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Instilling New Ways of Understanding the Innovation Process: Evidence-Based Heuristics from Student Innovation Experiences*

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In the workplace, engineers face complex technological landscapes, critical and nuanced user needs and societal problems, and intense rivalry from competitors. To address these challenges, engineering programs have increasingly emphasized knowledge, skills, and mindsets related to innovation. Yet, innovation is a complex phenomenon (spanning diverse processes and environments), which can make it challenging to provide these opportunities and frame them within appropriate learning contexts. Recently, researchers have explored course design heuristics to bring expert reasoning, creativity, and efficiency to course design tasks. This study seeks to develop course design heuristics for innovation education by building upon two previous studies. In the first study, phenomenography supported the identification of distinct and hierarchically-varied ways of experiencing innovation among engineering students. In the second study, critical incident technique and thematic analysis led to identification of experiences that supported more comprehensive ways of experiencing innovation. In the current study, we reverse engineer heuristics by investigating instructional approaches that facilitated the critical incidents and how they supported new ways of experiencing innovation. Thirty-one undergraduate engineering students from 13 different engineering majors and over 40 distinct innovative design experiences participated in this study. Through a collaborative, inductive content analysis process, we identified 55 strategies (or what we refer to as Innovation Heuristics) evident in the critical incidents (e.g., features of instruction, the learning environment). These strategies were categorized into seven themes: (1) contextualize; (2) situate; (3) guide; (4) support; (5) challenge; (6) motivate; and (7) extend. The paper describes and details each theme and the associated Innovation Heuristics that supported innovation learning, including key examples from the data and how they may be used by instructors.

Keywords: innovation, heuristics; course design heuristics; instructional strategies

1. Introduction

There are many reasons for promoting the inclusion of innovation-related learning experiences in engineering education. Most often, innovation is emphasized for ensuring competitiveness, such as enabling one's company or nation to be successful in an increasingly global marketplace [1, 2], or ensuring one has the competencies to be successful in the engineering workplace [3, 4]. As such, research has focused on identifying successful innovators, what characteristics set them apart from others [5, 6] and how they innovate [7, 8]. Such research presents potential learning targets for engineering educators [6] and suggests potential ways to support the development of innovation competencies among engineering students [9].

Interestingly, research into innovators' experiences demonstrates another important reason to promote innovation education for engineering students: personal satisfaction. Innovators have been found to enjoy both the process (e.g., tackling challenging problems) and outcomes (e.g., helping customers) of innovation [8]. Similar studies have found motivational fulfillment across a variety of levels based on participation in innovation projects [10], especially when projects are challenging but within one's zone of proximal development [11]. Hence, innovation learning experiences can support student learning in technical areas, promote deep engagement in such learning, and expand interests within engineering contexts.

In response to the above narratives, engineering programs and larger institutional initiatives have aimed to support innovation education for engineering students. These initiatives include dedicated and often interdisciplinary majors, minors, and certificate programs [12] as well as smaller-scale changes to extant courses and curricula. Still, many studies suggest that prevailing experiences and discourses in engineering education limit opportunities and inspiration for students to act

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innovatively and thereby inhibit innovation learning [13–15]. One possible reason for this limitation is the lack of studies that outline specific strategies, heuristics, or conditions that promote student innovation development (Atkins and colleagues [9] provide a notable exception). Another issue has been the framing of prior studies towards identifying convergences as opposed to variations in ways student experience innovation and the contexts in which they might learn to innovate [16, 17].

A series of recent studies examined how engineering students experienced innovation throughout a variety of curricular, co-curricular, and extracurricular engineering design projects [16–18]. Building on these studies, this study leverages a Design Heuristics framework [19, 20] to unpack the specific ways such learning occurred. Design Heuristics are "cognitive prompts that point designers towards exploration of design variations" [20, p. 606] and are intended to support students' development of design skills, such as effective concept generation and fixation avoidance. Similarly, in this study we generate empirically-driven Innovation Heuristics, a set of course design strategies that instructors can utilize to support students' innovation-related development.

2. Study Overview

The purpose is to present the engineering education community with a collection of Innovation Heuristics that have been displayed across a variety of students' innovation experiences that instructors can use to support more comprehensive or informed ways of experiencing innovation. This study builds directly on several other studies that have explored (1) variations in students' ways of experiencing innovation [16]; (2) the contribution of individual and contextual characteristics to students' ways of experiencing innovation [17], (3) critical incidents that contributed to more comprehensive ways of experiencing innovation [18], and (4) overarching pathways of innovation development among engineering students [21]. Here, through critical incident technique paired with thematic analysis, we address the research question, "What strategies, heuristics, or conditions promoted students' development or reinforcement of their way of experiencing innovation?"

The study proceeds as follows: (1) literature review: innovation and ways to support innovation learning, (2) theoretical framework: non-dualist ontology, (3) research methods: critical incident technique and thematic analysis, (4) results: themes and codes representing the Innovation Heuristics, and (5) closing discussion.

3. Literature Review

3.1 What is Innovation?

While definitions of innovation are myriad [22–24], recent studies have begun to unpack the overarching construct of innovation as it has been applied in different domains with different foci. For example, Garcia and Calantone [24] investigated conceptualizations of innovation across three domains: marketing, engineering, and new product development. They found conceptualizations to be related, primarily differing across two dimensions: scale of novelty (macro or micro) and type of change/discontinuity (market or technology). In another study, Bledow and colleagues [25] identified differences in innovation at the organization, team, and individual levels. Similarly, Golish and colleagues [26] investigated the technology development processes among academic and industry innovators, finding similar types of activities but differences in how much these activities were emphasized. Hence, the disparate definitions of innovation may indicate a complex, multi-faceted construct that manifests differently depending on context. In an engineering context, innovation can be described as the identification, development, and implementation of novel and useful ideas [6, 27]. Based on this definition, we ask, "What does that mean for engineering students and what they should learn about innovation?"

3.2 What Should Engineering Students Learn about Innovation?

Cropley and Cropley [28] developed a six-dimension taxonomy (the six Ps) to describe distinct facets of innovation. The constituent dimensions include product (i.e., outcomes of innovation), process (i.e., how innovation occurs), press (i.e., environmental conditions that support innovation), and person (i.e., characteristics of innovators), which is further subdivided into motivation, personal characteristics, and feelings. This taxonomy does not provide a prescriptive definition of innovation, nor what one should learn about it. Rather, it identifies distinct categories through which different descriptions of innovation can be understood and connected. For example, Cropley and colleagues [29] distinguished optimal attributes in each category based on stage of the innovation process (e.g., generation). Other differentiating factors could include type of innovation (e.g., macro/micro, market/technology [24]), type of setting (academia vs. industry [26]), level of innovation (e.g., individual, team, or organization [25]), and discipline (e.g., economy, business, technology, marketing [22]).

