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Exploring Student Perceptions of Capstone Design Outcomes*

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Capstone design courses are pivotal in engineering curricula, and understanding and assessing the resultant learning is critical to both researchers and practitioners. While current scholarship does provide tools for such assessments, most are based on outcomes derived through research with faculty, administrators, and various industry stakeholders. As a result, students' self-reported learning gains have been largely overlooked. Addressing this gap, this paper presents a qualitative thematic analysis that explores student perceptions of capstone learning. Drawing on 50 semi-structured interviews with 31 students from three different institutions, we describe four emergent themes: (1) Engineering Design Skills; (2) Teamwork and Communication; (3) Self-directed Learning Skills; and (4) Development of an Engineering Identity. These themes are generally consistent with current outcomes identified from other sources, but students' discussions also highlight areas of personal development that move beyond acquisition of technical and professional skills. That is, students' perceptions of their own learning in capstone reflect not only those outcomes currently desired by various stakeholders and accreditation bodies, but also outcomes that might be more subtle and less tangible than those demonstrated via traditional assessment approaches. Thus, we argue that in order to more meaningfully support student growth, both technical and professional, capstone faculty should incorporate opportunities to actively promote and provide evidence for the kinds of critical reflection that students engage in throughout the course.

Keywords: design learning; capstone design; engineering identity; professional development

1. Introduction

Capstone design courses are an important component of engineering curricula in the U.S.; by engaging senior-level students in extended open-ended projects, these courses expose students to the realities of contemporary engineering practice and prepare them for professional careers. Clear outcomes are critical to course design for this pivotal experience, and multiple scholars have characterized the skills needed for professional practice that form the basis for such outcomes [e.g., 1, 2–6]. In general, however, this work has focused on faculty and industry perspectives regarding what students *should* learn. What the field lacks, in contrast, are discussions of course outcomes from students' perspectives. To address this gap, we present a thematic analysis of interviews with capstone students from three institutions to answer the question: *How do students in engineering capstone courses describe their learning gains?*

2. Literature review

2.1 Trends in engineering capstone courses

The capstone course represents a culmination of students' undergraduate programs; it requires students to synthesize prior learning and work in teams to develop solutions to authentic engineering problems, often in conjunction with industry or community partners and other stakeholders [7, 8]. In many cases, the course may be students' only sustained design experience before entering the workforce; at a minimum, it typically represents students' last opportunity to develop a range of skills necessary for workplace competence. Course outcomes typically focus on applying knowledge to open-ended projects, working collaboratively in teams, managing projects, conducting research, and interacting with stakeholders [9].

To better understand these courses in the U.S., regular surveys by Todd, et al. [10], Howe [11, 12] and Pembridge and Paretti [13] have examined the topics commonly included in capstone courses across disciplines. Howe and Wilbarger [14] found that, compared to 1995 data, instructors in 2005 had not only increased the number of topics covered, but increased the focus on professional skills such as teamwork and communication. This trend continued in 2009 [13] as well as in 2015 [7]. More broadly, McKenzie, et al. [15] found that 70% of capstone practitioners reported assessing all ABET-mandated student learning outcomes in the capstone course.

2.2 Research on design learning outcomes

In addition to surveys of current practices, researchers have identified desired capstone outcomes. One major strand of such research is the *Transferrable Integrated Design in Engineering Education*

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(TIDEE) project. As part of this project, Davis, et al. [16] used a Delphi study of faculty and practitioners to develop the *Engineer Profile*, which describes engineering competence in terms of 50 observable behaviors along 10 dimensions. The dimensions span technical and professional elements and include roles such as Communicator, Collaborator, Self-grower, and Analyst that emphasize the diverse skills needed in engineering practice [17]. This profile has been leveraged to provide a conceptual framework for deriving and assessing design learning outcomes [3]. Within capstone courses, it has been used to develop an assessment framework that aligns outcomes from the *Engineering Profile* with performance measures that focus on four domains: personal capacity, team processes, solution requirements, and solutions assets [2, 3].

Capstone outcomes are also shaped by more general work in design learning. For example, Crismond and Adams [6] developed the *Informed Design Teaching and Learning Matrix* using a scholarship of integration approach [18]. They synthesized research on design practice, cognition, learning, and teaching to develop a matrix that links effective strategies of informed designers to learning goals and teaching strategies. The matrix describes differences in how beginning and informed designers scope problems, generate and represent ideas, conduct experiments, troubleshoot models, and reflect on and revise their work. The practices of informed designers help delineate appropriate learning outcomes, and the matrix provides strategies to facilitate the development of these practices. Related work on design learning by Atman and colleagues [19, 20] highlight expert practices such as iteration, breadth in problem scoping, generation of multiple design alternatives, and skill in information gathering that can further inform design learning outcomes.

2.3 Learning in problem- and project-based settings

More broadly, capstone courses are a subset of project-based learning (PBL) in engineering. As Kolmos and DeGraaff [21] argue, engineering project-based pedagogies closely parallel the problem-based approach developed in medical schools, and they use the term PBL as an overarching framework. Much of the research on PBL focuses on implementation, but studies that address learning highlight skills that intersect with the personal capacities and team processes of the TIDEE model. For example, Guignard [22] demonstrates the ways PBL can increase autonomy, ownership, and scientific knowledge. Similarly, Hmelo-Silver [23], in a review of the literature, describes five core goals of PBL: (1) knowledge flexibility, (2) problem solving, (3) self-directed learning, (4) collaboration, and (5) motivation, though she notes that more empirical work is needed to better understand student learning in PBL contexts.

