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Accepted manuscript

A Proposed Case-Based Learning Framework for Fostering Undergraduate Engineering Students' Creative and Critical Thinking

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Abstract

Scholars and international bodies have highlighted the need to foster undergraduate engineering students' creative thinking and critical thinking. Case-based learning is a name for a host of pedagogical approaches which are student-centered, requiring the instructor to act as an expert guide rather than a source of knowledge. These approaches make use of cases, thus contextualizing learning of discipline or practice-specific knowledge. This approach can help facilitate students' development of conceptual understanding and their thinking skills, as students work through and reflect on the process of solving cases. Despite the learning benefits of case-based learning, it has not often been implemented in undergraduate engineering education when compared with project- or problem-based learning. This paper outlines our proposal for a case-based learning pedagogical framework which aims to foster undergraduate engineering students' creative and critical thinking. The framework provides scaffolding of the learning process for students with a sequence of case-based learning implementations with varying levels of student autonomy. We begin by providing a theoretical background on problem-solving in engineering, creative thinking, and critical thinking, followed by a review of case-based learning in undergraduate engineering education. Next, we outline our proposed pedagogical framework, including guidelines for instructional design and implementation, as well as practical examples. We end with a discussion where we elaborate on the contributions and limitations of our work. Finally, we discuss potential challenges associated with the implementation of our approach and corresponding mitigations. This work contributes theoretical and practical insights for undergraduate engineering students' creative and critical thinking.

Keywords: Case-based learning, Creative thinking, Critical thinking, Engineering education, Undergraduate education

Introduction

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As the world becomes more volatile, uncertain, ambiguous, and complex (Scott, 2015), and with automation expected to spread rapidly to more sectors (Nedelkoska & Quintini, 2018), the need for problem-solvers who are creative and critical-minded has come to the fore in global job markets (World Economic Forum, 2016). Such need has become even more pronounced in science, technology, engineering, and mathematics (STEM) professions (Jang, 2016).

Educational organizations have also stressed the importance of fostering undergraduate STEM students' creative and critical thinking (ABET, 2019; Jamieson & Lohmann, 2012; National Research Council, 2013). However, despite the stated need for creative, critical thinking alumni of undergraduate engineering, many engineering-centric institutions of higher education neither emphasize nor encourage the acquisition of these thinking skills. Furthermore, those institutions fail to include acquisition of general abilities to tackle real-life problems into their curricula and pedagogy (Atwood & Pretz, 2016; Cropley, 2015; Jamieson & Lohmann, 2012; Author 1 & Colleagues; Valentine et al., 2019). Other studies have also shown that undergraduate engineering students' general creativity has decreased in recent decades (Kim, 2011) and that those students' creative problem-solving ability tends to decrease during their studies (Genco et al., 2012; Kazerounian & Foley, 2007). Regarding students' critical thinking, studies tend to show a mixed picture pointing toward overall stagnation rather than an increase or a decline (Sola et al., 2017).

As a response to the lack of pedagogy for fostering undergraduate engineering students' creative and critical thinking, we present a pedagogical framework that aims to enhance these thinking skills in the context of case-based problems. We call our framework *creative and critical thinking with case-based learning* or CCT–CBL. The framework is based on CBL, a pedagogical approach or set of approaches which make use of contextualized cases to facilitate student-centered learning. CBL is taught (and learned) through modeling of cases and working through potential solutions. CBL provides students with opportunities to develop their higher-order thinking, interpersonal, and problem-solving skills (Allchin, 2013) while allowing instructors to give students varying degrees of autonomy (Kulak & Newton, 2014).

The rest of this paper is organized as follows: first, we detail the theoretical background and literature of empirical studies on which our pedagogical framework is based. We then outline our proposed framework, including guidelines for design and implementation. We end by providing our concluding thoughts and outlining the contribution of this work.

Theoretical Background

In this section, we use Amabile's componential theory of creativity (1983) to base our theoretical background on addressing engineering problems, creative thinking, and critical thinking. Next, we cover empirical studies on CBL in undergraduate science and engineering education and the lessons learned from them.

Tackling Design Problems in Engineering

Design is a central activity in engineering and can be conceived of as a process in which engineers generate, evaluate, and specify concepts for solutions to problems while taking into consideration the constraints in the proposed solutions (Dym et al., 2005). Design problems tend to have multiple potential solutions and non-prescribed paths to solving them, requiring creativity (Jonassen, 2000) and critical thinking (Ahern et al., 2019).

Amabile's componential theory of creativity (1983) decomposes the process of solving problems like design problems into five major stages: the first stage constitutes identifying the problem at hand, i.e., understanding the nature of the creative problem space and the context of prospective solutions. Once the problem is clearly defined, next is the preparation stage, where necessary information is collected and activated. This information gathering stage relies on identifying the characteristics of the problem space and seeking for relevant information accordingly. Then, in the third stage, responses (i.e., proposed solutions) are generated based on the relevant information gathered in the previous stage and the requirements of the identified problem. In the fourth stage, the created response is validated by incorporating the existing factual domain-specific knowledge. Finally, in the fifth stage, i.e., the outcome stage, the process terminates, or the cycle begins in a new iteration, depending on the response validation process. If the goal is achieved (i.e., success) or no possible responses are generated (i.e., failure), the componential process of creativity is completed. Otherwise, in light of a certain level of progress made toward the goal, it is returned to the first stage, namely, the problem presentation stage (Amabile, 1983).

