Exploring Connections between Engineering Projects, Student Characteristics, and the Ways Engineering Students Experience Innovation

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Abstract

Innovation is a key competency in engineering. Researchers and educators have long explored the processes, attributes, and environments of innovators with an aim to support engineering students in developing the competencies necessary to innovate. Yet, innovation is a complex phenomenon with many potential paths. In a recent phenomenographic study of engineering students, we found eight distinct ways of experiencing innovation. While these different ways of experiencing innovation were not necessarily better or worse, they could be compared in terms of their comprehensiveness, especially with respect to the innovation process and the issues (e.g., technical, user, or business) that drove innovation. In this study, we performed a two-phase qualitative analysis to understand how individual characteristics of the engineering students and contextual characteristics of the engineering projects in which they encountered innovation intersected to influence them to experience innovation in one of the eight categories described in the earlier study. In the first phase, we used content analysis to catalog distinct individual and project characteristics and explore similarities among participants in each of the eight categories. In the second phase, we used thematic analysis to describe, at a more general level, how individual participants came to experience innovation in more comprehensive ways. Content analysis showed that individuals may be drawn to specific categories due to nuanced connections between individual and project characteristics, while thematic analysis demonstrated three general pathways to more comprehensive categories, including (1) comprehensiveness of the innovation project experience, (2) connections between project goals and an individuals' interests and values, and (3) acute or persistent tensions between current perspectives and innovation experiences. We discuss these results in depth and describe implications for teaching and learning engineering innovation.

Introduction

Innovation is a complex and challenging phenomenon with economic, societal, and humanistic implications. These implications are particularly important in the field of engineering, where innovativeness is considered a key competency and outcome of education[1,2]. Many recent studies have attempted to clarify how innovation occurs by investigating the personal characteristics[3,4], processes[5,6], and environments[7] that support and align with innovation. While these studies often suggest certain core facets, they also describe innovation as a diverse phenomenon with many potential pathways. For example, Ferguson and colleagues[3] identified 20 characteristics of engineering innovators through an iterative, qualitative approach. They noted that while experts reached strong consensus on the comprehensive list of characteristics, there is likely substantial variation in the characteristics among individual engineering innovators. Dyer, Gregersen, and Christensen[4] made similar observations in a related study of innovators in a variety of fields.

The above studies have been useful in engineering education as a way to set curricular initiatives, develop pedagogical strategies, and evaluate student outcomes; yet the variation in innovator's characteristics, processes, and environments presents complex challenges for educators. This is especially true in light of our recent phenomenographic study that uncovered variation in the ways engineering students experience innovation[8,9]. In this study, we identified eight categories that represented distinct ways that engineering students experienced innovation. These categories could be organized hierarchically along two dimensions: (1) core elements of the innovation *Process* (e.g., idea generation) and (2) *Focus* of innovation activities (e.g., technical issues), with each subsequent category adding at least one element along at least one of these dimensions. The eight categories, listed in hierarchical order from least to more comprehensive, included:

1. Realize a technological function
2. Redesign and realize to meet stakeholder-determined criteria
3. Clarify and solve a client problem
4. Identify and fill a market gap
5. Develop a new solution for client benefit
6. Develop a new solution to make a difference for users
7. Develop a new technology for societal progress
8. Develop a radically new technology

While each of these categories was labeled in terms of a specific approach and outcome, they were each comprised of unique cognitive and experiential differences. In other words, beyond specific individual differences, engineering students may understand, define, and approach innovation in at least eight distinct ways. Better understanding of these differences and how they come to be is an important step in supporting educators' efforts to facilitate the innovative development of engineering students.

Thus, the purpose of this study was to begin to unpack these eight categories. In particular, we focus on understanding how engineering students came to experience innovation in these distinct ways. Relying on the philosophical commitments of the original phenomenographic study (described in the *Theoretical Framework* section below), we employ a combination of content and thematic analyses to explore how an interplay between individual and project characteristics contributed to the unique ways students experienced innovation.

Theoretical Framework

This study is underpinned by a non-dualist ontology[10,11], which proposes a single world that is experienced by different people in different ways. This contrasts with social and individual constructivism, which differentiate the internal world of the individual from the external world in which individuals are situated. Within a non-dualist ontology, knowledge and awareness of a phenomenon (e.g., innovation) are constituted as an internal interplay between the individual and the phenomenon (i.e., a way of experiencing the phenomenon). An individual comes to experience a phenomenon in a particular way based on his or her unique experiences, perceptions, and mindsets (which may highlight or marginalize specific aspects of the phenomenon), and the aspects of the phenomenon that are present during his or her encounters

with the phenomenon[11,12]. Thus, an individuals' way of experiencing a phenomenon will be defined by a unique intersection of individual and environmental characteristics, and will always be incomplete.

To illustrate this concept, we present the hypothetical, and much simplified, case of two engineering students. The first engineering student, Philip, a senior in biomedical engineering, likes working across disciplinary boundaries and wants to change the world through human-centered design. The second engineering student, Vivian, a sophomore in mechanical engineering, enjoys the precision of technical design and aspires to run a large company. In the fall semester, both participate in an interdisciplinary project to develop an innovative medical assistive device during a summer internship. Through this experience, both contribute to the conceptual design and development stages, but as a more senior intern, Philip also sits in on strategic meetings. After this experience, Vivian begins to experience innovation as a rigorous technical design exercise, in which engineers work to meet technical requirements that management derives from user requirements. Philip begins to experience innovation as a collaborative activity to develop new, user-oriented technology through knowledge sharing and building. Thus, both take elements they encountered during the innovation project that were also important to them as engineers and individuals. Conversely, Philip neglects the strategic elements he encountered, perhaps because they are outside his engineering worldview. Vivian might have incorporated these elements into her way of experiencing innovation, but did not encounter them.

While the above example simplifies many factors, we hope it demonstrates how a non-dualist ontology might manifest to support different ways of experiencing innovation. In the the current study, we utilized this framework to investigate authentic engineering students in authentic engineering innovation contexts. We explored the interactions and intersections of individual and project characteristics and how they guided participants to each of the eight distinct ways of experiencing innovation based on authentic experiences. While the above example suggested that engineering-related goals and values may have caused individual students to connect to specific project attributes, this is only one possible way this process may have occurred. In this study, we attempted to remain open to all the ways individual and project characteristics might have interacted.

