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Characterizing capstone design teaching: A functional taxonomy

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Abstract

Background: Capstone design courses represent a critical juncture in students' development at the transition from school to work. However, few studies have systematically explored teaching in this context, leaving a significant gap in our ability to concretely describe faculty practices in ways that support subsequent explorations of the relationships between teaching practices and learning outcomes.

Purpose/Hypothesis: The aim of this study was to develop a comprehensive description of the pedagogical practices used by capstone design faculty from a functional perspective and provide researchers with a framework for subsequent work.

Design/Method: This study used qualitative methods to analyze interviews with 42 capstone faculty; the participants represent a stratified purposeful sample of respondents to a national survey. Analysis focused on descriptive coding, beginning with a priori codes, to define broad functions, supplemented with emergent coding to identify concrete practices used in the capstone context.

Results: The study resulted in a model of capstone design teaching that includes nine functions (challenge, protect, coach, promote employability, provide exposure, provide role models, accept and confirm, counsel, and build rapport) and 28 associated practices.

Conclusions: Capstone faculty use a range of practices designed not only to coach students through the engineering design process but also to more broadly prepare students for workplace practice and build their identity as engineering professionals.

KEYWORDS

instructional methods, senior (capstone) design, taxonomy, teaching skills, workplace preparation

1 | INTRODUCTION

Capstone design courses represent a critical transition between school and work, and as such are common sites for industry partnerships (Howe, 2010; Howe, Poulos, & Rosenbauer, 2016) and are essential components of programmatic assessment (ABET Engineering Accreditation Commission, 2017). To support the transition to work, these courses require students to apply life-long learning, engineering judgment, analytical decision-making, and critical thinking to address complex problems under a spectrum of social, environmental, and economic constraints.

For instructors, facilitating learning in this context involves markedly different practices from content-centered engineering classrooms. While many capstone courses include some new content knowledge, they typically do not focus on mastery of technical concepts. Instead, they develop students' ability to address open-ended problems by working collaboratively, drawing on prior knowledge, seeking new information, and generating and evaluating design alternatives (Howe, 2010; Howe et al., 2016; Pembridge & Paretti, 2010a; Todd, Magleby, Sorensen, Swan, & Anthony, 1995). Literature on capstone teaching uses terms such as mentor, facilitator, advisor, and coach, often interchangeably, to describe the roles that capstone faculty play (Bruhn & Camp, 2004; Howe, 2010; Howe, Rosenbauer, & Poulos, 2017; Kolmos & De Graaff, 2014; Manuel, McKenna, & Olson, 2008; Rover, 2000; Sternberg, Johnson, Moen, & Hoover, 2000).

As these terms suggest, the instructor–student dynamic is at the heart of capstone teaching, yet that dynamic remains ill-defined (Pérez, Elizondo, García-Izquierdo, & Larrea, 2012). Few studies have systematically explored teaching practices in capstone environments, though some foundational work exists. For example, Pérez et al. (2012) provide a typology of approaches to supervising capstone teams in computer science engineering that includes six domains: technology, arrangements, keep-alive (i.e., motivation), execution, meetings, and management. Their work highlights the different ways in which faculty engage with capstone students broadly, but does not address specific teaching practices. In contrast, Crismond and Adams (2012) describe the complexity of design learning and offer faculty a range of strategies to help students become informed designers. While their work provides a rich set of assignments to guide design learning, it does not address the breadth of domains identified in Pérez et al.'s (2012) typology. In their chapter on design education in the *Cambridge Handbook of Engineering Education Research*, Atman, Eris, McDonnell, Cardella, and Borgford-Parnell (2014) discuss research related to both learning and assessment, highlighting problem-/project-based approaches, but provide few details regarding design teaching practices.

Teaching practices were the focus of the 2014 Design Research Thinking Symposium, which gathered an interdisciplinary group of international scholars to analyze design review sessions from engineering, industrial design, and dance (Adams & Siddiqui, 2016). Several of the studies considered instructional practices in a mechanical engineering capstone course. For example, Adams, Forin, Chua, and Radcliffe (2016) used cognitive apprenticeship and pedagogical content knowledge (PCK) to analyze the complexity of instructors' engagement with students around design decisions. Tolbert, Buzzanell, Zoltowski, Cummings, and Cardella (2016) provided a detailed account of instructor feedback patterns and student responses related to the ambiguity of design, while Yilmaz and Daly (2014) explored instructor feedback relative to students' convergent and divergent thinking. Such studies offer important accounts of the ways instructor discourse shapes student learning in the context of design reviews.

