Engineering Creativity: Ideas from the Visual Arts for Engineering Programs

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ABSTRACT

Engineers being educated today must be creative and innovative. An important part of developing creative and innovative solutions is the framework within which students are taught to think and formulate ideas. The scientific method is among the first such framework taught to students as early as elementary school and reinforced into college. Within engineering curricula, students are introduced to an engineering design process. These methods are valuable but do not necessarily translate to developing creative ability that can be more broadly applied. In fine art programs, however, deliberate effort is made to develop creative abilities in addition to learning technical processes within which to showcase that creativity. This paper compares the scientific method, engineering design process, and creative methods taught in the fine arts. Through this comparison, commonalities are identified and insights from fine arts creative methods are applied to the engineering curriculum.

INTRODUCTION AND MOTIVATION

"Creativity (invention, innovation, thinking outside the box, art) is an indispensable quality for engineering, and given the growing scope of the challenges ahead and the complexity and diversity of the technologies of the 21st century, creativity will grow in importance."[1] These words were written in 2004 as the National Academy of Engineering (NAE) described what they envisioned of the engineer of 2020. The NAE includes creativity as one of six "engineering habits of mind" that successful engineers must develop, in addition to mastering technical content (the other five are systems thinking, optimism, collaboration, communication, and ethical considerations).[2] As the third decade of this century approaches, the indispensable nature of creativity for engineers is evident; calls for developing creative and innovative engineers have been made.

The 3rd Edition of the Civil Engineering Body of Knowledge published by the American Society of Civil Engineers (ASCE) articulates the knowledge, skills, and attributes that civil engineers need. Creativity is central to this – the words "creative" and "creativity" appear 62 times in the 172-page document. Creativity is listed as an important professional attitude and is described as essential to innovation which itself is "an essential part of engineering."[3]

The Structural Engineering Institute recognizes the importance of creativity and innovation and the negative consequences that the current prescriptive building and bridge codes and standards have on it. In their vision for the future of structural engineering, they describe a goal of better managing risk by returning "engineering judgment to the top of the list of reasons why structural engineers are valuable and why creative people aspire to be structural engineers."[4]

Creative people are drawn to engineering. Troublingly, however, there is evidence that those graduating from engineering programs are less creative than those who begin.[5,6] One reason for this may be the traditional focus of engineering education on specific procedures applied to well-constrained problems in which there is a single correct answer.[7] As Surovek and Rassati state, “focusing predominately on developing analytical skills at the expense of variable solution approaches limits the development of the divergent thinking skills needed for innovation.”[5] Another reason may be that there is little formal creativity training within engineering curricula leaving the development of necessary skills up to chance or individual interest.[6] As Sir Ken Robinson, an educator and expert on creativity, wrote: “Simply asking people to be creative is not enough. Children and adults need the means and the skills to be creative.”[8] While the aspirational documents of professional engineering organizations call for creative and innovative engineers in the future, the engineers currently being educated in classrooms around the country are being developed in ways that may reduce their inherent creative abilities or drive the most creative students to study other non-engineering disciplines.

Bruhl and Klosky suggested that deliberately developing creativity across an engineering curricula is necessary and will yield several positive effects: (1) encourage naturally creative students to remain in engineering, (2) help less naturally creative students improve these important skills, and (3) provide opportunities for students to experience the value that diversity plays in developing innovative solutions.[9] This paper aims to provide useful knowledge for engineering educators who want to incorporate creativity into their courses and curricula.

Artists, musicians, poets, and actors may come to mind more frequently than engineers when imagining creative people. People in these traditionally creative fields have valuable experiences to teach engineers and the educators entrusted with developing them through formal education. This paper provides insights from educating fine art students for application in engineering curricula and classrooms. One of the authors of this paper is a professor emeritus of fine art who has taught drawing, painting, printmaking, and other art courses for nearly 50 years. The other is a civil engineering associate professor who has taught engineering mechanics, structural analysis, and design courses for 7 years.