In this paper, we focus on the latter stages of problem-solving, as they are most suitable for CBL: *response generation* and *response validation*. In the response generation stage, creative thinking is crucial. Therefore, our proposed framework aims to enhance students' creative thinking through analogical reasoning. In that regard, we primarily focus on the schema theory (ref). The response validation stage, for which critical thinking is crucial, our framework aims to facilitate the process of thinking critically when making judgments about the validity of the generated responses.

Response Generation, Creative Thinking, and Analogical Reasoning

As previously mentioned, response generation is dependent on creativity. While no consensus exists regarding the standard definition of creativity, the two components which are most mentioned are *novelty* and *usefulness*. Novelty has been described by various terms, such as an idea being rare within a particular group (Runco & Jaeger, 2012), “uncommon” (Barron, 1955, p.478), or unique (Berg, 2014), while usefulness has been defined as utility, “adaptive to reality” (Barron, 1955, p. 479), effectiveness, or valuability (Berg, 2014; Runco & Jaeger, 2012).

Analogical reasoning (AR), which is the generation of analogies, is used to employ an existing solution to a similar, earlier problem to help solve a new problem (Holyoak et al., 2001; Schelhorn & Griego, 2007). Analogies have played a historical role in science and engineering breakthroughs (Holyoak & Thagard, 1995), and their use in problem-solving has been recorded and published across many science and engineering disciplines, such as computer science (e.g., Chilton, Petridis, & Agrawala, 2019), artificial intelligence (e.g., Goel, 1997), mechanical design (e.g., Linsey, Wood, & Markman, 2008), and industrial design (e.g., Çubukcu & Dündar, 2007; Dahl & Moreau, 2002). Furthermore, and highly pertinent for education, research demonstrates AR helps improve conceptual learning, which is crucial for education (Wolfe, Reyna, & Brainerd, 2005).

The literature discusses two types of AR—*transformational analogical reasoning* (TAR) and *derivational analogical reasoning* (DAR)—where the former involves mapping of structural relations between the source (existing solution) to the target (the problem at hand), while the latter involves applying the technique which had helped solve the source problem (Schelhorn et al., 2007).

TAR relies on constructing mental representations. It is by constructing these representations of the source and target objects that individual similarities between the objects are identified (Bonnardel & Marmeche, 2004). Gick and Holyoak (1983) suggested the underlying mechanism of TAR lies in abstracting the structural relations between the sources and extracting novel categories by mapping the abstracted relations onto the target problem (Holyoak et al., 2001).

Response Validation, Critical Thinking, and Judgment, and Decision-Making

The response validation stage in Amabile's componential framework of creativity includes the assessment of validity, i.e.., the correctness, usefulness, value, appropriateness, or the possibility of the response (idea or solution) being generated. Evaluating the validity of the response relies on the individual's domain-relevant knowledge and skills to test the response against the relevant criteria (Amabile, 1983).

The stage of response validation is reliant on the use of critical thinking, which is crucial for solving engineering problems successfully. Critical thinking in problem-solving involves the assessment of available information and making decisions based on such assessments (Ahern et al., 2019). In the seminal the Delphi report (Facione, 1990), experts report their definition of critical thinking as follows: "We understand critical thinking to be purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which the judgment is based" (p.3). Furthermore, the report outlines the tenets of critical thinking skills, namely, interpretation, analysis, evaluation, inference, explanation, and self-regulation. Among these tenets, interpretation and evaluation are the two most relevant to the response validation stage in Amabile's model.

According to the Delphi report, the interpretation skill is one of the critical thinking tenets and encompasses the following sub skills: (1) categorization, being able to describe and distinguish meaningfully distinct categories or phenomena and developing intuition to sort out relevant information; (2) decoding significance, being able to identify significant goals, values, and criteria when given different sources of information and; (3) clarifying meaning, using different techniques (e.g., analogies, figurative expressions) to remove ambiguity, thus clarifying the meaning of the problem at hand.

Another critical thinking promoting skill that is relevant to the response validation stage is evaluation. Evaluation, according to the report, is crucial for critical thinking as it enhances the ability to assess the inferential relationship among the arguments, solutions, or descriptions as well as the contextual relevance and significance of information (Facione, 1990).

In order to further explore the underlying mechanisms of these skills, we rely on fuzzy-trace theory (FTT), a cognitive theory about judgment and decision-making (Reyna, 2012). The theory has important implications for enhancing critical thinking through improving interpretation, meaning-making, evaluation, judgment, and decision-making. According to FTT, people are meaning makers and engage with cognitive activities (e.g., higher-order thinking skills, recalling, recognizing information, making decisions) by relying on mental representations (Brainerd & Reyna, 1990). Specifically, the presented information is mentally represented (i.e., encoded) in two different and independent forms, namely, verbatim and gist. Verbatim representations are superficial, whereas gist representations are meaningful yet vague (Brainerd & Reyna, 1990). Despite being imprecise and simple, gist representations are developmentally advanced and are associated with the bottom-line meaning, i.e., the essence, of the task. Gist representations focus on the most relevant features, whereas verbatim representations include irrelevant and superfluous information. The fuzziest mental representation is called categorical gist, and it is often the primary source of judgment, i.e., fuzzy processing preference (Reyna, 2012).