Yet few, if any, studies capture the full range of teaching practices across a semester or year-long project, where the learning outcomes encompass a full range of workplaces practices. The decennial national survey of capstone design faculty consistently reports teamwork, communication, and project planning among the top five topics covered in the capstone course (Howe, 2010; Howe et al., 2017; Todd et al., 1995). Similarly, empirical research on capstone students' experiences identified learning outcomes across four domains, including not only engineering design but also teamwork and communication with peers and with external stakeholders, self-directed learning, and engineering identity (Lutz & Paretti, 2017).

Even in the broader project-based learning literature, most research focuses on theoretical foundations and learning outcomes (Kolmos & De Graaff, 2014), with fewer studies addressing context-specific instructional practices. Exceptions include studies by Hmelo-Silver and others (Hmelo-Silver & Barrows, 2006, 2008; Savin-Baden, 2003) in non-engineering settings and the model of faculty practices in a first-year problem-based engineering course developed by Hunter (2015). Although these studies represent important beginnings, the centrality of capstone courses in students' transition from school to work suggests the need for work explicitly focused on this context. While engineering education research has deepened our understanding of teaching in content-centered courses, the literature is less clear on how capstone design instructors facilitate student development in this transitional, practice-oriented learning environment. The breadth of learning outcomes embedded in the capstone course as well as the scope of the domains identified by Pérez et al. (2012) helps define what capstone teaching encompasses but leaves open questions of how faculty enact such teaching. Without a concrete understanding of how capstone faculty teach, we argue that the research community cannot begin to evaluate the effectiveness of varying approaches or the underlying PCK needed in this critical space. To address this gap, this study addresses the following research question: What practices characterize teaching in capstone design environments?

Importantly, this characterization is only a first step in research on capstone design teaching. Because no detailed taxonomies of capstone teaching practices currently exist, our work is predominantly descriptive (though we do explore some patterns across participants). Most notably, we do not evaluate effectiveness or identify best practices for capstone teaching. Such evaluation is, in fact, highly complex and context-dependent because of the nature of capstone courses: students typically work in teams on open-ended projects, with each team and project posing different challenges that change over time. As a result, a best practice effective in one context may be disastrous in another. For example, as we have reported elsewhere (Paretti, Pembridge, Brozina, Lutz, & Phantanousy, 2013), the capstone faculty interviewed for this study described complex decision processes even in the narrow context of addressing teamwork problems: some problems require coaching the team leader, others are best suited to direct instruction with the team, and still others require one-on-one counseling with individual students. The approaches of the participants varied based on the existing team dynamic and the nature and timing of the problem (e.g., beginning, middle, or end of the project).

Work by Hunter (2015) on teaching practices in a first-year engineering course and by Adams et al. (2016) on coaching practices in design reviews shows similar findings: faculty in these contexts use and adapt teaching practices in what Adams et al. (2016) term an "improvisational" (p. 39) style based on a complex range of contextual cues. Substantial work remains in exploring how teaching practices impact student learning in capstone environments. We argue, however, that systematic explorations of these impacts first require a common language among researchers to describe what capstone faculty do; this study provides such a framework. To do so, we adopt a functional perspective, examining capstone teaching practices through a lens that pairs what with why.

Our study is informed by situated theories of learning (Johri, Olds, & O'Connor, 2014), particularly Lave and Wenger's theory of legitimate peripheral participation (LPP), which considers learning as "an integral and inseparable aspect of social practice" (Lave & Wenger, 1991, p. 31). LPP captures the ways in which individuals move from novice to expert through engagement in authentic sociocultural practices and interactions with more experienced individuals. It has been used to characterize design education broadly (Atman et al., 2014) as well as capstone design specifically (e.g., Hotaling, Fasse, Bost, Hermann, & Forest, 2012; Paretti, 2008). As Lave and Wenger (1991) note, LPP is not "a pedagogical strategy or a teaching technique" but rather "an analytic viewpoint on learning" (p. 40). It is this analytic viewpoint, with its emphasis on the role of social interactions in local contexts, that guided our decision to focus on faculty practices in terms of their ways of interacting with students with an emphasis on the goals of those interactions.

