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The Nexus of Entrepreneurship and Innovation in Engineering Education: Unlocking Engineers' Potential through Learning Experiences that Cultivate Self-Efficacy in Embracing New Ideas

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Abstract

In the dynamic realm of engineering, the blend of analytical prowess and practical ingenuity is increasingly vital. There is also a growing demand for engineers to exhibit creativity alongside business acumen and management skills. Reflecting this shift, higher education emphasizes the importance of engineering students learning innovation and entrepreneurship basics. This paper delves into pedagogical features that enhance engineering students' innovative and entrepreneurial self-efficacy, focusing on the skill-overlap known as "Embracing New Ideas" (ENI). We extend previous work by exploring how formal courses and on-the-job learning promote Embracing New Ideas Self-Efficacy (ENI-SE).

Drawing on insights from 25 years of engineering alumni at Stanford University, our research question focuses on enhancing ENI-SE. Surveys identified 39 individuals with high ENI-SE, whom we interviewed about their learning experiences in the project-based design course ME310 and beyond. Four essential learning areas for ENI-SE emerged: *Mastery by Doing, Real-world Connectivity, Interdisciplinary Exposure, and Supportive Learning Environment*.

We discuss how these areas were realized in ME310 and provide examples from other engineering courses. Furthermore, we hypothesize how features of these four areas might be adapted or adopted more broadly in the engineering curriculum. These findings not only highlight the overlap between entrepreneurship and innovation in engineering education but also offer a blueprint for integrating these key pedagogical practices into existing curricular designs, equipping students to become creators, drivers, and forerunners of novel ideas and change.

Keywords: Embracing New Ideas, Self-Efficacy, Pedagogies for Engagement, Mixed-Methods Research, Entrepreneurship, Intrapreneurship, Educational Impact, Project-Based Learning, Innovation Management

1 Introduction

In an era where engineering increasingly intersects with modern society's economic and social foundations, the role of the engineer is rapidly evolving. No longer limited to technical analytical prowess, practical ingenuity, and advanced technical skills – today's engineers are called to be highly creative, capable of invention, innovation and thinking outside of the box. They should be equipped with business and management acumen and be capable of dynamism, agility, resilience, and flexibility [1]. These are all qualities that resonate with being innovative and entrepreneurial; as such these qualities are compatible with a growing demand for engineers who contribute in fundamental ways to conceiving of and developing new products, processes and/or services. These efforts might be realized through new venture creation or within established organizations.

The growing intersection of innovation and entrepreneurship within engineering practices has mirrored a parallel emphasis in engineering education. There is a growing number of national initiatives that aim to weave essential concepts on entrepreneurship and innovation into the fabric of engineering education. For example: **VentureWell** (founded 25 years ago as the National Collegiate Inventors and Innovators Alliance, NCIIA, [2], **KEEN** (the Kern Entrepreneurial Engineering Network, founded in 2005, as a collaboration of over 55 colleges and universities in the United States, [3], and **EPICENTER** (the National Center for Engineering Pathways to Innovation, funded by the National Science Foundation and directed by Stanford University and VentureWell from 2011 to 2016, aiming to empower U.S. undergraduate engineering students by integrating entrepreneurship and innovation into their education [4], [5].

In response to this push to make innovation and entrepreneurial basics accessible to their engineering students, some colleges and universities have created opportunities for their students to engage in innovative and entrepreneurial learning and endeavors through Entrepreneurship Programs (offered as, for example, minors or certificates) and Centers (offering co- or extra-curricular activities) [6]–[8]. Particularly noteworthy is the growth over the last 20 years in the number of programs and centers and the growth in faculty support and involvement in such Programs and Centers [9].

Efforts to integrate entrepreneurial skills into existing engineering courses have been notable. For instance, Schar et al. [10] introduced a series of case studies in an introductory mechanics course, under the label of Scenario Based Learning. These case studies challenged students to apply their mechanics-based analysis skills to support product decisions involving business elements. Woodcock et al. [11] explored how an engineering capstone design course could help students learn entrepreneurial skills. Additionally, Iron Range Engineering had all majors undertake entrepreneurial projects, resulting in the development of a business plan [12].

Beyond the confines of specific majors, Loh et al. [13] discuss a second-major option for undergraduates at the National University of Singapore (NUS). This initiative allows students from any major to participate in multidisciplinary project work aimed at cultivating an innovative and entrepreneurial mindset. At the master's level, the University of Duisburg-Essen offers a Master of Arts in Innopreneurship, designed to equip students with the skills needed for self-employment or innovative roles within established companies [14].

Whereas the focus of our writing up to now has been on *the form* of innovation and entrepreneurship experiences for engineering students, an arguably more challenging topic is on *the what* of that education. The literature is not without varied and sometimes conflicting perspectives and opinions on this. Some argue for a clear demarcation between education for innovation and education for entrepreneurship [15], seeing that universities and colleges are "missing the boat" if they only focus on or prioritize entrepreneurial education (which according to these authors depends on strong innovative ideas, so therefore should follow more intense education on developing strong technical and innovation skills). In this sense, their reasoning is in line with organizational process models that show innovative activities preceding entrepreneurial activities [16].

Another author, Baumol [17], gives us a different lens through which to view innovation and entrepreneurship education in relation to the technical focus of an engineer's education: *"Education for mastery of scientific knowledge and methods is enormously valuable for innovation and growth…. but can impede heterodox thinking and imagination….On one side, education provides technical competence and mastery of currently available analytic tools to future entrepreneurs and others who will participate in activities related to innovation and* *growth. On the other side, education can stimulate creativity and imagination and facilitate their utilization. But the following hypothesis is at least tenable: educational methods that are effective in providing one of these benefits may act as an obstacle to the attainment of the other — the student who has mastered a large body of the received mathematical literature, including theorems, proofs, and methods of calculation, may be led to think in conventional ways that can be an obstacle to unorthodox approaches that favor creativity."*

While Baumol [17] writes about possible tension between the technical and non-technical aspects of an engineer's education and identifies the importance of creativity, and [15] advocates for the sequencing of innovation and entrepreneurial learning for these students, Zappe et al. [18] identify another foundational element of innovation (and by extension entrepreneurship) — namely, leadership skills. They go on to review (and critique) current educational practices for creativity, innovation, entrepreneurship, and leadership skills, suggesting more appropriate practices may be less structured.

The discourse of these authors [15], [17], [18] inspired us, in our current work, to:
1) Focus on the 'common ground' skills and mindset between innovation and entrepreneurship, as developed by Kempf et al. [19], and called Embracing New Ideas (ENI) (as summarized in Section 2.1). This nexus may be particularly "fertile ground" for considering engineering education's potential contributions to students developing innovation and entrepreneurial related skills.
2) Challenge Baumol's contention that education for technology competency and education for creativity are inherently at odds with one another, and instead propose a holistic approach to engineering education that fosters the overlap of both. To this end, we identified a course with lofty learning goals in both domains to study its contributions to ENI skills. This course (ME310) is described in Section 2.2.

Based on this, our research is guided by the question: *What factors enhance ENI-SE, based on the academic and professional learning experiences of engineering alumni? And more broadly, how can engineering education enhance the development of ENI-SE to empower engineering students' interest, intention, and action towards innovative and entrepreneurial outcomes?*

To answer this question, we used a mixed-methods, case study approach, starting with survey data from 25 years of engineering graduates who had all participated in an immersive project-based design course sequence (ME310) during their graduate studies at Stanford University. The course sequence became our case study for research. Our primary basis of analysis and observations included 39 course alumni we identified from the survey dataset who exhibited high ENI-SE, and who were either entrepreneurs or intrapreneurs. We interviewed these individuals about their experiences in ME310 and beyond to identify which factors enabled them to become creators, drivers, and promoters of new ideas. Section 3 describes the methodological details.

This research was undertaken not to undermine the distinctive features and characteristics of entrepreneurship and innovation (and their well-established and active lines of research-based/disciplinary/field-specific inquiry). It was rather aimed at identifying skill-related characteristics that were common between the two so that more educators (beyond those teaching courses with Entrepreneurship or Innovation in their course titles) might consider how they too could promote and play a role in educating engineering students who actively and responsibly 'embrace new ideas.'

This study not only contributes to academic discourse but also offers practical strategies for educators to empower engineering students with the skills to 'embrace new ideas,' ultimately nurturing the leaders and innovators of tomorrow.

2 Literature Review/Background

2.1 Relevant Self-Efficacy Measure and Social Cognitive Career Theory

In the realm of human behavior, self-efficacy holds profound importance, particularly in innovation and entrepreneurship. Several self-efficacy measures have been developed in the innovation and entrepreneurship research fields and tailored to the specific tasks that are assessed in this context (e.g., [20]–[24]). Innovation Self-Efficacy (ISE) refers to the individuals' confidence in their ability to innovate and engage in specific behaviors that characterize innovative people [23], [25], whereas Entrepreneurial Self-Efficacy (ESE) is the belief and confidence individuals have in their own capabilities to execute tasks aimed at entrepreneurial outcomes and pursuing new venture opportunities [20], [21]. ESE and ISE have become essential cognitive psychological constructs in the innovation and entrepreneurship research fields, since it has been proven that they have a great impact on innovative and entrepreneurial intention, behavior choice and performance [20], [26], [27].