2.4 Student perceptions of learning

As noted above, most research on learning in PBL broadly and capstone design specifically focuses on stakeholder expectations and course design, with some work also examining student design processes and products [e.g., 24]. However, little work has explored student perceptions to better understand both tangible and intangible outcomes in these critical courses. One notable exception is work by Pierrakos, et al. [4], who developed a quantitative instrument that asked students to self-report learning gains from their capstone courses. Based on a combination of course syllabi, NAE reports [25], and ABET outcomes [26], the authors developed an instrument containing thirty technical and twenty personal/professional learning outcomes. Technical outcomes focused on the design process (e.g., generate concepts and solutions, evaluate decisions, apply knowledge); personal and professional outcomes included communicating effectively, working in teams, and managing people, along with self-confidence, interest, and work ethic. Overall, students rated "personal and professional" learning gains higher than "technical" ones, with teamwork, communication, and peer learning most highly ranked. The study also compared student perceptions to those of course faculty. Although perceptions aligned on many items, in some cases students perceived higher gains (e.g., ability to set and pursue learning goals), while in other cases faculty perceived higher gains (e.g., taking initiative). The study highlights a broad array of outcomes from the course, although the instrument design does not capture outcomes that may fall outside the listed items or explore student perceptions of how and why these outcomes were achieved.

3. Methods

To address this gap and better understand student perceptions of their capstone experiences, we used a qualitative thematic analysis of student interview data. The data are a subset of the Expertise in Capstone Design Education (ExCDE) project, a multi-phase study of capstone teaching and learning [8, 13, 27]. Following a national survey of faculty and interviews with a subset of respondents, we conducted case studies of expert capstone educators that included observations of faculty/team interactions, interviews with faculty, and interviews with students. The student interviews provide the data for the present study. These interviews explored students' work on the project, interactions with project mentors, and perceived learning gains. Thematic analysis enabled us to focus on students' language to identify new or unexpected outcomes as well as outcomes predicted by previous research.

3.1 Research sites and study sample

Case studies were conducted with expert capstone educators identified through the first two phases of the ExCDE project and through snowball sampling from the project's advisory board. Institutional characteristics of the three sites are shown in Table 1, along with the number of participants at each site; because the first two phases showed few differences by major [28], case study participants were identified based on instructor expertise and availability, with institutional diversity as a secondary consideration. All programs had a one-year (senior) capstone course. Because we were interested in exploring learning within capstone design, data was not collected regarding employment information or professional development experiences prior to the capstone course itself (e.g., internships). While some sites had first-year design experiences, the capstone course represented the primary extended design experience in the curriculum. All participants were full-time students.

As indicated in Table 1, at two sites students were interviewed at the end of the fall semester and again at the end of the spring semester; at the third site, students were only interviewed at the end of the spring. Most interviews were one-on-one; however, we conducted one focus group with five participants at LP1 to accommodate student schedules. Interviews lasted 45–60 minutes; all interviews were audio-recorded and transcribed verbatim, and all identifying information was redacted prior to analysis. The full data set included 46 transcripts (45 interviews and one focus group) with 31 unique participants (several students participated in both the fall and spring interviews); one third of the participants were women.

3.2 Interview protocol

The interview protocol explored students' project experiences, interactions with mentors, and perceived learning. Fall and spring interview protocols were similar, although the spring interviews contained more detailed probes about student learning and workplace preparation. Influenced by critical incident techniques [29], students were also asked to describe a significant challenge and steps they took to overcome it to provide concrete examples of their experiences. The protocols are included in the Appendix.

3.3 Thematic analysis

The transcripts were analyzed using thematic analysis, following the six-phase process outlined by Braun and Clarke [30]: (1) becoming familiar with the data; 2) generating initial codes; (3) searching for themes; (4) reviewing themes; (5) defining and naming themes; and (6) producing the report. First, author 1 read the full data set to generate initial ideas, then second used open coding to identify and categorize statements in which students talked about or demonstrated learning. Third, these codes were sorted into clusters to organize concepts into preliminary themes. For example, the code associated with resolving team conflicts and the code associated with forming productive working relationships were clustered into a theme related to teamwork. The themes thus represent more complex constellations of outcomes than any single code. Across these initial phases, then, statements combine to form codes, which in turn combine to form themes; the themes, taken together, describe the central phenomenon: student learning in capstone design. The fourth phase focused on reviewing the themes and codes to ensure that both codes and themes were distinct and applied consistently, and that each theme was accurately represented by its supporting codes. In the fifth phase, we focused on developing precise definitions of each theme that highlighted its uniqueness as well as its contribution

Table 1. Description of Research Sites

Site	Discipline	Course Structure	Sample Population	Participants
LP1 Large, public	Mechanical Engineering	• >200 students • 1 coordinator • Multiple projects, with 1 faculty mentor per project • Coordinator provided regular lectures relevant topics	1 faculty mentor working with two separate teams	Fall: 10 Spring: 13
SP1 Small, private	General Engineering	• <50 students • 1 coordinator • Multiple projects with industry mentors • Coordinator provided regular lectures relevant topics	Course coordinator and all teams	Fall: 9 Spring: 7
LP2 Large, public	Chemical Engineering	• <150 students • 1 coordinator • Multiple projects with industry mentors • Coordinator provided regular lectures relevant topics	Course coordinator and all teams	Spring: 11

to our understanding of capstone learning, and in the sixth phase, we produced a comprehensive (unpublished) report from which this manuscript is drawn. Note that because not all participants were interviewed twice, and participants at LP2 were only interviewed once, we did not consider changes over time.