2 | RESEARCH DESIGN

Consistent with situated learning, we position ourselves as social constructionists, treating knowledge as constructed by and through individuals in interactions with one another and with larger systems (Patton, 2002). Thus, in this study, we focus on the ways in which faculty construct their experiences of teaching capstone design, focusing on what Patton refers to as "their reported perceptions, 'truths,' explanations, beliefs, and worldview" (p. 96). To do so, we use interviews with a stratified sample of 42 faculty to explore the ways in which they construct not only what they do, but also why—that is, the meanings they attribute to their practices. At the same time, consistent with Miles, Huberman, and Saldaña (2014), we approach this study as what they term "pragmatic realists" (p. 7); while we recognize the socially constructed nature of knowledge and meaning, we also seek to "mak[e] assertions and [build] theories to account for a real world that is both bounded and perceptually laden" and identify "a structure at the core of events that can be captured to provide a causal description of the most likely forces at work" (p. 7). While the taxonomy presented here is not intended to rise to the level of a theory, it does frame a causal structure that accounts for both what capstone faculty do in their courses and their underlying rationales. The data collection for this study was conducted under the approval of the Virginia Tech Institutional Review Board.

2.1 | Participants

The data are drawn from the second phase of a mixed-methods study that began with a national survey of capstone faculty (built on surveys by Todd et al., 1995 and Howe, 2010) exploring the structure and content of capstone courses (see Pembridge, 2011; Pembridge & Paretti, 2010a). To identify survey participants, the research team used contact information from department web sites and sent emails to 1,620 ABET-accredited programs requesting contact information for each program's capstone faculty; this approach yielded contact information for 1,258 capstone faculty, representing 40% of all ABET-accredited programs and 53% of accredited institutions. Survey links were emailed directly to these individuals, and 491 responses were received; this response rate of 39% is slightly above those reported by Todd et al. (1995) and Howe (2010) (26 and 35%, respectively). Details on the survey method and results are available in Pembridge (2011) and Pembridge and Paretti (2010a).

The survey included a final item asking whether respondents were willing to participate in a follow-up interview. Of the 491 respondents, 271 indicated willingness to be interviewed. To identify interview participants, we used stratified purposeful sampling (Patton, 2002) to maximize variation based on experience and discipline. With respect to experience, we used research by Berliner (1986, 2004) to develop a composite measure that included years of teaching, years in industry, and scholarly activities and recognition; a full discussion of this measure is available in Pembridge and Paretti (2010b). While experience does not necessarily imply expertise, the experience category combines not only years in academia and years teaching capstone design, but also years in industry—an important criterion given the role of capstone design in the transition from school to work—as well as involvement in the scholarship of teaching and learning in capstone design. Given that little

TABLE 1 Participant demographics

Field	Experience[a]			Position						Type of institution		Size of institution[c]		
	Low	Medium	High	Inst.	Rsch. Fac.	Asst. Prof.	Assoc. Prof.	Prof.	DH[b]	Public	Private	Small	Medium	Large
CEA	1	8	0	1	0	0	5	3	0	5	4	1	6	2
CHE	2	4	2	2	0	0	3	2	1	7	1	1	5	2
ECE	1	4	2	1	0	0	3	3	0	4	3	2	2	3
ISE	0	6	3	1	0	0	2	5	1	8	1	1	4	4
MAO	3	3	3	2	0	1	3	3	0	6	3	3	4	2
Total	7	25	10	7	0	1	16	16	2	30	12	8	21	13
Percent	16.7	59.5	23.8	16.7	0.0	2.4	38.1	38.1	4.8	71.4	28.6	19.0	50.0	31.0

Abbreviations: CEA, civil, environmental, and architectural engineering; CHE, chemical engineering; ECE, electrical and computer engineering; ISE, industrial systems and manufacturing engineering; MAO, mechanical, aerospace, and ocean engineering.

[a]Low: more than one standard deviation below the mean expertise score; medium: within plus/minus one standard deviation of the mean expertise score; high: more than one standard deviation above the mean expertise score.

[b]DH: Department Head.