Literature Review

Research on How Students View, Approach, and Output Innovation Based on Individual and Project Characteristics

Innovation is a complex phenomenon that encompasses a variety of outcomes, environments, processes, and competencies. For example, Golish and colleagues[5] identified no less than 133 tasks and activities utilized in developing innovative technologies. Further, professional innovators demonstrate a range of characteristics and competencies that may not be the same for any two innovators[3,4]. As such, innovation may be understood in different ways based on individual characteristics and the contexts (i.e., projects and their unique features) in which they encounter innovation.

Previous literature has demonstrated several individual and project characteristics that may affect the way engineering students experience innovation. Many of these studies focus on how individual or project characteristics improved innovative outcomes of student design work[13-15], and thus do not directly explore how students come to experience innovation differently based on these characteristics and their interplay. Still, such studies may provide indirect insights into how individual and project characteristics affect student understanding and experience of innovation (i.e., how these aspects affect specific competencies and how those competencies relate to different understandings of innovation) and may also help situate the results of the current study in the broader knowledgebase. Previously identified individual characteristics include: academic year and academic discipline. Previously identified project characteristics include: targeted innovation and entrepreneurship pedagogy, autonomy and authenticity, and team composition.

Many innovation-related studies have focused on differences between first-year and senior students. Within this work, first-year students and seniors have demonstrated different engineering design approaches[16] and self-reported knowledge, skill, and attitudes (KSAs) related to innovation[17,18]. Senior students tended to demonstrate more advanced design approaches and more complete KSAs, suggesting that students move towards more comprehensive ways of experiencing innovation during their undergraduate careers.

Other studies explored innovation competencies through project deliverables and idea generation outcomes. Genco and colleagues[13], for example, compared the innovativeness of conceptual design solutions produced by first-year students and seniors. They found that first-year students were more innovative than seniors and suggested the difference might be due to seniors focusing solely on technical aspects of the design problem, while first-year students scoped the problem more broadly and did not rely upon the technical approaches learned over an undergraduate engineering career. This result could, but does not necessarily, indicate a more comprehensive understanding of innovation among the less experienced first-year students. In a follow-up study, however, Kershaw and colleagues[19] found no significant group differences between first-year and senior students. In longitudinally comparing students on the same task during their junior and senior year, Kershaw and colleagues also found that students uniformly outperformed their junior scores as seniors. They suggested that year-to-year curriculum may play a role in these differences, as juniors may have not yet been introduced to ways to apply their deepened technical knowledge to innovative design outcomes, as seniors had.

These studies begin to demonstrate how engineering curricula, through influencing expertise and mindsets, can affect student approaches, competencies, and perhaps perspectives related to innovation. A separate aspect of curriculum, academic major, has also been shown to affect how students characterize innovation. A recent cross-case analysis demonstrated differences in way the chemical, civil, and mechanical engineering students described innovation[20]. These characterizations tended to align with major themes in each student's academic discipline. Thus, students may be strongly affected by the overarching contexts in which they have come to understand engineering.

More acute encounters (i.e., specific project characteristics) have also been shown to affect students' innovation-related capabilities, knowledge, and awareness. One key factor seems to be specific pedagogical interventions. For example, students who have participated in

entrepreneurship courses often report greater knowledge, skills, and attitudes related to innovation[17,18]. Further, students who received targeted training in empathic design produced more innovative concepts on a follow-up design task[21]. Additional project characteristics, including team composition and characteristics of the design problem, also have made a difference. For example, Svihla and colleagues[14] observed that the interaction between authenticity and freedom to negotiate the design project improved innovation-related project outcomes among engineering students. Further, team gender composition has been shown to affect innovative project outcomes[15,22]. Collectively, these and the above results begin to demonstrate some of the ways engineering students may come to understand innovation in more or less comprehensive ways, but further study is need to synthesize such knowledge into a more cohesive and actionable framework.

Results from a Phenomenographic Study on How Students Experience Innovation

We have engaged in a multi-year phenomenographic study to investigate the distinct ways engineering students experience innovation[8,9]. In this section, we provide a summary of applicable results, within which the current study of individual and project characteristics can be understood.

Phenomenographic analysis revealed eight distinct categories of description representing qualitatively different ways that engineering students experienced innovation during their engineering design projects. Each category was comprised of the experiences of three to seven participants who shared critical and distinct elements in their individual ways of experiencing innovation (see Table 1). Thus, these categories represented composites, that could be applicable to a variety of engineering students, rather than solely the individual participants.

While the eight categories are numbered 1–8, the numbering does not entirely represent progression from less to more comprehensive ways of experiencing innovation. The first four categories do represent expanding awareness across two key dimensions: *Focus* and *Process*. The final four categories, while each more comprehensive than the first four categories, are all at the same level of awareness on the *Process* dimension. While they differ on the *Focus* dimension, these differences represent varied priorities rather than different levels of comprehensiveness.

The *Focus* dimension described the primary purpose of innovation and key guiding influence, inspiration, and considerations of innovators in their work. The three elements of this dimension were *technology*, *users*, and *business*. In less comprehensive categories (1–4), this dimension represented participants' expanding awareness of focus areas within innovation, moving from solely technological, to adding user considerations, to adding and prioritizing business considerations. The more comprehensive categories (5–8) each contained technology, user, and business aspects, but to different degrees. Here, there were tradeoffs between each of the aspects (i.e., participants tended to prioritize one aspect over the others).

Table 1. Selected Aspects of Each of the Eight Ways of Experiencing Innovation

Category	Focus	Process Elements	Context Boundaries	Key Activities
1 – *Realize technological function*	Technological aspects only	Idea realization only	Self-contained project	Design-build-test
2 – *Redesign and realize to meet user criteria*	Technological and user aspects	Idea generation and realization	Community-contained project	Idea generation; design-build-test
3 – *Clarify and solve a client problem*	Technological and user aspects	Problem scoping, idea generation and realization	Community-contained project	Problem analysis; idea generation
4 – *Identify and fill a market gap*	All aspects; focus on business aspects	Problem finding and scoping, idea generation and realization	Market-contained project	Problem finding; market analysis
5 – *Develop new solution for client benefit*	All aspects; focus on business and user aspects	All process elements within macro-iterative cycle	Open-ended project	Problem scoping; understanding stakeholder needs
6 – *Develop new solution to make a difference for users*	All aspects; focus on user aspects	All process elements within macro-iterative cycle	Open-ended project	User interaction; problem scoping; user testing; idea generation
7 – *Develop new technology for societal progress*	All aspects, focus on technological and user aspects	All process elements within macro-iterative cycle	Open-ended project	Task delegation; modeling and development; functional testing
8 – *Develop radically new technology*	All aspects, focus on technological aspects	All process elements within macro-iterative cycle	Open-ended project	Technical research; idea development; experimentation; prototyping

The *Process* dimension described the phase(s) of an engineering project during which innovative activity occurred. Participants within one category may have been aware of phases outside their category's placement, but their descriptions of the innovation experience were predominantly limited to the phases aligned with their category. For example, Category 1 participants acknowledged idea generation, but did not substantively incorporate it into their innovative experience. This dimensions began with an awareness of innovation as the realization of a given idea or concept and expanded to add additional, increasingly early phases (i.e., idea generation to problem scoping to problem finding). Categories that represented more comprehensive ways of experiencing innovation contained each of four phases describing a single engineering project from beginning to end, but also added an element acknowledging that these projects existed within a larger developmental cycle (i.e., an individual innovation need not occur within the confines of a single project and could continue to be improved during follow-up projects or inspire others to develop future innovations).

