledge, but, because it is poorly understood. My purpose in this chapter has been to suggest that there is no real reason why it cannot be better understood – it IS well-defined, and there IS a wealth of empirical research and theoretical understanding that supports it. There remains, however, a failure to diffuse this knowledge among engineering and other STEM educators.

To conclude, I offer twelve strategies that can help drive curriculum and programme design to enhance creativity. It is important that these are pitched at a strategic level. There is little value, for example, in discussing brainstorming as a specific creativity method unless this is placed inside a framework that supports all four Ps of the creativity concept. STEM students will only develop creativity as a genuine graduate quality – as an emergent property of their education – if these strategies permeate their curricula as a system, and are not simply tacked on in a reductionist, piecemeal fashion.

The twelve strategies are derived from Sternberg’s (2007) conceptualisation of creativity as a habit. Three things promote the habit of creativity (Sternberg, 2007, p. 3) and should serve as general principles for curriculum and programme design in STEM disciplines. First, students must have the opportunity to engage in creativity. This must be woven throughout courses in an integrated and mutually reinforcing manner. Second, students must receive positive encouragement as they engage in tasks requiring creativity. Third, students must be rewarded when they demonstrate the desired creativity.

Sternberg (2007, pp. 8–15) then outlines twelve strategies that guide the development of the creativity habit. This is not to suggest that every aspect of STEM learning must be transformed. There will remain many areas of the curriculum that are best served by convergent approaches – there is, after all, still only one right answer to the question “what is 2+2?” . However, wherever practical, these strategies should be used to guide the development of creativity as a desirable and vital graduate quality:

- **Redefine problems** – to make good choices, students need practice at making choices. When those choices don’t work out, students need the opportunity to try again. To achieve this STEM students need the opportunity to engage in projects which are presented as more open-ended and flexible. Highly constrained, or over-specified, projects do not allow the student to develop this skill.

- **Question and analyse assumptions** – students must be encouraged to ask questions, and not just accept the problem as we give it to them. This can be achieved partly through the way in which faculty respond to questioning, as well as the way in which faculty establish a “press” in which a questioning mindset is valued and modelled.

- **Sell your creative ideas** – students need to learn how to persuade others of the value of their ideas, i.e. to justify their ideas. Team-based activities, as well as competitive elements to student projects, engender an environment in which the students must become adept at selling their ideas, both to each other, and to faculty.

- **Encourage idea generation** – we want students to get practice at generating ideas, but with constructive criticism. This should be encouraged intrinsically – as a necessary component of the activities the student undertakes – and extrinsically – by teaching students
specifically how to engage in divergent thinking. In other words, students need to be taught (or perhaps, reminded) how to think divergently, and must also be given plenty of opportunity to use this rediscovered skill.

- **The role of knowledge** – to be a creative engineer, you first need to be a competent engineer. The principle for the student here is about broad preparation and not overspecialising. In other words, encouraging students to see the value in developing other knowledge and skills. You never know when your knowledge of biology, for example, might give you an idea for solving a mechanical problem. Indeed, the growing field of biomimetics suggests that biological sciences may prove to be an exciting and valuable area for “broadening” education for engineering and other STEM students. This principle also supports the value of diverse internships and work experience during the STEM student’s time at college.

- **Identify and surmount obstacles** – we must present students with challenging tasks, so that they build resilience. We need to give them opportunities to fail, and try again. Certainly in project work, but even in other courses, students need to develop an understanding that engineering, for example, is usually not simply a matter of rolling out a predetermined solution. Every problem is unique and bound by a unique set of constraints. What worked in another situation may not work in this one. Students who understand this are able to focus their energies on finding the new solution, rather than trying to puzzle out why the old solution doesn’t work (and may never work).

- **Encourage sensible risk-taking** – students need the opportunity to try something, even though it might not work. They need to learn how to assess risks and judge that the risk is acceptable. This can be encouraged as simply as making it clear to students that they won’t be punished for mistakes, both in terms of their grades, and in real terms (for example, if they damage an integrated circuit in the course of a practical class). Clearly, they need to be taught which risks are OK, and which are not. Connecting some electronic components on a breadboard in a new way is a sensible risk; forgetting to wear safety goggles when operating a drill press is not. However, if we overreact to the former, we encourage an extremely risk-averse mindset in which the student never takes sensible risks.

- **Encourage tolerance of ambiguity** – by presenting students with ill-defined problems. Creative people recognise that ambiguity gives them more space to be creative. This can be as simple as breaking away from a typical “lab” paradigm of “here’s the sheet for today’s lab class. Follow the instructions” that is familiar in many STEM disciplines. Instead of giving students a highly structured “menu” for a lab class, for example in electronics, give them a more open-ended problem statement that requires them to deal with the ambiguity and think more independently. Rather than a set of instructions along the lines of “put component X on your breadboard. Now connect component Y to component X, touch your voltmeter probe to point Z and write down the number on the voltmeter” we can achieve the same outcomes by saying to students “Today I want you to find out as much as you can about how transistors work. You have everything you need in the lab, so go for it!” This may make students uncomfortable at first, but with the right encouragement they will begin to take this uncertainty in their stride. When faced with ambiguity, some people close down and do nothing, while others see the ambiguity as an opportunity to try different things. We want our creative STEM professionals to be of the latter mindset.

- **Build self-efficacy** – allowing students to see that they can be creative, so they don’t fall into the “I’m not creative” self-fulfilling prophecy. Simply requiring creativity as an assessable component of, for example, project work, will allow students to see that they can be creative, and that their creativity is an asset. This requires faculty to understand creativity,
and how it is manifest in engineering products and other STEM outputs, and to encourage students to build this in to the work they do.

- **Find what excites them** – help students explore a broad range of areas of their chosen discipline so that they have a better chance of finding the part that really turns them on. A wide variety of broadening subjects, as well as the opportunity for diverse, real-world projects, sponsored by real-world organisations, gives students the best chance of finding their chosen field before they graduate.

- **The importance of delaying gratification** – foster a sense that sometimes you need to work a little longer and harder to get the reward. Pushing students to the full extent of their abilities is necessary. Both in regular coursework, and in project work, we must ensure that students have the opportunity to push boundaries. This may require more flexibility in assessment, so that each student can be pushed to his or her limit, without always being assessed in a norm-based fashion. In every case, however, as faculty we should have the option of pushing students beyond their comfort zones.

- **Provide a favourable environment** – STEM educators also need to role model creativity. We need to demonstrate our own flexibility, openness, tolerance for ambiguity and resilience – indeed all twelve of the items mentioned. More simply, we need to demonstrate that we understand what creativity is, why it’s valuable and why it’s in the curriculum.

**Note**

The Royal Academy of Engineering published the report *Creating Systems that Work: Principles of Engineering Systems for the 21st Century* in June 2007. Among six principles that the report presents as necessary for “understanding the challenges of a system design problem and for educating engineers to rise to those challenges” (p. 11) is an ability to “be creative”. The report further recognises the key role that creativity plays in successful engineering and defines creativity as the ability “to devise novel and... effective solutions to the real problem” (p. 4).

**References**