[c]Small: 5,000 undergraduates or fewer; medium: 5,001–20,000 undergraduates; large: more than 20,000 undergraduates.

is known about what constitutes experience in capstone teaching, we adopted the following relative measure based on the full pool of survey respondents. A summative normalized score of experiences was calculated for each participant. Participants who had a score within one standard deviation of the mean normalized score were classified as "medium" experience, while those with scores more than one standard deviation below the mean were classified as "low" experience, and those with scores more than one standard deviation above the mean were classified as "high" experience. The interview pool included respondents ranked high, medium, and low to ensure variation in experience levels; given that a majority of survey respondents were at the medium level (Pembridge & Paretti, 2010b), we oversampled at that level.

With respect to discipline, we identified an equal number of respondents from each of five major groupings: chemical (CHE), civil/environmental/architectural (CEA), electrical/computer (ECE), industrial and systems (ISE), and mechanical/aerospace/ocean (MAO). Secondary selection criteria included representation across role (course coordinator or instructor, individual project advisor), faculty rank, and institutional characteristics (private/public, institutional size); we did not collect race or gender data on the survey and thus did not use those variables in sampling. We identified 60 potential interview participants using these criteria, with a minimum target of 40 interviews; this target was selected to yield 6–10 participants at each expertise level and in each disciplinary grouping. Recruitment emails were sent to all 60 individuals during the summer of 2010, with two follow-up invitations. This process yielded 42 interview participants (36 men and 6 women); data analysis demonstrated that this pool was sufficiently large to reach saturation. Table 1 summarizes the demographic profile of the interview participants, and Table 2 summarizes two salient items in the experience construct: years of experience in capstone teaching and years of experience in industry. Importantly, in addition to having substantial experience in capstone teaching, 90% of the high-experience participants and 64% of the medium-experience participants have four or more years of industry experience, compared to only 43% of those in the low category. Each interview participant received a $30 Amazon gift card.

2.2 | Data collection

Consistent with social constructionism (Patton, 2002), to obtain participant perspectives, we employed semi-structured interviews using the critical decision method (CDM) framed by general questions about participants' approaches to the course. CDM is particularly appropriate for a situated perspective because it is used to model tasks in naturalistic environments characterized by high time pressure and limited opportunity for deliberation (Klein, Calderwood, & Macgregor, 1989). Originally used to study decision-making in emergency incident response (Klein et al., 1989), it has been used in engineering education to identify how engineering educators make decisions (Huang, Yellin, & Turns, 2007; Sattler, Turns, & Gygi, 2009; Yellin, Huang, & Turns, 2007) and how individuals choose career pathways (Foster, Wigner, Lande, & Jordan, 2015). Although capstone faculty typically do not experience the same types of time pressure found in emergency incidents, they supervise multiple teams on open-ended projects with no known solution and must often make in-the-moment decisions as they guide teams

TABLE 2 Key experience indicators

Experience level	Percent of participants				
	8 or more years	6–7 years	4–5 years	1–3 years	<1 year
	Capstone design teaching experience				
High	60	30	10	0	0
Mid	52	16	20	12	0
Low	0	0	43	29	29
	Professional/industry experience in capstone field				
High	80	0	10	0	10
Mid	36	8	20	20	16
Low	43	0	0	0	57

through technical and nontechnical challenges. As a result, CDM was used to solicit details about capstone teaching that address both explicit and tacit knowledge and explore how participants used their knowledge to make decisions (Klein et al., 1989). In doing so, it enabled us to explore faculty beliefs and explanations about their teaching practices in the context of specific, locally grounded events.

CDM uses a semi-structured, incident-based approach in which the researcher guides participants in selecting a representative incident and providing a detailed narrative of their actions, decisions, and rationales (Klein et al., 1989). To capture faculty approaches to capstone teaching as comprehensively as possible, we embedded CDM within a set of more generalized questions about the course. The question sequence was designed to provide context and elicit recall of memories associated with the context (Patton, 2002), and allowed us to elicit both situation-specific and generalized teaching practices and beliefs:

1. (General) Describe your approach to teaching the capstone design course.
2. (CDM) Describe a situation where a design team was having difficulty due to a lack of content knowledge, design knowledge, or teaming issues.
3. (General) What are the most important things you do as a design educator?
4. (General) Is there anything else that you would like to add to the interview that we may not have covered?