These results have begun to uncover the different ways engineering students experience innovation, and aspects within which experiences that may differ. However, the current study explores how individual and project differences contributed to these experiential differences.

Methods

In this study, we employed a combination of content analysis[23] and thematic analysis[24] approaches to explore how individual and project characteristics contributed to the ways 33 engineering students experienced innovation. We began by utilizing content analysis to identify individual and project characteristics common to each of the eight categories described in the previous section, as well as how they influenced students towards specific categories. We followed this analysis by employing thematic analysis to explore broader themes relating to how students came to experience innovation in more and less comprehensive ways, beyond their connections to specific categories.

Participants

Participants included 33 engineering students across 13 different majors who had participated in over 40 unique innovation projects. The participants were each enrolled in a large Midwestern university and were targeted to achieve maximum variation along four key factors: prior engineering project experience; academic major, gender, and year in school. Participants received a small cash incentive for their time. Table 2 presents a representation of these participants along the four key factors (based on a student self-report survey). Participants are listed by a pseudonym they selected.

Data Collection

The engineering students each participated in a 1–2 hour semi-structured phenomenographic interview[25]. The purpose of these interviews was to elicit student's perspectives and experiences with innovative design. The interviews occurred in six stages defined by the topical focus of the questions: participant background, initial definition of innovation, experiences during innovation projects, comparison of innovative and non-innovative projects, general conceptions of innovation, and closing thoughts. One difference between these interviews and standard phenomenographic interviews was an increased emphasis on participant background questions. This emphasis was added due to the importance of developing an empathic understanding of the participant in phenomenographic research[26], while also supporting deeper and more comprehensive portraits of each participant for the current study. Students also completed a short multiple choice and open-response survey to collect demographic information. All interviews were audio-recorded transcribed for analysis.

Data Analysis

During the first phase of analysis, we utilized content analysis to identify and understand characteristics that supported each way of experiencing innovation. We began analysis by open coding the participant interviews to capture as many potential characteristics as possible. We iteratively refined this initial codebook to eliminate redundant codes, merge similar codes, and split codes that represented multiple characteristics. Once a final codebook was set, we began a phase of axial coding, to identify all instances of each characteristic.

Table 2. List of Participants by Category, Major, Year, Gender, and Design Experience

	Pseudonym	Major	Year	Gender	Engineering Design Project Experience
Category 1	Ajay	First-year	First-year	Male	Design competition club teams
	Jerry	First-year	First-year	Male	Design competition club team; Personal projects
	Leon	Electrical	Sophomore	Male	Student organizations, Personal projects
	Matt	Mechanical	Senior	Male	Sophomore design, Service learning
	Michael	Biological	Senior	Male	First-year engineering course; Senior design
	Socrates	Civil	Senior	Female	Internships, Student organizations, First-year engineering course, Graduate-level course projects
	Theresa	First-year	First-year	Female	N/A
Category 2	Alex	Aeronautical	Sophomore	Male	Course projects, Service learning, Internship
	Dante	Agricultural	Junior	Male	Service learning
	Hannah	Chemical	Sophomore	Female	Service learning, Design competition club team
	Snow	Mechanical	Senior	Male	Co-op
Category 3	Caroline	Industrial	Senior	Female	Course projects, Internship
	Maria	Industrial	Junior	Female	Internship, Class Projects, Student Organization
	Marshall	Aeronautical	Senior	Male	Design classes; Internships
	Tony	Industrial	Senior	Male	Service learning, Senior design
Category 4	Esteban	First-year	First-year	Male	Self-initiated start-ups; First-year engineering design projects
	Fred	Agricultural	Junior	Male	Undergraduate research, Service learning
	Jessica	Biological	Sophomore	Female	Course projects, Club projects, Personal projects
	Ron	Mechanical	Sophomore	Male	High school science fair, First-year engineering course
Category 5	Ella	Industrial	Senior	Female	Internships, Service learning, Personal projects, Service learning club
	Penelope	Biological	Senior	Female	Service learning, Design/business plan competition
	Verdasco	Mechanical	Junior	Male	Service learning, First-year course project
Category 6	Elon	Mechanical	Senior	Male	Co-op, Internships, Sophomore design, Design competition club team, Personal projects
	Sarah	Chemical	Senior	Female	Service learning, Internships
	Sharon	Biomedical	Junior	Female	Co-op, Service learning
	Summer	Electrical	Junior	Female	Internships, Service learning
Category 7	Dana	Aeronautical	Senior	Female	Senior design, Junior-level design course, Internship
	Dylan	Biomedical	Senior	Male	Senior design, Internships
	Maxine	Mechanical	Senior	Female	Service learning, Internships, Senior design
	Taylor	Computer	Senior	Female	Junior-level course projects, First-year engineering course, Internship, Student organizations, Personal robotics project
Category 8	Chris	Nuclear	Graduate	Male	Long-term personal start-up
	John	Acoustical	Senior	Female	First-year engineering course, Service learning, Internship
	Vespasian	First-year	First-year	Male	Service learning, Family business, Personal projects

Codes were split into two categories based on the theoretical framework: individual characteristics and project characteristics. Individual characteristics included any aspect of one's interests, knowledge, skills, attitudes, and background that the participant made apparent during the interview. These characteristics were the focus of the initial participant background phase of the interview, but also arose throughout the interview. Because these codes arose from a single

interview, they certainly do not comprehensively describe all characteristics of the participants. However, they do indicate aspects the participants felt salient to discuss in the context of an interview focused on their experiences with innovation and in response to questions about (a) their personal and academic interests and background, (b) their experiences with innovation, and (c) their general conceptions of innovation.

Project characteristics included any aspect of an innovation project a participant discussed. These included but were not limited to contexts (e.g., internship), stakeholders involved, individual responsibilities, activities and tasks encountered, and project requirements. Once again, these codes represented project aspects students felt relevant to the questions and responses within the interview and did not necessarily cover all possible aspects of the projects in which they encountered innovation. Table 3 presents a selection of example codes and excerpts.