Cropley and Cropley's [28] taxonomy provides a useful framework to organize engineering education research on innovation and innovation learning. Table 1 maps their six Ps to recent studies of engineering students [10, 14, 15, 30–40]. Hence, Table 1 highlights the diversity of knowledge, skills, and attributes engineering students might be expected to learn but often do not.

The complexity of innovation has also given rise to an awareness of diversity in the ways engineers can understand and engage in innovation. In a study of 45 engineering innovators, a set of 20 characteristics (e.g., experimenter, passionate, user-focused) of innovative engineers were co-constructed [6]. While these characteristics tended to be robust in the perspectives of the participants, not all engineering innovators would demonstrate all 20 characteristics. Further, different characteristics tended to be useful during different phases of the innovation process. Ferguson and colleagues [41] expanded this study to identify distinct innovation personas evidenced by individual participants.

Table 1, in alignment with much of the empirical research, largely focuses on the limitations of engineering students' innovation learning. Another way to approach the question of innovation education is to ask how environments might be structured to support the multiplicity of ways engineering students become innovators. Fila and Hess [42] offer one approach with this perspective. Specifically, they explored the distinct aspects of innovation engineering students reported learning during various critical experiences. Six themes categorized student learning outcomes pertaining to (1) development of personalized and experiential definitions of innovation; (2) contextualized awareness of phases, processes, or activities contributing to innovation, (3) understanding of how one's mindset and approach contributes to innovation; (4) perceptions of conditions required for innovation; (5) recognition of interstitial elements that contribute to innovation; and (6) views of the self as innovator. This list suggests that students often embrace myriad outcomes pertaining to innovation learning, which studies focused on one distinct aspect of innovation learning may fail to capture. Further, this study demonstrates the often personal and/or contextualized nature of engineering students' innovation learning outcomes. While Fila and Hess' [42] study indicates various learning outcomes, other research has identified potential instructional design considerations for promoting students' learning of innovation.

3.3 Where, When, and How do Students Learn about Innovation?

While folk knowledge has long propagated the myth of the innate innovator, recent work shows that many innovation characteristics can be learned [6] and that individuals can find unique ways to be innovative and contribute to innovation [7, 16, 41]. Thus, engineering educators may focus on helping individuals understand their unique, pre-existing innovative capacities and help them grow those capacities throughout time [41].

Much emphasis has been placed on interdisciplinary programs that target innovation learning goals, such as awareness of and methods to promote creativity, knowledge about innovation, human and societal aspects of innovation, and product development processes [12]. While these types of programs have shown effective results, many engineering students often do not participate in such programs. For example, a recent study found only nine such programs that catered, at least in part, to engineering students [12]. Further, a recent survey of 501 engineering students across three universities that offered programs specializing in innovation processes and outcomes found that only 29% had taken at least one course related to those programs [30].

Table 1. Innovation Research Outcomes Mapped in Innovation Categories

Category	**Example research outcomes related to student behaviors and experiences**
Person – motivation	• Engineering students experience diverse motivations to innovate, often spanning intrinsic-extrinsic spectra within individual projects [10] • Engineering students report limited career goals related to innovation, but these goals tend to increase with participation in business-related programs [30]
Person – characteristics	• Engineering students often demonstrate limited design creativity [31] • Engineering students demonstrate limited awareness of realistic innovation competencies [32]
Person – feelings	• Engineering students report low creative confidence and perceived importance of creativity [15, 33, 34]
Product	• Senior engineering students produce less innovative conceptual designs than first-year engineering students [14] but more practical designs [35] • Engineering students often struggle with the feasibility-novelty paradox [36]
Process	• Engineering students emphasize early stages and technological aspects of the innovation process [37]
Press	• Engineering students demonstrate more innovative processes and outcomes in diverse teams [38, 39] • Engineering students' innovativeness is aided by problem authenticity and ability to negotiate the scope [40]

Learning about innovation seems to occur throughout an undergraduate career. Educators rely on integration of innovation-related activities in traditional courses, integration of aspects of innovation throughout the curriculum, and even innovation-focused extra-curricular activities. However, prevailing messaging in engineering curricula may conflict with or marginalize such learning due to over-specialization and an emphasis on factual knowledge [13] and decreasing prioritization of creativity across the curriculum [15]. For example, Davis & Amelink [35] found that, while senior-level engineering students tend to report higher confidence in their innovative skills than first-year engineers, they also were more likely to disconnect innovation from engineering. Such findings are antithetical to Radcliffe's [6] argument for innovation as a meta-attribute of engineering education.

How students learn about innovation may be as important as where they learn about it. For example, a recent study explored critical incidents that supported engineering students' innovation learning [18]. This study identified ten distinct types of critical incidents, including immersion in novel ecosystems and reflecting on project conditions. More importantly, this study showed that learning occurred in a variety of contexts and project experiences, including internships, co-curricular design projects, traditional courses, capstone and cornerstone design courses, and personal projects. In another study, Atkins and colleagues [7] identified six strategies (e.g., expose students to compelling challenges and real-world problems) for the development of innovation, that might be integrated within individual courses or throughout the curriculum, based on interviews with 60 innovators. When considering the personal and contextual nature of innovation learning outcomes [16, 42], such variety and integration of learning experiences may be key.

3.4 Literature Review Summary

In short, innovation is a complex phenomenon with many competing and overlapping definitions. Various studies have been conducted in the context of engineering education and have identified potential student outcomes and instructional design choices that have improved or inhibited students' development of innovative skills, knowledge, and mindsets. The diversity of approaches and outcomes supports the need for a succinct set of Innovation Heuristics that instructors can utilize to support innovative learning for their unique student populations.

4. Theoretical Framework

This study is situated within a non-dualist ontology [43]. Non-dualism suggests that learning, represented as coming to experience a phenomenon in a new way, manifests relationally between the individual learner and the phenomenon itself. Thus, learning is not solely internal to the learner or externalized to the phenomenon being learned. Within this interplay, learning stems from (1) the unique experiences, perceptions, and mindsets one brings to their encounters with the phenomenon and (2) the aspects of the phenomenon that are present, or at least perceived to be present, during these encounters [43]. A learner engages with elements of a phenomenon that are available in the learning context and within their scope of awareness. The learner then incorporates them into their way of experiencing the phenomenon, as connections become evident and inconsistencies are resolved. Thus, these elements coalesce (and change over time and through new encounters) into a "way of experiencing" the phenomenon that is unique, incomplete, and in flux [43].