Across these phases, we included several measures to support validity and trustworthiness. To check the consistency and clarity of each code, a second coder applied selected codes to a subset of the data set; discrepancies were negotiated to consensus and code definitions were clarified as needed. Code definitions and representative segments were also shared with a larger group of trusted peers for further review and clarification. In addition, both authors reviewed all segments of selected codes against each other to ensure that the codes represented unique, coherent constructs, that they were applied consistently, and that the definitions fully captured the ideas embedded in the segments. Similarly, to check the clarity and consistency of the themes, the authors reviewed the code groupings with one another and with a group of trusted peers, again clarifying definitions and modifying groupings as needed to ensure that the conceptual boundaries of each theme were distinct and coherent. Author 1 then reviewed the names and definitions for both codes and themes, and discussed them with author 2; as a final check, both authors reviewed the full data set to ensure that the codes were applied consistently, and a third coder applied the codebook to a subset of transcripts.

4. Results

Four themes emerged regarding students' perceptions of learning in capstone design: (1) Engineering Design, (2) Teamwork and Communication, (3) Self-directed Learning, and (4) Engineering Identity. Table 2 provides the definitions of each theme, and the following sections describe the themes in detail, including the associated codes and representative quotations; quotations are delineated by participant and school ID.

4.1 Engineering design

Engineering design skills represent those acquired by progressing through a systematic design process, including the knowledge, tools, and disposition needed to complete a long-term, realistic engineering project. For clarity, we have grouped the codes into two subthemes: Planning Skills and Execution Skills.

4.1.1 Planning skills

Planning skills, listed in Table 3, concern the planning and conceptual stages of design, including skills in identifying problems, developing ways to evaluate proposed solutions, and managing work across a long-term project.

Problem definition. Most models of engineering design emphasize the importance of defining the problem and determining the scope [5, 31, 32]. It is not surprising, then, that a key skill students learned was the ability to determine the boundaries of a problem to arrive at a manageable scope. Students learned to obtain the information needed to appropriately define their problems and developed strategies for modifying the scope in light of new information and in light of the context and constraints of the course. Moreover, they described more fully understanding the need to bound problems and learned to make informed judgments about how and where to determine those bounds.

Design requirements. Engineering design models also typically include establishing requirements, criteria, and constraints to evaluate design solu-

Table 2. List of Emergent Themes and Their Operational Definitions for Student Perceptions of Capstone Learning Outcomes.

Theme	Operational Definition
1. Engineering Design	*Both theoretical and practical knowledge resulting from engagement in a formal, systematic design process.* The process provides students with opportunities to define a complex engineering problem, develop strategies for solving the problem within a team, and implement tests and evaluative measures to determine the effectiveness of different design solutions.
2. Teamwork and Communication	*Interpersonal communicative skills learned through engaging in teamwork and managing the different kinds of relationships within senior design, both internal and external to the design team itself.* Students described the development of interpersonal skills as well as strategies for optimizing team performance through conflict resolution and effective coordination of information.
3. Self-Directed Learning	*Autonomous learning skills and dispositions acquired throughout participation in capstone.* Students described learning how to do independent research, find and vet resources, and leverage contacts with other professionals to learn about project details. Self-direction also facilitates a sense of ownership over both the project and students' learning more broadly.
4. Engineering Identity	*Students coming to see themselves as engineers from an identity perspective.* This includes discussions of seeing value in the work of the engineering profession, feeling included in a larger community of engineers, feeling competent in one's skills and abilities as an engineer in the future, and a perceived congruence between how engineers think and their own cognition.

Table 3. Codes for Engineering Design—Planning Skills

Code	Representative Quotations
Problem Definition	So it was hard to jump right into it, because it was tough to really wrap our heads around what the actual problems were and what we actually needed to do. And that's one of the things that [our mentor] was really good at was saying 'ok here's what your pitch is like, it's your spec and planning report. You need to identify like mission statements, impediments, areas of interest, areas of research, things of that sort.'. . . It was half the battle was figuring out what we needed to learn, let alone just learning it. [Student 4, LP1]
	[. . .] the biggest thing I think I would say I would learn was, really finding out the needs at the beginning. And who knows if they were willing to give it, give those to us at the beginning of the project, but if we could've dug those out earlier, our project would have gone a lot smoother. But we weren't asking the right questions, either, at the beginning of the semester, to draw those out. So, I think we needed to sit down and, rather than jumping into the redesign, we needed to sit back and try to address everything, and ask all the questions we could to try to draw out as much as we could. [Student 5, LP1]
Design Requirements	And we made this list of about 40 different things and we said which ones are the most important, and we went through and made values for a lot of them, like making approximations of like how much we think this would cost, [inaudible] system, running it per month, electricity. We made all these values of like how fast it would get rid of the trash and then we tallied it all up and we made a conclusion of like which one we think is like the best like 2 or 3 and then were gonna go there. Because like a lot of the metrics we can't really say without being there, of like what the people are gonna need. [Student 1, SP1]
Project Management	So [our mentor] definitely, and I've noticed I think I've gotten better at it, minding what needs to occur for the project to be a success and then more so what I'm doing. Because you know you have to break these big problems, something tis complicated, you have to break it down into smaller chunks. Making sure those small chunks you're working on are helping chip away some big question marks you have and some big check marks you have. . . [Student 4, LP1].
	We all had different strengths and we were able to like identify that and work on that. Like I was one of the few people in the group who knew what grammar was, and so I did a lot of the reading and editing and things like that whereas other people were really into doing a lot of the hardcore math and things like that and designing the actual equations for it, which was good. [Student 1, LP2]

