Teaching and Assessment of Innovation and Creativity in Civil Engineering: Why? How? Now!

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Abstract

The goal of this paper is to inspire and equip civil engineering educators to integrate creativity and innovation in their teaching practices. Among the six strategic goal statements adopted by the ASCE Board of Direction is "Civil Engineers develop and apply innovative, state-of-the-art practices and technologies." Engineering education should set the stage for these skills and mindsets. In the recent activity to update the Civil Engineering Body of Knowledge (CEBOK3), creativity and innovation was proposed as a new outcome. Ultimately, it was decided to integrate these concepts explicitly into two of the twenty-one outcomes in the CEBOK3: Professional Attitudes (creativity) and Professional Responsibilities (innovation). In addition, these ideas were integrated into the text to help individuals fully understand the outcomes associated with critical thinking and problem solving, breadth in civil engineering areas, design, technical depth, sustainability, communication, teamwork & leadership, and lifelong learning. Rubrics for creativity and innovation in the cognitive and affective domains are provided. Some individuals argue that creativity cannot be taught and/or assessed. However, there are numerous examples that contradict these concerns. Problem based learning, building physical models, the analytic hierarchy process, the KEEN Innovator program, a leaderless classroom approach, and field trips are examples of methods that have been used to teach creativity and innovation. Methods used to assess creativity and innovation in engineering education settings include the Torrance Test of Creative Thinking, Purdue Creativity Test, revised Creative Engineering Design Assessment, and the CREAX test. We recommend that educators incorporate innovation and creativity into their teaching, in order to retain the best and brightest students in civil engineering and better prepare future civil engineering professionals.

Introduction

Creative thinking is both the capacity to combine or synthesize existing ideas, images, or expertise in original ways and the experience of thinking, reacting, and working in an imaginative way characterized by a high degree of innovation, divergent thinking, and risk taking. Creative thinking, as it is fostered within higher education, stems from an understanding of connections and can only be expressed productively within a particular domain. While demonstrating solid knowledge of the domain's parameters, the creative thinker, at the highest levels of performance, pushes beyond those boundaries in new, unique, or atypical recombinations, uncovering or critically perceiving new syntheses and using or recognizing creative risk-taking to achieve a solution.

There are widespread calls for creativity and innovation among engineers (e.g. NAE *Engineer of 2020*, [1]). Within the International Engineering Alliance's 'Graduate Attributes and Professional Competencies' [2] innovation is included among five attributes of complex activities conducted by engineers (EA5, p. 8). The National Society of Professional Engineers (NSPE) lists among its eight values "innovation through creative application of math, science, and engineering" (p. 6), states that "tomorrow's successful and relevant professional engineer" will need to be "creative and innovative" (p. 12), and weaves the ideas of creativity and innovation into four outcomes

(engineering science, problem solving, design, and professional attitudes) [3]. Creativity is linked to design as an outcome in the *Environmental Engineering Body of Knowledge* [4]. For example, creativity an important "way of thinking" to achieve sustainable design [5].

Sociologists/economists recognize engineers as part of the "creative class" that drives economic development in the modern economy [6]. Civil engineers have at times been left out of the discussion because of the size and time scale of our products. We do not produce prototypes that allow us to tinker and tweak our designs. We do not have orchestrated unveilings of new products that replace old models every year. Nevertheless, the ability of the civil engineering profession to continue to meet the needs of society will require innovation at a pace similar to other disciplines. As a community, we have already begun to recognize this need and advocate for methods that can increase the creativity and innovation allowed in civil engineering projects. Performance Based Design (PBD) is an example where the creativity of solutions can flourish by removing conventional code-based prescriptions. PDB requires fundamental knowledge but allows the freedom to connect and apply that knowledge in new forms. The creative idea becomes an innovation when it is built or implemented and proven through operation. However, an innovation does not become disruptive and alter society without diffusion of that knowledge [7]. Other civil engineers need to hear about, form an opinion of, and either implement or reject the innovation in other projects. The creative/ innovative cycle from formulation to diffusion needs to be done at all scales: profession, company, and individual.