Aligning with a non-dualist ontology and framing learning in terms of ways of experiencing presents several implications for this study. A way of experiencing represents a lived understanding that ties together elements of the phenomenon (i.e., what they learn) and how they have been experienced (i.e., how they have learned it). In this way, learning is more closely tied to action (doing), approach (process), and experience (lived and perceived). For example, a student might be aware that innovations often go through many iterative cycles but might not *experience* this iterative element until they have gone through similar iterations or connected this element to prior experiences in some meaningful way.

The framework of heuristics provides a means to understand how such experiences may be crafted to support innovation learning within the non-dualist frame. Heuristics originated in psychology to describe cognitive rules of thumb or biases problem solvers used to quickly make judgments or decisions, often related to complex problems [44–46]. More recently heuristics have been translated to the work of designers [19] and educators [47, 48] to understand strategies experts in these fields have used to transform their products and learning environments, respectively. Often, these studies deconstruct the output of designers to reverse engineer the strategies applied in their development. Here, we leverage participants' first-person accounts of the learning environments that proved effective in their innovative development to identify the overt and indirect strategies that informed those learning environments. Hence, in this study, we seek to extend heuristics to the domain of innovation education in engineering in order to develop practical strategies that others can utilize to support innovation learning.

5. Methods

5.1 Sample and Participants

Participants included 31 engineering students enrolled in a large Midwestern university (see Table 2). These participants were recruited to ensure variation in three demographic factors that previous research suggested might influence perspectives and approaches related to innovation: academic major ([49]), year in school ([14]), and gender ([50]). In addition, we sought variation in the contexts in which students had experienced engineering design and/or innovation. Each of these factors demonstrated some influence on types of innovation learning experienced by the participants in follow-up studies [16–18, 21].

5.2 Data Collection

The research participants each completed a semi-structured interview lasting 1–2 hours. These interviews were developed as part of a larger study [16] to elicit participants' experiences with and conceptualizations of innovation within engineering. The interviews occurred in six stages: (1) participant background, (2) initial definition of innovation,

Table 2. Participant Overview

Pseudonym	**Engineering Major**	**Year**	**Gender**	**Engineering Project Experience**
Ajay	First-year	First-year	Male	Design competition club teams
Alex	Aeronautical	Sophomore	Male	Course projects, Service learning, Internship
Caroline	Industrial	Senior	Female	Course projects, Internship
Chris	Nuclear	Graduate	Male	Long-term personal start-up
Dana	Aeronautical	Senior	Female	Senior design, Junior-level design course, Internship
Dante	Agricultural	Junior	Male	Service learning
Dylan	Biomedical	Senior	Male	Senior design, Internships
Ella	Industrial	Senior	Female	Internships, Service learning, Personal projects, Service learning club
Elon	Mechanical	Senior	Male	Co-op, Internships, Sophomore design, Design competition club team, Personal projects
Esteban	First-year	First-year	Male	Self-initiated start-ups; First-year engineering design projects
Fred	Agricultural	Junior	Male	Undergraduate research, Service learning
Hannah	Chemical	Sophomore	Female	Service learning, Design competition club team
Jerry	First-year	First-year	Male	Design competition club team; Personal projects
Jessica	Biological	Sophomore	Female	Course projects, Club projects, Personal projects
John	Acoustical	Senior	Female	First-year engineering course, Service learning, Internship
Leon	Electrical	Sophomore	Male	Student organizations, Personal projects
Maria	Industrial	Junior	Female	Internship, Class Projects, Student Organization
Marshall	Aeronautical	Senior	Male	Design classes; Internships
Matt	Mechanical	Senior	Male	Sophomore design, Service learning
Maxine	Mechanical	Senior	Female	Service learning, Internships, Senior design
Michael	Biological	Senior	Male	First-year engineering course; Senior design
Penelope	Biological	Senior	Female	Service learning, Design/business plan competition
Ron	Mechanical	Sophomore	Male	High school science fair, First-year engineering course
Sarah	Chemical	Senior	Female	Service learning, Internships
Sharon	Biomedical	Junior	Female	Co-op, Service learning
Snow	Mechanical	Senior	Male	Co-op
Summer	Electrical	Junior	Female	Internships, Service learning
Taylor	Computer	Senior	Female	Junior-level course projects, First-year engineering course, Internship, Student organizations, Personal robotics project
Tony	Industrial	Senior	Male	Service learning, Senior design
Verdasco	Mechanical	Junior	Male	Service learning, First-year course project
Vespasian	First-year	First-year	Male	Service learning, Family business, Personal projects

(3) experiences during innovation projects, (4) comparison of innovative and non-innovative projects, (5) general conceptions of innovation, and (6) closing thoughts, with the most time being spent discussing experiences with and conceptions of innovation (stages 3 and 5). An increased emphasis was placed on eliciting the participants' educational background, building empathy for the participant, and increased follow-up questioning to provide additional personal and contextual detail that would prove useful in identifying how specific strategies supported innovation learning. Participants also completed a short survey to collect demographic information and received a small cash incentive for their time. All interviews were audio-recorded and later transcribed for analysis.

5.3 Critical Incident Technique

The primary source of data for this study was segments of interview transcripts that detailed critical incidents related to the ways participants experienced innovation. These critical incidents were identified in a previous study [18] based on three criteria, per established guidelines of critical incident technique [51]:

1. **Connection to topic** – Description or demonstration of one or more aspects of understanding or approaching innovation. Direct connections to innovation were preferred, but this connection could be inferred from a participant's way of experiencing innovation or contextual cues in the interview.
2. **Detailed description** – Articulation of an experience or series of experiences that are attributable to the aspect(s) of their way of understanding or approaching innovation.
3. **Evidence of change** – A clear change, refinement, or crystallization in one's view of innovation, especially as it addressed aspects of that participant's way of experiencing innovation, resulting from the experience or series of experiences.

A total of 140 incidents were identified based on a subset of 16 out of the 31 participants. For the current study, we identified 122 additional incidents among the remaining 15 participants using the same procedures. Each incident spanned between one paragraph and four pages of transcript and featured a discussion of anything between a personally meaningful "eureka" moment and a subtle revelation based on repeated and/or long-term exposure to one or more facets of innovation.