Kempf et al. [19] introduced a different approach to considering innovation and entrepreneurship related self-efficacies and examined their nexus or overlap, coining the term "Embracing New Ideas Self-Efficacy" (ENI-SE) as a unified measure that encapsulates an individual's confidence across both innovation and entrepreneurship. As described in their 2023 paper: *"The idea of possible "common" elements of entrepreneurship and innovation (where the circles overlap) made us revisit their seemingly distinctive attributes and characteristics in more detail. We began to identify that they both rely on "the ability to conceptualize what has yet to become reality" [28]. This ability may depend on the integration of several attributes, including an individual's curiosity about and observation of the world, a tendency/drive to question (or even push against) the status-quo, in-depth knowledge in at least one domain [17], and creativity and imagination skills. We call this overarching/combined ability "to conceptualize what has yet to become reality" one of "embracing new (and perhaps useful) ideas," or Embracing New Ideas (ENI), for short."*

Kempf et al. [19] developed a 'common ground' measure called Embracing New Ideas-Self Efficacy (ENI-SE), consisting of the items listed in Table 2.1. ENI-SE attempts to capture an individual's confidence in generating, through various means, potentially useful new, unique, or novel ideas. They used Lent's Social Cognitive Career Theory (SCCT) [29], [30] as the organizing framework for Self-Efficacy, as shown in Figure 2.1. SCCT connects Self-Efficacy to Actions (Behaviors) through Interests, Choice Goals and Contextual Influences. They linked ENI-SE to ENI-Behavior (a complementary construct they developed) and a variety of workplace and work-assignment features, as well as demographics. Their data for developing these new Self-Efficacy and Behavior Constructs, and creating a descriptive model came from a sample of over 700 engineering alumni working in a variety of roles and job functions.

Building on the work of [19], the current study explores educational experiences that support engineering students' learning to engage in creating and promoting new technologies, innovations, and ventures – in other words, engineering students developing a proclivity for creating *the new*. We leverage the SCCT framework to link Learning Experiences and the enhancement of ENI-Self-Efficacy, querying specifically *which learning experiences or approaches facilitate individuals developing ENI-SE.*

Table 2.1 ENI-Self-Efficacy , N_{survey}=719 (from Kempf et al. [19])
(scale of 0-4, from *Not Confident* to *Extremely Confident)*

Embracing New Ideas Self-Efficacy Items (0-4 Scale on Confidence)	Mean (SD)
Overall	2.78 (0.72)
Survey Items	
● Generate new ideas by observing the world	3.03 (0.90)
● Actively search for new ideas through experimenting	2.96 (0.90)
● See new market opportunities for new products and services	2.22 (1.12)
● Create products that fulfill customers' unmet needs	2.62 (1.00)
● Discover new ways to improve existing products	2.92 (0.90)
● Connect concepts and ideas that appear, at first glance, to be unconnected	2.92 (0.85)

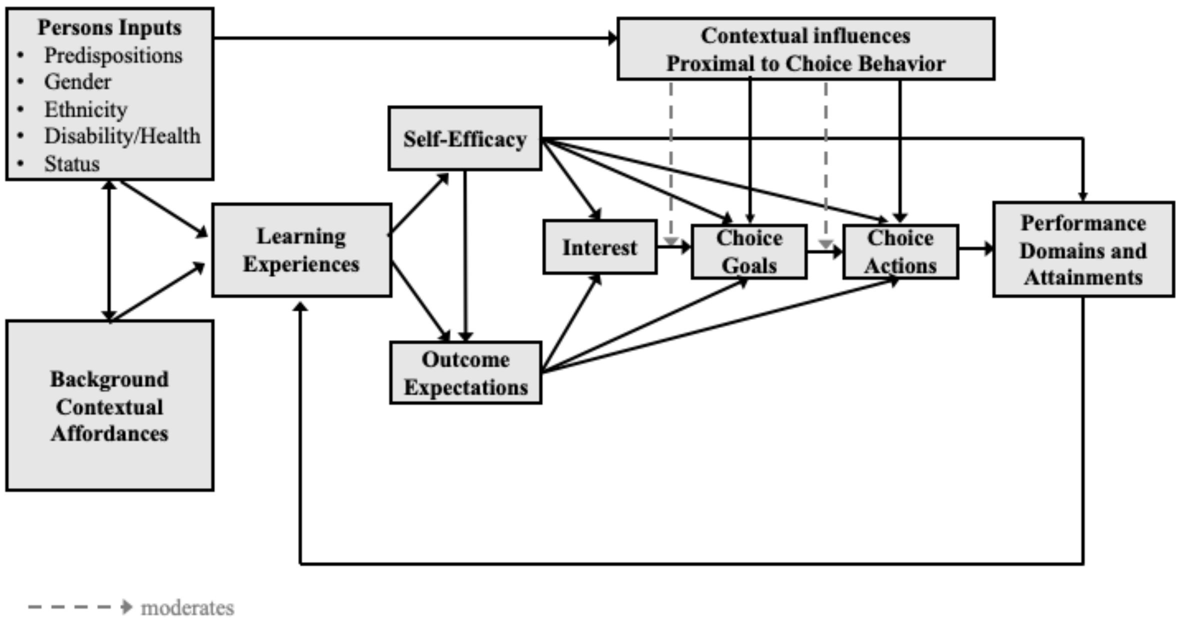

Figure 2.1 Social Cognitive Career Theory (SCCT) [29], [30]

We aim to uncover the educational influences that mold students into adept idea creators, facilitators and 'embracers', spotlighting those who have journeyed through the immersive 9-month project-based course in Mechanical Design (ME310) during their graduate studies. Our investigation seeks to pinpoint the transformative aspects of ME310 that catalyze entrepreneurial and intrapreneurial prowess, identifying both the course's strengths and its gaps. The methodology underpinning our exploration of this select group is detailed in Section 3 (Methods). Prior to that, we describe the focus of our case study, the ME310 course sequence (Section 2.2) and the alumni survey from which the interviewed entrepreneurs and intrapreneurs were selected (Section 2.3).

2.2 Our Case Study Focus – ME310

Stanford University's ME310: Project-Based Engineering Design Innovation & Development course challenges students to work in teams to explore design innovation opportunities in areas of interest to partner companies from diverse industries. This year-long course sequence has engaged graduate engineering students in industry-sponsored projects where they learn to navigate various phases of integrated design since 1967. More on the evolution of the course can be found in [31]–[36].

The contexts, needs and requirements of each project are open for student teams to discover and specify for themselves. The learning journey includes iterating the processes of studying potential contexts, need finding, benchmarking, ideation, prototyping, testing, analysis, refinement, and pivoting – continuously pursuing innovative solutions. Prototype milestones occur every two to three weeks. Measures of success are not predicated on whether the prototypes work or fail, but on how much is newly learned from each phase of building, debugging, and testing (how "well" does it work, rather than whether it works or not). The final delivered solution prototype is expected to be demonstrably functional and have enough resolution and fidelity execution quality to project credibility.

At its heart, ME310 is an engineering design course in which students are introduced to a situation where engineering-based improvement is (believed to be) possible. Working in teams, the students are required to question the situation through observations, interviews and "fact finding," and to even question how or for whom improvement is defined. They can, and often do, reframe the problem at hand, to develop solutions that are novel or innovative for the context. It is this ambiguity (and learning to navigate it) and support of an iterative engineering design process (involving prototypes to learn forward with) that are critical in students developing confidence in ENI. The learning experience throughout ME310 has been likened to entrepreneurship tiger team [37] akin to start-ups wrestling with new technology and new applications through their engineering practice.

2.3 The Survey that Grounds this Work

In the Summer of 2020, a research survey was deployed to graduates of ME310 from AY1993 through AY2017 as part of studying career pathways and course impact. This line of inquiry (sponsored by the Hasso Plattner Design Thinking Research Program) is part of a larger set of studies by the Stanford University Designing Education Lab that are looking at engineers' professional decision-making and pathways.

The survey was deployed through the Stanford University's School of Engineering Dean's office, which maintains an alumni email list. The 122-question survey collected data/information responses on:

1) Career paths and plans of ME310 graduates (31 items)
2) Alumni's attitudes and perspectives on the various components of the ME310 curriculum (44 items), and
3) Current alumni attitudes and perspectives around self-efficacy related to innovation, entrepreneurship, design thinking and engineering (47 items).

301 alumni completed the survey, representing a 41 percent response rate. Additional details of the development and deployment of the survey can be found in [34]–[36]. There were 267 responses in the final cleaned dataset. The survey has served as the basis for the development

of the ENI-SE measure (by [19] and as described in Section 2.1) and for several qualitative research studies (e.g., [38]).

2.4 Innovative Entrepreneurs and Intrapreneurs – Definitions

By way of background, we take as our working definition of *entrepreneur* as an individual who recognizes and creates opportunities and builds new companies called entrepreneurial ventures or startups which are based on those newly developed business opportunities [39], [40]. In contrast, *intrapreneurs* are not founders who start their own ventures, but employees who exploit new business opportunities within their employer organization [41] and are heavily involved in innovation in their assignments. They usually develop new opportunities that create, market, and expand innovative products, services, technologies, or methods *within* their organization [42].