Civil engineering is no different from other disciplines in recognizing the importance of creativity and innovation, with publications promoting creativity in civil engineering dating back nearly 30 years (e.g. [8], [9]). The Vision for Civil Engineering in 2025 states: "The civil engineer embraces attitudes conducive to effective professional practice… exhibit[ing]: Creativity and entrepreneurship that leads to proactive identification of possibilities…" [10]. Further, the aspirational vision of civil engineering in 2025 states: "We use ingenuity, creativity, and innovation to create whole projects that are more than the sum of their parts" (p. 53); "Civil engineers, as a result of their… innovative and creative outlook lead… to contribute significantly to enhancing the quality of life…" (p. 102). Stouffer et al. state "What "normal" civil engineers do is inherently creative" [11]. In March 2018 the ASCE Board of Direction adopted six strategic goals statements, the first of which was: "Civil Engineers develop and apply innovative, state-of-the-art practices and technologies." [12]

Engineering education as a whole may need to focus greater attention on fostering creativity and an innovation mindset among students. The National Academies report "*Rising Above the Gathering Storm*" [13] encouraged the NSF to "sponsor research into the processes involved in teaching creativity, inventiveness, and commercialization in technical environments." (p. 470). NSF's 10 Big Ideas includes NSF 2026, which seeks to invest in "bold foundational research questions that are large in scope and innovative in character" that will "capture the imagination of critical stakeholders" [14]. The American Society of Mechanical Engineers included "greater innovation & creativity" among seven areas targeted for change in education by 2030 [15]. In a study of engineering students, among 23 design activities, ~38% of the first-year students rated creativity among the six "most important" design activities, while ~8% fewer students included creativity among the top six as seniors [16]. Within mechanical engineering at Pennsylvania State University, results suggest that students view the environment / climate as decreasingly supportive

of innovation and creative thinking over their four years, and that the "originality and flexibility of ideas generated" by the students also decreased across the curriculum [17]. Genco et al. [18] also observed that seniors were less innovative than first-year students in completing a design task. Seymour and Hewitt noted the lack of practical application of material as among the reasons students leave STEM [19]. Thus, it appears that many engineering programs could devote greater attention to fostering creativity among students.A number individuals have encouraged greater integration of innovation and creativity into civil engineering education [11, 20-23]. For example, Arciszewski [24] notes:

> Reconnecting civil engineering with creativity and with doing nonroutine work can generate excitement. We can transform civil engineering education by teaching students how to become creative people—inventors leading the generation of novel solutions that contribute to the fundamental needs of society and advance our civilization. ….Our hypothesis is that one of the most important keys to the survival and growth of our profession is creativity…. Unfortunately, today's civil engineers are not well educated in how to be creative and how to develop novel and nonroutine solutions. This is a dangerous situation for our profession, which must be radically improved… if we want to fulfill our obligations to society as well as remain attractive to talented students." (p. 1-2)

Higher education more broadly has considered its role in fostering creativity. Creativity and innovation are included among skills of increasing importance in the workforce at large (e.g. 2022 skills outlook, growing #1 analytical thinking and innovation, #3 creativity, originality and initiative, [25, 26]). However, being innovative/ creative is also a skill with a large gap in the extent that employers believe college graduates are prepared [27]. The Association of American College and Universities (AACU) developed and endorses a so-called VALUE rubric for creative thinking (Table 1) [28]. As is evident, the engineering design process models the capstone level of solving problems. Engineering educators may find common ground with colleagues campus wide in promoting creative thinking among students.