Prior research shows that the gist-based mechanism described directly above influences the extent to which people make good judgments (e.g., Author 2 & Colleague, 2020; Corbin et al., 2015; Reyna & Farley, 2006;). In fact, overreliance on superficial and literal representations, i.e., verbatim representations, could be misleading because it is the gist-based thinking that helps individuals to extract the meaningful categorical representations that help them to make good judgments (e.g., Author 2 & Colleagues, 2022; Reyna & Lloyd, 2006).

Research shows that relying on gist representations fosters the ability to recognize categories (qualitative, simple yet productive categorical gists, such as “some” vs. “none”), identify significance and relevance of information in a given context, and extract the essence Reyna, 2012; Reyna & Farley, 2006, Reyna & Brainerd, 1991). The ability to operate on gist improves as expertise increases (Reyna & Lloyd, 2006). Therefore, in a learning environment, as students gain more expertise in a subject matter, they are expected to make better judgments about the problem that they are solving, which then ultimately improves their skills that are crucial for critical thinking. In particular, as expertise increases, individuals become better at recognizing relevant factors about the problem that they are solving (Ericsson & Simon, 1998) and discriminate solutions based on the patterns that are not accessible to a novice (Klein & Hoffman, 1993).

Case-Based Learning in Undergraduate Engineering Education

The origins of CBL are in professional education, specifically in medicine, business, and law. CBL is a name for a host of pedagogical approaches which are student-centered, requiring the instructor to act as an expert guide rather than a source of knowledge. These approaches make use of specific occasions (cases), thus contextualizing learning of discipline and/or practice-specific knowledge (Allchin, 2013). CBL can help facilitate students' development of conceptual understanding along with their thinking skills, as students work through and reflect on the process of solving cases.

As a field with an established tradition in CBL, medical education can offer us evidence-based ways for classifying CBL implementations. Kulak and Newton (2014) classified CBL implementations in medical education into five types, varying by degree of student direction over their learning (student autonomy). Table 1 summarizes these types of CBL in general terms which can also apply to fields outside of medical education.

Table 1 Types of case-based learning implementations and their respective learning progressions. Adapted from Kulak and Newton (2014)

Case-based learning type Degree of student autonomy	Learning progression[a]
Lecture-based Very low autonomy	1. Case is given as an example to complement a lecture about domain-specific knowledge. The case, test results, learning issues, and reasoning are all integrated into a descriptive narrative (story) 2. Instructor may or may not ask students to connect the case to the lecture
Directed Low autonomy	1. The case is fully described, and all data and references are provided. All the learning issues are provided as directed questions 2. A lecture is given to provide required domain-based knowledge for understanding the case 3. Each group solves all the questions and presents their answers 4. The instructor facilitates a general discussion with the whole class to find answers and consensus
Interrupted Medium autonomy	1. The case is not entirely described and the topics to be learned are given as questions 2. Discussion or homework is done within groups to develop tentative solutions 3. More details on the case are given to further develop the topic Information is integrated and the case is concluded
Jigsaw High autonomy	1. As a prerequisite, all students should know the domain content basics, as this form of CBL requires them to integrate concepts. So, this type of CBL may or may not begin with a lecture 2. Case is provided to multiple groups. Each group receives only one of multiple learning topics, phrased as questions 3. Each group solves their question, so they become "experts" at it 4. New groups are formed with one "expert" from previous groups, so each member shares their answers to questions 5. The group integrates all answers into a general solution to the case
Problem-based learning Very high autonomy	1. Depending on the learning goals, a full or briefer version of the case is given out. No questions are provided to any group, and there is no lecture 2. Case development depends on students' initiative and contributions. Each group develops their own questions. It might be used entirely without lectures. Requires clear definition of what is known, what is unknown and what needs to be known. Learning issues may go beyond the stated topic but remain related to it

[a]For engineering education, "question" may be replaced with "problem" and "answer" may be replaced with "idea" or "solution"

The commonly used acronym “PBL” stands for either *problem-based learning* or *project-based learning* (Chen et al., 2021). A key difference between problem- and project-based learning is that in the former, problems are usually presented to students without prior study (Pease & Kuhn, 2011), while in the latter, several small projects are usually given as part of a course, or the entire curriculum is organized around projects instead of subjects (Mills & Treagust, 2003). As such, project-based learning involves knowledge acquisition, while problem-based learning involves knowledge application.

However, CBL and problem-based learning are also viewed as wholly distinct approaches by some. In CBL, problems are defined to an extent, and the problem-solving process is guided to one degree or another; in problem-based learning, the introduction of the problem/s is open-ended and less defined than in CBL; and the problem-solving process is less guided than in CBL (Srinivasan et al., 2007). In other words, problem-based learning leaves more of the *preparation* stage of problem-solving to students than CBL does (see section “Tackling Design Problems in Engineering” above). In this way, CBL scaffolds students’ learning more so than problem-based learning but does not present problems in a way that is as authentic as in problem-based learning.