This is not the first document to describe ways to develop and train engineers to be creative. In fact, there are books on this topic. Walesh’s book, written for engineering students and practitioners, describes the importance of whole-brain thinking and offers practical methods to bring creativity into the engineering design process.[10] Engineering design textbooks often include discussions about creative processes for use in the idea generation phase of design. For example, Dieter and Schmidt offer suggestions to support creative thinking, describe barriers to creative thinking that engineers should be aware of, and provide a variety of creative thinking methods.[11] Niku’s engineering design textbook opens with several chapters about creativity before describing the design process. In these chapters he offers a background on whole-brain thinking and provides a variety of exercises to develop creative thinking abilities. He then goes on to describe creative problem solving techniques that can be incorporated into the design process.[12]

These published texts are valuable but are not targeted at educators seeking to develop creativity skills in their undergraduate students outside of design courses. Walesh’s book comes closest but, while interesting and valuable, does not provide clear ideas for implementation within typical engineering courses. Building on the work of Sternberg and others, Cropley offers principles and strategies for incorporating the development of creativity in engineering curricula. Many of these center around the idea of providing more opportunities for students to engage in creativity throughout the curriculum.[13] Baillie and Walker offer case studies of how creativity may be integrated into three different courses (first year mechanical engineering, materials science, and a physics seminar).[14]

Too many times in our engineering programs, we assign constrained problems and projects in our courses until the capstone design project appears at the end of the program requiring students to apply creative problem solving and develop innovative design solutions. Instead, it is vital that students have opportunities to practice and develop creative skills from the beginning of the program. Rather than giving our students projects that require them to use creative approaches and hoping they can rise to the challenge, this paper provides information and techniques to help our students develop the necessary skills to do so. Courses of study or experiences directly encouraging creative thought, at best, should precede working in historically structured courses such as engineering. Doing so will develop future engineers who will be better prepared to "think outside the box." Innovative conclusions to otherwise conventional problems will be more easily discovered.

WHAT IS CREATIVITY AND INNOVATION?

Before going further it is important to explain what exactly is meant by creativity and innovation. These words are often used but definitions of them differ. Consider the concise definition of creativity put forth by Robinson: "the process of having original ideas that have value."[8] It is important to note that creativity requires imagination (to generate original ideas) but is more than imagination alone. As Robinson explains, "imagination can be an entirely private experience of internal consciousness … Being creative involves doing something. It would be odd to describe as creative someone who never did anything. To call somebody creative suggests they are actively producing something in a deliberate way."[8]

Creativity contributes to but is not synonymous with innovation. Consider the definition included in ASCE's Civil Engineering Body of Knowledge: "innovation is a new idea, process, or device that alters societal ways of doing or being. … It stems from creative thinking, which includes the capacity to combine or synthesize existing ideas and expertise in original ways."[3] Therefore, being innovative requires one to first be creative and being creative requires one to have an active imagination. From an education perspective it is important that we first encourage imagination and develop creativity in our students before expecting them to be innovative.

The skills necessary to be creative can be taught and learned. Before describing specific skills, however, it is valuable to understand creativity more broadly. First, creativity is not the same as inspiration. That is, to be creative requires preparation and effort. Cropley summarized the cognitive aspects of creativity in a list:

1. Possession of a fund of general knowledge
2. Knowledge of one or more special fields
3. An active imagination
4. Ability to recognize, discover, or invent problems
5. Skill at seeing connections, overlaps, similarities, and logical implications (convergent thinking)
6. Skill at making remote associations, bisociating, accepting primary process material, forming new gestalts, etc. (divergent thinking)

7. Ability to think up many ways to solve problems
8. A preference for accommodating rather than assimilating
9. Ability and willingness to evaluate their own work
10. Ability to communicate their results to other people.[15]

From this list, a few observations can be made. Creativity is a combination of knowledge, skills, abilities, and attributes. Traditionally, education has focused on developing students' knowledge. Skills require instruction to learn and opportunities to practice and receive feedback. Abilities need to be identified, demonstrated and honed. Finally, desired attributes must be encouraged.