Even though the fields *innovation* and *entrepreneurship* share some characteristics, not all entrepreneurs innovate [43]. Although intrapreneurs combine innovative and entrepreneurial behaviors, they are tightly linked to existing enterprises. Therefore, this current research work focuses on *the joint* attributes of these two fields, innovative and entrepreneurial behavior, with a particular emphasis on those behaviors enacted in technical endeavors (i.e., technical innovative entrepreneurship and intrapreneurship).

3 Methods

3.1 Research Design and Methodology

This study aims to identify the academic and professional learning experiences of ME310 alumni that have impacted the development of their ENI-SE. To explore how to further promote ENI-SE in engineering education, this research used a mixed-methods approach. Specifically, we deployed a *sequential explanatory research design*, by which qualitative research is built on original quantitative results [44], [45]. Using the *participant selection model*, we used the results of a quantitative survey [34], [35] to identify a focused subgroup of ME310 alumni who were most pertinent to the research context for subsequent qualitative exploration [45], [46].

This study design was apt for our research question, since it provided the necessary depth and chronological coherence, beginning with a review of survey results and followed by our team's in-depth interviews and qualitative data analysis.

The qualitative portion of the study is anchored in Eisenhardt's theory building approach using case studies [47], ideal for exploring under-researched areas and forging new connections among observed phenomena [48]. Consistent with most studies using qualitative data (e.g., [49], [50]), the fundamental source of this study's theory building data stems from semi-structured interviews, as these provide a remarkably effective and efficient technique for gathering information-rich data from numerous and highly knowledgeable informants who view the focal phenomena from diverse perspectives [51].

Distinct from traditional entrepreneurship studies, this work transcends mere new business creation to probe the broader entrepreneurial mindset within a technological innovation context. For this reason, entrepreneurs (e.g. (co-)founders of technology business ventures) and intrapreneurs in existing technological organizations are the primary basis of analysis of this research study, with their responses as the unit of analysis, to illustrate the literal replication logic applied.

3.2 Participant Recruitment

To effectively recruit potential interview partners, we defined recruiting criteria via theoretical sampling [51] to identify individuals capable of providing rich insights to answer the defined research question.

We sought the perspective of both entrepreneurs and intrapreneurs to fully capture the multifaceted essence of the entrepreneurial mindset in a technologically innovative context, and thereby the nexus of entrepreneurial and innovative behaviors. In doing so, we aimed to build on prior work by Newman et al. [52], which stressed that "*entrepreneurial thinking and acting is not only crucial with respect to classical entrepreneurial outcomes such as venture creation and growth, but also influences intrapreneurship within more established businesses, and can also be considered as a general skill-set that assists the individual to proactively manage his/her own career in times of uncertainty and change.*"

For intrapreneurs, we selected candidates from our survey pool who were engaged in entrepreneurial endeavors within a large corporation or in small and medium-sized enterprises (SMEs), and who demonstrated high levels of ENI behaviors. Examples of such activities include discovering new ways to improve existing products, seeing new market opportunities for new products and services, or creating products that fulfill customers' unmet needs. Employment titles and more detailed open-ended answers further informed our selection.

As a result, our recruitment strategy was anchored in five main criteria:
1) Moderate to high average ENI-SE score (as defined in Table 2.1) on ME310 survey
2) Current position: founder or employee in a small, medium, or large corporation
3) Moderate to high average Embracing New Ideas-Behavior (ENI-B) score (as defined in [19])
4) Survey-proportionate gender balance
5) Survey-proportionate generational balance from 1993-2017

Out of 75 contacted ME310 graduates, 52 percent (39 alumni) formed the total interview sample. This cohort included 67 percent (25) males and 33 percent (14) females, reflecting an adequate representation of the overall survey gender distribution. Figure 3.1 shows an even ME310 generational spread of the interviewees, which mirrors the diverse perspectives of study participants with a range of experience levels. Furthermore, 46 percent (18) of the interview partners were founders while 54 percent (21) were intrapreneurs at the time of the study.

The average ENI-SE score of the 39 interviewees (ENI-SE=3.25, SD=.48) was significantly higher (p=0.00) than the remaining survey pool of 228 (ENI-SE=2.90, SD=.16). Additional details on the 39 interviewees, along with their assigned pseudonym, are shown in appendix Table A.

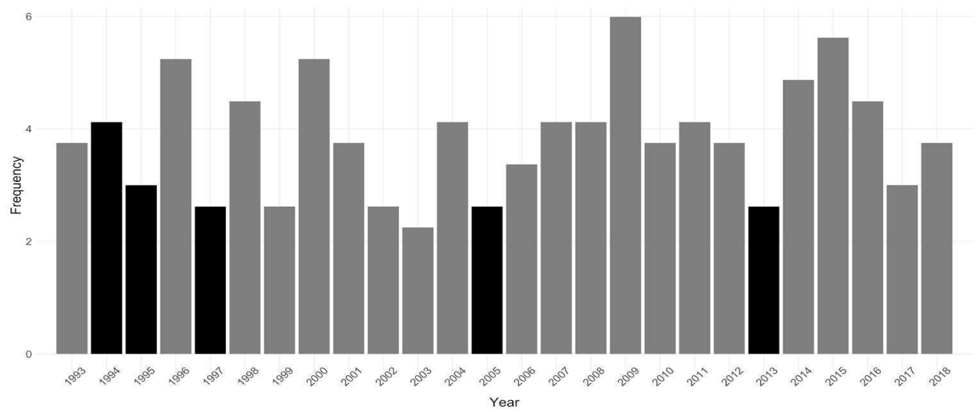

Figure 3.1 Distribution of all survey respondents by the year they completed ME310. Light gray bars indicate that at least one participant in that year was also among the 39 who were selected for interviews in the current study. N_{survey}=267, $N_{interview}$=39.

3.3 Data Collection

This study utilized semi-structured interviews to gather qualitative data, enabling a comprehensive understanding of the participants' nuanced experiences [46]. Our interview protocol was meticulously designed with a structured framework to ensure consistency and comparability among responses, drawing from best practices in exploratory qualitative research [48]. It aimed to explore common attributes between innovative individuals and founders without limiting participants' responses. Ethical approval was obtained from Stanford University's Institutional Review Board, and interviews were conducted via Zoom with consent for recording. Twenty-six hours of interview recordings were captured and transcribed, and transcripts were anonymized to ensure confidentiality. More information on the strategy and philosophy of the interview protocol design can be found in [53].

3.4 Data Analysis

To delve into the learning experiences that enhanced the nexus of entrepreneurial and innovative self-efficacy (ENI-SE) of ME310 alumni, we employed qualitative content analysis (QCA) [54], utilizing inductive coding and theme development ([55], [56]). This approach aimed to uncover textual language nuances ([56]) and identify common patterns and themes among interviewees' responses ([58], [59]). Using MAXQDA (Release 20.3.0), we systematically organized interview quotations into thematic categories, refining our coding schema iteratively ([46], [60]). This process, akin to axial coding, allowed us to dynamically adapt our coding scheme to align with emerging themes, resulting in 15 key coding themes grouped into four overarching constructs ([61], [62]). We also assessed the frequency of mentions within categories to gauge the relative importance of each theme, contributing to more generalizable findings. These findings are detailed in Figure 4.1. More on the data analysis approach can be found in [53].

4 Results

This section presents the key findings from the qualitative data analysis of interviews conducted with engineering alumni. We focused on discerning the ENI-SE-cultivating factors within the realm of engineering education, drawing from a rich tapestry of our participants' learning experiences. Our approach prioritized common themes and recurring insights, ensuring the applicability and generalizability of our findings.

The core of our gained insights encompasses experiences from the ME310 course and extends to broader academic and career reflections. This comprehensive view not only bridges the gap between academia and professional practice but also illuminates the shared traits of entrepreneurial and innovative behavior that can be effectively fostered in educational environments.

Our research derived the following propositions that underscore the academic settings conducive to fostering a mindset geared toward ‘embracing new ideas.’ These insights are systematically organized in Table 4.1, referred to as “the [4x15].” This categorization crystallizes 15 themes, each encapsulating a unique facet of mindset, knowledge, or skill our 39 interviewees deemed essential for becoming confident in embracing new ideas. These 15 themes are organized into four overarching constructs: Mastery by Doing, Real-world Connectivity, Interdisciplinary Exposure & Knowledge, and Supportive Learning Environment. Of these 15 themes, nine were derived from experiences in ME310 (white boxes), two from the larger university milieu (light gray boxes), and three from their on-the-job experiences (dark gray boxes).

Table 4.1 Themes Influencing ENI-SE (source: own illustration). White (covered in ME310), Light Grey (covered in higher education), Dark Grey (learned on the job).