5.4 Data Analysis

We used thematic analysis [52] to explore strategies that supported innovation learning within the critical incidents. Thematic analysis is an inductive process that supports the identification of patterns, themes, or categories within a dataset. Here, the themes represented broadly defined categories for supporting student innovation learning. Each theme comprised a series of codes that represented more specific and/or nuanced strategies, or Innovation Heuristics. Strategies were based on either approaches taken by an instructor or supervisor, organic features of the learning and/or work contexts, or participants' post-hoc reflections of how one or more events occurred. Strategies needed to be related to the learning evident in the critical incident, but participants did not need to explicitly describe this connection. We did not base analysis on a priori themes or codes to allow results to be situated in students' relationships with innovation. We adapted Braun and Clarke's [52] recommendations and used a five-stage process:

1. **Reading and rereading the critical incidents** – As researchers were familiar with data from previous studies, this process re-familiarized researchers with the scope and details of the data with the new research focus in mind.
2. **Generating emergent codes** – Coding began as an open process without a priori codes. The lead researcher initially reviewed approximately half the dataset (140 critical incidents from 16 participants). Individual codes represented potential strategies for supporting innovation learning. After a series of discussions with two additional researchers (Stage 4), the lead researcher revisited the initial half of the dataset to check all codes and potential themes (Stage 3) with refinements, and then analyzed the second half of the dataset to identify additional codes.
3. **Identifying themes –** We refined, consolidated, and categorized codes to identify larger patterns in the data. Codes represented strategies to support innovation learning, whereas themes provided a way to organize the individual strategies and provided a broader picture of how instructors can support innovation learning.
4. **Checking codes and themes** – The three researchers reviewed both the individual codes and the overarching themes in an iterative process. The lead researcher developed the initial set of codes and themes. The two additional researchers then reviewed these codes, themes, and their comprising excerpts. The three then dialectically discussed agreements and disagreements and refined the codes, themes, and coding through an iterative process (i.e., moving between Stages 2–4). This process helped

ensure (a) codes were appropriately described and represented authentic strategies, (b) coded critical incidents matched their code description, and (c) themes were broadly supported by their individual codes and incidents as well as the data at large.

5. **Building narratives** – During this step, we further described the themes as categories of strategies to support innovation learning among engineering students. The focus here was threefold: (a) to accurately convey the themes and their comprising strategies, (b) to explore how the themes and strategies supported innovation learning, and (c) to present sufficient detail to support understanding and utility in the engineering innovation teaching and research communities.

6. Results

Thematic analysis resulted in 55 strategies organized among seven distinct themes: (1) contextualize; (2) situate; (3) guide; (4) support; (5) challenge; (6) motivate; and (7) extend. The themes represent overarching methods that engaged participants in innovation learning during engineering design projects. The strategies represent specific techniques to enact the broader themes. In the following sections, we discuss each of the themes, using specific strategies and key instantiations (e.g., interview excerpts) to demonstrate important features of these themes.

6.1 Contextualize: Introduce, highlight, or simulate authentic conditions for innovation

Table 3 provides a description of the eight contextualize strategies. Several contextualize strategies (e.g., *whole process*, *long-term*) provided students with extensive involvement in the processes of design and innovation. Through students' immersive involvement in innovation projects, they were able to experience more comprehensive and complex aspects of these processes. Other strategies (e.g., *users*, *business considerations*, *need/gap*, and *broader utility*) highlighted aspects of innovation work beyond technological development. Oftentimes, the technical work was still a focus, but this work was situated in a broader social and/or economic context. Finally, multiple strategies (e.g., *real-world*, *tangible*) provided students with physical experiences. These strategies featured aspects related to the potential or actual development and implementation of innovative solutions.

Contextualize strategies were often evident when participants discussed their professional and co-curricular experiences, wherein these strategies tended to manifest as natural features of the working environment. However, such strategies were also directly utilized by instructors within engineering courses. For example, Jessica described a project during which she and her team developed a novel breakfast bar for busy college students within a biological engineering class. Innovation learning in this project was supported by multiple contextua-

Table 3. Strategies Aligned with the Contextualize Theme

Strategy	Description
Whole Process	Allow students to experience projects from initiation to some reasonable finish. This experience includes awareness of and/or participation in multiple stages, tasks, or aspects of innovation, rather than a targeted subset of processes and activities. In particular, the whole process emphasizes distinct behaviors and experiences throughout and across aspects of the innovation process.
Long-Term	Involve students in continuous projects that are not constrained to the typical quarter, trimester, or semester term of a university. These projects may provide a more realistic sense of duration, complexity, level of involvement, and development cycles.
For Users	Involve students in design projects in which they will be designing something for real-life users or simulated users with rigorous, detailed considerations.
Business Considerations	Involve students in design projects that are situated within authentic business contexts in which financial, market, and/or strategic considerations influence the students' work. This may be in a real industry setting or simulated in a course project.
Need/Gap	Involve students in design projects that originate from a client need or a market gap.
Broader Utility	Highlight contributions made by project work beyond the development and implementation of the product. This might include building business and/or client relationships that will support future projects, changes made to the community during the course of the project, or improved future capacity to innovate as a result of innovating. This involves allowing students to see the effect (beyond functionality, efficacy, and user acceptance) in the real world.
Real-World	Involve students in design projects with the goal or intent of potentially or actually implementing them in the real world (without, necessarily, a focus on users).
Tangible	Ensure that projects lead to students developing some relatively complete, observable outcome (e.g., an implemented solution, a physical prototype, a working application, a detailed system). This object can provide a point of reflection throughout project activities and to culminate the project.

lize themes, including *whole process*, *for users*, *business considerations*, *need/gap*, and *tangible strategies*. The *long-term* and *broader utility* strategies did not often manifest in single semester courses, like the one Jessica described, but were demonstrated by instructors on several yearlong capstone and service learning design projects discussed by participants.

6.2 Situate: Introduce students to others who will share or highlight different perspectives or place students in situations where they will become aware of new perspectives

The twelve situate strategies (Table 4) promoted student awareness and development of new perspectives related to innovation and the processes that support it. Many of the strategies promoted interactions with others who provided or demonstrated different viewpoints (e.g., *industry interactions*, *cross-disciplinary interactions*, *diverse teamwork*). Through these interactions, students often generated new perspectives, expanded their understanding of innovation, or identified mindsets that they perceived as helpful (or detrimental) to innovation. Additional strategies focused on inducing new perspectives by immersing participants in novel settings (e.g., *with users*, *professional settings*, *novel cultures*) or functional roles (e.g., *roles*, *outside expertise*, *comfort zone*, *preferred approach*). These immersive strategies were not as direct as the interactive strategies, thus new perspectives were developed experientially rather than observationally. Finally, two strategies made participants aware of the accomplishments, approaches, progression, and mindsets of others (e.g., *historical innovation*, *peer innovation*). Students often compared these perspectives to their own, which led to the realization of ways that they were contributing to innovation in existing projects, or new means by which they might contribute.