Table 1. AAC&U VALUE Rubric for Creative Thinking [28]

Sub area	**1 Benchmark**	**2**	**3**	**4 Capstone**
Acquiring competencies	Successfully reproduces appropriate exemplar	Successfully adapts an appropriate exemplar to own specifications	Creates entirely new object, solution or idea appropriate to the domain	Reflect: evaluates creative process and product using domain-appropriate criteria
Taking risks	Stays strictly within the guidelines of the assignment	Considers new directions or approaches without going beyond the guidelines of the assignment	Incorporates new directions or approaches to the assignment in the final product	Actively seeks out and follows through on untested and potentially risky approaches to the assignment in final product
Solving problems	Only a single approach considered and used to solve the problem	Considers and rejects less acceptable approaches to solving problem	Having selected among alternatives, develops a logical consistent plan to solve the problem	Develops logical consistent plan to solve problem, recognizing consequences of solution and articulating reason for choosing solution
Embracing contradictions	Mentions in passing alternate, divergent, or contradictory perspectives or ideas	Recognizes the value of alternate, divergent, or contradictory perspectives or ideas in a small way	Incorporates alternate, divergent, or contradictory perspectives or ideas in an exploratory way	Integrates alternate, divergent, or contradictory perspectives or ideas fully

Sub area	1 Benchmark	2	3	4 Capstone
Innovative thinking	Reformulates a collection of available ideas	Experiments with creating a novel or unique idea, question, format, or product	Creates a novel or unique idea, question, format, or product	Extends a novel or unique idea, question, or product to create new knowledge or knowledge that crosses boundaries
Connecting, synthesizing, transforming	Recognizes existing connections among ideas or solutions	Connects ideas or solutions in novel ways	Synthesize ideas or solutions into a coherent whole	Transforms ideas or solutions into entirely new forms

Creativity and the CEBOK3

In the process of developing the third edition of the *Civil Engineering Body of Knowledge* (CEBOK3) the CEBOK Task Committee seriously considered adding creativity and innovation as a stand-alone outcome. On the first constituent survey in winter 2017, civil engineers were asked to consider the importance of creativity and innovation among 10 potential outcomes for inclusion in the CEBOK (in addition to rating the importance of the 24 existing outcomes in the CEBOK2; more details in [29]). The average rating for creativity and innovation was 3.88 on an importance scale from 1 to 5, among ~300 responses. This ranked it 23rd among 34 outcomes. Thus, to avoid an overly large laundry list of outcomes in the CEBOK3 (which included 21 outcomes), it was decided that creativity and innovation should not be a stand-alone outcome. Creativity is included in Outcome 19 – Professional Attitudes and innovation is called out explicitly in Outcome 20 - Professional Responsibilities (sub-parts extracted into Table 2).

In the cognitive domain, creative thinking and innovative solutions are essential skills engineers must possess to identify and solve the technical challenges facing society now and those of the future. Undergraduate (UGrad) students should be taught to identify and explain creative and innovative thinking among important professional attitudes and responsibilities of civil engineers, then practice applying the skills during mentored experience (MExp). In the affective domain, civil engineers must exhibit innovative and creative thinking to advance the work to address societies challenges and problems not yet identified. For entry into the profession, a practicing civil engineer should move beyond valuing creativity and innovation to integration of creativity and innovation into the work performed by civil engineers. This process begins by making undergraduate students aware of creative and innovative thinking and providing them opportunities to practice these skills. Mentored experiences enhance the value of creativity and innovative thinking in solving civil engineering problems. Ultimately, creative and innovative thinking must be advanced by the individual in their area of practice, through self-directed learning (SelfDev) guided by lifelong learning.

The importance of creativity and innovation is also evident in the CEBOK3 by integrating these ideas into the rationale and supporting text to help individuals understand eight additional outcomes: 8 – critical thinking and problem solving; 12 – breadth in civil engineering areas; 13 – design; 14 – technical depth; 15 – sustainability; 16 – communication; 17 – teamwork & leadership; 18 – lifelong learning.