CONSTRUCT 1 **MASTERY BY DOING**	*CONSTRUCT 2* **REAL-WORLD CONNECTIVITY**	*CONSTRUCT 3* **INTERDISCIPLINARY EXPOSURE AND KNOWLEDGE**	*CONSTRUCT 4* **SUPPORTIVE LEARNING ENVIRONMENT**
THEME 1A **TRAINING AND REPETITION** Repeated exposure to and training of innovation and entrepreneurship associated tasks.	*THEME 2A* **REAL-INDUSTRY PROJECT-BASED WORK** Exposure to real industry allows for practical problem-solving.	*THEME 3A* **HUMAN-CENTERED DESIGN** Utilizing the user-centric design thinking approach to understand the right pain points and value propositions.	*THEME 4A* **CULTURE OF FEEDBACK** External recognition and critical feedback for validated learning and effective iterations.
THEME 1B **FAILURE** Viewing Failure as a valuable learning experience.	*THEME 2B* **BIG PICTURE SYSTEMS THINKING** Looking at the big picture within a larger systems context.	*THEME 3B* **SOCIO-EMOTIONAL TRAINING** Learning to effectively communicate ideas with others and foster buy-in.	*THEME 4B* **ECOSYSTEMS FOR INNOVATION AND ENTREPRENEURSHIP** Cooperating with other departments, local incubators, start-ups and hackathons
THEME 1C **HANDS-ON ITERATIVE PROTOTYPING MINDSET** Building-to-think mindset through feedback-induced iterations.	*THEME 2C* **SMALL BUSINESS TEAM SIMULATION** Working in small teams for creative idea building in a collaborative context.	*THEME 3C* **BUSINESS KNOWLEDGE** Complementing technical skills with business knowledge to ensure sustainable long-term innovation success.	*THEME 4C* **INNOVATION AND ENTREPRENEURSHIP FOSTERING CULTURE** Inspiring and challenging culture that normalizes failure and encourages risk-taking.
THEME 1D **DEALING WITH AMBIGUITY** Exposure to the ambiguous through challenging assumptions, intentional discomfort, time pressure and lack of structure.	*THEME 2D* **EMOTIONAL CONNECTION TO THE PROBLEM** Developing a personal and emotional connection by understanding the why behind the project.	*THEME 3D* **INTERDISCIPLINARY PROJECT MANAGEMENT** Wearing different hats that prompt a breadth of skills and critical thinking.	

The ensuing sections (4.1 to 4.3) delve deeper into each construct, presenting a nuanced understanding of how these constructs shaped the ENI-SE of engineering graduates. This exploration not only answers our central research question but also lays the groundwork of how educational environments can be optimized to cultivate future innovators and entrepreneurs. To protect participant identities, we have employed pseudonyms, with the first letter denoting their role as Entrepreneur (E) or Intrapreneur (I), and the second letter indicating their gender as Male (M) or Female (F). Detailed profiles with background information of our interviewees can be found in the appendix in Table A.

4.1 Learning Experiences in ME310 related to ENI-SE

<u>Training and Repetition (1a) [MASTERY BY DOING]</u>

A significant majority of our interviewees, 28 out of 39 (72%), underscored the profound impact of repetitive engagement in innovative and entrepreneurial tasks on boosting their ENI-SE. One interviewee, EM1, succinctly captured this point with the statement: *"I think it was the repetition of doing things that made me learn the most, and that built confidence in my abilities."* This sentiment is echoed widely, with interviewees drawing parallels between enhancing self-efficacy and physical muscle strengthening through consistent training. They liken the process to leveraging neuroplasticity, which like muscle development through exercise, reinforces self-efficacy with repeated innovative and entrepreneurial tasks. This repeated exposure to these tasks trains the necessary skills to successfully perform them and thereby strengthens one's perceived self-efficacy in that domain. As IM7 insightfully noted: "*It grows over time, with repeated training. Just like when your body gets fitter as you train."*

The concept of skill development as an evolutionary journey to gain mastery was a recurrent theme. Echoing this perspective, EF1 refers to Gladwell's concept from the book 'Outliers' [63]: *"You spend ten thousand hours doing something, you become a master in it. It's true! Training and repetition, and your confidence booms when it becomes like second nature."*

Furthermore, the importance of experiences in mastering the entire design thinking process is crucial for learning how to navigate ambiguity in uncertain situations.

These insights underscore the value of persistent engagement in relevant innovative and entrepreneurial tasks as a key driver in developing ENI-SE.

<u>Failure (1b) [MASTERY BY DOING]</u>

Seventeen out of thirty-nine interview participants, accounting for 44 percent, reflected on how their past failures evolved into pivotal learning experiences, thereby enhancing their growth abilities and confidence in their innovative and entrepreneurial capabilities. EM10 encapsulates this sentiment by emphasizing the necessity of active engagement and willingness to embrace failure: *"What made me more confident in my abilities are four words: more failure than success. [...] And so, if you don't go out and try as hard as you can, you don't learn as much, it doesn't matter if you fail, but then you've done the best you can and you learn from that experience and then you move on and take these learnings with you."*

This perspective is echoed by EM4, who highlights the instructive nature of failures being valuable to avoid pitfalls in the future: *"The bigger learning experiences are sort of when you mess up, you can learn from them. If you were to do something and everything were to run* *smoothly, you might have some false confidence in going into the next thing. So, I feel like all the bumps in the road are actually the valuable parts."*

This section illustrates the profound impact of embracing and learning from failures, underscoring its role in developing self-efficacy in the realms of innovation and entrepreneurship.

<u>Hands-on Iterative Prototyping Mindset (1c) [MASTERY BY DOING]</u>

A significant portion of ME310 alumni, 33 out of 39 (85%), acknowledged the profound impact of the iterative hands-on 'building-to-think' concept in fostering their ENI-SE. This approach extends beyond mere physical creation, embodying a mindset of rapid iteration and continuous adaptation. It emphasizes the essence of prototyping to rapidly test and iterate, thereby steering the product development process efficiently in the right direction. This perspective is further bolstered by IF10, who correlates prototyping with a growth mindset, highlighting its role in psychological empowerment and confidence building: *"Prototyping is always an iterative process combined with a growth mindset. So, I think empowering people psychologically with those kinds of skill sets and mentalities is crucial. The confidence increases by doing that too."*

This iterative prototyping mindset also plays a crucial role in acclimatizing individuals to ambiguity by reducing uncertainty through engaging in a process of validated learning and quick assumption testing. EF2 aptly underscores the value of this key aspect in enhancing confidence and adaptability necessary for successful innovation and entrepreneurship: *"Prototyping is not going to be perfect, but it's going to take that learning and build on it, and indirectly you build your confidence in the process too."* Additionally, this mentality highlights exploring the right problems first and alleviates the traditional pressure to find immediate, perfect solutions, as IM2 observes: *"I think a lot of times we're sort of taught to find a solution right away. And this [prototyping] removes the pressure. You really want to explore the space a lot before you start to narrow down to a concept. So that piece really gives you confidence that you can go pursue new things."*

These insights collectively underscore the value of a hands-on, iterative approach in fostering self-efficacy related to embracing new ideas in innovative and entrepreneurial endeavors.

<u>Dealing with Ambiguity (1d) [MASTERY BY DOING]</u>

The ability to navigate ambiguity emerged as a pivotal skill in fostering ENI-SE, as observed by 27 out of 39 interview participants (69%). This skill is honed through diverse exposures, enabling individuals to amalgamate past experiences and forge pathways through uncertain situations and come up with creative and innovative solution ideas. Interestingly, the learning to handle ambiguity need not always stem from direct personal experience but can also be learned from historical lessons and observations of what others did before, as MN5 suggests: *"You also gain a lot of confidence when you can connect different things together and connect the dots. You don't always need to experience it from zero, but you can read and observe and learn from history. [...] A lot of smart people have come before and don't reinvent the wheel."*

Moreover, the participants acknowledged that the rapid changes in the digital era are heightening the need for a broader knowledge base to effectively handle ambiguity in leadership roles. IF10 highlights the significance of exposure to varied perspectives as a catalyst for innovative and entrepreneurial thinking, by advocating: *"I think cultivating the horizontal component, that breadth, and getting exposure is also extremely important. […] I really wish I had more opportunities to be more exposed to different things. It's just so important for innovation and entrepreneurship. You need to see more and really open up your mind to different perspectives, because that's where innovation happens, it is when you connect the dots between two seemingly unrelated ideas."* This sentiment is also echoed by IM1, who emphasizes the unlocking potential of a wide breadth of knowledge in fostering creative problem-solving skills in ambiguous contexts.

An interesting aspect perceived by our participants to be helpful in dealing with ambiguity is the value of learning through intentional discomfort, time pressure and lack of structure. EM8 reflects on this, acknowledging the real-world applicability of coping with uncertain and stressful situations encountered during the educational journey: *"The discomfort, stress and anxiety that comes from having to solve a problem that is very ambiguous, I think is a good one that is great for real life. I didn't appreciate it during ME310, but now I find myself more confident in knowing that I'll figure things out regardless*."

These insights highlight the importance of embracing diverse experiences and perspectives as a cornerstone in developing the capability to adeptly manage ambiguity, a key aspect of developing ENI-SE of future innovators and entrepreneurs.