For a more comprehensive list of knowledge, skills, attributes, and abilities, Thagard, organized 50 habits of successful scientists into six categories. This list included cognitive habits ("make new connections", "expect the unexpected", and "be persistent"), emotional habits ("get excited"), social habits ("be sociable"), and global considerations ("use the world").[16] Within each category, there were specific habits listed. Some of these relate to the list of ten cognitive aspects summarized by Cropley above. A few habits are unique and important to mention. For example, Thagard identified a benefit to using analogies to link things together and to work on multiple projects at the same time. A nonlinear approach to work often leads to discovery of connections between topics. This is one way innovative solutions are discovered. This is not to suggest that problem solving should be haphazard. Thagard describes the importance of organization and following a systematic approach. Importantly, emotional habits center around the idea that the person enjoys what they do, is naturally curious, does not bore easily, likes asking interesting questions, and is persistent to develop or discover answers to those questions.

There are important connections from these aspects of creativity to engineering. Within engineering education, students are expected to develop general and specific knowledge. ABET criterion require this and the Fundamentals of Engineering Exam tests this knowledge. Students are also expected to develop desirable skills such as computer aided design, machining and manufacturing techniques, or project management. Within ABET, there are other non-technical abilities identified that must be developed within an engineering program such as communication, ethics, and teamwork. Also within ABET, there are desirable attributes described such as "consideration of public health, safety, and welfare."[17]

WAYS OF APPROACHING PROBLEMS

Solving problems is central to engineering. The first two ABET student outcomes make this explicit: "(1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics, [and] (2) an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors."[17]

Disciplines have a variety of ways to approach problems. In this section, three different methods are described: the scientific method, the engineering design process, and the creative process common to visual arts. A summary of each method, its attributes, and a comparison between the three is provided in Table 1.

The Scientific Method

In scientific disciplines, one of the first methods taught to students is the scientific method. As described in one source "The *scientific method* has five basic steps, plus one feedback step: (a) Make an observation, (b) Ask a question, (c) Form a hypothesis, or testable explanation, (d) Make a prediction based on the hypothesis, (e) Test the prediction, [and] (f) Iterate: use the results to make new hypotheses or predictions."[18]

This method is linear and methodical for good reason: by providing a very specific framework with clear processes for each step within the method, scientific principles can be clearly understood. From an analytical perspective, the scientific method makes sense. Variables are limited and controlled in such a manner as to ensure cause and effect can be accurately related.

Iteration within the scientific method occurs one of two ways. First, if the test procedure is not providing meaningful data it may be because of a flaw in the procedure. In this case, the procedure must be refined. In some cases, this may take several iterations before the test yields meaningful information. Secondly, if the hypothesis is not proven valid, a new hypothesis may be formed or the question being asked may be changed.[19]

Creativity is not explicitly stated within the scientific method, however, effective application of it provides dividends within the process. For example, the more imaginative and creative the brainstorming is for possible answers to the question, the more likely an innovative idea will develop, and the rest of the scientific method can be used to test it. The notion of iteration (step 6) depends heavily upon the creative process in which new things are tried until a workable solution is developed.

Solutions are judged in this method by whether they support the hypothesis or not. This is an objective judgment which may lead to iteration, as discussed above. There is little, if any, subjective evaluation involved in the scientific method.

The Engineering Design Process

In engineering curricula, many programs introduce students to an engineering design process. One description of this process is "a series of steps that guides engineering teams as we solve problems. The design process is iterative, meaning that we repeat the steps as many times as needed, making improvements along the way as we learn from failure and uncover new design possibilities to arrive at great solutions." This source goes on to describe seven steps: (1) "Ask: Identify the need & constraints", (2) "Research the problem", (3) "Imagine: develop possible solutions", (4) "Plan: select a promising solution", (5) "Create: build a prototype", (6) "Test and evaluate prototype", and (7) "Improve: redesign as needed."[20]

At first glance, the engineering design process may appear to be linear. However, iteration is inherent in this cyclical process as an idea is refined, tested, and improved. Specifically, step (7) requires redesign which prompts the engineer to return to at least step (4) in the process and perhaps to even earlier steps.