tions. Students in this study discussed the importance of both defining and measuring design requirements, and described using these requirements to inform decision-making. The process of defining metrics helped students explore different aspects of the problem space and incorporate multiple, sometimes competing, constraints and criteria into their solutions. They described using their own engineering knowledge along with stakeholder input to unpack the initial design prompts and create project-specific metrics.

Project management. More broadly, planning skills included learning to manage the complexity of a large-scale team project. Design, as multiple researchers have noted [33, 34], is a social activity involving the collective action of diverse team members. Managing this work, including identifying, scheduling, and delegating tasks, is thus a critical skill, but one that students have few opportunities to develop outside project work. Not surprisingly, then, a number of students described learning to manage projects and plan work more effectively in their capstone courses. They discussed the importance of managing work distribution and described strategies for delegating tasks to optimize group performance and maintain project timelines to meet goals.

4.1.2 Execution skills

In addition to planning design projects, participants gained skills in executing those projects. Once participants scoped their problem and developed solution paths, they moved into development and testing, and described multiple learning gains resulting from the active, hands-on experiences, as listed in Table 4.

Handling ambiguity/uncertainty. Iteration is ubiquitous in engineering design, in part because design is a process of continuously reducing uncertainty and ambiguity in the problem space to arrive at a feasible solution [32]. In this study, students talked about both experiencing uncertainty and ambiguity and learning ways to handle those experiences. They noted the ways experiments produced conflicting results, resources were delayed, and decisions had to be made with incomplete information. Such experiences helped them learn to enter design situations expecting change and seeing flexibility as critical to success. This awareness helped them learn to develop contingency plans and to anticipate and adjust to an array of unexpected issues.

Testing and modeling. Full design cycles require mechanisms to test potential solutions, and participants described learning to develop such solutions through simulations, prototypes, experiments, and other kinds of modeling. Examples included learning to use new modeling software, running statistical performance analyses on equipment, and developing mathematical models to predict system behaviors. Such learning often operated at two levels, providing students with skills in particular testing or modeling techniques that

Table 4. Codes for Engineering Design—Execution Skills

Code	Representative Quotations
Handling Ambiguity/ Uncertainty	And when you inevitably realize that you've screwed up, something else will work once you need to adjust it in some way. So, design for adjustability, and design for change because no matter what you think, and no matter what preconceptions you have, they're always wrong. Yeah, I'd say, in a nutshell from him, your preconceptions are wrong, so know that from the get-go, and deal with it. [Student 5, LP1]
Testing and Modeling	So we were thinking before about doing like an isotherm test, which is something that [our mentor] had thought of us doing. And it kind of finds the equilibrium of whatever media that we're using and the solution that it's filtering for us. So we were thinking of doing that, but this [external advisor] told us that maybe we should do that afterwards once we find that like something is working, if we run the filters through now before seeing stuff happen. So then we do the isotherm and find like theoretically this is the best case scenario, this is how well it will work if it's working at its full capacity. [Student 2, SP1]
Learning through Doing	It's essentially like a shopping list that you go out and if you have a [chart] and you know how to read it, is the other part, you can basically build a radar from a [chart.] Because it tells you what frequency you need, what power radar you need, what size antenna, all this other stuff so you can basically take the [chart] and build a radar just going off of the information there. So we wanted to make sure that was as accurate as possible and as good as possible. [Student 3, SP1]
	But at the end of the day, things never behave perfectly in real life and [our mentor's] seen how a lot of things behave in real life. So [our mentor] understands the theory behind it, but then he's got practical knowledge. And that's what makes it more believable. Because when you talk to a professor and they just like keep on quoting the text book and they say 'ooh read this here and this there.' And you're like 'ok great. I haven't looked at that yet, I've seen these equations and it's nice to see them in this light, but at the end of the day I need more practical knowledge.' Ok it says I can do this, but then if I do it is it actually gonna work? [Student 4, LP1]

varied by project, but also providing them with a more general understanding of the role of testing and modeling in design.

Learning through doing. Lastly, students described developing "hands-on" or "practical knowledge" as they moved designs from paper to reality; their projects provided critical experiential learning that translated textbook knowledge into practice. Such knowledge ranged from acquiring CAD skills to create buildable designs to learning to navigate a machine shop and understand the different processes available. Thus, *Learning through Doing* describes not only skills students acquired as they used different engineering tools, but also the practical ingenuity and heuristics needed to use those tools in real-world contexts that often differed markedly from theoretical ideals.