Real-Industry Project-based Work (2a) [REAL WORLD CONNECTIVITY]

In our study, an overwhelming majority of interviewees, constituting 90 percent (35 out of 39), underscored the formative impact of engaging in project-based work that tackled real-world industry problems during their academic tenure. This hands-on experience provided practical context to their theoretical academic learning, thus forging a vital link between classroom theories and practical real-world application. EM3 encapsulated this sentiment by sharing: *"I learned from ME310 the value of partnering with industry to bring in real world projects. […] It's like: this is a real problem. And if we're giving it to you, it's because we haven't figured it out ourselves yet. This gave me so much confidence in my capabilities to figure out things, identify opportunities and prove it to myself and everyone else."* This convergence of industry collaboration and theoretical learning does not only augment technical proficiency but also provides a rich learning ground that helps students understand the relevance and application of their academic learning in real-life scenarios. IF2 underlines the importance of such experiences in bridging the gap between academic and practical realms: *"How you help the universities transition or fill the gap between academia and practice is understanding how these frameworks you learn apply out in the real world. […] Industry exposure through real-industry projects is so important, because there's so much to learn on the ground."*

The input from these alumni provides insightful evidence of the effectiveness of integrating real-world industry projects into the academic curriculum for enhancing ENI-SE.

Big Picture Systems Thinking (2b) [REAL WORLD CONNECTIVITY]

Over half the engineering alumni, 54 percent (21 out of 39), identified holistic, big-picture systems thinking as a crucial component in fostering their confidence in innovative and entrepreneurial capabilities. This perspective shift involves understanding intricate systems from diverse stakeholder viewpoints and grasping the nuances of product or service commercialization. To cultivate this comprehensive approach of systems thinking, it is essential to transcend basic problem-solving and encompass the understanding of the complete ecosystem of a product or service, including stakeholder perspectives, marketability, and consumer demand. Students should learn to develop marketing strategies and engage with potential customers, analyzing the market's reception and financial feasibility of their ideas. EM13's reflection on the significance of seeing the broader context, beyond mere problem-solving, underscores this point: *"I think what gave me confidence in innovation and entrepreneurship is understanding the bigger picture. It's not just solving a problem, but also trying to sell it to someone, having someone pay for it. […] Asking questions like: what's the problem you're solving? Who are you solving it for? Why are the alternatives inferior, and why is now the right time to solve this? What's the market opportunity?"*

Expanding on this, integrating this big-picture perspective early in the learning process is crucial for understanding the strategic 'why' behind tasks from the outset. This approach, which includes strategic recognition of larger problems and opportunities, equips students with a more comprehensive understanding of their projects and their potential impact in the real world. EM14 notes the importance of understanding the strategic reasons behind tasks and the value of thinking strategically in entrepreneurial contexts: *"I think I would have appreciated more of 'this is why we're doing it'. […] I think I would have liked the big picture view a bit earlier, because a focus on the big and then bringing it down to the concrete, particularly in an entrepreneurial environment, is also important to understand what you're trying to tease out. Either big problems or big opportunities and always kind of looking and thinking strategically and understanding the strategic elements of it and the "why" would have been helpful for me. And the reality is that a lot of students need to think in a more 'big picture' way."*

This section highlights the critical importance of big-picture systems thinking in enhancing engineering alumni's ENI-SE, emphasizing the need for an expansive understanding of complex systems and stakeholder perspectives in modern engineering practice.

Small Business Team Simulation (2c) [REAL WORLD CONNECTIVITY]

A significant portion of the interviewees, 59 percent (23 out of 39), underscored the importance of team-based work in nurturing ENI-SE. Collaborative work is a crucial skill, as most real-world innovations and entrepreneurial ventures arise from teamwork. The self-organization and reciprocal learning within teams that simulates real business environments also speaks to the value of team dynamics. Beyond mere team formation, the theme of collaboration is an interplay of idea pieces built on each other among multiple interdisciplinary individuals, as most creative and innovative outcomes often emerge from collaborative efforts across diverse disciplines.

To bridge the academic-industrial divide, it is imperative that engineering students not only learn effective teamwork but also acquire skills in effective team leadership and management. IM5 highlights the importance of integrating mental models focusing on human relations and group management in university education, mirroring real-world professional demands: *"In universities generally, the mental models around human relations should play a bigger role. Like we talk about having a breadth of knowledge, I think more on managing groups and interpersonal relationships. It makes a huge difference and that's what really happens* *professionally in the real world too."* Similarly, EM8 touches on the necessity of new graduates being adept at delegation and teamwork to successfully transition into the industry: *"What I'm trying to think about is what are the biggest gaps or what are the biggest shocks that a new college graduate coming into industry will have to learn and be confident in. I think one would be the skill of learning how to delegate and work effectively on a team."*

These insights emphasize the need for engineering education to incorporate team dynamics and leadership skills to prepare students for the complexities of real-world innovation and entrepreneurial challenges.

Human-centered Design (3a) [INTERDISCIPLINARY EXPOSURE & KNOWLEDGE]

A resounding majority of the interviewees, representing 97 percent of our cohort (38 out of 39), affirmed the pivotal role of a user-centric design thinking approach in enhancing their ENI-SE. This approach, rooted in empathetically understanding user needs before devising solutions, is seen as transformative in fundamentally shaping the engineer's mindset. IF10 highlights the transformative nature of this approach in boosting confidence and direction: "*This user-centered design is really about putting users at the center; it is about understanding the problem before going in and making a solution. So, to me, that way of thinking is really life-changing, it gives me so much more confidence in my capabilities and the direction I'm going in."*

When it comes to innovation and entrepreneurship in engineering, it is about the commercialization of the technologies in the market. The core of this methodology lies in its ability to marry engineering with market needs, urging students to understand customers and find the right pain points to develop technologies that are 'actually' needed. The design-thinking framework is praised for its proactive problem identification process, involving keen awareness and observation, which precedes iterative feedback-induced solution development. EF2's experience with her ME310 team, which led to a patent, exemplifies the practical benefits of this method. IM1 advocates for a broader educational perspective and a paradigm shift from traditional engineering education, encouraging engineers to think beyond their technical roles and focus on problem-solving as a primary intention: *"I would stop teaching engineers that they're just engineers. […] The intention starts with a problem that you want to solve and then you apply engineering to it. And so, I would almost say the flexing of the 'why' and the 'who' with all of those need finding elements, are even more important and give you confidence in pursuing these endeavors."*

EM10 underscores the necessity of aligning technological prowess with market viability, pointing out the futility of technology that fails to resonate with the market needs: *"It's good to have a great technology, but if you can't develop in a way that can address a real market, in a way that the market can actually accept it and adopt it, you've got nothing."*

Theoretical exposure to design-thinking alone is insufficient, it is the practical application of this method that provides students with richer, confidence-building experiences. Directly engaging with end-users affirms the universality and efficacy of this approach, enabling them to apply these skills broadly across diverse contexts.

This section emphasizes the critical role of design thinking in shaping engineering education to foster innovative and entrepreneurial mindsets and ENI-SE.

Socio-emotional Training (3b)) [INTERDISCIPLINARY EXPOSURE & KNOWLEDGE]

In the realm of fostering ENI-SE, 41 percent of interviewees (16 out of 39), highlighted the significance of communication and social emotional training. This emphasis reflects the importance of effectively conveying ideas and rallying support for entrepreneurial and innovative endeavors. EM1 sheds light on the dual importance of discipline in idea execution and the art of storytelling in engineering, emphasizing that both are inseparable for success: *" I've learned that telling the story of engineering is just as important as the engineering, but you can't have one without the other."* Similarly, IM4 points out the need for engineers to enhance their psychological and social emotional skills, as effective communication and storytelling are equally crucial as technical proficiency: *"There's maybe some more psychological and social emotional training element to it. I think that often engineers need more of that as it would give them more confidence in their innovative and entrepreneurial capabilities […] It's not just about doing the math and the engineering, but it is also about how well you communicate with people and definitely how you tell the story."*

Cross-cultural communication also emerges as a key skill in today's globalized work environment. EM2 recalls the challenges and subsequent confidence gained from working with a diverse global team during ME310, underscoring how these experiences are instrumental in navigating a world where cross-cultural interactions are commonplace: "*I still remember how challenging it was to work with the global team in ME310 […], however it was a relevant learning experience. It played out time and time again in my career. It gave me more confidence to navigate in such a globalized world where you have cross-cultural communication. That was a pretty powerful lesson during academia."*

These insights underscore the value of integrating holistic skills, like communication and cross-cultural training, in engineering education to prepare students for the complexities of the modern, interconnected world.

Culture of Feedback (4a) [SUPPORTIVE ENVIRONMENT]

The significance of external validation and feedback is underscored by 12 out of 39 interviewees (31%), highlighting it is pivotal in bolstering confidence within the realms of innovation and entrepreneurship. IM4's experience shows the value of mentorship and peer support in building self-assurance: "*What helps is certainly your mentors, your supervisors, your peers that support you and help give you some confidence in your abilities."* EM2 complements this pointing to the affirmative impact of receiving constructive feedback from external stakeholders like customers and investors: "*If you're on the right track, then you get plenty of data, plenty of feedback from the outside, the world tells you you're on the right track. Customers like it. Investors like it. Clients like it."* In addition to that, the autonomy and trust that the ME310 teaching team placed in students notably amplified their confidence and facilitated further skill refinement.