The lack of instructor training, challenges in choosing suitable assessment methods, and the need to train students in these non-traditional learning methods often stand in the way of implementing PBL and CBL. In addition, studies on CBL are under-published in undergraduate engineering education, so educators have little insight to draw from. A comprehensive review of PBL in engineering education revealed that CBL is rarely implemented and that most PBL implementations in this field are project-based (Chen et al., 2021). Corroborating this view, a Google Scholar search we conducted for “undergraduate engineering education” AND “problem-based learning” led to 1,120 results, while our search for “undergraduate engineering education” AND “case-based” led to 184 results. It therefore appears that the benefits of CBL to undergraduate engineering education are yet to be fully explored and communicated to educators.

Case-based reasoning (CBR) is a type of DAR which relies on previous experience. In CBR, problem-solvers rely on approaches and skills which proved successful for solving problems (cases) in a similar domain to solve the problem at hand. Unlike TAR, CBR pertains to the process of solving the target challenge and not to the content of the solution. To successfully engage with CBR, the problem-solver must either have knowledge and expertise of solved problems or have access to detailed solved cases (Kolodner, 2014). CBR should not be confused with CBL; while CBR is a kind of reasoning, CBL is a pedagogical approach or set of approaches.

Case-Based Learning in Undergraduate Engineering Education

To provide input for the design of our pedagogical framework, we conducted a literature search and review of CBL in undergraduate engineering education. Our review is not meant to be exhaustive but rather identify the most relevant literature for our aims. To this end, we conducted two Google Scholar searches, the first specific and focused and the second less so, to make sure we find as many relevant papers as possible.

Our first search was for “undergraduate engineering education” AND “case-based.” We limited our search to the years 2010–2021. Our search yielded 183 results. We also searched for “engineering education” AND “case-based” AND (“critical thinking” OR “creative thinking”), within the same range of years. We received 2810 results. From these, we took only the papers in the first five pages—50 in total. Thus, our review included 233 papers.

Figure 1 details our process for excluding works which were not relevant to our review.

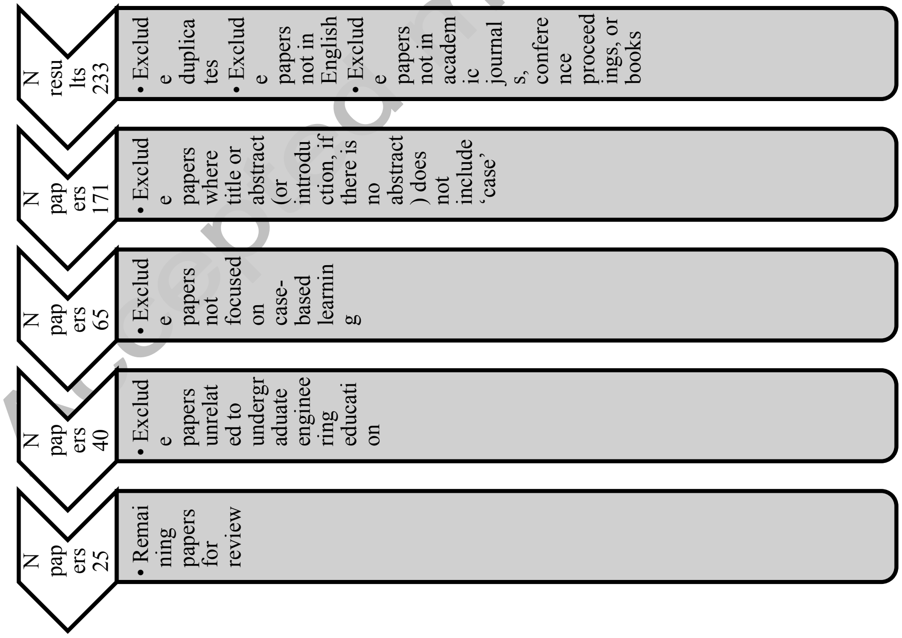

Fig. 1 The process of excluding works for our literature review

Following the exclusion process, we were left with 25 papers to review: 14 journal articles, 10 conference proceeding papers, and one book chapter. Twenty-one papers reported on empirical studies: 18 involved only students as participants, one involved only instructors as participants, and two involved members of both populations as participants.

Twelve empirical papers are specific to an engineering discipline. These include papers in civil engineering (Flynn et al., 2016; McWhirter & Shealy, 2017, 2020; Shen & Zhu, 2011; Zhu & Ibrahim, 2016), mechanical engineering (Jayaram, 2013; Yadav et al., 2019; Yadav et al., 2014; Yadav et al., 2013), network engineering (Cifuentes et al., 2010; Jing & Qi, 2015), aeronautical engineering (ER, 2014), and chemical engineering (Yau et al., 2013). Nine empirical papers were not specific to any engineering discipline but instead concerned aspects of engineering; ethics, which is cross-disciplinary (Baligar & Joshi, 2017; Bombaerts et al., 2019; Kisselburgh et al., 2016; Martin et al., 2021; Nielsen & Christiansen, 2015; Sivaraman, 2019; Winiecki & Ackler, 2020); and geoscience and geotechnical engineering—a multidisciplinary subject (Ingeman-Nielsen & Christensen, 2011).

Table 2 categorizes the empirical papers included in our review by the way in which cases are integrated into the educational setting. Table 3 details the categories of student assessment which were included in each empirical paper we reviewed. We excluded four papers from this table: three which did not report any concrete results, whether descriptive or inferential (Cifuentes et al., 2010; Jing & Qi, 2015; Shen & Zhu, 2011), and another paper which only reported on data collected from instructors (Martin et al., 2021). We also did not include in Table 3 variables which only appeared in one paper.