4.2 Teamwork and communication

The second key theme focuses on outcomes related to working with others in an engineering context. Learning related to teamwork and communication included two dimensions: internal team practices and external stakeholder practices.

4.2.1 Internal team practices

Many of the teamwork and communication skills students developed involved learning to work with team members, as shown in Table 5.

Interpersonal skills. Interpersonal skills focus on working with diverse individuals in a team environment. Students described becoming aware of the individual differences people bring to situations, and learning to leverage that awareness to create productive interactions. That is, they learned to

Table 5. Codes for Teamwork and Communication—Internal Team Practices

Code	Representative Quotations
Interpersonal Skills	Dealing with people. Just picking up the signals, like of when you might need to worry about someone getting their work done, like if you think something is going to happen, just realizing that what someone says might not actually be the truth, or if they're able to complete their work on time. [Student 3, LP2]
	And like seeing those relationships forming, because like, really a valuable experience, too, like, and just working with these people that have completely different backgrounds and completely different knowledge bases and completely different areas of expertise and that they're really interested in, you know. [Student 1, LP1]
Conflict Resolution	And people work differently, like schedules get busy, so you have to wait things out, and just being very honest and communicating with one another and trying not to, like not to get to the point where everyone's being passive-aggressive at one another. So just when it felt like it was getting a little off track, we were just like, all right, let's sit down and talk about it. What's happening? Who's mad at who? What's happening? [Student 3, LP2]
Coordinating Information	But then, from like the team dynamic standpoint, I think just getting everybody to be on the same page, which is kind of similar I guess to making sure all the bits and pieces line up, but making sure everybody is at the same stage of like the design process and making sure due dates are being withheld and stuff. [Student 4, LP2]

attend to and work with a wide range of personalities and backgrounds in ways that helped avoid conflict and enabled each team member to be most productive. Several students also described moving beyond awareness of difference to appreciation for the value of different perspectives in design.

Conflict resolution. In addition to working with diverse individuals in ways that maximized productivity and minimized conflict, students also learned to resolve conflicts when they arose. Given the duration and scale of most capstone projects, conflicts are almost unavoidable. Most often, tension arose when a team member failed to complete assigned tasks. Participants reported developing both knowledge and skills to ease these and other tensions, including strategies such as constructive criticism, discrete conversations, and facilitated conversations (i.e. with the project mentor). Participants reported learning to confront rather than ignore problems with team members in order to both minimize down time and facilitate positive teamwork.

Coordinating information. Students also discussed skills associated with coordinating information flow among team members to keep everyone informed and on task. That is, in addition to the project management skills noted earlier (i.e., planning, delegating, scheduling, etc.), students learned the importance of sharing information to keep the team updated and on track. They both recognized the need for and learned to use strategies such as weekly report-outs, email chains, and group chats to ensure that no information was lost and that individuals had the information needed to complete interdependent tasks.

4.2.2 External stakeholder practices

In addition to working with team members, students also described learning to interact with clients, mentors, and others external to the team. By interacting with engineers and clients in a professional capacity, participants learned to develop and maintain positive relationships with a range of external stakeholders, as indicated in Table 6.

Professional communication. As might be expected from faculty's emphasis on written and oral communication [7, 11, 13], students in this study reported learning to construct a wide range of reports and status updates to communicate relevant, appropriate messages to various audiences. By preparing presentations for external stakeholders and composing technical reports for mentors, students gained experience with different modes of professional communication and learned to adapt communication to audience needs. Equally important, in informal communication such as emails and in-person conversations, students learned more subtle professional standards and expectations; they learned to tailor their communication styles as well as speech patterns and behaviors based on, for example, the attendees of a given meeting and contextual factors.

Navigating stakeholder interactions. Students also learned to navigate often complex and conflicting relationships with various project stakeholders. Thus, where *interpersonal skills* address navigating relationships *within* the team, *stakeholder interactions* address similar navigation with individuals *outside* the team. These individuals included clients, who both provided information about project scope and critiqued students' ideas as the project developed, as well as users, government employees (e.g., especially in civil engineering projects), or regulators. They also included instructors and mentors, who often mediated between clients and teams to model effective relationship strategies. As students developed their projects, they learned the importance of responding to and negotiating with these individuals to both maintain positive relationships and develop viable solutions—often in the case of shifting or conflicted expectations and requirements.

4.3 Self-directed learning

The third theme, linked closely to the open-ended nature of typical capstone projects, focused on students' developing capacity to learn independently, conducting research and seeking out resources and experts relevant to their project domain. This self-directed learning had four distinct

Table 6. Codes for Teamwork and Communication—External Stakeholder Practices

Code	Representative Quotations
Professional Communication	Well, one of the valuable lessons that I learned was learning to communicate efficiently and quickly with people even that aren't my peers or maybe my professors or, so it has helped me in that I am more able to contact people that I am not familiar with and know how to address them and formulate what I want to say concisely so they respond back to me. [Student 5, LP2]
Navigating Stakeholder Interactions	Yeah, so I mean that kind of support and then also maybe support of how to interact with our liaisons when they're having different ideas instead of adding your own idea too, and then saying well maybe we should go look in this direction. Because we were getting, like [our mentor] was saying 'well economics should be the focus.' And then one of our liaisons was saying 'well no we don't care about economics at all.' So it was really like polarized because everybody had different backgrounds so it was hard to try to balance that with us. [Student 4, SP1]