Being creative and using imagination is more explicit in the engineering design process than the scientific method. Specifically, step (3) asks the engineer to "imagine." Some engineering design textbooks describe methods developed to inspire creativity and improve the variety of solutions engineering teams develop.[11,12]

Results from this process are judged at two specific steps. After initial ideas are developed in step (3), they are conceptually evaluated before step (4). The prototype is explicitly evaluated in step (6) to quantify how well it meets the design criteria. This is largely an objective evaluation but may include subjective judgment for certain design criteria (e.g. aesthetics or ease of use).

The Creative Process

In visual arts, the creative process is often described in four phases: (1) Preparation, (2) Incubation, (3) Illumination, and (4) Implementation.[21] Some sources also include a fifth phase, Evaluation, before or after Implementation.[22]

Preparation requires what would traditionally be called “work” – developing technical skills, gathering and reviewing background material, or studying new topics even if those topics seemingly are unrelated to the challenge at hand. Some visual arts practitioners call this “fooling around.” While this may not sound particularly creative, it is vital to the process because creativity cannot occur without technical competence in the specific discipline as well as the accumulation of diverse experiences (items 1 and 2 on Cropley’s list).

Incubation requires both a conscious and subconscious mind experience. One may not even be aware that refinement is occurring. Albert Einstein described this experience: “As one grows older, one sees the impossibility of imposing your will on the chaos with brute force. But if you are patient, there may come that moment when while eating an apple, the solution presents itself politely and says ‘Here I am.’”[23] Liu and Schonwetter explain that the subconscious is best activated through relaxation.[7] Therefore, the incubation phase can easily be disrupted by the hurried nature of one’s life: patience is necessary.

Illumination is the “Eureka” moment when the idea begins to come together. This may happen most any time, even when one is not directly involved with the challenge. Pablo Picasso offered a slightly contrasting opinion: “Inspiration exists, but it has to find you working.”[a] In either case, out of the percolations of the incubation period, the solution begins to become visible and one is able to identify what may very well be the finished idea, which becomes visible in the “mind’s eye.”

Implementation is when the finished idea receives refinement ultimately leading to the “light of day.” Because the journey from initial challenge to conclusion may not conform well to set schedules and deadlines, the creative process is most effectively experienced as an open-ended assignment. This is achieved in visual arts programs through assignments for which students may generate completely different works. These types of assignments differ from those designed to develop technical skills in which the submissions from students look largely the same.

[a] This quote is an English translation of Picasso’s statement “La inspiración existe, pero tiene que encontrarte trabajando” in Tomás R. Villasante (1994), Las ciudades hablan: identidades y movimientos sociales en seis metrópolis latinoamericanas. p. 264.[28]

Unlike the scientific method, this not a linear process at all. It is also not as neatly cyclical as is the engineering design process. In fact, preparation and incubation often occur simultaneously as one considers the problem, studies, thinks, sleeps, practices, explores, and goes about daily activities. Even during the implementation phase it is common to continue to think and explore while refining the work.

It is important to highlight that to be creative, specific technical skills must be developed. Many may master the technical skills for a visual arts discipline including brush strokes, pen-and-ink techniques, or the use of chemical etching processes for intaglio printing. However, it is far less common for students to employ these techniques in truly creative and innovative ways. Those who do may introduce a work that defines for others a new way to approach an old challenge. They are more likely to find their work displayed in galleries and museums.

Judging what work warrants display and celebration requires largely subjective evaluations although there are objective measures as well – often referred to as conventions. When presenting one's innovative accomplishments to the public, the creator must be ready to defend them against "push-back" from those who still follow conventions of the day. The creative artist must proceed with confidence. An extraction from the Saul Bass film "Why Man Creates," describes this challenge: " Have you ever thought that radical ideas that threaten institutions then become institutions that reject radical ideas that threaten institutions?"[23] Subjectivity is inherent in judging creative work.

SIMILARITIES AND DIFFERENCES

As summarized in Table 1, there are important similarities between the scientific method, engineering design process, and creative arts methods. Each provides a framework within which to develop solutions and each requires a variety of knowledge, skills, and abilities to apply. Each requires creativity to be applied. In the scientific method and engineering design process, creativity is most applicable in phases in which ideas are being generated (at the start or when deciding how best to iterate).