Table 3. Example Codes from Content Analysis

Code Category	Code - Description	Example Coded Excerpt
Individual	**Help others** – participant describes or demonstrates a passion for helping others through their engineering work	I guess being able to help people is the biggest thing for me, especially with EPICS, and then, in general, with everything I work on. I'm somebody who is ... I'm always looking at the bigger picture. I want to see where the end result is. I like to keep that in mind. I like to see how what I'm doing, no matter how tedious it is. If I'm sitting there, trying to learn how to solder as a chemical engineer, that, in the end, this is going to help, that this is going to be something that can make a difference in someone's life or in whatever the need may be.
Individual	**Competitive** – participant describes or presents self as competitive, enjoys besting others or proving them wrong	Ego. Yeah. I'm right. Everyone else is wrong. Just, it didn't work this way and then I'll show my professor and he'll be like, "Ah, I still don't think there's a way to do it." And I'm just like, "Oh yeah? Well, I'm going to prove you wrong!" And then I'll go try other things. I would say that comes into play a lot. It's just there's, I'm going to find some way to make this work.
Project	**Client-driven** – project is sponsored or commissioned by a particular stakeholder	Due to the scope of the competition, it was more for industrial purposes, because it's funded by the [anonymized organization]. So, they were looking for new products where they could make money. So, it kind of also taught me that you can't just do whatever. Where you project stems from comes from who's funding it and what it's for. So, different competitions and different research labs can have different purposes. Even if it all would be beneficial stuff, sometimes you have to focus on something that's more industry-driven.
Project	**Specific functional requirements** – project is driven by specific functional requirements given to the project team	What we needed to do for the project was we needed to have a plane that was autonomous, could fly for at least 15 minutes, be able to carry a payload, carry a certain weight or just a block, and it should be about to have a camera that could focus in on certain targets in the ground and then take that information and send it back to a computer that was however far away it was.

During the second stage of analysis, we identified individual and project characteristics that were common to each of the eight ways of experiencing innovation. To assign a characteristic to a

specific way of experiencing innovation, we required that the characteristic be coded in at least 75% of the transcripts aligned with that category. Ultimately, this conservative threshold meant that all or all but one of the participants in each category discussed each characteristic that would be assigned to that category.

During the final stage of analysis, we utilized thematic analysis to explore broader themes related to how participants came to experience innovation in one of the eight ways identified in the previous study. Thematic analysis is a flexible, iterative method that can be used to explore latent and/or semantic meaning in a data corpus[24]. Here, we utilized content analysis results as a baseline and focused on the underlying patterns that facilitated movement between and into different ways of experiencing innovation. We followed a six-step process similar to that described by Braun and Clarke[24]. These steps included:

1. Re-reading the data multiple times (both considering and bracketing previous results of content analysis)
2. Generating initial codes (different from the individual and project codes generated during content analysis)
3. Sorting and reframing codes, and identifying themes
4. Reviewing themes in light of coded extracts, the whole data set, and the previous content analysis results
5. Defining the themes
6. Creating final descriptions

After several iterations of this process, we arrived at three unique themes. We took care throughout the process to ensure that all findings were authentic to the data and were consistent with the previous results and literature. We did so by consistently looking back at the data, previous findings, and knowledgebase when arriving at new insights, and only completing analysis when the themes were consistent and meaningful with respect to the data, content analysis results, and broader understandings of innovative development among engineering students.

Results

Content Analysis

Content analysis revealed a total of 56 unique personal characteristics and 46 unique project characteristics described by the participants. After identifying which characteristics were described by at least 75% of participants in each category, 18 personal characteristics and 25 project characteristics remained as potentially important to the way a participant experienced innovation. A complete listing of these codes is provided in Table 4.

In the eight following sub-sections, we describe these codes category by category and explore how their interplay may have facilitated participants coming to experience innovation in the distinct way described by the category. Thus, these results present a detailed and specialized view of the phenomenon. We report more general trends in the *Thematic Analysis Results* section.

Table 4. List of Individual and Project Characteristics Common to the Categories of Innovation

Category	Common Individual Characteristics	Common Project Characteristics
1. Realize a technological function	• Limited design experience • Enjoys emergent problem solving • Perfectionism/optimizing • Competitive	• Specific functional requirements • No real-world context
2. Redesign and realize to meet stakeholder-determined criteria	• N/A	• Specific functional requirements • Awareness of link between given requirements and stakeholder needs • Current solution in place but not effective
3. Clarify and solve a client problem	• Enjoys variety in professional work • Liaison between technical and lay people	• Client-driven • Develop process/system for company to improve efficiency • Immersion in client environment
4. Identify and fill a market gap	• Interest in starting own business	• New product development • Course project • Required market analysis aspect
5. Develop a new solution for stakeholder benefit	• Wants to make a difference through engineering • Desires inclusive team/company culture • Connects to content aspects of major • Systems thinking	• Client-driven • Frequent interaction with or reminders of key stakeholder(s) • Outside comfort zone and expertise • Large team
6. Develop a new solution to make a difference for users	• Primary goal is to help people • Wants to make a difference through engineering • Desire to bring new and interesting things into existence	• Frequent and emphasized user interaction/research • Project meant to benefit a specific user group or community • Extra- or co-curricular
7. Develop a new technology for societal progress	• Interested in management role • Choice of major linked to personal interests	• Novel problem required new technology • Course project (mostly senior design) • Milestone-based project • Autonomy in topic and process • Task delegation
8. Develop a radically new technology	• Highly motivated within specific areas of interest • Competitive • Interest in creating "cool" and novel technology • Enjoys applying scientific knowledge to engineering problems	• Self-initiated • Within business or forming business • Worked as individual or pair • Novel problem • Required research and scientific theory application

Category 1: Realize a Technical Function

This category was marked by a focus on the technical aspects of innovation and an iterative, design-build-test approach. Participants defined this as innovation because they were solving problems that were new and complex to them. Most of their encounters with innovation were spent building/developing a solution and modifying it based on functional performance during tests. Participants demonstrated a limited awareness of user or business issues with relation to innovation.