The situate strategies were particularly important

Table 4. Strategies Aligned with the Situate Theme

Strategy	Description
Industry Interactions	Create opportunities for students to interact with industry professionals in meaningful ways. This includes apprenticeship-style opportunities, as well as other interactions that can highlight new perspectives or even the professionals' limited perspectives based on long-term roles and/or contexts.
Cross-Disciplinary Interactions	Encourage students to interact with and learn from the approaches, mindsets, and perspectives of peers in other disciplines. This can be in informal interactions or more specific collaboration. This may involve considering why someone in another discipline took a surprising action and/or comparing others' approaches to one's own.
Diverse Teamwork	Ensure that students work on teams with individuals who have different perspectives, ideas, approaches, and functions from themselves. This may be the result of demographic, background, expertise, or other differences.
With Users	Create opportunities for students to interact with the users and/or clients/stakeholders for whom they're designing. Often this involves structuring interactions such that students experience user worlds and take their perspectives.
Professional Settings	Have students spend extended time (e.g., in internships or repeated site visits) in the industry or client contexts in/for which they will be developing products. This immersion should highlight key features of the innovation process in a professional setting.
Novel Culture	Have students spend extended time working in novel contexts (e.g., a new workplace, a different country, with different co-workers) that has distinctly different perspectives, norms, and operations than what they're used to.
Role	Specify distinct roles for students so they can experience unique facets of innovation from a distinct perspective. This may be a feature of their direct function or responsibilities on the team or a more organic occurrence based on their interactions with and distinctions from teammates. Some example roles include project lead, technical specialist, sub-team member, intern, etc.
Outside Expertise	Have students work on innovation projects that focus on technical content with which they are not familiar. Students need to catch up with this content (often seeing the importance of technical expertise and/or their ability to develop it during a project), but also see the project in a new light (from outside of technical expertise).
Comfort Zone	Require students to utilize new approaches and/or take on different mindsets during innovation projects. This may include confronting students with situations in which they'll have to try new approaches or take new mindsets to succeed.
Preferred Approach	Place students in novel contexts so they can see their common approaches in a new light.
Historical Innovation	Make students aware of the processes, mindsets, and outcomes of notable innovation projects and their innovators. This may be overt, through targeted activities, or from creating an environment in which students will naturally consider such innovations.
Peer Innovation	Make students aware of the innovative work their peers are doing or have done, often in comparison to their own work. This can include highlighting past student projects, having students in class work on the same project in different teams, or enrolling students in external innovation or business plan competitions.

for helping participants understand how they were innovative or how they might yet be innovative. For example, in *industry interactions* Ella, Sharon, and Tony observed and learned novel approaches and mindsets of their industry peers. They saw how their current approaches might be lacking and identified new ways to engage in the open-ended problems of innovation. Ella observed the iterative and experimental nature of her R&D lab-mates. Sharon saw how engineers and technologists leveraged years of expertise making healthcare products during ideation. They also saw how their coworkers' perspectives had narrowed based on workplace experience and functional roles, which limited their ability to generate and consider novel ideas, and how taking an outsider's perspective could benefit the identification and development of innovative solutions. However, it should also be noted that while immersing students in other perspectives was transformational for some, others noted similar situations without evidencing engagement with or change in perspectives and mindsets.

6.3 Guide: Require specific actions, approaches, or outcomes, especially to demonstrate the experience and importance of these elements

The eight guide strategies (Table 5) required participants to engage in specific tasks, design under specific constraints, and utilize specific approaches to promote awareness of key innovation tasks, processes, conditions, and mindsets. Each of these strategies supported awareness of innovative actions and mindsets that participants may have overlooked or have been discouraged from pursuing during their prior curricular experiences. The key strategy in this category was *requirements and constraints*, wherein instructors specified functional requirements and constraints based on user, business, regulatory, and technical factors, or modified the scope, duration, procedures, and logistics of a project. Other strategies deeply engaged students in key innovation procedures, each imbued with a distinct mindset (e.g., *empathic user research*, *open ideation*, *experimental iteration*, *contextualized analysis*). Finally, other strategies encouraged participants to consider and engage in specific behaviors or activities (e.g., *association*, *existing designs*, and *purpose*).

By applying the guide strategies, instructors and supervisors required participants to engage with engineering design in new ways and resolve their prior approaches and mindsets with those more conducive to innovation. For example, Sarah recounted a vivid example of the *existing design* strategy during a service-learning design project. Her team had been struggling to deliver a teamwork platform for grade schoolers that utilized a robotic arm. When she found an existing robotic arm that served their purposes, the instructor required her team to utilize that robotic arm rather than con-

Table 5. Strategies Aligned with the Guide Theme

Strategy	Description
Requirements and Constraints	Set project requirements and/or constraints to target specific innovation learning outcomes. This may be topical (e.g., users, business, technical, regulatory), logistical, scope-wise, procedural, duration, etc.
Empathic User Research	Require students to engage in user research activities. These activities can vary in type and scope, but they must require students to take an empathic stance toward users (e.g., through observation of and reaction to user challenges, simulation of user experiences).
Open Ideation	Ensure students engage in dedicated ideation sessions related to their project. These sessions must be structured to support free consideration of many various, novel, and potentially infeasible ideas.
Experimental Iteration	Allow/require multiple iterative cycles and encourage students to freely try out new ideas. This may be through setting a process of experimentation and iteration or highlighting such mindsets and giving opportunities to enact them.
Contextualized Analysis	Ensure that students thoroughly explore their design problems, user understanding, and new ideas with proper research, analysis, and documentation. This may be to ensure they have accurately captured user needs, contextual specificities, extant market gaps, theoretical principles, and that their proposed solutions do not already exist. This may also include decision-making, systems-level, and visualization activities to see the broader picture of the design, system, and context.
Association	Require/empower students to make novel associations between topics (e.g., from their expertise) and/or concepts that lead to potentially innovative ideas. More often, it will involve environmental conditions that support association than overt encouragement to do so. This involves students making associations or syntheses of ideas, rather than demonstrating associations made by others.
Existing Designs	Encourage (or require) students to utilize existing designs in the development of their own innovations. This may include starting from an existing design, incorporating or adapting one throughout the process, or considering existing designs as prior art.
Purpose	Have students consider their future/ongoing designs as they will be implemented in a user/community context. How will they work? What will be the immediate and long-term effects? How might it expand to other contexts?

tinuing to design one of their own. Sarah had initially overlooked this option based on cheating policies in prior courses but later came to embrace its incorporation. She realized the design goal revolved around the team learning platform and not the development of a new robotic arm technology.

Sarah's approach was further supported by *empathic user research* and *purpose* strategies. While these latter themes might seem to overlap with situate strategies (e.g., *with users*, *novel culture*), they acted more as complements. The situate strategies immersed Sarah in an authentic context where she could engage with users, identify their needs, and consider how the product she was developing might affect them. The guide theme structured her engagement within this context by providing directions for engaging in user research and introducing activities where empathic perspectives would be salient.