This collective insight illustrates the profound role constructive feedback and external validation from both the educational environment and the broader professional community play in enhancing students' ENI-SE.

4.2 Supportive Learning Environment – Learning Experiences from The Larger Academic Environment

<u>Ecosystem for Innovation and Entrepreneurship (4b) [SUPPORTIVE ENVIRONMENT]</u>

Forty four percent of interviewees, 17 out of 39, recognized the value of an ecosystem supportive of innovation and entrepreneurship, emphasizing the enhancement of ENI-SE through practical engagement beyond traditional coursework. These supportive ecosystems, featuring partnerships with local incubators or co-op programs with startups, provide a rich on-the-ground learning environment. EM3 highlights the importance of integrating students into real-world business settings to gain diverse experiences, suggesting internships with small businesses as a pathway to understanding the entrepreneurial landscape: *"Connect with local incubators and have students do internships with those small businesses. Before you try to go out and start your own small business, see if you can become part of a small business and get to wear some of those different hats and see what goes on in that small business environment. […] Building and utilizing such an ecosystem is really important for developing those skills and letting the students get the experience and enhancing their confidence as well."*

IF10 further underscores the value of competitions and hackathons in developing presentation and storytelling skills crucial for entrepreneurial and innovative success: *"It was more about telling a story, talking about why the issue that you're trying to resolve really matters. And delivering that solution in a way that makes sense to people. And doing these things just lets the confidence in my capabilities boom, so having such an environment with such opportunities is definitely very beneficial."*

This blend of academic and experiential learning underlines the critical role of a supportive ecosystem in developing confidence and skills necessary for embracing new ideas and intra-/entrepreneurial success.

<u>Innovation and Entrepreneurship Fostering Culture (4c) [SUPPORTIVE ENVIRONMENT]</u>

Over half of the interviewed engineers, 54 percent (21 out of 39), attributed their confidence in innovation and entrepreneurship to the pervasive culture at Stanford University, extending beyond the confines of the ME310 course. The environment, characterized by a community actively engaged in starting companies and innovating products and services, serves as a potent catalyst for self-belief in similar endeavors. EM4 comments on the inspirational aspect of being immersed in such an entrepreneurial atmosphere, noting the confidence gained from observing peers' successes: *"I think one of the biggest things that are so impactful is just being around people at Stanford. It's the culture there. I think a lot of people who go to Stanford are thinking about starting companies or thinking about new ideas and talking about them and doing stuff… A reasonable number of friends started companies and knowing that other people are doing it sort of gives you a little more confidence in doing it yourself."*

EM9 found that with such inspirational culture comes challenging motivation conducive to growth: *"Through Stanford's environment and culture I'm challenged to come up with slightly new ways of doing things, and I feel like that's one of the things that has contributed to the confidence I have in my capabilities and to keep developing that."* Furthermore, EM13 pointed out the importance of a culture that encourages risk-taking and normalizes failure, highlighting its pivotal role in cultivating robust ENI-SE and a mindset geared towards innovation and entrepreneurship: *"During my experience at Stanford, entrepreneurship was normalized and failing was okay and that definitely makes a difference in your mindset and confidence to go and try things out."*

These insights shed light on how a supportive university culture not only encourages students to explore new ideas for venture building and product/service innovation, but also significantly enhances their self-assurance in navigating the intra-/entrepreneurial landscape.

4.3 Elements Missing from The Academic Environment

Emotional Connection to The Problem (2c) [REAL WORLD CONNECTIVITY]

Fourteen out of thirty-nine engineering alumni, 36 percent, highlighted the importance of emotionally connecting with problems, noting a gap in the ME310 course in this regard. They emphasized the difference between being assigned a problem and discovering one independently. This emotional investment in problem discovery is deemed crucial for perseverance and genuine engagement. Alumni advocate for a more involved approach to problem-solving, suggesting opportunities for personal engagement with problem identification challenges. EM3 exemplifies this sentiment, emphasizing the transformative impact of engaging with personally resonant problems: *"Coming up with an idea and a product is important if you're going to be an entrepreneur or intrapreneur. So, one of the differences is in ME310, the focus was more on somebody bringing you a problem. […] One of the big differences with entrepreneurship is identifying things and coming up with the problem yourself, and I think by doing that early on, one would develop more confidence in the skills needed."*

EM10 highlights a potential disconnect between academic exercises and passion-driven pursuit, suggesting that emotional connection to problems is crucial for sustained engagement: *"Part of not pursuing entrepreneurship or the project itself after the ME310 course, is because the students are not emotionally connected to the problem that they're working on. And so, by giving them a problem that they have to solve, it becomes a homework problem that they get graded on and they get done and they learn all sorts of great stuff. […] But if you want somebody who's going to go after a problem and then really become tied to that, then they need more room for listening to global experts on overall problems. […] Give students the opportunity that if a great idea comes out of those events to go work on that."*

This nuanced approach to problem identification underscores the need for emotional investment in the curriculum, fostering a learning environment that cultivates a deeply rooted drive to innovate and solve problems.

Business Knowledge (3c) [INTERDISCIPLINARY EXPOSURE & KNOWLEDGE]

A majority of interviewees, 27 out of 39 (69%), identified a deficiency in engineering education regarding entrepreneurial and innovative business knowledge. This gap affects their confidence in navigating the business landscape, hindering engineers from fully engaging in product development's lifecycle – from ideation to sustainable commercial success. Alumni narratives highlight the recurrent issue: innovative projects often fail due to lacking business strategy, as exemplified by IM5's venture: "*I did not study business in* *school. I think that's a gap that should be filled for engineers. […] We started a company with a terrific technologically innovative product but in the end, it went bankrupt because the business side wasn't sustainable*."

Alumni emphasize the need for integrating business principles into engineering education to prepare engineers for entrepreneurial roles – not just to innovate but to translate their innovations into viable, market-ready solutions. EM12 stresses the lack of preparation for negotiating and strategic planning: "*"We were struggling with negotiating with angel investors and VCs. How do you build that projection plan for a startup? Even as an engineer, because a lot of entrepreneurs are engineers. […] And those are some skills which none of us were really prepared for, and I feel some amount of exposure on that would have given me more confidence*."

IF10's automotive industry experience underscores the necessity for engineers to understand business models and data monetization: "*What do you do with big data, monetization, business models, potential partnerships? So, maybe if we had more of a business component to this, that would have been amazing for my confidence in these skills*."

These experiences illustrate the evolving role of engineers, requiring a well-rounded skill set encompassing business acumen and strategic planning. Reimagining engineering education is crucial to equip graduates with the tools needed to navigate the modern technological and economic landscape.

Interdisciplinary Project Management (3d) [INTERDISCIPLINARY EXPOSURE & KNOWLEDGE]

A third of our interviewees, representing 13 out of 39 alumni engineers (33%), highlighted the significant role of interdisciplinary project management in fostering ENI-SE. This approach not only equips students with the versatility required in today's multifaceted intra-/entrepreneurial landscape, but also mirrors the dynamic role-switching often encountered in startups and innovative ventures. EM11 notes the necessity of adapting to multifaceted roles within small teams, suggesting that such experiences at the university significantly bolster confidence and preparedness for diverse challenges: *"There are a lot of small companies or small teams in the entrepreneurial and innovative field where everyone has to wear a lot of different hats, to play different roles. You need to learn how to become a quasi-expert in other disciplines."*

Echoing this sentiment, EM10 advocates for incorporating students from diverse disciplines into engineering projects, emphasizing the value of cross-pollination of ideas and fostering a dynamic thinking environment: *"I believe it's very important in academia to make sure that you are potentially integrating in students from other programs that aren't necessarily engineering focused. I think that this gives you the most opportunity to think dynamically. And so, having those additional skill sets brought into that program could be really helpful and useful."*

These insights emphasize the importance of engaging in roles across various disciplines within project management, highlighting its critical role in mimicking real-world innovative and entrepreneurial demands.

5 Discussion

Table 4.1, derived from the insights of 39 engineering-educated entrepreneurs and intrapreneurs, stands out for its inductively identified [4x15] elements important for nurturing ENI-SE. It categorizes 15 essential skills, mindsets, knowledge, and methods—many homed in the ME310 course (e.g., hands-on iterative prototyping mindset), some from broader university experiences (e.g., innovation & entrepreneurship fostering culture), and others from on-the-job learning (e.g., business knowledge). But do these items, taken as learning experiences, stand up to accepted (and proven) practices that advance learning?

Our discussion begins by providing evidence that the [4x15] items in Table 4.1 are "sound advice" in representing good teaching and learning practices, by validating them against established educational frameworks. In this context we consider Bandura's Social Cognitive Theory [64] and "How Learning Works: Eight Research-based Principles of Smart Teaching" (HLW) [65], and other evidence markers of good practices.