There were clear connections between individual characteristics and the approach to innovation within this category. Participants enjoyed emergent/hands-on problem-solving and held optimization/perfection oriented mindsets. As the innovation projects required participants to meet specific functional requirements, they began to focus on how to meet those functional requirements in a micro-iterative, hands-on way (i.e., slowly improving a single design option) rather than attempting to better understand the underlying problem or develop multiple solution options to pursue. This interplay manifested in the design-build-test approach that became a key feature of this category. Matt described this approach as "barnyard engineering" and enthusiastically described it in the excerpt below:

> I believe the term is, "barnyard engineering," where we got an idea, we sketched it out, discussed it within our team, realized, "Is it going to work? It's going to work." Then, we built around that idea of, "All right. We know what we want to do. We know what it needs to do." It's just, "How are we going to make the parts fit together?" We did our prototyping with a little bit of trial and error, when it came to the machining, which, in pretty much any of my machining experiences, has been what's gone on, is that trial and error when you're prototyping is completely okay, and that not everything is a 3D CAD model that takes hours to build, just to figure out how two parts work together. Sometimes, you just need to sketch it, and build it, and test it, and see what went wrong, see what worked, and then just iterate off that. (Matt, Senior, Mechanical Engineering)

Another key individual characteristic was that this was the first major engineering design experience for all but one of the participants in this category. As a result, many of the participants noted that they used this experience to learn about engineering design and larger projects. As Jerry described below, he attempted to learn from senior members of the team and understand innovation as constituted in that specific context. Because these projects focused on technical aspects of engineering and meeting functional requirements without consideration of user/societal and business issues, these aspects of innovation were likely beyond the participants' awareness.

> I was thinking that I had no idea what was going on. I'll pick it up as I went along. Because when I went into this, again, I had no experience whatsoever. People around me had been doing robotics for years, they had been working on RC planes for years, and they basically explained to me what had to be done to get these tasks accomplished. And through I was able to learn, for one thing, how to do it in the first place, and then after that learn how the design process worked… Because I was seeing how they were thinking, because they took notes, then I was able to emulate that. (Jerry, First-Year Engineering)

Category 2: Redesign and Realize to Meet Stakeholder Criteria

Category 2 was not much different than Category 1. It featured a design-build-test approach to solution development and focused on meeting specific functional criteria. Two key differences were: (1) innovators considered user/stakeholder needs an important driving focus of their work

and (2) innovation involved a substantial idea generation component to envision alternative solutions before pursuing one option.

Content analysis revealed no individual characteristics shared by the four participants in this category. These participants demonstrated disparate interests, mindsets, engineering goals, and previous experiences. The only similarity was that all participants were in their sophomore or junior year. Due to the lack of common individual characteristics, project characteristics seemed to play an important role in influencing the way these participants experienced innovation. Most critically, the awareness of a link between user/stakeholder needs and the functional requirements seemed to inspire participants to consider users/stakeholders in their project work. Thus, innovation became something more than solving a novel technical problem. Hannah, who appreciated the more technical aspects of engineering, described this added commitment to users.

> In this situation, meeting for specifications for the project partner. So, there's certain things like safety, cost, ability to break it down and fit in that locker. So, we needed to fit it into all these categories, and not all of our designs necessarily fit in. Whichever one fit in best was ultimately, well, innovative. Creative is going to be like, wild, out of the box. We had to be innovative with limits. I think if you're innovative with no specification, that opens all kinds of doors. In this situation, being innovative was making sure that we had the best design with fitting all the specifications. (Hannah, Sophomore, Chemical Engineering)

Category 3: Clarify and Solve a Client Problem

This category was marked by an extensive analysis stage during which innovators observed, collected data on, and attempted to deeply understand a problem context before ideating and developing a new solution. This experience of innovation was tied to supporting a specific stakeholder group, but required the unique expertise and background of the innovator to view those stakeholders' problems in a different way.

The participants in this category tended to enjoy variety in their engineering work and wanted to pursue careers in which they could act as liaisons between technical and lay people. It is no surprise that they connected to client-driven projects with strong human-interactive elements. Through these projects, they could bridge the gap between lay people (who had a problem) and the technical experts needed to solve their problems, and apply the unique expertise and perspectives they had developed by pursuing their variety of engineering and technical interests. For example, Tony described how his unique knowledge led an innovative solution for clients.

> It's just we use our previous knowledge that we had from a previous course or previous internships and applied it to something that the client had, but their own employees had never thought of before, just because, I think it comes back to the bubble analogy. They just were operating with a set, set of constraints and rules and not looking at new things, or coming up with new ideas that they couldn't even imagine that they could use this machinery in that respect. So, coming to a problem with a new set of ideas and knowledge I think helped us make that difference. (Tony, Senior, Industrial Engineering)

Category 4: Identify and Fill a Market Gap

Innovation in this category was creating a solution that would be successful in a specific market because it offered substantial improvement over existing solutions or solved a problem that was not previously solved. A key activity here was identifying an underserved market and a problem therein to solve. While innovators in this category considered technological and user aspects, they focused on whether the solution would achieve market success (i.e., profitability, market acceptance).

All the innovation projects within this category were situated in different engineering design courses, yet each focused on new product development and required participants to analyze markets and finances. These aspects tied directly into each of the participants' interests in starting their own businesses. For example, Esteban referred to his innovation project as a first step towards that goal.

> I really want to have my own company in the future. I'm not exactly sure what it will be or what the details are, but I want that. That's my goal. And that's a fairly large goal and to get there I need to do a whole bunch of smaller things. Maybe I need to find friends that also may want to start a company with me. But I felt like coming up with my own design, my own product was the first step to having my own company in the future. (Esteban, First-Year Engineering)

Category 5: Develop a New Solution for Stakeholder Benefit

Innovation in this category focused on creating new solutions to benefit a specific client. Innovators cared about many stakeholders, including teammates, users, and others. However, they prioritized client needs due to an awareness of who the project was intended to serve and reliance on client-provided resources. Innovators realized they could better serve other stakeholders' interests (including their own) and further advance technology through a series of small, client-serving advancements.

The aspect of innovation as a stakeholder-serving activity arose from a complex interplay of individual and project characteristics. These projects were primarily client-driven in that participants' resources were provided by clients and overall project success was determined by meeting client needs. Participants were personally invested in using engineering to make a difference, thus the overarching client-centeredness of the projects provided a means through which participants could make a difference. However, this focus on making a difference for others allowed participants to consider a variety of other stakeholders during innovation, as noted by Ella.

> It was about more than just the product itself. It was also about all of the implications that solving this problem had for everyone involved with the product. It makes a better product for the consumer. It would make, in this particular case, the clean up process for all of the operators much easier. It would improve the profits of the company because the waste would not be as high. It was not just the product that was affected. It was also

everybody tied to the product, and the process of making that product. (Ella, Senior, Industrial Engineering)

Category 6: Develop a New Solution to Make a Difference for Users

Innovation in this category focused on making change for a specific user group. This process involved developing a deep understanding and concern for the users, as well as the context in which the solution would be implemented. While technical, financial, and resource constraints played a role, the innovators prioritized meeting the users' needs. This often included eliminating options that would be more technologically or personally interesting and novel than those that better served users.