6.4 Challenge: Encourage or require students to engage with difficult aspects of innovation or take on other challenges that lead to innovative behavior, outcomes, or learning

The eight challenge strategies (Table 6) encouraged participants to engage with the more difficult aspects of innovation processes. Collectively, these strategies highlight the difficult aspects of innovation. More importantly, they encourage participants to either engage in innovation projects or refine more mundane engineering projects into bona fide innovation projects. Three of these strategies (*defend*, *communicate*, and *fail*) had participants consider, reconsider, or revise their ideas, solutions, and approaches based on communication with or feedback from an audience. Other challenge strategies (*initiate*, *risk*, and *into the unknown*) focused on instructors encouraging participants to push themselves and take on new challenges related to innovation. Finally, the *emergent* and *limit resources* strategies engaged participants in the daily challenges of innovation work.

Dana provides an exemplar incident to unpack. Specifically, Dana described how her senior design project started as an "ordinary" engineering design project in which her team intended to do just enough to earn a sufficient grade and, thereby, graduate. However, by encountering *emergent problems*, being required to *communicate* her ideas and *defend* them to both industry and academic audiences, feeling pressure to *initiate* new responsibilities, and exploring novel solutions that carried some *risk* and brought the team *into the unknown*, the project became an innovation project and supported various lessons about the nature of innovation, how it occurs, and her involvement in it.

Challenge strategies often overlapped with strategies from other categories. For example, when Elon learned that the novel safety guard he had developed for a mechanical press had been scrapped based on user acceptance, he reflected on his lack of

Table 6. Strategies Aligned with the Challenge theme

Strategy	Description
Defend	Challenge students to defend their work and ideas by providing conflicting opinions or challenges. This may involve playing devil's advocate, or having their peers do the same, or making students aware of conflicting views of others. This may also provide motivation to prove others wrong.
Communicate	Require students to describe their project or product and its innovativeness to others. The emphasis is not the feedback they receive, but the critical thinking they do in describing and preparing to describe their work/product.
Fail	Give students the freedom to substantively fail in various innovation aspects (e.g., non-functioning prototypes, team breakdowns, dissatisfied clients) and allow them the opportunity to struggle through, learn from, and move past these failures. Such failure should be large enough for students to make sense of their approaches and environments, and how they led to the failure. This strategy proved to be an especially potent sense-making tool that inspired large changes and insights regarding innovation processes, but this often occurred serendipitously.
Initiate	Encourage students to work on projects that stretch them or go beyond basic requirements (e.g., start-ups, technology development, work for others) and take on new responsibilities.
Risk	Encourage students not to play it safe and attempt to develop their potentially infeasible solutions. This may involve not penalizing students for taking such risks or providing opportunities and resources to overcome risks that do not succeed.
Into the Unknown	Involve students in or urge them towards projects that have no obvious or known solutions and/or solution path (either globally or locally).
Emergent	Set complex problems and environments such that students deal with many unexpected issues throughout their projects. Ensure that the development process is not static or streamlined so that students must learn to adapt. While these may be considered mini-failures, they are not at the same degree as those in the Fail code.
Limit Resources	Reduce the resources students are typically afforded to inspire students to focus on specific areas and aspects of their projects, or creative ways to explore those areas.

user consideration and engagement and his "selfishness" as a "young engineer" trying to make "the most complex thing," and incorporated more user-oriented, problem-focused practices during later projects.

6.5 Support: Create opportunities and environments that are conducive to positive cognitive, physical, and emotional well-being with respect to the difficulty of innovation and that ensure student learning has appropriate scaffolding in place for development

The eight support strategies (Table 7) focused on providing or introducing structures to mitigate the cognitive, physical, and emotional challenges of innovation. In this way, they were often focused on creating conducive and nurturing environments for learning (e.g., *nurturing environment*, *extend expertise, teamwork*, *balancing*). Strategies generally focused on scaffolding experiences such that participants had the necessary confidence, guidance, and opportunities to engage with innovation work. Some of these strategies are akin to "hard scaffolds" or the pre-existing supports that students can leverage as needed (e.g., *extend resources*, *structure*). Others were more akin to "soft scaffolds" or student- and situation-specific support (e.g., *be there*, *feedback*). Of course, instructional design choices may have also designed systems for students to receive feedback from peers and advisors as needed (e.g., *nurturing environment*, *feedback*).

The individual support strategies tended to overlap less within individual incidents than strategies within many other themes. Instead, they often overlapped across other themes, as specific learning outcomes were generally supported by other categories. For example, Esteban recounted seeking to make an unbiased decision regarding which design to pursue among several options. His instructor enacted the *be there* strategy by working with Esteban to understand his needs, pointing him to an applicable decision-making tool, and providing input as he used the tool. This enactment coincided with several contextualize strategies (*for users*, *whole process*, *tangible*), which complicated his initial decision, and several challenge strategies (*defend*, *emergent*, *into the unknown*), which reduced his certainty and pushed the limits of his current expertise. Hence, the support strategy of *be there* was relevant here given the conditions developed by the contextualize and challenges strategies the instructor utilized in organizing the initial project.

6.6 Motivate: Organize projects and environments such that students are motivated to deeply engage with their innovation work and see it through

The seven motivate strategies (Table 8) ensured that participants felt a stake in their innovation projects and were motivated to push past any challenges or struggles. Several of these strategies dealt with identifying personal connections to their innovation projects. The *interest* strategy ensured that participants found intrinsic motivation to engage with innovation through interest in the project topic, activities, or potential outcomes. The *valued contributor* and *find niche* strategies ensured that participants felt they were important parts of teams engaged in innovation and found their unique

Table 7. Strategies Aligned with the Support Theme

Strategy	Description
Extend Resources	Provide a sufficient or surplus level of resources (physical, financial, human) to students as they work on their innovation projects. Extending resources may support bolder projects and student confidence in success of challenging projects.
Structure	Provide an appropriate amount of structure to the processes students utilize in their projects. This may include providing a common structure for all students based on expectations, or flexibly adding/reducing structure based on emergent needs. Generally, this approach favors finding balance between autonomy and feeling lost.
Be there	Provide emotional and intellectual support to students as needed. This involves regular interactions with student project teams (e.g., frequent check-ins, being in the lab/field with them).
Nurturing Environment	Immerse students in a positive, motivating working environment in which they will enjoy and trust their peers, feel free to take risks, feel supported, and want to work hard every day.
Feedback	Provide regular feedback on student innovation work and progress, either as an instructor or through external review (e.g., users, clients, experts).
Extend Expertise	Provide some grounding or scaffolding in the way students will attempt to extend their technical expertise during innovation projects. This may involve working with familiar technology or applying new expertise in familiar or guided settings.
Teamwork	Organize teamwork such that students work and communicate well with their collaborators and that team issues do not interfere with the rest of the innovation work and/or learning.
Balance	Ensure that students feel some pressure to succeed, but not so much pressure that it becomes overwhelming. This may involve placing them in key roles, but not setting expectations too high.

ability and opportunity to contribute. Other strategies focused on ensuring participants felt some control, ownership, and necessity of their work through ensuring *open-ended* problems and projects and providing *autonomy* in working processes and project directions. Finally, *rewards* and *wins* provided external motivation to engage in innovation work and recognize when participants had contributed to innovation or learned something about it.