Each includes an element of judgment. In the scientific method this judgment is objective as the hypothesis is tested while in the engineering design and creative processes, the judgment has an element of subjectivity. This judgment is important: as Robinson writes, "Creativity is not only about generating ideas; it involves making judgments about them. It involves elaborating on the initial ideas, testing and refining them and even rejecting them in favor of others that emerge along the way."[8] If you replaced the word "creativity" with "scientific discovery" or "engineering design", the point would be equally valid.

While these similarities are instructive to teachers helping students make connections between subjects, concepts and methods, perhaps more interesting are the differences between the scientific method, engineering design process, and creative arts methods. A most significant difference is that the creative arts process is often circuitous rather than direct. Contrastingly, most sources describe the scientific method as a linear process which has been shown to have a negative effect on creativity.[24] The scientific method also emphasizes convergent reasoning as opposed to most creative processes which are described as divergent.[25] The finished product developed within the creative process may have wandered significantly distant from the initial challenge or idea. This is unlikely when applying the scientific method to test a specific hypothesis. Concerning linear versus circuitous process, engineering design is somewhere between the scientific method and the creative process and is a more cyclical process.

Table 1 Summary and Comparison of Methods

	Scientific Method	**Engineering Design Process**	**Creative Process**
Steps or Phases	(a) Make an observation (b) Ask a question (c) Form a hypothesis, or testable explanation (d) Make a prediction based on the hypothesis (e) Test the prediction (f) Iterate: use the results to make new hypotheses or predictions Source: [18]	(1) Ask: Identify the need & constraints (2) Research the problem (3) Imagine: develop possible solutions (4) Plan: select a promising solution (5) Create: build a prototype (6) Test and evaluate prototype (7) Improve: redesign as needed. Source: [20]	(1) Preparation (2) Incubation (3) Illumination (4) Implementation (5) Evaluation Sources: [21] and [22]
Process	Linear with some iteration	Cyclical	Circuitous
Creativity Applied	Steps (c) and (f)	Steps (3) and (7)	Phases (2), (3), and (4)
Creativity Impediments	Emphasis on inductive reasoning	Risk of focus on analytical reasoning	Cultural conventions
Judgment	Objective	Objective and subjective	Primarily subjective

ON JUDGMENT

Determining what is creative is a subjective decision but one that is important for engineering educators to be comfortable making. Unlike judgment within the scientific method in which the hypothesis is either confirmed or not, the judgment about a creative work does not necessarily have repeatable experimental data to support it. An understanding of how a critique is accomplished within a fine arts program is helpful for engineering educators determining how best to judge or assess creativity within engineering projects.

Critical judgement of a student’s creative project most effectively begins with a question the response to which subjectivity of the artist is revealed. While it may be easy to address assigned objectives such as the implementation of visual elements and principles of visual organization or use of materials, understanding where the artist has been and what life experiences inform their art is vital to communication; and communication is the essential reason for making works of art. The critique then centers on two fundamental components, form and content – physical characteristics and meaning.

Physical characteristics include the effective use of the medium, techniques and tools as well as the application of visual elements and principles, which are building blocks equivalent to the vocabulary of the spoken word . In other words, does the work demonstrate technical competence? Content addresses how well these physical characteristics communicate who the artist is and the intended meaning within the work of art. Every creative work should be in part a signature of the artist as well as a story about the artist's intended communication.

Critical judgment in the arts is heavily influenced by the past. Study of art history, other artists, and important works is central to the education and development of an artist. This is done formally during college courses and informally as part of general personal study often focused specifically on gaining inspiration for a new project. Study focuses on technical methods and details while paying attention to cultural context and the personal life of the artist. Study also includes connecting fundamental elements and principles of composition to the work being investigated. Doing so enables an artist to make connections with universal themes and principles, develop their own ability to carefully critique work, and build their knowledge which informs future work.

WHAT DOES THIS ALL MEAN?

Because it is important that engineers develop creativity skills in order to produce innovative solutions, it is equally important that engineering educators learn how to help students develop those skills along with technical content. It is inadequate to assume or hope that students will develop these critical skills on their own. Engineering educators can learn from the creative methods taught by art educators and the way creative works are assessed and critiqued.