In exploring Question 2, the interviewer used an extensive series of prompts consistent with CDM (Pembridge, 2011) to capture how participants identified the problem, what their goals were, what actions they took, why, and to what extent the situation was typical for capstone teams. Pembridge conducted all interviews primarily by phone (39), with three in-person interviews. The interviewer used each participant's survey responses to prepare for the interview and identify additional potential prompts. Each participant was interviewed only once, with interviews lasting approximately one hour. All interviews were audio-recorded, transcribed verbatim, and anonymized for analysis.

2.3 | Data analysis

Analysis of the interview transcripts was guided by Miles and Huberman (1984), Patton (2002), and Miles et al. (2014) to develop descriptive codes that capture the ways faculty described their capstone teaching. We employed the a priori codes described below to provide an initial categorization, then allowed open codes to emerge from the data to refine and contextualize these categories and provide a functional taxonomy of practices.

2.3.1 | A priori codes: Kram's model of mentoring

As noted earlier, discussions of capstone teaching use terms such as mentor, coach, role model, or advisor (Vesilind, 2001). Given not only the existing work on design education cited earlier but also the broader research on mentoring and coaching, we turned to the literature to identify a potentially fruitful model to serve as an initial framework for data analysis. Given the prominence of "mentoring" as a term used to describe capstone teaching (particularly in the decennial national surveys by Todd et al., 1995 and Howe, 2010), we focused on mentoring models as viable starting points. After reviewing multiple models

(Pembridge, 2011), we selected the one proposed by Kram (1985) in part because of its prominence in the literature, but more importantly, given the role of capstone design in the transition from school to work, because of its use in both academic and workplace settings.

Kram developed her model based on two industry studies, one at a large public utility corporation and one that sampled multiple Fortune 500 companies. Scholars have since used the model in collegiate settings, including graduate school (Tenenbaum, Crosby, & Gliner, 2001), medical education, and teacher education (Johnson, Rose, & Schlosser, 2007). This model's usefulness in these latter two domains is particularly salient because both commonly incorporate realistic, practice-based pedagogies that echo engineering capstone courses. The model's applicability across academic and corporate domains made it a useful starting point for our investigation. However, we are not arguing that Kram's model is the "best" description of capstone teaching; rather, as borne out by our subsequent analysis, it offered a productive set of initial codes for categorizing faculty practices. Of equal importance is that its functional orientation enabled us to develop a taxonomy organized not only by what faculty did (the practices themselves) but also by the goals of those practices with respect to student learning and development.

Kram's model (1985) divides mentoring into two domains: career and psychosocial. The career domain consists of five functions that prepare or promote protégés in their careers. *Sponsorship* describes the ways mentors publically support protégés by recommending them for key moves or promotions. *Exposure and visibility* describes the ways mentors give protégés opportunities to demonstrate their competence for senior members of the community. *Coaching* refers to the ways in which mentors advance protégés' skills through guidance, direction, and feedback. It is tied to providing *challenging assignments*, in which mentors create opportunities that allow protégés to build their skills. Finally, mentors *protect* protégés from negative interactions or consequences.

Kram's (1985) psychosocial domain includes four functions that support the personal and emotional selves of protégés', including their sense of competence, identity, and effectiveness. *Role modeling* describes ways in which mentors exhibit attitudes, values, and behaviors they want protégés to emulate. Mentors offer *acceptance and confirmation* as they actively support and encourage protégés. Mentors also offer *counseling* when protégés experience situations that create internal conflicts. Where coaching focuses on career-related knowledge and skills, counseling focuses on personal development. Finally, mentors and protégés typically develop *friendships* that allow protégés to interact more comfortably with those in authority.

2.3.2 | Codebook development

These nine functions served as a priori codes to begin characterizing the capstone teaching practices represented in the interviews. The qualitative data analysis software MAXQDA (Standard Version 12; 2016) was used for coding. Five transcripts, all at the medium-expertise level, were selected for initial analysis and coded by Pembridge using these a priori codes but also seeking practices that fell outside the model. Kram's (1985) nine functions proved sufficient to capture all practices discussed by participants, and each was present. However, definitions for each function were modified iteratively to more closely capture the capstone environment. For example, while Kram's (1985) concept of "friendship" reflects the relationships that develop between mentors and protégés at work, it does not appropriately describe faculty–student relationships; instead, the concept of "rapport" emerged as an alternative function. At the same time, specific practices or components associated with each function began to emerge as subcodes. We each reviewed the modified definitions and emergent subcodes against the coded segments and together refined the definitions.