In general, these strategies supported innovation learning at two levels. First, agency, personal connection, and perceived value ensured that participants engaged in innovation experiences (or found ways to promote more routine experiences to innovative ones). This enabled the innovation learning supported by strategies in other categories. Second, by reflecting on how these strategies supported innovation, they came to refine their definitions and general understanding of innovation as a construct and tended to develop deeper understandings of how they connected to and participated in innovation.

Importantly, these incidents often saw overlap with several others. For example, Chris recounted an example wherein he sought to redesign a Geiger counter to utilize alternating current rather than direct current. His instructor discouraged Chris due to project feasibility while simultaneously (and perhaps unintentionally) motivating Chris to prove him wrong. In such a way, Chris began blazing his own path, communicating with various others about his idea, gathering informal feedback, and iterating on various design modes. In Chris's example, there was a cyclical relationship between failure and success. As he states, "You have defeat, it's like 'Oh, well, how do I win? Let's try this and see if that works.'" Chris's experience may not be directly transferrable to other contexts, but it vividly portrays how, by supporting students' intrinsic motivation, instructors can contribute to their innovation learning.

6.7 Extend: Focus on the long-term development of and engagement with innovation, especially emphasizing sense-making activities that span one's career, experiences, and personal and professional lives

The four extend strategies (Table 9) emphasized longer term and more personal approaches to innovation learning that complemented and relied upon the more direct and experiential strategies of the other six themes. Two strategies (*multiple projects*, *persistent messaging*) focused on the long-term educational career of the participant. Here, participants learned by comparing project experiences and responding to the messaging evident in and spanning experiences beyond that of a single course or project. The remaining two strategies (*reflection* and *everyday innovation*) encouraged participants to make sense of their innovation experiences, through in-the-moment or long-term reflection or exploring connections between innovation experiences and perspectives and one's everyday life.

In many cases, extend strategies were not overtly utilized by instructors or supervisors. Instead, they involved participants naturally making sense of larger experiences that occurred during their engineering design projects and throughout their educational career. For example, Sarah completed several engineering design projects (some innovative, some not innovative) as part of her work with a service learning organization. She compared these experiences to identify key features of her innovation experiences and developed nuanced understandings

Table 8. Strategies and Descriptions Aligned with the Motivate Theme

Strategy	Description
Rewards	Inspire students by demonstrating the tangible successes of past peers; motivate students to keep going by providing praise/encouragement and tangible rewards for their future successes.
Open-ended	Ensure that potential design outcomes are truly open-ended, allowing students to deal with ambiguity and shape the outcome, and do not suggest a given solution.
Interest	Ensure that projects are connected to student interests in some way (topic, target users/clients, technical content, approaches, alignment with career goals, etc.). Students may find unknown interests during project work, so this may also involve adapting to students growing interests. This may also involve encouraging students to consider whether and how projects are aligned with their interests.
Valued Contributor	Ensure that all students play important roles on the project. While not all students may be leaders or develop key innovative ideas, they must have important input, feel respected by their collaborators (including supervisors), and be involved in key project decisions and moments.
Autonomy	Ensure that students feel a substantial amount of control over the innovation process. Per prior strategies, processes may involve some necessary structure, but students should not find this structure restrictive.
Find Niche	Encourage students to, or place them in situations where they must, identify their unique expertise and abilities that can uniquely contribute to the innovation project.
Create Wins	Create opportunities within the project for students to experience smaller victories to keep them excited and motivated.

Table 9. Strategies Aligned with the Extend Theme

Strategy	Description
Multiple Projects	Ensure that students participate in several different innovation projects, especially those that feature different requirements, environments, approaches, and conditions. Instances of this strategy should see students comparing their experiences.
Persistent Messaging	Provide consistent and long-term messaging (e.g., throughout an undergraduate career) related to aspects of innovation (e.g., mindsets). This messaging may provide an alternative or conflicting perspective that students compare against their experiences and values.
Reflection	Create opportunities for students to reflect on general or specific aspects of their experiences, actions, and learning. Instances of this strategy demonstrate students making "in-the-moment" insights or specifically discussing their reflective activities during or after innovation projects. This may involve students asking questions, comparing experiences and perspectives, considering how innovation affected oneself and one's views, considering the role innovation plays in one's life, making sense of long-term or multiple experiences, etc.
Everyday Innovation	Ensure that students consider how and when they act innovatively in their daily life, outside engineering.

of innovation by identifying similar and different features of the projects. She, and others, often used non-innovative engineering design and laboratory projects as contrasting examples from her multiple innovation experiences. Similarly, Ella, Maria, and others associated aspects of their innovation work with everyday experiences, leading to a broader view of innovation that expanded beyond engineering and engineering coursework.

While these strategies may be enhanced by participants' natural tendencies to make sense of their experiences, providing multiple, varied experiences and persistent messaging may provide conditions to better support such sense-making. Further, several participants noted that the interview procedure itself prompted some of their reflections related to this theme. Instructors and supervisors might leverage similar questions or interview structures to prompt such sense-making.

7. Discussion

7.1 Overview of Themes

This study identified 55 strategies for promoting innovation learning among engineering students. These strategies were organized into seven themes: (1) contextualize, (2) situate, (3) guide, (4) challenge, (5) support, (6) motivate, and (7) extend. While these strategies and themes were identified through retrospective interviews with engineering students at different levels of innovation expertise, they echo those suggested by a similar interview study of 60 noted innovators [9]. Atkins' and colleagues offer six suggestions for promoting innovation learning, which align well (as noted) with the contextualize, situate, challenge, support, and motivate themes:

- Expose students to compelling challenges and real-world problems (aligns with contextualize and motivate).
- Situate students in experiential or hands-on learning environments (aligns with contextualize).
- Focus on students' expectations about failure (aligns with challenge).
- Expose students to various collaborative experiences (aligns with situate).
- Guide students through the processes of defining and articulating good problems and ideas (aligns with *structure* strategy within the support theme).
- Utilize case studies to portray experiences of successful (and unsuccessful) innovations (aligns with *historical innovation* strategy within the situate theme).