We then go on to consider the implications of the [4x15] items for teaching practices and course design in engineering more broadly. This is part of advancing a conversation around the collective responsibility of engineering degree programs (and not just courses with entrepreneurship and innovation in their titles) to contribute to educating engineering students who are engaged with embracing new ideas.

5.1 Comparison of the Four Main Areas to Learning Theory (e.g., Bandura) and the Eight Research-based Principles for Smart Teaching

Mastery by Doing (Propositions 1a-1d): The concept of mastery by doing underscores the importance of repetitive tasks in strengthening student skills, much like how regular physical exercise builds muscle strength. Bandura's theory emphasizes the significance of mastery experiences in boosting self-efficacy [66]. Interestingly, we found that failure within a supportive environment can enhance learning and self-efficacy by providing valuable lessons.

These propositions also go in line with the views of other researchers who explain that prototyping, with an emphasis on rapid-feedback-induced iterations, reduces the uncertainty by engaging in a process of validated learning and ensuring that pivots are efficient and effective [67]–[69]. It is also consistent with HLW Principle Six on "What Kinds of Practice and Feedback Enhance Learning?" in [65], specifying that feedback should be actionable and timely. Furthermore, the iterative prototyping aspect is an approach that focuses on problem exploration prior to solution finding [70], [71].

Real-world Connectivity & Interdisciplinary Exposure (Propositions 2a-2d, 3a-3c): Real-world exposure and interdisciplinary learning are essential for fostering confidence in innovation and entrepreneurship. Industry projects allow practical application of skills, highlighting the relevance of education to real-life situations. Interdisciplinary experiences broaden perspectives and boost adaptability, suggesting educational methods should blend real-world tasks and interdisciplinary approaches for optimal learning. This aligns with HLW's 4th Principle, advocating for authentic tasks to illustrate abstract concepts vividly ([65], p.100).

Interdisciplinary exposure bolsters confidence in innovation and entrepreneurship, as seen in Propositions 2b, 2d, 3a, and 3b. McGee et al. [72] and Schar et al. [23], [25] emphasize the importance of diverse interdisciplinary experiences beyond engineering in promoting ENI-SE.

Supportive Learning Environment (Propositions 4a-4c): A supportive learning environment significantly shapes students' self-efficacy in innovation and entrepreneurship. Social persuasion, like verbal encouragement and witnessing others' successes, influences students' beliefs about their capabilities [64]. Creating an environment that fosters risk-taking and learning from failure is paramount for academic institutions to effectively nurture innovation and entrepreneurship. Aligning teaching strategies with these principles enhances student engagement and success.

5.2 Educational Implications

Given these findings, it is clear nurturing ENI-SE is vital for student career readiness. Institutions must do more than teach technical skills; they must shape belief systems and confidence [73]. Courses should blend real-world tasks, interdisciplinary approaches, and supportive environments to empower students. Table 5.1 summarizes these points, with Appendix Boxes B1-B3 detailing ME310 activities.

Table 5.1 Educational Implications Tied to the Four Major Constructs

Mastery by Doing
• Incorporate repetitive training to enhance skills progressively • Emphasize the importance of learning from failure to foster critical thinking • Integrate hands-on prototyping activities to teach problem-solving skills • Guide students in becoming comfortable with ambiguity to promote adaptability and resilience
Real-world Connectivity
• Include real-industry projects in the curriculum to provide practical experience • Encourage big-picture thinking through thought exercises and case studies • Foster teamwork by assigning projects that require collaboration • Stimulate students' problem-solving skills by allowing them to identify and develop solutions to real-world problems
Interdisciplinary Exposure and Knowledge
• Incorporate human-centered design processes to enhance problem-solving skills • Provide training in socio-emotional communication to improve collaboration • Integrate business knowledge into the curriculum to complement technical skills • Promote interdisciplinary project management to develop a breadth of skills and dynamic systems thinking
Supportive Learning Environment
• Implement continuous feedback sessions to enhance learning • Foster an ecosystem that supports innovation and entrepreneurship by increasing opportunities and resources • Invite experienced professionals to lectures to provide vicarious experiences and normalize failure

By embracing these principles and implementing them effectively, educators can inspire active participation and confidence in their students, ultimately fostering a culture of innovation and entrepreneurship within academic settings.

The [4x15] items outlined in Table 4.1 were derived from interviews with high ENI-SE ME310 graduates who participated in the 9-month project-based mechanical engineering graduate course titled "Global Engineering Design Thinking, Innovation, and Entrepreneurship" (AY24 course title) over the past 25 years. While few engineering programs offer such an extensive 9-month experience, especially for undergraduates due to competing ABET requirements and resource limitations, we explored how the essence of these items could be integrated into existing engineering courses. There may be opportunities to add in content in cornerstone and capstone design courses, as well as throughout the range of engineering science courses. As examples:

Engineering Design Courses could consider how to expand the types of projects presented in Capstone and Cornerstone Courses, making sure that there is ambiguity in the "problem statement" (Proposition 1d, Table 4.1). Course instructors may need to set the design prompts so that there is not a solution-dependent problem statement. This might require setting/negotiating new expectations with project sponsors (e.g., students are developing a proof of concept vs. something that is ready to go to market), going out to a broader set of stakeholders (beyond "companies"), and assisting faculty leads in becoming more comfortable with leading a more "open ended" problem design courses. This may be a shift from engineering technology or engineering optimizing type problems to future design or ambiguous design prompts [74]. Notable exemplars that give students considerable "upfront" freedom in defining and scoping the problem are EPICS at Purdue (Engineering Projects in Community Service; where projects begin with identifying a community need [75]) and the course 2.009: Product Design Processes at MIT [76].

Engineering Analysis Courses could include additional context (like case studies) for how the course's analysis techniques allow students to see the "real world application" of the techniques, and how the techniques need to work in concert with other elements of product realization (e.g., physical prototypes, marketing decision) (Propositions 2a and 2b). This could include a founder guest speaker whose start-up uses the associated technical content in concert with an engineering design process to provide value for their customers. The conversation could also expand to the guest's career decision making in founding their own company and career trajectory. Students could also be given the opportunity to identify a question they want to answer with the course's analysis techniques; this has the potential of helping with students' sense-making, intrinsic motivation to problem solve, and connecting personally and emotionally with a problem they care to solve (Proposition 2d). There is a growing number of technical courses that have a culminating project assignment at the end of the course to help make this sort of individual connection.

Makerspaces and makerspace-based Courses are also robust opportunities to give students the chance to define the problem they want to solve through design and making (Proposition 2d). This is also an opportunity to introduce human-centered design approaches (Proposition 3a), and for students to create a series of prototypes that allow their design ideas to be incrementally evaluated (Proposition 1a, 1b, 1c). Both the space and the supporting coursework can be adapted to have students imagine and create and develop skills and abilities that relate to being an engineering student and maker.

Student Academic Advising is another way to encourage students to consider how their educational experiences (inside and outside the classroom) are helping them grow as idea generators. For example, the [4x15] could be used as a “Reflection Tool” for students who are interested in being “idea makers” (i.e., wanting to be high in ENI-SE) to assess how well they are doing in their formal education, extra-curricular activities and internships in developing the skills, mindsets, knowledge and methods that entrepreneurs and intrapreneurs have described as being important in being an “idea maker.” This may support and extend the possibilities of what it is to think like an engineer—to be a collaborator, inventor, problem-finder, etc., in addition to being nimble with engineering analysis.

6 Conclusion, Limitations and Future Research

Combining insights from 39 entrepreneurial and intrapreneurial ME310 engineering alumni, we unveiled impactful course learnings that bolstered their confidence in generating new ideas, a phenomenon identified as Embracing New Ideas Self-Efficacy (ENI-SE) [19]. These 39 individuals also shared insights into learnings beyond the course that played a pivotal role in developing this confidence. We have categorized these learning experiences into four major learning dimensions (Mastery by Doing, Real-world Connectivity, Interdisciplinary Exposure and Knowledge, Supportive Learning Environment), encompassing skills, knowledge, and mindsets ranging from dealing with ambiguity to acquiring business knowledge to applying human-centered design.

Our discussion illustrated the alignment of these learnings with evidence-based teaching practices in entrepreneurship education and higher education practices more broadly. We then delved into potential implications for engineering education, exploring how these learnings might be integrated into non-entrepreneurial or innovation contexts. By bridging theoretical teaching practices with tangible educational outcomes, this exploration not only highlights the integral role of diverse learning experiences in fostering innovation and entrepreneurship but also challenges current educational paradigms by suggesting integrations beyond traditional entrepreneurial and innovation contexts.

However, this work is not without its limitations, which also pose opportunities for future research. Firstly, our sample size is small, consisting only of those who scored high on ENI-SE. Exploring differences within the high group or considering those who did not score as high could yield valuable insights. Additionally, employing a survey methodology may enhance the veracity of our findings.

Furthermore, our study focused on a special graduate course at a highly selective university. Expanding the scope of graduates to undergraduate courses or a more general group of college-educated engineers who became entrepreneurs and intrapreneurs could offer a broader perspective on educational experiences supporting their journey.