Table 2 Empirical papers classified by integration of case/s into the learning setting

Integration of case/s into educational setting	Citations
Embedded: one or more cases embedded throughout course or module	Bombaerts et al. (2021); Ingeman-Nielsen and Christensen (2011); Jing and Qi (2015); Winiecki et al. (2020); Yau et al. (2013)
Multi-standalone: one or more standalone cases implemented in multiple courses	Cifuentes et al. (2010); Kisselburgh et al. (2016); McWhirter and Shealy (2017); Nielsen and Christiansen (2015)[a]; Zhu and Ibrahim (2017)
Single-standalone: one or more standalone cases, each implemented in one course	Baligar & Joshi, 2017; ER (2014); Flynn et al. (2016); Martin et al. (2019); McWhirter and Shealy (2020); Nielsen and Christiansen (2015); Shen and Zhu (2011); Winiecki et al. (2020); Yadav et al. (2010, 2019)
Assessment: standalone case/s used for summative learning assessment in course	Sivaraman (2019)

[a]The paper describes course-specific cases and non-specific cases

Table 3 Empirical papers on case-based learning in undergraduate engineering education and reported student assessments

Authors and publication year	Category of student assessment						
	Conceptual understanding	*Confidence in learning*	*Creative thinking in response generation*	*Critical thinking in response validation*	*Knowledge- or skill-based achievement* [a]	*Motivation or engagement for learning*	*Satisfaction with learning*
Bombaerts et al. (2021)					X	X	
Baligar and Joshi (2017)			X	X	X		
ER (2014)					X		
Flynn et al. (2016)						X	
Ingeman-Nielsen and Christensen (2011)						X	
Kisselburg et al. (2016)				X			X
Martin et al. (2019)				X	X		
McWhirter and Shealy (2017)		X			X		
McWhirter and Shealy (2020)		X		X	X		
Nielsen and Christiansen (2015)						X	X
Sivaraman (2019)				X			
Winiecki et al. (2020)		X			X		
Yadav et al. (2010)							X
Yadav et al. (2014)	X	X			X	X	
Yadav et al. (2019)	X				X	X	
Yau et al. (2013)				X	X		
Zhu and Ibrahim (2017)	X						

The dependent variables are indicated with an "X"

[a]The specific achievement being measured depended on the context of the study

As Table 3 shows, five empirical papers described studies wherein critical thinking in response validation was assessed, and one paper described a study wherein creative thinking in response generation was assessed.

The remaining reviewed five papers did not concern empirical studies but rather focused on proposals for pedagogical frameworks or environments, ethics in engineering (Beever & Brightman, 2016; Morrison, 2020), or engineering leadership (Jamieson et al., 2021), both cross-disciplinary aspects of engineering education: multidisciplinary, including industrial and mechanical engineering (Ranky, 2010), and network engineering (Cifuentes et al., 2010).

Our Proposed Pedagogical Framework

We designed a CBL-based pedagogical framework for undergraduate engineering education based on three types of papers relevant to this topic: framework proposals, reviews, and empirical studies (see "Case-Based Learning in Undergraduate Engineering Education" section above). Our framework aims to foster undergraduate engineering students' creative thinking and critical thinking. The framework provides detailed guidelines on instructional design, student training in CBL, and tools for assessing creative and critical thinking.

We name our proposed framework CCT–CBL, which stands for *creative* and *critical thinking with case-based learning*. The framework fully covers two stages of Amabile's CPS model (1983), *generation* and *validation*, where generation is associated with the fostering of creative thinking, while validation is associated with the fostering of critical thinking.

In CCT–CBL, a case in a specific engineering domain is presented to students. The case may contain explicit or implicit problems. The learning progression in CCT–CBL includes three types of CBL, implemented in the following order: lecture-based, directed, and jigsaw (see Table 1). This sequence allows scaffolding of the CBL process for students, so they can tackle the less directed and more autonomous jigsaw approach with greater success. It also allows instructors to work through their instructional design and instruction from the simple to the complex. Each CBL type serves different learning objectives which build on each other, and they should all concern the same topic but include different cases and embedded problems.

Case Study Selection: Source and Target

In CCT–CBL, the instructor is expected to choose three cases: the first for the lecture-based CBL module (preparation case), the second for the directed CBL module (source case), and the third for the jigsaw CBL module (target case). In all three instances, instructors should select relevant and instructive cases which can facilitate students' analogizing. Case instructors should first clearly identify the problem that the case communicates. Herreid (1997) explains the factors that make a good case in his work *What makes a good case*, where he elucidates that cases should communicate a story, include relevant phenomena, and enable students to apply concepts taken from the case in their domains. Drawing insights from Friedman and Sage (2004), we identified a list of criteria that the instructors could use when selecting a valid case, which we describe in Table 4. Table 5 details an example case that fulfills all the criteria outlined in Table 4.