The alignment between this study of engineering students and the perspectives from successful innovators studied by Atkins and colleagues [9] highlights the importance of immersing students in realistic innovation contexts, connecting to and developing their motivations, demonstrating unique perspectives, ensuring they engage with substantive challenges, and scaffolding such experiences. Each of these overarching strategies can be considered a keystone of engineering design experiences that support innovation learning.

Yet, the current study also highlights the more guided and personal aspects that may be valued by engineering students. For example, the guide theme and the *structure process* and *feedback* strategies from the support theme emphasize direct guidance from instructors and supervisors. Some have observed messaging and narratives in engineering that mitigate student engagement with innovation [13, 15]. The guide strategies may counteract such effects by ensuring that students have concrete innovation experiences within engineering that are promoted by instructors who overtly value such actions and expertise. Similarly, the other support strategies may provide a nurturing environment where innovation does not seem so daunting, echoing findings that engineering students' innovation projects often fall within their zones of proximal development [11]. Further, studies have shown the variety of aspects that may motivate students to engage with innovation [10], but still show that students are largely unmotivated to pursue innovation-related career goals [53]. The motivate strategies observed here may provide the drive to engage with challenges, as has been observed in successful innovators [8]. Overall, the student-centered themes of guide, support, and motivate demonstrate that while knowledge and skill development are important (e.g., [12]), developing students' mindsets, drive, and passion may be just as essential.

7.2 Utilizing Themes and Strategies

While each of the seven themes tended to be important, each providing a unique facet to innovation learning during engineering design projects, it is unlikely and perhaps unreasonable to assume each of the 55 strategies can or should be incorporated into a single engineering design experience (and some, like *multiple projects*, would be impossible). Previous studies have found differing personas among engineering innovators [41] and different ways of experiencing innovation among engineering students [16]. Further, previous exploration of this dataset revealed that both personal and contextual factors may influence the way engineering students learn about innovation [17]. For example, throughout analysis we observed several instances of participants reacting to similar strategies in different ways. Hence, no single strategy is likely to influence innovation learning among all engineering students in the same way. Instructors might consider which individual strategies would be most appropriate for their contexts and students. Further, due to the variety in students' preferred learning styles, providing flexibility and a variety of strategies is likely advisable. Still, as most participants reported at least one instance of each theme, it may be critical to leverage strategies in each of the seven themes during engineering design projects and innovation activities to create a holistic innovation learning experience.

Instructors may find it useful to treat each of the three levels of findings (categories, heuristics, examples of heuristics in use) differently, as guided by three questions. For the category level, instructors might ask, "Did we?" or "What do we?", as a check to ensure they cover each of the key themes observed in students' innovation experiences. For the heuristic level, instructors might ask, "How should we?" or "How might we?", treating heuristics as inspiration to generate new teaching methods, learning environments, or course/curriculum implementations that enact each of the seven themes. Using heuristics as inspiration for ideation has proven successful in other populations, such as engineering students [20]. Finally, instructors might ask, "How did you?" or "What do you?", as they explore ways others have employed Innovation Heuristics in similar or disparate contexts. This could support those struggling to find appropriate ways to implement targeted heuristics or looking to build community and could be bolstered by the creation of a larger database or network of such examples.

Instructors might also consider ways to synergistically employ Innovation Heuristics from different themes to aid cohesion and efficiency in their courses and curricula. One way to accomplish this could be to start by identifying relevant contextualize strategies (e.g., based on instructional priorities, student preferences and preparedness, and available human and material resources), and use those conditions as an anchor point for applying strategies from other themes. First, the contextualize strategies could inform which situate and guide strategies would be relevant and how they might be applied. For example, the *business considerations* contextualize strategy could be paired with *industry interactions*, to highlight key perspectives, and *requirements and constraints*, to specifically target relevant business aspects of the project. Second, the contextualize strategies could suggest applicable motivate and support strategies, while also considering how these strategies might balance difficulty from challenge strategies that are also applicable to the context. For example, the same *business considerations* might allow instructors to require that students embrace *risk* in their project work and *defend* their ideas and solutions, but might also suggest they *be there* to support students through their novel and challenging work and motivate them with potential *rewards* or aligning the business aspects with student *interest*. Finally, instructors could incorporate reflection activities (e.g., extend strategies) throughout the project so that students draw connections to other project experiences and their everyday lives. While these suggestions provide specific cross-strategy considerations, the 55 strategies could also be used individually as ideation prompts for less structured course and curricular transformations; such a consideration aligns well with how Design Heuristics are more traditionally utilized in other disciplines [20].

7.3 Limitations

This study contains a few notable limitations. First, the data utilized is based on retrospective interviews with engineering students where students' experiences with and conceptions of innovation were the primary emphases. Hence, while specific strategies that contributed to their way of experiencing innovation were often described, this was not the interview focus. Second, given the data collection modality, participants may have been unwilling to share certain experiences, or some experiences may have simply been outside of their awareness at the time of the interview. Third, several strategies seemed to influence different participants in different ways. For example, certain challenge strategies were received positively by some students but negatively by others. Fourth, space and scope limitations limited our ability to highlight all strategies and specific variations of strategies. Furthermore, it disallowed us to incorporate participants' voices to the extent that we would have liked and may have benefitted readers with specific, rich descriptions of strategies and their manifestations.

8. Conclusion

This study investigated the experiences of 31 engineering students as they engaged with a variety of innovation projects across a variety of settings. Utilizing a hybrid of critical incident technique and thematic analysis, within a Design Heuristics framework, we identified 55 strategies (Innovation Heuristics) that supported engineering student innovation learning. These strategies were organized into seven overarching themes that could be used to transform course, curricular, and informal learning experiences. Individual strategies might be used to inspire more modest changes to extant courses, experiences, or curricula, while larger, interconnected groupings of strategies and themes might inform more structured changes and developments. In general, it is likely prudent to incorporate each of the seven themes (contextualize, situate, guide, challenge, support, motivate, and extend) but instructors should consider a variety of contextual factors (e.g., student preferences and preparedness, resources and constraints) when selecting and utilizing individual and/or combinations of Innovation Heuristics.

This study also suggests several areas for future work. First, while the strategies and themes are expansive and connect to prior studies, additional strategies might be identified through alternative means. This could include similar studies with different participants (e.g., professional engineering innovators, innovation educators) and additional means of data collection (e.g., documentation from and observations of effective courses and programs). Second, it was beyond the scope of this study to identify the specific effects of individual strategies and effective combinations of such strategies. Intervention studies could investigate effectiveness of individual or combined strategies. Similarly, follow-up interview or observation studies could more deeply explore how strategies interact, and how they resonate with different students. Ultimately, we hope this study and the Innovation Heuristics presented provide fruitful strategies for educators to support innovation learning among their students and provides a context for future research into the contexts and mechanisms of innovation learning among engineering students.

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