Table 2. CEBOK3 rubrics that include creativity and innovation [30]

Cognitive Outcome	**Level 1 Remember**	**Level 2 Comprehend**	**Level 3 Apply**	**Level 4 Analyze**	**Level 5 Synthesize**
19 – Professional Attitudes	**Identify** professional attitudes relevant to the practice of civil engineering, including creativity, curiosity, flexibility, and dependability. (UGrad)	**Explain** professional attitudes … including creativity, …. (UGrad)	**Apply** knowledge of professional attitudes … including creativity, ... (MExp)	**Illustrate** professional attitudes … including creativity, ... (MExp)	**Integrate** professional attitudes … including creativity, ...
20 – Professional Responsibilities	**Identify** professional responsibilities relevant to the practice of civil engineering including safety, legal issues, licensure, credentialing, and innovation. (UGrad)	**Explain** professional responsibilities … including … innovation. (UGrad)	**Apply** professional responsibilities … including … innovation. (MExp)	**Illustrate** professional responsibilities … including …innovation. (MExp)	**Integrate** professional responsibilities … including …innovation. (MExp)
Affective Outcome	**Level 1 Receive**	**Level 2 Respond**	**Level 3 Value**	**Level 4 Organize**	**Level 5 Characterize**
Professional Attitudes	**Acknowledge** professional attitudes relevant the practice of civil engineering, including creativity, curiosity, flexibility, and dependability. (UGrad)	**Practice** professional attitudes … including creativity, …. (UGrad)	**Value** professional attitudes … including creativity, …. (MExp)	**Establish** professional attitudes … including creativity, …. (SelfDev)	**Advocate for** professional attitudes … including creativity,….
Professional Responsibilities	**Acknowledge** professional responsibilities relevant to the practice of civil engineering, including safety, legal issues, licensure, credentialing, and innovation. (UGrad)	**Examine** professional responsibilities … including … innovation. (UGrad)	**Value** professional responsibilities … including … innovation. (MExp)	**Form** judgements about professional responsibilities … including … innovation. (SelfDev)	**Advocate** for professional responsibilities … including … innovation.

A substantial number of write-in comments on the three constituent surveys that were part of the development process for the CEBOK3 indicated ways respondents felt creativity and/or innovation were important in engineering practice. Examples include:

> Creativity/Innovation - If you just "follow the book" then no new areas of engineering would arise and we would simply "follow the check list". Innovation/creativity is critical in any project even in just understanding the history behind the "rules". … Without creativity & innovation, public would not get best engineering from our practice.

> …complex problems cut across disciplines. So engineers must think on their feet, be creative problem solvers, be able to understand, analyze, and articulate the clients requirements and always look for better solutions that what they used in the past... Tomorrow's problems… will be solved by thinking differently and holistically in the real world in which we live.

> Changing materials and methods require constant updating of current technology, creativity and analytical thinking.

> It is [ ] critical for the civil engineers to have a "bigger" voice in the decision-making process, and for this we need to be more creative and to think about individual projects as being a part of an entire system (as opposed to being assembly line workers following standards and codes).

> Creativity, critical thinking, and interpersonal skills are what used to differentiate engineers from technicians. They helped engineers to become known as leaders. That has been lost.

Comments also illustrated the ties among creativity and innovation with other outcomes in the CEBOK, examples include:

> Creativity is essential for future solutions to complex problems. Critical and Analytical thinking is necessary for creative solutions.

> …ability to creatively solve problems within the technical, legal, financial and sustainable criteria must frame all civil engineering solutions.

> Creativity and innovation… could be incorporated into design and sustainability. Sustainability is attained up to a level of "Analysis" in Bloom's taxonomy in BOK2. The next level up "Synthesis" allows for plenty of room for creativity and innovation.

A number of write-in comments stressed that undergraduate education must incorporate creativity and innovation:

> Civil engineers don't magically become creative and innovative later in their careers. We must foster this during the pre-licensure period.

> Any job that does not require creativity and innovation can be automated and done by robots. Are we training engineer robots? or are we training problem solvers?

> Creativity should be promoted in our profession as much as is reasonable. The smartest tend to be the most creative and if we shun that part of a young person's interest, we will lose that valuable talent to another profession.

> Civil engineering is being left out of the innovation centers that are becoming so popular on campuses and proving to be highly effective in expanding the learning opportunities for students. To meet the problems of tomorrow, civil engineers need to be creative, be able to think critically and have analytical thinking skills.