The authors do not suggest that students should not be taught the scientific method and engineering design processes. Both are valuable tools that have been historically shown to generate important discoveries and solutions to complex problems. Rather, the authors suggest that in addition to emphasis on these two rather linear processes that develop convergent reasoning skills, engineering educators should also teach students creativity processes and provide opportunities for students to practice the skills associated with these more divergent processes.

Specific actions that engineering educators can take include:

1) Require engineering students to take at least one fine arts studio course early in the curriculum (ideally within their first year). While the study of art history or theater appreciation is valuable, the practical experience with the creative process, particularly the critique, makes taking a studio course critical. To make this requirement even more effective, consider linking specific courses in the arts with courses within the engineering curriculum and invite faculty members from both disciplines to engage in conversations and periodic critiques. When a student registers for either of the two courses, the linked course would be automatically added to the student's schedule. The National Academies of Sciences, Engineering, and Medicine describes the educational benefits of deliberate integration of arts and humanities with engineering curricula (and vice versa) – integration well beyond general education requirements.[26]
2) Do not rely only on fine arts courses to develop creativity skills in your students. Integrate open ended problems throughout the curriculum and include creativity as a part

of the assessment. It is important that students see that creativity is an inherent part of the learning[14] and engineering.

3) Integrate the development of creativity skills and abilities into the teaching of the engineering design process. Rather than teaching only processes that have been shown to develop more creative ideas, students should also be taught skills that improve creative thinking. Most importantly, students must be given opportunities to practice creative thinking and provided with specific feedback about how well they are developing.
4) Employ something like an art critique to provide feedback to students about their creative products. A capstone design presentation should be followed by a faculty and student discussion not just about the technical content of the work, but also about the level of innovation and the creative process by which the engineers developed their solution.
5) Interact with fine arts faculty on your campus. Organize events to expose more engineers to the creative arts and encourage engineering students to engage with art students about the creative process. One example of a program doing this is the Virginia A. Myers NEXUS of Engineering and the Arts at the University of Iowa which offers a space in which art and engineering students interact, explore, and learn from each other.[27]
6) Highlight engineers who are/were also artists (professionally, or as a hobby) to demonstrate the value that practicing the arts has on the mind and life. In some cases, there may be examples in which the art experience directly affected their engineering practice. In other cases, it may be a way to showcase a multi-dimensional person.

CONCLUSION

This paper has briefly summarized two methods that engineers are introduced to and apply in a variety of contexts during their education: the scientific method and the engineering design process. These are necessary but incomplete in the development of creative and innovative engineers. Students must be taught the creative process and provided with opportunities to practice and develop the skills necessary to employ it. Importantly, students must receive feedback about their creative processes and products in addition to feedback on mastery of technical content. Unless this is done throughout engineering curricula, the call for creative and innovative engineers to solve future problems will be incompletely answered. Engineering educators have an obligation to ensure this call is answered and answered well. They must integrate specific creative experiences into the curriculum. Learning from our creative arts colleagues is an excellent place to start.

REFERENCES

1. National Academy of Engineering. *The Engineer of 2020: Visions of Engineering in the New Century*. Washington, D.C.: National Academies Press; 2004. doi:10.17226/10999

2. Katehi L, Pearson G, Feder M. The Status and Nature of K-12 Engineering Education in the United States. *Bridg*. 2009;39(3):5-10. https://www.nae.edu/File.aspx?id=16147.

3. Committee on Education of the American Society of Civil Engineers. *Civil Engineering Body of Knowledge: Preparing the Future Civil Engineer*. 3rd ed. Reston, VA: American Society of Civil Engineers; 2019. https://ascelibrary.org/doi/book/10.1061/9780784415221.

4. Structural Engineering Institute. *A Vision for the Future of Structural Engineering and Structural Engineers: A Case for Change*.; 2013. http://www.asce.org/uploadedFiles/visionforthefuture.pdf.

5. Surovek A, Rassati GA. Is Structural Engineering Education Creating Barriers to Innovation and Creativity? In: *6th Structural Engineers World Congress*. Cancun, Mexico: EERI; 2017.