Table 4 Case selection criteria as adapted from Friedman and Sage (2004)

Criterion	Description
Evidence	Whether the case provides reasonable evidence, which could be in the form of documentation, archival records, interviews, direct observations or indirect observations
Inclusion of multiple perspectives	Whether the case includes and synthesizes the perspectives of the case actors
Reliability	Whether the conclusions and inferences that are made about the case are consistent across individuals who analyze the case
Internal validity	Whether the evidence presented in the case explains the causal relationship among the relevant variables
Construct validity	Whether the concepts explained in the case are legitimately operationalized
External validity	Whether the findings and inferences made about the case are generalizable and correspond to the real-world examples

Table 5. Case study summary for the Kansas City Hyatt Regency walkways collapse. Adapted from Rabins, Harris, and Pritchard (2009)

Case details	E	MP	R	IV	CV	EV
Stakeholders: Havens Steel Company and the engineering design team, G.C.E. International, Inc., a professional engineering firm, the owner, Crown Center Redevelopment Corporation	X	X			X	
Underlying problem/conflict: Disputed communications between the fabricator and the design team. The fabricator changed the design. G.C.E. stated that on three separate occasions they requested on-site project representation during the construction phase; however, these requests were not acted on by the owner (Crown Center Redevelopment Corporation), due to additional costs of providing on-site inspection	X	X	X	X	X	X
Presented Data: Archival records indicating the number of deaths and injuries due to the accident. Sworn testimony reports indicating that Havens talked to the G.C.E engineers for change approval yet "G.C.E. denied ever receiving such a call from Havens"	X					
Condition leading to conflict: Engineers' failing to meet the requirements, management's denial of on-site inspection requests due to costs			X	X	X	X
Results: Major engineering failure resulting in ceiling rods failing, collapsing on a crowd, which resulted in 114 deaths and more than 200 injuries, engineers losing licenses, firms going bankrupt, legal suits submitted	X		X		X	
Inference: "A vivid example of the importance of accuracy and detail in engineering design and shop drawings (particularly regarding revisions), and the costly consequences of negligence in this realm"			X		X	X

The relevant features of the case are indicated with "X" mark to exemplify good case characteristics
E evidence, *IM* inclusion of multiple perspectives, *R* reliability, *IV* internal validity, *CV* construct validity, *E* external validity

Table 6 outlines the CCT–CBL learning progression.

Table 6 CCT–CBL learning progression

Stage	Learning objective/s	Instructional steps
Preparation	1. Acquire baseline domain-based knowledge required for next stages 2. Acquire CBL proficiency required for next stages 3. Learn how to apply *transformational analogical reasoning* (TAR)	1. Assess students' creative thinking and critical thinking 2. Deploy Lecture-based CCT–CBL module 3. Deploy Directed CCT–CBL module
Generation	1. Learn how to apply *case-based reasoning* (CBR) 2. Apply CBR and TAR to generate ideas for solving a design problem 3. Practice creative thinking	1. Deploy Jigsaw CCT–CBL module 2. Assess students' creative thinking
Validation	1. Practice in evaluating and comparing solution ideas 2. Practice critical thinking	1. Facilitate students' refinement of their ideas 2. Facilitate students' evaluation, comparison, and selection of ideas 3. Assess students' critical thinking

Preparation

To successfully engage with CCT–CBL, students must have sufficient knowledge about the case study and about the CCT–CBL learning progression. To achieve this goal, we included two preparatory CBL modules within CCT–CBL: lecture-based CBL and directed CBL.

Step 1: Assessments of Thinking Skills

The preparation stage of CCT–CBL begins with individual assessments of students' creative thinking and critical thinking, to establish each student's baseline for both thinking skills. Suggested instruments for assessing creative thinking and critical thinking are listed in Tables 7 and 8, respectively.

Table 7 Instruments for assessing creative thinking

Instrument name	Key constructs
The Test for Creative Thinking–Drawing Production (TCT-DP) (Urban, 2005)	Continuations, completion, connections made with a line, connections made to produce a theme, boundary breaking that is fragment dependent, boundary breaking that is fragment independent, perspective, humor, and affectivity, unconventionality, speed
Widening, Connecting, Reorganizing (WCR) Test (Antonietti, Colombo, & Pizzingrilli, 2011)	Effectiveness, pervasiveness, compatibility, generalizability, interactivity, a modular structure, to be open to the group and to each person, to be motivating, to be empowering

Table 8 Instruments for assessing critical thinking

Instrument name	Key constructs
Universal Intellectual Standards (Paul & Elder, 2019)	Clarity, relevance, significance
The California Critical Thinking Skills Test (Facione, 1990)	Interpretation, analysis, evaluation, inference, explanation
Watson-Glaser critical thinking appraisal (Watson, 1980)	Inferences, recognition of assumptions, deduction, interpretation, and evaluation of arguments.

Step 2: Deploy Lecture-Based CCT–CBL Module

Next, instructors deploy the lecture-based CBL module. The content of the lecture is determined by a baseline domain knowledge assessment deployed to individual students. This module aims to ensure students can engage effectively with the content of the subsequent cases and with CCT–CBL. The instructor presents the preparation case, covering the stages of (1) *preparation*, (2) *generation*, and (3) *validation*. Following the lecture, another knowledge assessment is conducted to ensure that all students have reached a satisfactory understanding of the case-based domain knowledge.

Step 3: Deploy Directed CCT–CBL Module

In the CCT–CBL module, students apply TAR to a target case. This module begins with the *preparation* stage where the instructor covers domain knowledge relevant to the case and explains to students how to apply TAR:

1. Read the target case.

2. In a short paragraph, describe the challenge contained within the target case and one or more usefulness criteria for solving it.
3. Read the source case.
4. In a short paragraph, describe the challenge and its solution as contained within the source case.
5. Identify and describe one or more analogies between the source and target challenges (one per each usefulness criterion), across the identified usefulness criteria.
6. Based on your analogies, generate creative ideas for solving the challenge.