Moreover, the Social Cognitive Career Theory (SCCT) models SE as an outcome of learning experiences. In our study, we used SE as a selection criterion for identifying the 39 ME310 graduates to interview, and their ENI-SE measurements were taken several years after completing the course. While we assume these individuals possess accurate memories regarding learnings inside and outside of ME310 contributing to confidence in idea generation, a follow-on longitudinal study tracking a cohort of ME310 students from pre- to post-SE measurements and extending into the professional world could further validate the tight connection between identified learnings and confidence in idea generation.

The thesis “The Making of an Entrepreneurial and Innovative Engineer: Academic and Professional Learning Experiences that Promote Entrepreneurial and Innovation Self-Efficacy” [53] outlines additional limitations and future research suggestions, acknowledging the need to explore the lasting impact of education.

Despite the challenges, this study urges educators to seek insights from graduates, even years after their time in the classroom. These individuals offer a unique perspective on the long-term effects of education in supporting their professional journey. In this paper, we have specifically examined the impact of one educational experience on those who evolve into idea generators. By incorporating ENI-SE and its implications into engineering educational course designs, additional leverage that translates the innovative and entrepreneurial potential of students into actionable reality could be gained. This in turn contributes to the growth of the innovation and entrepreneurship ecosystems at universities that breed the leaders of tomorrow.

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Appendix A: Interviewees' Background Information

Table A: Background information on interview participants. First letter denotes Entrepreneur (E) or Intrapreneur (I), and the second letter Male (M) or Female (F).

	Current Position	Field	Previous Experience
EM1	Founder and CEO	Language, technology, utility	Project and engineering management in the consumer electronics and medical technology fields
EM2	Founder and Principal Engineer	Engineering and design consulting	Engineering management in the medical technology field
EM3	Co-founder, CEO, COO of 3 startups	Engineering services, product development and wearable robotics technologies	Associate professor (Innovation and Engineering), researcher and author, product management in the military field
EM4	Co-founder	E-commerce	Co-founder and CEO of a startup in the virtual and augmented reality field (startup was based on ME310 project and got acquired by another company), lead capture engineering in consumer electronics
EM5	Head of Intellectual Property	Renewable energy	Co-founder of 2 startups in the medical technology field, entrepreneur-in-residence, IP strategy and R&D engineering in the medical technology and automotive fields
EM6	President	Engineering consulting services	Engineering management in failure analysis and reliability of mechanical systems
EM7	Founder and CEO, Venture Partner/Investor, Adjunct Mechanical Engineering Lecturer	Nanotechnology	Co-founder and CEO of 2 startups in the entrepreneurial product development business and the food and beverage industry, design research consulting in the internet and computer hardware field
EM8	Co-founder and CEO	Computer software (artificial intelligence and machine learning)	Software design engineering in the consumer electronics field
EM9	Founder and CEO, Stanford PhD candidate	Mobility and renewable energy	Co-founder and CEO of 3 startups in the technology design and research consulting field, design and user interface engineering in the internet services field
EM10	Founder and CEO, Board of Trustees Member	Environmental Services	Co-founder and CEO of 2 startups in the bioengineering field, funding faculty of a university and systems engineering in the aerospace field
EM11	Co-founder and Vice President of Product Design and Development	Medical technology	Senior product consulting, product development engineering and program management in the medical technology field
EM12	Director Product Development, Angel Investor, Startup Mentor	Information technology and services	Founder and vice president of 2 startups in the computer software sector
EM13	Founder and CEO, Board member in 2 companies	Food and beverage, farming	Senior vice president in strategy and operations in the computer software field, senior managing director in the financial services sector, management consulting
EM14	Founder and CEO	Information technology and services	Co-founder and CEO of a startup in the energy sector + VP Marketing and controls, analyst engineer in the automotive field
EF1	Founder and CEO	Computer software, manufacturing	Product design engineering and management in the consumer electronics field

EF2	Founder and Principal	User experience research consulting	User experience research and product development in the information technology, internet services and engineering design fields
IM1	Design Engineer	Automotive	Mechanical and product design engineering in consumer electronics field
IM2	Hardware Product Manager, Co-founder	Consumer goods, engineering services	Product management in the manufacturing field
IM3	Professor	Materials science and engineering	Product management in the manufacturing field
IM4	Senior Director of Global Marketing	Medical technology	Strategic marketing in the healthcare sector, development engineering the biomechanical field
IM5	General Manager and Vice President	Medical technology	Vice President of engineering and product management in the medical technology field, founder and CEO of a web-based tool and application service provider startup
IM6	Product Manager, Stanford PhD candidate	Biotechnology	Product management in the biotechnology, aerospace and automotive fields
IM7	Vice President Product Management and Marketing	Computer hardware	Co-founder and CEO of startup in the consumer electronics field, product innovation consulting, management and development in the electronic manufacturing and computer hardware and software industries
IM8	Vice President of Product Realization	Biomedical technology	Product management engineering in the medical device sector
IM9	Product Manager	Big Data, artificial intelligence enterprise software	Teaching in the E-learning field, R&D in the aerospace sector
IM10	Vice President of Global Quality, Environment, Health, Safety	Engineering technologies, energy	Director of quality and global advanced manufacturing engineering in the automotive industry
IM11	Business Development Director, Managing Director and Strategic Advisor for innovative healthcare technology ventures	Medical technology	Co-founder and corporate development in the medical technology field, venture partner in the venture capital and private equity sector
IF1	Product Executive	Software user experience	Design engineering in hardware user experience
IF2	Senior Project Manager, MIT PhD candidate	Medical technology, innovation strategy	Project management in the healthcare and biomechanical sector, co-founder of an NGO aimed at raising entrepreneurial intention of youths
IF3	Data Scientist	Internet services	Data science and product management in consumer electronics and computer software
IF4	Vehicle Integration Manager	Automotive	Vehicle engineering management in automotive noise and vibration
IF5	Director, Program Manager	Technology incubator	Product design engineering in the internet services field
IF6	Clinical Assistant Professor	Healthcare	R&D engineering in the manufacturing industry
IF7	Senior Product Manager	Consumer electronics	Product design engineering in the information technology services and consumer electronic fields
IF8	Senior Systems Program Manager and Core Team Lead	Information technology and services	Engineering program management in the consumer electronics and computer hardware fields

IF9	Product Design Engineer	Consumer electronics	Interaction design engineering in the medical technology field
IF10	Global Connectivity Product Manager	Automotive	Software engineering, supply chain engineering, product management and engineering in the automotive, consumer electronics and internet services and energy industries
IF11	Mechanical Engineering Designer	Internet services	Engineering design in the internet services, automotive and plastics fields
IF12	Associate Professor	Information and computer science	Product management and interaction design engineering in the computer software sector, R&D in the entertainment and automotive industries

Appendix B: Activities in ME310 that Contribute to Growth Areas

BOX B.1: Key activities in ME310 contributing to Mastery by Doing

ME310 incorporates multiple course elements that require using the same design thinking process in each activity. Students engage in identifying needs and requirements, emphasizing with users and stakeholders, brainstorming, diverging and converging, and pivoting on ideas. ME310 students also experience failure and develop their hands-on iterative mindset through activities like the 'Paper Bike' (where they test prototypes to failure to maximize learning), or 'Funky System' (where they build quick system prototypes to decide on the scope of implementation), or building functional prototypes to identify integration issues. ME310 has a phase where it was more of an exploratory prototype before students decided on their topic, and then after deciding on their specific topic, they had a second round of prototyping session where they built on top of the previous solutions. Furthermore, one of the design and prototyping strategies of ME310 is challenging assumptions (to expand design space and opportunities) to encourage students to feel more comfortable with uncertainty, where they start with limited information and an ambiguous problem. ME310 also applies intentional discomfort, time pressure and lack of structure to the students (as that is how it is in the real world too). Through the various ME310 activities students get exposed to and by going through the whole design thinking process, students learn how to connect past experiences together and get more comfortable with ambiguity.

BOX B.2: Key activities in ME310 contributing to Real-world Connectivity

ME310 engages students for an academic year in industry-sponsored projects where they experience various phases of integrated design thinking through engineering fabrication. This is operationalized in the multi-disciplinary, project-based learning and design engineering experience curriculum which underlines both connections with real-world industry through sponsored projects and global collaboration with international academic partners. This helps fill the gap between academia and practice by understanding how these frameworks you learn apply out in the real world. ME310 goes beyond engineering, by looking at the macro-environment, users and different stakeholders. Students design solutions that go beyond a physical prototype and work on understanding the problem from all the different stakeholders' perspectives. ME310 lets students get out of their comfort zone, go work with external suppliers and develop marketing materials. Additionally, one of ME310's course elements is collaboration and project & team management. Working in small teams as if you're in a startup.

BOX B.3: Key activities in ME310 contributing to Interdisciplinary Exposure and Knowledge

The whole ME310 course is based on the core values and skill sets of human-centered design thinking. ME310 teaches students that they are not just engineers. ME310 also has elements of business model development and thinking about monetizing the idea. ME310 had people from different engineering backgrounds to promote critical thinking and wearing different hats and learning from each other and integrating different perspectives. Moreover, in ME310 students have to pitch their ideas and develop storytelling techniques. They also learn cross-cultural communication by trying to work effectively and collaborating with global teams.