Participants in this category shared two often-competing interests with respect to their engineering innovation work. First, they desired to make a difference for others, especially for the direct-users for whom they designed. Second, they desired to create interesting, new technological solutions using their technical expertise. They eventually opted for the human-centered elements with respect to innovation, most likely due to the projects they encountered. Each of these projects involved designing for specific users and featured frequent, meaningful interactions with, or reminders of, those users. As Sarah noted, participants often needed to halt their pursuit of novel technological solutions in favor of those that were more appropriate and useful for users, coming to define innovation in terms of how well a solution accounted for user needs.

> The traditional thought for how a lot of students, especially on our team where we have a lot ECE students and things like that that are very technically-focused. They think of innovation as, "We can make this bigger, better, faster, stronger," and have all these capabilities. To me, it's important to think about innovating on the side of what makes it better for the user and what makes it more effective than what makes something exciting to an engineer. That's different than what makes something exciting for your user. (Sarah, Senior, Chemical Engineering)

Category 7: Develop a New Technology for Societal Progress

As in the previous categories, innovation in Category 7 was an incremental process. Innovators worked to develop small advancements that eventually (i.e., through a series of potentially unrelated projects) culminated in something substantially novel. Innovators were aware of both societal/user and business implications, but focused on doing so through small, but important, technological advancements. Thus, innovation was mostly a technical experience, involving many modeling, simulation, prototyping, and experimentation activities, that also incorporated overarching economic and societal concerns.

The projects related to this way of experiencing innovation resembled, surprisingly, well-structured course projects other participants often described as not being innovative. The projects in this category, however, shared two key features that differentiated them from non-innovative projects discussed by those in other categories. First, participants experienced substantial autonomy with respect to topic and process. Second, participants attempted to address globally

unsolved problems. As Maxine described, participants experienced strong motivation to take these projects beyond expectations (i.e., to contribute small-scale technological breakthroughs) due to their novelty and alignment with personal interests.

> Just being invested in the project. I think with engineers, once you start working on something, you get more attached to it. Having an interest in the topic, 3D printers, learning that we're doing something that people haven't done before, so those are motivators for me to actually be more interested in the project. (Maxine, Senior, Mechanical Engineering)

Category 8: Develop a Radically New Technology

Innovation in Category 8 was developing new technology that was game-changing in a specific industry. The process was technology-centric and required a deep understanding of and new perspective on content knowledge. The innovator developed an idea for a new technology by applying scientific and engineering principles in new ways, and worked to turn the idea into a feasible prototype, product, or venture. While this process typically did not involve directly considering users' needs, participants were often aware of, and sometimes motivated by, how their technological and scientific advancements could affect the lives of many.

It was difficult to separate the individual and project aspects in this category because the projects described therein were self-initiated and based on the participants' interests, expertise, and mindsets. These participants were highly motivated in their own unique areas of interest (and experienced limited motivation outside those areas), enjoyed competing with others and proving themselves right, and desired to create new and groundbreaking technology. The projects they initiated represented unique combinations of topical interest, key technological implications, and substantial technical and personal challenges to fuel their competitive side. As John indicated, due to the substantial connection between personal and project elements, the innovator began to associate with the innovation itself.

> Almost like bragging rights I want to say, because there's something that I worked on out there that's being sold to people everywhere I can be like, "I worked on that. That's here because of me." I guess it's kind of almost selfish bragging is what it is. But it's also really cool because if it is innovative and it is brand new people, even with the iPhone people are like, "Whoa! that's so cool!" Think of it like it kind of makes you a little proud inside you, like "Yeah, it is kind of cool and I'm cool." So, I feel like that's almost like you associate yourself with my product. Maybe it's like some sort of you put your time into it so you want to be associated with good things. (John, Senior, Acoustical Engineering)

Thematic Analysis Results

Building upon the content analysis results, which demonstrated how individual and project characteristics interacted to support the eight distinct ways of experiencing innovation, thematic analysis unveiled three broader trends in how engineering students came to experience innovation in more and less comprehensive ways. These three themes included:

1. Incomplete project experiences encouraged incomplete perspectives (and vice versa)
2. Alignment with personal goals and interests facilitated connections with specific aspects of innovation while marginalizing others
3. Being confronted with failure or persistent tensions supported new perspectives

Theme 1: Incomplete project experiences encouraged incomplete perspectives (and vice versa)

As the theme title suggests, the degree to which the innovative project experience covered a wide range of innovation-related elements affected the comprehensiveness of the way the participant experienced innovation. Projects that featured limited exposure to innovation process phases (e.g., participant only worked in the development phase) or focus areas (e.g., the participant only encountered technical roles), presented participants with fewer aspects of innovation with which to connect and incorporate into their own way of experiencing innovation, and thus tended to result in less complete experiences of innovation. This was especially true for participants with limited prior engineering design experience (such as those in Category 1). These students had few situated, authentic perspectives to bring to the encounter with innovation and thus tended to assimilate key project features into their own understanding of innovation.

A comparison of Ajay's and Marshall's experiences provides one example of this pattern. Individually, Ajay and Marshall described themselves in similar ways. Both favored technical aspects of engineering work, focused on setting themselves apart from others, and described themselves as perfectionists who enjoyed optimization. Further, both had limited project experience, and therefore naïve conceptions of innovation, before the projects in which they described encountering innovation. However, these two projects differed substantially. First, Marshall performed a more prominent role in this innovation project by co-initiating the project, scoping the problem, and fulfilling a variety of tasks. Ajay was a novice contributor to a project sub-team and was not involved in project planning or the initial phases. Further, Marshall's project was situated within an internship and involved real users and clients, and real-world implications of project success. Ajay's project involved a realistic, but ultimately simulated, design problem with no real stakeholders or implications of project success (beyond personal/team satisfaction and resume-building). As a result, Marshall came to experience innovation in a more comprehensive way than Ajay (Category 3 compared to Category 1), that involved expanded user considerations and integration of problem scoping elements.

Conversely, projects that entailed deep immersion or frequent confrontation with specific innovation-related elements often inspired participants to incorporate those elements into their ways of experiencing innovation. Penelope, in category 5, described a key example of how this happened for her.