Next, the target case is described with all the information required for addressing the challenge provided, and the challenge is stated directly and explicitly. Students then engage with the generation stage, applying TAR in groups for solving the challenge. The instructor should provide students with one or more source cases.

Below is an example of how this process of TAR can be implemented. We took this example from a team of participants in an in-person workshop for engineering faculty which the first author conducted during summer 2022 (Authors, 2022).

- Target case: https://en.wikipedia.org/wiki/Basic_fighter_maneuvers.
- Target challenge: “Design a solution for round-the-clock delivery of aid and supplies to city dwellers affected by a severe earthquake.”
- Source case: https://en.wikipedia.org/wiki/Basic_fighter_maneuvers.
- Source challenge: “How fighter aircrafts make basic fighting maneuvers (dogfighting).”[1]
- Analogy A, aerial maneuverability: “To manage energy of the flying object, the analogy could be made with the fighters who use their potential energy (the yo-yo maneuver) to take advantage on their opponent and create sharp turns with high speed.”
- Analogy B, detection of humans under rubble: “To detect humans in earthquake areas, the analogy could be made with the fighters which have a radar system.”

Finally, student groups continue to *validation*, where they evaluate ideas according to predetermined success criteria, provided by the instructor. This step ends with each group selecting

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[1] https://en.wikipedia.org/wiki/Basic_fighter_maneuvers

an idea to present. The directed CBL module ends with student groups presenting their selected, refined ideas in class, followed by general discussion in class moderated by the instructor.

Generation

Step 1. Deploy Jigsaw CCT–CBL Module

This module begins with a lecture about the process of jigsaw CCT–CBL. Following this lecture, the instructor introduces a new target case to students, with all the information required for solving the challenge contained in it. The overall challenge is divided into sub-challenges.

Next, the instructor provides students with instructions on how to apply CBR:

1. List the domain-relevant key concepts included in the source case.
2. List the methods and skills which proved effective for solving the challenge in the source case—the case which was the target case in the previous module.
3. Read the target case provided to you.
4. List the domain-relevant key concepts included in the target case.
5. Identify key concepts common to both cases—source and target.
6. Describe the challenge contained within the target case.
7. Focusing on understanding these key concepts, at first apply, the same approaches and utilize the same skills for solving the challenge contained in the target case.

Students are then divided into groups, and each group is given a sub-challenge related to the target case. Students work in groups to solve the challenges. First, each group tackles their challenge using CBR and TAR. The instructor should provide students with new analogies (source cases) for TAR.

Once each group selects a solution for their challenge, new groups are formed to ensure that each new group includes a representative student of the previous groups. In the next round, representative students discuss their solution, and the group integrates the discussed solutions. In the final round, each group presents their integrated solution to the rest of the class, and the instructor facilitates a discussion with the aim of achieving class consensus on one solution.

Step 2: Assess Students' Creative Thinking

The generation stage ends with assessment of each student's creative thinking (see Table 6).

Validation

In this module, instructors facilitate student discussions on the solutions generated in the previous module.

Step 1: Facilitate Students' Refinement of Their Ideas

This step focuses on discussions about the refinement of ideas, which relies on identifying the gist of verbatim details of the generated solutions. First, students need to identify the gist of each idea, specifically addressing the success criteria. For instance, for the design challenge of the disaster response drone design example, which was provided in the "Preparation" section, the gist of the generated solutions could be encoded as traveling with more speed, involving less risk of failure, or moving more flexibly. These gist representations, i.e., more speed, less risk, and more flexibility, are what makes a solution successful. The process of extracting the gist, therefore, helps students identify the most relevant success criteria.

Extracting the gist is associated with expertise (Reyna, 2012); therefore, the instructor has an important role in helping students identify the essence of the generated ideas. Equally important is for instructors to help students identify the verbatim details of the ideas. Verbatim details are irrelevant or superfluous information that novices (students) are likely to unnecessarily focus on.

Instructors can use to scaffold the gist extraction process for students by using the following prompts (adapted from Reyna (2018)'s operational definitions of gist):

1. How would you summarize the essential bottom-line of the idea?
2. What is relevant and irrelevant to the success of the solution?
3. If you were to provide a title for a narrative relevant to the generated idea, what would that be?

These questions will help students communicate the gist with clarity. Refining the ideas based on the gist extraction process relies on critical thinking. Students need to recognize the breadth and depth of the solution, the context in which it is relevant to the challenge, and its significance to the challenge.