> …the ability to create/innovate -- to try to do what has not been done -- is at the heart of engineering, whether one is involved in practice or academia. From Day 1 of their formal education, the CE student should see the value of and learn how to have to develop a problem-solving and creative/innovation mind set. Consider a creativity/innovation outcome and/or a creativity/innovation thread throughout the rubric.

> Creativity and innovation is creating the technologies that underlie the infrastructure of tomorrow. There will be innovation in infrastructure, the question is how big of a role will CE's

play in driving that innovation? Standards, codes, and professionalism are extremely important in Civil Engineering, but we are squeezing out innovation in the process. How do we uphold important aspects of practice yet encourage and make room for innovation?

Only a few comments noted reservations about including creativity / innovation in the CEBOK3 and/or education. For example:

> Large scale creativity and innovation is stifled by professional standards for negligence, i.e., trying something new that is arguably outside normal standards and practices is a punishable offense.
>
> Although the 4 attributes listed *[in professional attitudes]* (creativity, curiosity, etc) are important, I think integrity, honesty and respect are far more important.
>
> You want to encourage creativity in the curriculum but this would sometimes be at odds w/ appropriate coverage of some core areas
>
> While professional attitudes described here are desirable, the details do not support the need to include this outcome in the BOK. It is unclear if curiosity, creativity and flexibility can be taught.
>
> Creativity-- Doubt if can be taught to do, but can be shown how to recognize.

Rubrics for Creativity and Innovation in Civil Engineering

Although creativity and innovation are woven into a number of outcomes in the CEBOK3 [30], educators may find it helpful to have stand-alone rubrics; examples of cognitive and affective rubrics are provided in Table 3 and 4, respectively. In the cognitive domain, levels 1 to 4 could be incorporated into engineering education; levels 1 and 2 in a basic introductory engineering design course, common in the first-year of many programs; level 3 in a civil engineering design course, including capstone design; a case study might be an approach to reach level 4. Alternatively, levels 3 and 4 could be learned and/or reinforced on-the-job during mentored experience. Levels 5 and 6 might not be achieved until after professional licensure or by more senior engineers.

The integration of creativity education could help undergraduate students reach affective domain levels 1 and 2, receive and respond. Valuing creativity and innovation could also begin as a student, but should be reinforced during mentored experience. Level 4 is most likely self-developed during lifelong learning. Not all individuals will become advocates for creative and innovative thinking (level 5), but some who view these attributes as critically important may take on this role (e.g. Stuart Walesh).

Table 3. Proposed Cognitive Domain Rubric for Creativity and Innovation

Cognitive Domain Level of Achievement	**Demonstrated Ability**
1 – Remember (remember previously learned material)	**Identify** processes and conditions that stimulate creative thinking and methods for the diffusion of innovation.
2 – Comprehend (grasp the meaning of learned material)	**Explain** the role of creativity and innovation in the engineering design process.
3 – Apply (use learned material in new and concrete situations)	**Apply** techniques for creative thinking and innovative solutions to civil engineering problems.
4 – Analyze (break down material into its component parts so that its organizational structure may be understood)	**Analyze** the effectiveness of creative thinking and innovative solutions to civil engineering problems.
5 – Synthesize (put learned material together to form a new whole)	**Integrate** techniques for creative thinking and innovative solutions to solve complex civil engineering problems.
6 – Evaluate (judge the value of learned material for a given purpose)	**Evaluate** practices and requirements to achieve creative and innovative solutions to complex civil engineering projects.

Table 4. Proposed Affective Domain Rubric for Creativity and Innovation

Affective Domain Level of Achievement	**Demonstrated Ability**
1 – Receive (be aware of, be willing to receive, and be attentive to a particular phenomenon or behavior)	**Acknowledge** the need for creative and innovative thinking.
2 – Respond (actively participate in an activity, attend to a task, and react to motivation)	**Participate** in creative and innovative thinking.
3 – Value (attach value to a particular object, phenomenon, or behavior)	**Value** the impacts of creative and innovative thinking in the practice of civil engineering.
4 – Organize (sort values into priorities by contrasting different values, resolving conflicts between them, and creating a unique value system)	**Integrate** a commitment to creative and innovative thinking in the practice of civil engineering.
5 – Characterize (follow a value system that controls behavior that is pervasive, consistent, predictable, and a defining characteristic)	**Advocate** for creative and innovative thinking.