> We originally talked about making a water filtration system to be used in developing countries, but then due to the scope of the competition, it was more for industrial purposes because it's funded by the [anonymized funding source]. So, they were looking for new products where they could make money. So, it kind of also taught me that you can't just do whatever. Where you project stems from comes from who's funding it and what it's for. So, different competitions and

different research labs can have different purposes. Even if it all would be beneficial stuff, sometimes you have to focus on something that's more industry-driven, I guess. So, yeah, I kind of just formed the team and we just started meeting. And [the clients] had bi-weekly "all" meetings that kind of led you in the right direction… I realized whatever you're doing the project for matters. For example, if NSF is funding your project, you should make sure that you keep their goals in mind when you're doing your research because they're not going to give you the money if they don't see that what you're doing is impacting the future. So that research might be different than if you're funded by a company that wants you to be able to make this new product or this new process that would help them make their products faster, or a new plan for their company to be able to succeed better. So even if you're doing something for a company and you're like, "Oh, well this could help so many more people if we did it this way." But sometimes it's like, "But that's not what they asked for." So, you need to stay on track. And marketing it to consumers and the company you work for is important. (Penelope, Senior, Biological Engineering)

Theme 2: Alignment with personal goals, interests, and expertise facilitated connections with specific aspects of innovation while marginalizing others

Participants also tended to view, where possible, innovation through the lens of their unique interests, goals, and expertise. If they were not confronted with paradoxical project aspects or tensions, participants aligned their experiences of innovation with their prior conceptions and abilities. For example, each of the students in Category 6, which focused on utilizing human-centered design to develop novel improvements for user groups, had a personal passion for helping others through engineering. They connected to the project aspects that aligned with the user aspect of innovation, while minimizing other elements such as business considerations. For example, Sharon completed her innovation project on a front-end innovation team at a large personal care products manufacturer. While business decisions affected her work, she considered these as external to the primary innovation experience. She contrasted her innovation experience in that position with another project that was more strongly influenced by the business side and contained fewer human-centered elements.

And there was research that mom's thought that if the inside of the diaper is blue that means it's more absorbent. Doesn't mean anything, but to them somehow— there's this market research that—it's more absorbent if it's blue, which is crazy. Doesn't make any sense. But then that was the change we had to go with, because that's what the market people wanted and that's what the people that the ideas went through, the manager, the—and it goes up to whoever makes the actual decision. They thought it was the best choice and so we had to go through with that, which, it was a change, but it was a change that we knew was not going to make a difference. It was not something that we thought was a good idea, but it was something that we had to do. So, I would say that that's not innovation because it was a useless change. (Sharon, Senior, Biomedical Engineering)

It may be that participants more often defined innovation in terms of projects that aligned with their personal interests and expertise. Participants in this study described a variety of projects as both innovative and non-innovative. Projects described as innovative by students in one category and were often described as not innovative by students in another. For example, Chris (Category 8) described a non-innovative project that resembled projects described in Category 3: a course project with an industry client. The project focused on analyzing a problem of the industry client and identifying more effective ways to solve that problem. Unlike participants in Category 3, he did not find this project innovative because it was outside his preferred topic areas and expertise, and, further, because did not require significant technological developments on his part.

> My senior design project was very much not innovative at all. [A large technology company] was our sponsor and asked us to look at hydrogen diffusion in zircalloy metal and look at its embrittlement processes in a nuclear reactor… They asked us to look at it and try to model it and everything and it was super hard and we had no idea what we were doing. And it turned out one of the professors here had done it forty years ago and developed a preliminary model... That was, one, super un-innovative on [the company's] part, and two, we as the seniors in the senior design didn't have to innovate at all. We took the mathematical model and coded it as an Excel macro and that was our senior design. (Chris, First-semester master's student, Nuclear Engineering)

Theme 3: Being confronted with failure or persistent tensions supported new perspectives

While connection to personal goals, abilities, and interests sometimes facilitated deeper understandings of innovation, these were often limited based on the individual student. Some of the more pronounced examples of students coming to experience innovation in more comprehensive ways came from experiencing failure on previous potentially innovative projects or encountering tensions between prior understandings of innovation and facets of current experiences. For example, Sarah (Category 6) frequently experienced a tension between human-centered and technological interests. She ultimately came to experience innovation as aligned with understanding and meeting user needs, but continued to expand her awareness of innovation through dealing with this tension.

> I probably would've looked into doing something that you could make it be able to carry a heavier load. If you could create an arm that you could say, "Pick up this book, and turn it over," sort of thing, something like that, to give a little bit more capability. I think that could be more innovative. But at the same time, thinking about what the actual need was, for the user, there wasn't a need to innovate on that. It was the idea here is to teach about how robotics work, how biology works, and working in a team. Serving those needs, there wasn't necessarily a need to innovate on that side of things. (Sarah, Senior, Chemical Engineering)

Often these tensions connected to the level of technological advancement participants could produce within constraints, resources, time, and their own expertise and the advancements they desired (or previously associated with innovation). More specifically, participants tended to align

the level of technological advancement required for innovation with the level of technological advancement they encountered on their own projects. Often, even in the more comprehensive categories, this level was rather low. A key difference between more comprehensive and less comprehensive categories, was that those in more comprehensive categories, like Penelope below, tended to understand how these limited advancements gradually built on one another to produce larger innovations over time.

> I feel like innovation is taking simple steps maybe to make a complex thing. So, it wouldn't be that one person or one team is going to solve the innovative product. So being innovative is multiple groups focusing on smaller things to end up making something that's not as simple. But, also, sometimes it's only simple things, but—Because a new gadget or whatever is innovative, but it's probably innovated because someone ended up making the little microchip a little bit smaller and someone changed the screen of the phone to do something a little bit different. So, it's a bunch of little stuff that ends up making an innovative product. (Penelope, Senior, Biological Engineering)

In addition to experiencing and consistently confronting tensions, failure provided a more acute means for participants to arrive at deeper understandings of innovation. Often, this failure allowed participants to identify aspects of their own experiences or perspectives that were limited and came to add to these perspectives through key project experiences. For example, Elon previously described having an individualistic, technology-centered, and artistic perspective to engineering innovation. He wanted to be uniquely responsible for novel technological developments based on his unique vision. In applying this approach to the development of a safety guard for machinists at a manufacturing plant, he developed an "overly complex" and "unwieldy" device that frustrated the users and inhibited their proficiency and efficiency. The device was scrapped and Elon remained distressed at failing to develop an effective solution and letting down his users. As a result, he came to experience more of the user-centered aspects of innovation and deepened his understanding of innovation through reflection and future projects.

Discussion

In this section, we attempt to unpack the content and thematic analysis results and suggest potential implications for engineering education practice.