Table 7. Codes for Self-Directed Learning

Code	Representative Quotations
Searching for/ Utilizing External Resources	I think the point of the capstone process is to teach yourself and learn for yourself because that's what you're going to have, you're going to be like cut, the string, the marionette strings of school and scholastic life are going to be cut from you when you go out in the world and you're going to have to create your own things, you have to create your own opportunities and your own projects and stuff like that. You have to figure stuff out on your own. [Student 5, SP1]
	I'm a lot more comfortable like e-mailing somebody I don't know to ask some questions, or it's things like that [. . .]. [Student 3, SP1]
Time Management	And, you know, manage your time within a project and set goals for yourself and what you want to accomplish, even if you don't meet them, but know what you're working towards, that you're working towards some sort of goal [. . .]. [Student 1, LP2]
Work Ethic	Well, I think the great thing about this project is that if you put in the work, you'll see the results. It's basically that down to its finest details, really. If you put in time, it'll be worth it. But you have to be committed to put in the time and it just boils down to that. [Student 6, LP1]
Ownership of Learning	It's not about the grade. It's about you actually have to want to have some sort of other motivation in this project too. You have to be motivated to succeed and to present a product that you're proud to put your name on. And that's interesting too. Having something like that. [Student 7, LP1]

components, as shown in Table 7, that address both learning strategies and attitudes associated with autonomous learning.

Searching for and utilizing external resources. Because students rarely possess all the knowledge needed for their project, they must typically seek out knowledge and information from resources beyond the classroom setting. Participants thus gaining skills in searching for and utilizing both information and human resources. They learned to find and use scholarly and popular resources (e.g., product web sites), as well as to identify and reach out to experts both within and outside the university. Importantly, beyond simply locating the necessary information, students described "learning how to learn" from such resources to develop knowledge they could use and apply to the project at hand.

Time management. Self-directed learning, however, involves not only finding and using resources, but managing one's time to both set goals and carry out tasks. And while capstone courses are substantial time commitments, students also have other courses and responsibilities. Thus, participants developed strategies to keep track of and regulate time spent on the project while managing other commitments. Participants discussed setting and keeping personal deadlines and milestones in addition to those developed by the team to ensure their own progress and help them stay on top of their project responsibilities.

Work ethic. Time management is key in part because in absence of regular weekly problem sets, capstone courses require students to set their own assignments and schedules to make progress. The open-ended nature of the course, in turn, helped several students recognize the importance of a strong work ethic; they had, that is, a very clear sense that the project would only be as good as the effort they put forth, and that as professionals they needed to put in the necessary time to produce a quality product.

Ownership of learning. Closely linked to work ethic, participants described the ways in which the capstone project helped them take responsibility for and ownership of their learning. As they developed their own plans, set their own milestones, accomplished tasks they laid out for themselves, and contributed to their team's mission, they recognized their need to be responsible for their learning—to identify what they needed to know and seek out the necessary resources to enable them to produce high-quality work. At the same time, they described a genuine interest in achieving successful outcomes, and pride in their accomplishments. This ownership, in turn, facilitated students' efforts to acquire the necessary information and skills, manage time, and work at their best level, making their learning not only independent but also self-motivated.

4.4 Engineering identity

The final theme addresses the ways in which students developed their identities as engineers, which included both a richer understanding of the profession and a new understanding of themselves as engineers.

4.4.1 Understanding the profession

With respect to the profession, students described gaining both a better understanding of workplace expectations and a deeper appreciation for the discipline, as shown in Table 8 .

Expectations for work. A key component of identity is understanding the relevant domain. Given capstone courses' position as a bridge from school to work, it is not surprising that a number of

Table 8. Codes for Engineering Identity—Understanding the Profession

Code	Representative Quotations
Expectations for Work	[The project has] given me an understanding of how things work. [. . .] I think one of the biggest thing has always been how does my education fit into a possible job opportunity and now I can see how all the things that I've learned over the last years in college can fit into all this like, all this group work and all the you know like all the little bits and pieces of the technical classes that I've taken that are all of a sudden getting together into this one project. [Student 3, SP1]
Appreciation for Discipline	And I think, I think in the fall, I mean, if someone would've asked me what I wanted to do after graduation, I probably would've been less likely to say like I want an engineering job in [my project area] or like this kind of thing. And it's really interesting and I've learned a lot about like the actual technical side of like [project domain] and I think I'd be more willing to work in a job that does like this specific kind of thing. [Student 6, SP1]

students described learning in terms of understanding of engineering work and engineering workplaces. They identified multiple elements of their projects that helped them better understand how engineering work happens in practice, and many of the skills noted in previous sections, including ways of interacting with professionals, creating various documents and presentations, handling ambiguity, and negotiating between theory and practice, emerged not only as skills in themselves, but as insights into the "the real world" of engineering work.

Appreciation for discipline. In addition to helping students understand professional expectations, the capstone projects also inspired students and reignited their appreciation for the discipline. Students described increased interest in and value for engineering work. Some noted how the course introduced them to aspects of the field that increased their engagement, while others who began the course uncertain about whether to pursue engineering careers reported that their projects exposed them to work that made the field more attractive.

4.4.2 *Belonging to the profession*

Students' understanding of the profession was often accompanied by an increased sense of their own identity as engineers, as illustrated in Table 9.