Teaching Creativity / Innovation

Creativity and innovation can in fact be taught, despite what some believe. An excellent summary of the literature on various approaches was provided in [31]. Problem-based learning in the context of real problems may be the most powerful approach, and there are a number of "thinking tools" that can facilitate students' divergent thinking during the idea generation phase ([32] provides an excellent summary of many of these tools including analogical thinking, attribute listing, and idea checklists). More complex problems often drive the need for more creativity. In reviewing the new definition of complex problems as defined in the ABET Accrediting Criteria for Engineering Programs (2019-2020) "complex engineering problems include one or more of the following characteristics: involving wide-ranging or conflicting technical issues, having no obvious solution, addressing problems not encompassed by current standards and codes, involving diverse groups

of stakeholders, including many component parts or sub-problems, involving multiple disciplines, or having significant consequences in a range of contexts." Service-learning projects in engineering may be particularly impactful in this regard (e.g. [33]).

Comments on the CEBOK3 surveys indicate that it is important the students are made aware of the creative and innovative practices in civil engineering as first year students, to help attract and retain individuals who self-identify as possessing these traits. This is perhaps a natural fit, given that many first-year courses incorporate design and/or project-based learning. Shah [34] described an elective course for first-year students in creative design at Ohio Northern University that was first introduced in 1973; in the design project, 20 points of 140 were awarded based on evidence of creativity. An introductory course "Creative Art of Structural / Civil Engineering" (CASCE) provides many ideas including field trips and active-learning [35]; http://casce.princeton.edu/. A sustainable design problem was integrated into a first-year engineering course that provided students an opportunity to exercise creativity, but the instructors noted that most designs were not very creative; however, no scaffolding of creativity or innovation were noted in the description of the project [36]. Christy and Lima [37] included a module about engineering creativity in a first-year engineering design course. The module framed creativity as encompassing 7 principles following the example of Leonardo da Vinci, and then students did exercises to develop their skills in each of the 7 areas.

In fall 2018, Bielefeldt explicitly added one class period to discuss innovation in a 1-credit Introduction to Civil Engineering course. As a pre-lecture assignment, students were given a choice of selecting among six short online readings (e.g. [38-42]) and writing a short (300-500 word) reflection on what they learned. During class, creative bridge designs from an earlier assignment were highlighted and a short hands-on activity was conducted. This small introduction to innovation and creativity is deemed a "microinsertion".

Given that innovation is situated with the Professional Responsibilities outcome in the CEBOK3 and creativity within the Professional Attitudes outcome, an ideal location for teaching these skills might be courses that focus on professional issues [43]. In the senior year, students could create portfolios demonstrating mastery using a competency matrix. This requires students to "engage in the creative process of selection, reflection and description regarding what they have learned" [37].

Creativity can also be integrated into core civil engineering technical courses. Zheng et al. [44] described the integration of modules on nanotechnology and creativity into a "Construction Materials" course that included a laboratory. Mini competitions to encourage creativity were added into the laboratories associated with an introductory structural engineering design and structural concrete course [45]. Faculty may also be able to bring their research to the classroom as examples of innovations / creative approaches to civil engineering problems.

Capstone design is another good opportunity to highlight the importance of creativity and innovation, and integrate opportunities for students to practice these skills. Oswald Beiler [46] described how a civil engineering capstone design course was evaluated for alignment with KEEN (Kern Entrepreneurship Education Network) outcomes, using KEEN rubrics. The author explored the first course in a two-course sequence, focusing on a feasibility study project and a global perspectives essay. The analytic hierarchy process (AHP) was integrated into a capstone design

course for mechanical and aerospace engineers to facilitate a creative process as a team of four senior students designed an autonomous robot boat [47]. The process is similar to a traditional weighted criteria decision matrix approach but with refinement that can help guide the divergent – convergent thinking processes that are characteristics of creative design thinking.