Discussion of Content Analysis Results

Content analysis revealed between three and nine characteristics common to each of the eight categories (i.e., ways of experiencing innovation). These included individual characteristics such as "primary goal is to help people" (Category 6) and project characteristics such as "client-driven" (Categories 3 and 5). We further explored the intersections of these characteristics within each category. These findings are complex and may be most useful when considering specific students, projects, and forms of innovation.

While we do not expect these findings to provide a recipe to inspire all engineering students to experience innovation in a specific way, they can be used to inform both instructors and students

as to why students might struggle with specific aspects of innovation while engaging with others, and provide opportunities for formative assessment, targeted instruction, and student reflection. For example, they may help an instructor understand why an intrinsically motivated student with specific technical interests (i.e., a student likely aligned with Category 8) might struggle to innovate on a stakeholder-immersive, client-driven project resembling those aligned with Category 3. The instructor and student might then discuss and begin to resolve the tensions between the students' individual characteristics, way of experiencing innovation, and project characteristics.

Content analysis results also demonstrated that many of the previously identified characteristics (such as academic year and major) did not directly factor into the ways the participants in this study came to experience innovation. This is not surprising as the previous studies addressed different phenomena (i.e., innovation competency rather than way of experiencing innovation). Still it is important to note that, in general, the initial characteristics were more broadly defined than those identified in this study. When investigating competencies, outcomes, perspectives, and experiences related to innovation among engineering students, researchers and educators may wish to consider more nuanced and underlying factors, such as those identified here through content analysis.

Discussion of Thematic Analysis Results

Thematic analysis revealed three themes that were more generally applicable across the population of students who participated in this study. These themes indicated that (1) incomplete project experiences encouraged incomplete perspectives (and vice versa), (2) alignment with personal goals and interests facilitated connections with specific aspects of innovation while marginalizing others, and (3) being confronted with failure or persistent tensions supported new perspectives.

The first two themes demonstrate the importance, as an instructor targeting innovation, of knowing students' prior understandings of and dispositions towards innovation and designing appropriate projects around this knowledge. Students with limited innovation experience tended to align with the unique aspects of the specific innovation projects they encountered. Instructors who teach such students have a valuable opportunity guide their students toward desired aspects of innovation, but also have a responsibility to ensure these aspects will be desirable and beneficial to the students. A more general rule would be to imbue innovation activities with the most comprehensive form of innovation that is feasible in that setting, so that students have the opportunity to experience a variety of innovation elements.

Conversely, instructors may encounter students with highly entrenched mindsets, who are predisposed to specific ways of experiencing innovation and resist other aspects of innovation. Instructors can leverage students' preexisting mindsets to develop engaging innovation projects (i.e., those aligned with students' predispositions) and support development toward the more comprehensive ways of experiencing innovation to which they are already predisposed. For example, an instructor might find that several students favor human-centered design and other aspects related to Category 6, but demonstrate less comprehensive ways of experiencing innovation (e.g., they currently align with Category 1 and have not yet integrated user issues and

process elements such as problem finding to innovation). He or she could enhance the user-oriented aspects of a course design project (e.g., facilitating user interactions, testing, and collaborative redesign) to encourage engagement and draw connections between user considerations and higher-level innovation process elements to support development toward a Category 6 way of experiencing innovation. The instructor might then explore other ways (e.g., via persistent tension, see discussion of the third theme below) to highlight additional learning objectives related to innovation.

The third theme demonstrated the most powerful means through which engineering students came to experience innovation in more comprehensive ways: (1) persistent tensions between aspects of the innovation project and one's current way of experiencing innovation and (2) acute instances of failure. Persistent tensions caused individuals to reconsider their perspectives and experiences related to innovation by repeatedly demonstrating the presence and importance of other aspects of innovation. These instances often occurred over time (e.g., long-term project or multiple distinct projects) and required students to acknowledge how the new and conflicting ways of experiencing innovation would support desired outcomes. Instructors who wish to utilize persistent tensions should highlight the value new ways of experiencing innovation can provide through authentic, lived examples, and remain diligent as students gradually incorporate new elements into their ways of experiencing innovation.

Utilizing acute failure may be more feasible in short-term educational settings. In such instances, students utilized approaches (aligned with their current ways of experiencing innovation) that led to non-innovative and undesirable project outcomes. Examples from the data showed that it was important for students to care deeply about the project outcomes and recognize how their current ways of experiencing innovation contributed to the failure. Thus, instructors must first understand the limitations in their students' ways of experiencing innovation and then design projects in which they are likely to "fail". For example, instructor who wishes to demonstrate how innovation occurs over time, from project to project, might play into their students' desires to develop highly novel and interesting new technology but set up design projects in which such novelty would be rewarded yet implausible (e.g., adding novelty as an assessment criterion but limiting time and resources). Once students develop designs that are novel and unfeasible, the instructor can then lead a discussion around the iterative nature of innovation and how students can target smaller advancements that lead to larger developments. It is important here that "failure" would be formative rather than summative to provide students the opportunity to reflect and grow.

Conclusions

This study explored the connections between characteristics of engineering students, project aspects, and the way individuals experienced innovation. Through content analysis, we found key connections between individual and project characteristics that facilitated alignment with specific ways of experiencing innovation. These findings can help educators understand the diversity in students' backgrounds, expertise, and attitudes and how they may uniquely interact with different engineering innovation (and design) projects.

Through thematic analysis, we identified three broader themes in how engineering students came to experience innovation in increasingly comprehensive ways. These themes demonstrated that (1) key project characteristics tended to define how students came to experience innovation, especially among innovation novices; (2) engineering students gravitated towards ways of experiencing innovation aligned with personal and professional interests, goals, and values in the absence of intervening project characteristics; and (3) engineering students often developed more comprehensive ways of experiencing innovation when they encountered persistent tensions and acute failures related to innovation. These results suggest that more comprehensive individual mindsets and projects can support more comprehensive ways of experiencing innovation, but the most effective tools, especially for supporting transitions among students with highly entrenched perspectives and mindsets, can be the use of failure and persistent tensions.

In future work, we hope to expand on these findings in three areas. First, these findings were based on students' experiential reflections. Classroom studies could provide new insights and applications. More specifically, future studies should explore nuances in how transitions to more comprehensive ways of experiencing innovation occurred in authentic settings and how such transitions can be best supported in a variety of educational settings. Second, we interviewed 33 engineering students in this study. Future work among new student populations and in new innovation contexts could highlight additional individual and contextual characteristics, and the interactions thereof, that affect the way students experience innovation. Finally, while we explored how students came to experience innovation in certain ways, more work needs to be done to understand how these characteristics affect student abilities and expertise, and how they can be effectively incorporated into classroom pedagogy and co-curricular activities.

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