Step 2: Facilitate Students' Evaluation, Comparison, and Selection of Ideas

Once students refine the candidate solutions by distilling the essence of the ideas, they compare and contrast the options. The instructors could facilitate discussions to help students extract the gist. Below are some prompt questions that are adapted from the operational definitions of gist discussed in Reyna (2018):

1. Given the context of the challenge, what information about the candidate ideas is relevant and significant when choosing the best ideas? Example is design flexibility important in an urban disaster response context?
2. What is the essence of this selection process? Example is selecting the solution that maximizes saving more human lives
3. Given the context of the challenge, what are the potential outcomes of each solution? Example is the solution that provides more speed is likely to save more human lives if the disaster occurs in urban areas. The solution that provides more maneuver capability is likely to save more human lives in urban areas.
4. Which are the categorical or ordinal contrasts that each option entails? Examples are more speed, more sustainability, more maneuver capability, less risk of failure, and more sustainable performance with longer battery life.
5. What superficial or arbitrary details of the idea that should be dismissed? For example, if there is enough infrastructure to provide sufficient battery recharge stations, then the battery life can be encoded as a negligible success criterion when selecting the idea, trivial to the selection process.
6. What is ultimately at the heart of the selection process? What is the most important issue that cannot be dismissed? For example, if the drone solution is being generated for an urban earthquake response in a metropolitan area, maneuver capability is the most important because the drone must move flexibly in a chaotic urban area.

These questions aim to help to facilitate the classroom discussion to select the most appropriate solution idea option. Students are expected to recognize their assumptions about the solution candidates (e.g., battery life is the most important factor; maneuver capability is only important in urban disasters). The instructor plays an important role particularly in challenging students' assumptions and guiding them to think critically about their inferences about the solutions.

Discussing the solution options, the class reaches a consensus and wraps up the discussion by verifying if their final solution indeed addresses the challenge presented in the target case and provides creativity elements (novelty and usefulness).

The aforementioned steps are meant to generate meaningful classroom discussions to foster students' critical thinking. These discussions can be enhanced when the instructors follow a structured framework to encourage and promote high-quality discussions. A high-quality classroom discussion should incorporate building each other's comments by supporting previously stated responses or critiquing each other's responses (Author 2 & Colleague, 2022). Instructors should facilitate a discussion where students compare and contrast their perspectives with their peers' and help this process to refine their thinking and identify meaningful categories of information. Critiquing each other's responses will help them to decode significance of the solutions and question and thus clarify the meaning of the problem-solving objectives.

To facilitate response validation discussions and promote students' critical thinking, we recommend instructors follow the steps outlined in the structure and stages of learning modules developed by Kisselburgh et al. (2016). According to their framework, after establishing the knowledge basis, instructors should facilitate discussions to achieve with the following focal objectives: perspective taking (listening, questioning each other's perspectives while taking own perspective), compare and contrast (assessing own solutions with the principles), inducing conflict (incorporating experts' multifactorial opinions), decision-making and justification (debating and defending their own responses), and finally meta-reflection (reflecting on their own thinking via self-regulation and monitoring).

Step 3: Assess Students' Critical Thinking

Finally, the instructor assesses students' critical thinking by the instrument(s) provided in Table 7. This assessment process can be done on students' sketches and written documents or can be done based on the oral discussions

Discussion

In this paper, we outline the need, design, and methodology for CCT–CBL, a case-based learning pedagogical framework intended to foster the creative and critical thinking of undergraduate engineering students. Through the CCT–CBL learning process, students engage with the preparation, generation, and validation stages of creative problem-solving (Amabile, 1983) by completing CBL modules of increasing learner autonomy.

Contribution and Limitations

In this work, we provide two theoretical contributions: first, a literature review of CBL studies in undergraduate engineering education research, including various classifications of these studies, and second, in designing the CCT–CBL framework, we integrated concepts from creative problem-solving (Amabile, 1983) with CBL (Allchin, 2013), for the first time in undergraduate engineering education research.

The practical contribution of our work lies in a detailed methodology for fostering students' thinking skills while addressing problems in engineering design. It offers instructors a practical set of tools that they could use to both enhance and assess students' creative and critical thinking through cases. However, our framework requires evaluation for its validity, reliability, and efficacy in fostering students' creative and critical thinking. We recommend carrying out a future study in which the framework will be deployed with a large enough sample of undergraduate engineering students.

Potential Challenges and Mitigations for Implementation

The CBL–CCT framework requires instructors to design and implement three different CBL modules, each one of a different type (lecture, directed, jigsaw). For instructors who are new to CBL, it is suggested to begin with lecture-based or directed CBL at first and proceed to design and implement the jigsaw CBL module once they are comfortable with the other modules.

Another potential challenge for instructors would be the use of the assessment instruments for creative and critical thinking, such as the ones outlined in Tables 7 and 8. Using these instruments depends on familiarity with their use. For the first iteration of deploying these instruments, we suggest piloting their use with students and not use them for formative or summative assessment purposes. Once instructors are comfortable with deploying and interpreting the results of an instrument, it can be integrated into instruction.

Finally, some instructors may simply not have enough time to implement the entire process of CBL–CCT with their students. In such as case, we would suggest skipping the teaching of TAR and CBR, i.e., the teaching of how to generate analogies, altogether. Instead, instructors can begin with a lecture about the case and proceed directly to the jigsaw CBL module while providing their students with ready-made analogies for the generation stage.

Conclusion

In this paper, we introduce a pedagogical framework for undergraduate engineering education which aims to foster students' creative thinking and critical thinking, both of which are crucial skills for engineering career readiness and success. Drawing insights from analogical reasoning, students can improve their ability to map the solutions presented in each case into a similar, yet novel, open-ended challenge. We encourage the piloting and evaluation of the framework presented in this paper in a variety of undergraduate engineering education settings.

Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Conflict of Interest

The authors declare no competing interests.

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