Most curricula will not have space to accommodate an entire course devoted to creativity and innovation. However, this type of course could be offered as an elective. An example of this course was provided by Matson, a professor of environmental engineering, and Horner, the director of a minor in engineering leadership [48]. A broad idea from the course that might be transferable to other settings is the "leaderless classroom" approach. The instructors characterize this as a "radical approach" where "students [are] almost entirely responsible for their own learning", including determining the grading process, how to use class time, and the course content. While most faculty (and students) would not be comfortable with this model for an entire course, a module using the approach could be effective. The instructors note how students struggled at the beginning of the semester, but note "the culture created by this environment embraces intelligent fast failure." Another example of a full course is OLS 35000 Creativity in business and Industry [49]. The course included a Creative Problem Solving assignment that required individual students to "identify a personal or work related problem and construct a physical model to represent the problem and its creative solution." The models were constrained to be constructed primarily of popsicle sticks (>70%). The physical model was found to be an important facet in facilitating growth in students' creativity, based largely on student survey responses. A third example is the ECE490DI Creativity in Engineering course at Valparaiso University that includes field trips as an impactful activity [50].

Another idea to consider is microinsertions of creativity at multiple points in the curriculum. This could be similar to models of "ethics across the curriculum", whereby numerous courses have small opportunities for ethics discussion. This "across the curriculum" approach might be effective for instilling a mindset of creativity in students and may be important given that the subtle "hidden curriculum" within engineering may in fact stifle creativity [51]. For example, if the majority of courses are highly constrained and offer few opportunities to exercise creativity (e.g. math, science, and engineering science courses that predominate the early years of the curriculum), students may feel that creativity is not valued in engineering. Redesigning some assignments in every civil engineering course to allow students some degree of freedom and choice in their approach could counter this prevailing trend. The VALUE rubric for creativity and innovation [28] brings this idea to mind. Curricula with a design spine or extensive integration of open-ended problem-based learning likely already fulfill this aim. Programs choosing to pursue this approach are encouraged to include faculty development in their process; [52] describes this for an Industrial Technologies degree program in Madrid.

As a final example of teaching creativity and innovation, the Franklin W. Olin College of Engineering was established to provide graduates with an opportunity to combine the "know how" with the "know why" and the "know when" [53]. An Olin College engineering degree program is designed to provide opportunities for students to think creatively and solve complex problems to create engineer-innovators. Classes are taught in a studio space so that students can tackle real world problems and faculty serve as coaches rather than instructors [54]. Although an extreme example of integrating innovation and creativity in engineering curriculum, the success of the

school and their programs are testament to the ability to integrate creativity and innovation into engineering curricula.

Assessment of Creativity / Innovation

There are many methods that can be used to assess student creativity; some of the approaches that have been used in engineering are summarized in Table 5. A complete analysis of these methods is beyond the scope of the current paper; readers are referred to [55-57] for a good overview. These methods differ widely in complexity, length, and specific sub-elements of creativity that are assessed. Some are indirect self-evaluations and others are direct but require subjective ratings of student work. Instructors trying to enhance creativity in students via intentional integration in their courses are encouraged to use demonstrated methods for assessment. For example, Garcia and Garcia [58] used the CREAX tool and found that students earning degrees in different engineering disciplines differed in abstraction (highest in mining engineering), connection (lowest in mining engineering; largest variance in industrial engineering), and audacity (highest in forestry engineering). They also found that overall creativity was higher among final year mining engineering students compared to first-year students (average 66.2 vs. 61.3), with the largest differences in audacity (+12).