6. Sola E, Hoekstra R, Fiore S, McCauley P. An Investigation of the State of Creativity and Critical Thinking in Engineering Undergraduates. *Creat Educ*. 2017;08(09):1495-1522. doi:10.4236/ce.2017.89105

7. Liu Z, Schönwetter DJ. Teaching creativity in engineering. *Int J Eng Educ*. 2004;20(5):801-808.

8. Robinson K. *Out of Our Minds: The Power of Being Creative*. 3rd ed. Chichester, West Sussex, UK: John Wiley & Sons, Inc; 2017.

9. Bruhl J, Klosky JL. Inclusive Teaching: A Call for Creativity (WIP: Work in Progress). In: *ASEE Mid-Atlantic Regional Conference*. New York, NY: American Society for Engineering Education; 2019.

10. Walesh SG. *Introduction to Creativity and Innovation for Engineers*. Hoboken, NJ: Pearson Education, Inc.; 2017.

11. Dieter GE, Schmidt LC. *Engineering Design*. 5th ed. New York, NY: McGraw-Hill; 2009.

12. Niku SB. *Creative Design of Products and Systems*. Hoboken, NJ: John Wiley & Sons, Inc; 2009.

13. Cropley DH. Promoting creativity and innovation in engineering education. *Psychol Aesthetics, Creat Arts*. 2015;9(2):161-171. doi:10.1037/aca0000008

14. Baillie C, Walker P. Fostering creative thinking in student engineers. *Eur J Eng Educ*. 1998;23(1):35-44. doi:10.1080/0304379980230105

15. Cropley AJ. Fostering creativity in the classroom: General principles. In: Runco M, ed. *The Creativity Research Handbook*. Vol 1. Cresskill, NJ: Hampton Press; 1995:83-114.

16. Thagard P. How to be a successful scientist. In: Gorman ME, Tweney RD, Gooding DC, Kincannon AP, eds. *Scientific and Technological Thinking*. Mawah, NJ: Lawrence Erlbaum Associates; 2005:159-172. doi:10.4324/9781410611314

17. ABET. Criteria for Accrediting Engineering Programs, 2019-2020. https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/. Published 2019. Accessed December 26, 2019.

18. Khan Academy. The scientific method. https://www.khanacademy.org/science/high-

school-biology/hs-biology-foundations/hs-biology-and-the-scientific-method/a/the-science-of-biology. Published 2019. Accessed December 24, 2019.

19. Science Buddies. Comparing the Engineering Design Process and the Scientific Method. Science Buddies. https://www.sciencebuddies.org/science-fair-projects/engineering-design-process/engineering-design-compare-scientific-method. Published 2014. Accessed December 26, 2019.

20. TeachEngineering. Engineering Design Process. https://www.teachengineering.org/k12engineering/designprocess. Published 2019. Accessed December 24, 2019.

21. Gilkey C. The 4 Steps of the Creative Process. Productive Flourishing. https://www.productiveflourishing.com/demystifying-the-creative-process/. Published 2008. Accessed December 24, 2019.

22. Taylor J. The Five Stages of the Creative Process. https://www.jamestaylor.me/creative-process-five-stages/. Published 2014. Accessed December 26, 2019.

23. Bass S. *Why Man Creates*. United States: Pyramid Films; 1968. https://vimeo.com/22113008.

24. Roberto MA. *Unlocking Creativity*. Hoboken, NJ: John Wiley & Sons, Inc; 2019.

25. Surovek AE, Cropley DH, Jensen DH, Benning JL. The Creative Designer: Educating Divergent Thinkers in a Convergent Climate. In: *Structures Congress 2015*. Vol 2020. Portland, OR; 2015:755-768.

26. National Academies of Sciences Engineering and Medicine. *The Integration of the Humanities and Arts with Sciences, Engineering, and Medicine in Higher Education: Branches from the Same Tree*. (Skorton D, Bear A, eds.). Washington, DC: The National Academies Press; 2018. doi:10.17226/24988

27. The University of Iowa. NEXUS Program. https://www.engineering.uiowa.edu/college/nexus-program. Accessed April 14, 2020.

28. WikiQuote. Pablo Picasso. https://en.wikiquote.org/wiki/Pablo_Picasso. Accessed December 26, 2019.