Thinking like an engineer. Part of developing a group identity involves perceiving congruence between one's own values, customs, and ways of being and those of the group [35]. Thus, part of developing an engineering identity involves, in short, thinking like an engineer. Students described new ways of thinking and acting based on the capstone courses that they perceived as uniquely aligned to engineering. They talked about this engineering thinking in terms of ways of viewing problems, breaking them down, representing them in abstract forms, and related strategies, and they positioned their own work on the project in terms of these approaches—they described themselves, that is, as approaching the projects with the mindset of an engineer.

Integration into the community. A second component of identity development involves recognition from others [36, 37]. Thus, part of developing an engineering identity is a sense of belonging to and being recognized by the community of engineers. Students reported such belonging as they interacted with professionals in and outside of university settings, noting that people treated them as colleagues and professionals. Such treatment helped participants see themselves not as students but as members of the engineering community.

Increased role competence. Finally, students reported increased confidence in their engineering competence, suggesting that the project helped them come to see themselves as workplace-ready engineers. Like belonging, competency beliefs are key to domain identification [38]. Participants in this study

Table 9. Codes for Engineering Identity—Belonging to the Profession

Code	Representative Quotations
Thinking Like an Engineer	This is an engineering course. It isn't just like a pick-up-a-wrench-and-smack-something, you use what you've learned over the past three years and apply that before you take a step forward, you know. That's the point of engineering, why also you're here to get the degree you can like apply it. So whenever we did do that, we always had great results with just taking a step back and, you know, think about it from an engineering standpoint, taking smaller steps rather than big, rash ones. [Student 8, LP1]
Integration into Community	I really do think that's one of the biggest things, was the fact that [our mentor] treated us like adults, he treated us like full engineers, full workers, kind of giving like, "I'm going to give you guys a shot . . ." [Student 9, LP1]
Increased Role Competence	And for me I learned a lot about just if you set your mind to something, you can do it. I mean, I didn't really know too much about cars in general before I started this project... And then, beyond that, like I just knew that going into the engineering field now that I feel totally comfortable that I can do the job that they expect me to do. [Student 10, LP1]

Table 10. Distribution of Themes Across Transcripts

Theme	Number of Transcripts (n = 46)*	Percent of Transcripts	Number of Spring Transcripts (n = 27)**	Percent of Spring Transcripts
Engineering Design	45	98%	26	96%
Teamwork and Communication	45	98%	26	96%
Self-Directed Learning	44	96%	26	96%
Engineering Identity	40	87%	22	81%

* 45 individual interviews and 1 focus group of 5 students; focus group data was not broken down by participant.
** 26 individual interviews and 1 focus group of 5 students; focus group data was not broken down by participant.

reported increased confidence in their abilities to meaningfully contribute to the engineering profession as a result of their capstone learning experiences. They described feeling prepared to meet the demands of professional engineering practice, and confident in their ability to succeed in future engineering roles as they enter the workplace.

4.5 Patterns across participants

The four themes described here represent the full spectrum of learning outcomes identified by students across sites and interviews, regardless of the number of participants who mentioned a given code or theme. To contextualize these findings, Table 10 summarizes the number and percentage of transcripts mentioning each theme.

As indicated, each theme was nearly universal across both the entire data set and, importantly, in the spring data collected at the conclusion of the course. Engineering Identity occurred marginally less frequently; still, more than 80% of the transcripts noted this theme. Perhaps equally important, all but one transcript (an individual interview) included 3 of the four themes, and 36 transcripts (75%) contained all four themes.

5. Discussion

The themes identified here intersect with and expand on outcomes identified in previous studies. Engineering design, teamwork and communication, and self-directed learning, in particular, share common elements with the solution requirements and assets, team processes, and personal capacity areas defined by Davis et al. [3] as well as the roles identified in their Engineer Profile [16, 17]. Students' attention to problem definition and design requirements for example, map to Davis et al.'s solution requirements, while testing and modeling link to solution assets. Similarly, both project management and the internal team practices echo the team processes, while the components of self-directed learning align with personal capacity, as well as with ABET's emphasis on life-long learning and PBL's emphasis on self-directed learning. These intersections are notable because Davis et al. derived the profile and subsequent performance areas through research with faculty and industry; our data points to the ways in which students' perceptions of learning gains under expert faculty align with these desired outcomes. Moreover, because we asked students to think about valued learning, especially in terms of job preparation, our findings suggest that participants saw these outcomes as important to their future work. Students' emphasis on these outcomes also aligns with the top learning gains identified in Pierrakos et al.'s [4] survey—work ethic, communication practices, identifying design requirements, recognizing the need for life-long learning, and consulting with outside experts.

At the same time, students' responses highlight outcomes that, though implicit in prior research, have received less explicit attention. For example, handling ambiguity and uncertainty is implied in several Engineer Profile roles, but not addressed explicitly. Pierrakos, et al. [4] included perceived competence in "operating in the unknown," which offers a more explicit parallel, as do discussions of problem-based learning more broadly [e.g., 21]; students' own language here allows us to better understand how students saw unexpected circumstances and unplanned outcomes increasing their comfort with flexibility and change. Similarly, discussions of not only communicating professionally but navigating relationships with stakeholders move beyond the attention to audience and internal communication highlighted in Davis et al.'s work to address a more nuanced understanding of working relationships within and beyond engineering teams. They also enrich our understanding of items like "communicate effectively" and "apply interpersonal skills to manage others" in Pierrakos et al.'s survey [4] by situating such skills in the context of stakeholder interactions and team processes.