Table 5. Creativity and Innovativeness Assessment Methods

Method	Notes	Citation
CEDA = Creative Engineering Design Assessment	Product design via divergent thinking, convergent thinking, constraint satisfaction, problem finding, and problem solving; total time for assessment ~25 minutes for 5 design problems with five parts each; artifacts from the exercise evaluated by judges	[56, 57]
CPS = creative personality	Self appraisal	[56]
CREAX	Self assessment, free online (http://www.testmycreativity.com/) forty items that can be completed in about 10 minutes or less; eight elements evaluated: abstraction, connection, perspective, curiosity, boldness, paradox, complexity, and persistence; combine into overall global value.	[58]
CRT = cognitive risk tolerance	35 self-report items on 0 to 9 Likert scale	[59]
CT = creative temperament	Special purpose scale of the California Psychological Inventory (CPI)	[56]
Owens Creativity Test	Designed to measure divergent thinking / fluency in engineering, published in 1960 but unable to find examples of use	Cited in [60]
PCT = Purdue Creativity Test	Measures divergent thinking; Fluency (12 items), flexibility (8 items), total score; developed in 1960, multiple versions available	[57]
TTCT = Torrance Test of Creative Thinking	Measures aspects of creative potential based on three activities / pictorial questions: fluency (number of solutions), flexibility (number of categories of the responses), originality, elaboration, resistance to premature closure; well known outside engineering	[61]

Less formal measures of creativity may also be appropriate. Design-based courses often use customized assessment rubrics. Providing these rubrics to students can guide them in determining the important elements of the project. Thus, making creativity or related ideas part of the evaluation rubric communicates to students that this is an important and valued element in the design process. Within mechanical engineering, the rubric for capstone design projects included creativity under 'personal abilities', rated on a scale from 1 to 9 ranging from 'doesn't move away from status quo,

not open to new ideas' to 'open to new ideas and methods of improvement' as meeting expectations to 'strives for new ideas, thinks outside of the box' [62]. The students used the rubric to rate themselves and group members, discussed ratings with professor and developed plans to improve. Klawans et al. [63] described the use of an expert panel to evaluate creativity.

A highly simplistic indirect measure of students' affective perceptions around creativity have been incorporated into the graduating senior survey of civil engineering students at the University of Colorado Boulder. Among 24 items related to the ABET Criterion 3 a to k outcomes and other issues, students were asked to rate their perceptions of the importance and personal achievement of the ability to think creatively. The specific text stated: "Please rate how well you feel your CU Engineering education equipped you in the following areas and the importance of these areas. Ability to think creatively. Achievement scale: 1-not at all, 2- not very well, 3-moderately well, 4-very well, 5-extremely well. Importance scale: 1-not at all important, 2-not very important; 3-moderately important; 4-very important, 5-extremely important." Results are summarized in Figure 1; showing an average self-rated ability of 3.6 versus an importance of 4.3. There has long been a significant gap between students' "importance" and "achievement" ratings. Among the 11% of the students who rated their achievement as 1 or 2, all rated the importance at 4 or 5. Thus, while students appear to acknowledge the importance of creative thinking in civil engineering (affective domain level 1), most believe that their abilities to be creative and innovative could be improved.

Conclusions

Creativity and innovation are important attitudes and skills for civil engineers in practice. A recognition of the importance of these attributes and calls to improve these competencies have appeared for more than 25 years by the professional societies influencing the civil engineering profession. Higher education can foster creativity and innovation using a variety of teaching approaches and a range of methods to assess success. In particular, complex, open-ended design problems may foster students' creativity. Civil engineering educators are encouraged to critically review their own programs to evaluate whether they are graduating students who are prepared to be creative and innovative in their practice, in alignment with outcomes in the third edition of the CEBOK. Individually, each instructor can consider ways to integrate creativity and innovation into the courses that they teach. A widespread commitment to instilling the mindset and basic tools for creativity and innovation in civil engineering students will ultimately benefit both the profession and society, contributing to safer, more sustainable, and resilient infrastructure. Beyond the educational environment, a young engineer's mentored experience can reinforce the creativity and innovation groundwork laid in the higher education experience positively influencing the civil engineer throughout their career.

Acknowledgements

The authors acknowledge the input of colleagues on the CEBOK3 committee and civil engineering practitioners and educators that invested their time to provide input into the CEBOK3 process.

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