While the first three themes intersect with outcomes identified by faculty and industry, the impact of capstone courses on students' engineering identity has received less attention, even though identification with engineering has been shown to predict career choice [38, 39]. Work by Davis et al. [3, 16, 17] focuses on external performance measures rather than beliefs, as do studies of design competence by Crismond and Adams [6] and Atman et al. [19, 20]. Pierrakos et al.'s [4] survey includes competence beliefs, but not belonging. Qualitative researchers have explored identity in engineering, including in capstone courses [e.g., 40, 41], but have not necessarily considered identity development as a core course outcome. Yet students in this study came to see themselves as practicing engineers through their capstone courses, and in doing so, formed critical beliefs about themselves and the profession. Such development aligns with Wenger's concept of communities of practice [36], which does highlight identity as a key part of learning. Students' interactions with one another and with professionals developed their sense of belonging, which in turn bolstered their confidence for both the course and their professional careers.

Finally, we note that all four of the themes described by students, including identity, align closely with the practices and goals of capstone faculty identified in earlier phases of the ExCDE project [13, 28]. Though a full discussion of that alignment is beyond the scope of this paper, interviews with faculty highlighted the ways in which faculty explicitly sought to promote not only the technical, planning, and professional skills of Engineering Design and Teamwork and Communication, but also Self-Directed Learning (including work ethic and ownership of learning) and Engineering Identity (including not only competence beliefs, but belonging within the community).

6. Implications

The four themes identified here point to important strategies for teaching and assessment. Crismond and Adam's [6] work on developing informed designers offer a range of useful strategies to support design competence, while the practices of expert mentors identified previously [28], including coaching, role modeling, building rapport, exposing students to professional practice, and supporting students' self-perceptions, provide strategies for more broadly developing students technical, professional, and personal skills and beliefs. Capstone faculty shape both students' understanding of engineering work and their engineering identities, making it critical that faculty approach these courses with a full range of practical teaching, coaching, and mentoring strategies. Such strategies may be even more important in working with underrepresented students such as women and minorities, as prior research in this area highlights higher barriers to belonging and self-confidence for these groups [e.g., 40, 42]

In addition to informing teaching, our findings also highlight the need for assessment practices that better capture student development. While instructors nationally note a range of approaches to evaluation, including logbooks, peer feedback, and individual assignments, the vast majority rely on some combination of a final report, final presentation, and final product, with only 15% of faculty reporting assessment methods such as interviews or journals [15]. However, while reports and presentations provide evidence of some of the outcomes identified in this study, they are limited in their ability to discern individual growth. One useful approach to capturing such growth is via project portfolios [43, 44]. Learning portfolios ask students to both provide evidence of and reflect on their development; these reflective narratives support and elaborate on the evidence and provide students a space to describe their learning more deeply. Work by Paretti [44, 45] on portfolios in design education and work by Adams et al. [46] on reflective practice in design suggest that this approach may be a significant addition to existing assessment approaches by providing a way to monitor student development, enhance reflexivity, and demonstrate individual development.

7. Conclusion

In summary, the findings from this multi-case study of student perceptions of learning expand our understanding of the range of capstone design outcomes, including not only a more nuanced sense of how students perceive and value technical and professional skills, but how the course helps them develop as both life-long learners and engineering professionals. Many of the findings are congruent with outcomes desired by faculty and industry, but they also highlight the ways in which, under the guidance of expert mentors, students developed both a more sophisticated understanding of engineering practice and an increased sense of identity as capable engineering professionals. The capstone environment is rich with opportunities for learning the realities of contemporary engineering practice, and while more work remains to be done to link specific teaching and assessment practices to specific outcomes, the student voices presented in this study highlight the breadth and depth of learning achieved in this critical course.

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Appendix: Interview Protocols

Fall

1. Could you tell me a little about your project?
2. Is there one mentor/project advisor that you'd say is your primary mentor/project advisor?
3. Please describe your interactions with that person.
4. Is there anyone else who has served as a mentor/project advisor for you or your team? Please describe those interactions.
5. How would you describe the strengths or advantages of the other people you have interacted with?
6. What things have you learned from your mentor/advisor that you think will be most helpful as you move into your career?
7. Was there any kind of mentoring or guidance that you didn't get that you wish you had?
8. Is there anything else you would like me to know about your experiences with mentors or this class as I try to understand "good teaching" in this kind of environment?

Spring

1. I'd like to start by understanding your project, so can you tell me about your project?
2. Now I'd like to talk a little more specifically about the faculty mentor(s) you worked with on the project. Who would you say is your primary faculty mentor or advisor on the project? Can you describe your interactions with that person?
3. Are there any other mentors/advisors that you interact with? What are those interactions like?
4. Now I'd like to step back again and understand a little more about what you believe you've learned from the project. What was your biggest challenge on this project, and how did you deal with that challenge?
5. What are the most valuable things you believe you've learned from this project?
6. What do you plan on doing when you graduate?
7. How do you see the class preparing you for that situation?
8. Thank you for your time, is there anything else you would like to add that we maybe haven't covered, as I try to understand "good teaching" in this environment?

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