The resulting codebook included Kram's (1985) original definitions (for reference), the new definitions for each function, and each function's corresponding subcodes and definitions. Using this revised codebook, Pembridge recoded the initial five interviews and coded an additional 20 interviews (five from each discipline grouping, all at the mid-level of expertise); no new codes emerged at the function level, but new subcodes were developed at the practice level. The coded segments were then exported to an Excel document, and we each reviewed all coded segments to further refine definitions for each function code and subcode. This initial version of the model was published in Pembridge (2011). The codebook was then given to a third researcher, who coded five interviews from the initial set of 25 for training and triangulation. Once consensus was reached on the code definitions, Kram's definitions were removed from the codebook, and the third researcher coded the remaining 17 interviews for the primary functions.

Paretti then conducted a full review of all coded segments across the 42 interviews and applied the subcodes to the remaining 17 interviews, tracking any changes to coded segments using comments and memos within MAXQDA (Standard Version 12; 2016) to maintain an audit trail. No new codes or subcodes emerged during this phase, confirming that the data set had reached saturation; notably, however, several subcode definitions were refined as the pool of associated segments grew. We then met to review all function and subcode definitions as well as the coded segments. After negotiating differences to consensus, we agreed on the final codebook defining the capstone design function codes and the practice subcodes. Paretti then reviewed the full coded data set a final time to ensure that the full codebook was applied consistently.

2.4 | Trustworthiness

While the making and the handling of the data for this study were done prior to the development of Walther, Sochacka, and Kellam's quality framework (Walther, Sochacka, & Kellam, 2013), the procedures described here support this framework's five types of validation. We highlight the correspondences briefly here. Theoretical validation (consistent with both situated learning and social constructionism) is supported through the use of interviews with a purposeful sample of participants emerging from an earlier phase of the project as well as through the selection of an a priori framework to initiate analysis. Procedural validation (fit between reality and the resulting taxonomy) is supported through the use of survey responses to guide interview prompts (i.e., triangulation) in conjunction with critical incident interviewing to elicit concrete accounts of practice as well as through the overall approach to data analysis (i.e., iterative coding of increasing subsets of the data to test and refine definitions, use of multiple coders to check author biases). In addition, though beyond the scope of this article, surveys of students of selected interview participants (Pembridge, 2011) and subsequent case studies combining observational data with student and faculty interviews (Lutz, Hixson, Paretti, Epstein, & Lesko, 2015; Lutz & Paretti, 2017) provide further support.

Process validation is supported through the use of audio recordings, cleaning and checking of transcripts, a clear audit trail in the development of the codebook, and regular checks on the consistency of code application across coders. Communicative validation (relevance to the community) is supported through (a) the researchers' close adherence to and review of the interview data as the codes were developed; (b) the refined, regular peer debriefing not only between and among the authors and other coders but also with the authors' research group; and (c) the presentation of various iterations of the taxonomy at both the annual American Society for Engineering Education conference and the biannual Capstone Design Conference. Pragmatic validation (connection to reality) is supported through both the diversity of respondents sought (by engineering field, experience level, institutional context) and the discussion of the findings with the project's external advisory board. This board consisted of a group of expert capstone faculty from across the country who regularly publish on capstone design pedagogy.

With respect to our positionalities, James Pembridge earned an undergraduate degree in aerospace engineering, which included a capstone design course, and subsequently observed capstone courses as a graduate student. Marie Paretti taught capstone design for nine years in two different engineering departments using a team-based, project-oriented approach with projects provided predominantly by faculty research. Both authors are experienced engineering education researchers with expertise in qualitative methodologies. While these experiences facilitated understanding of participants' descriptions, we also kept our analysis grounded in the data and used external coders, peer debriefing, and other strategies to help bracket our biases.

3 | FINDINGS

While the functions developed by Kram (1985) provided a productive set of a priori codes, our analysis led to new definitions for each function, along with associated concrete practices, that together account for the academic setting and breadth of roles faculty serve in capstone design courses. Note that while Kram's distinction between career and psychosocial functions may be useful for workplace contexts, the distinction was less clear in the capstone context and was eliminated from the codebook. Table 3 presents the resulting nine functions associated with capstone design teaching.

The following sections describe each function in detail as well as define and illustrate the associated practice subcodes. Because of the number of practices, we have included representative quotations in summary tables for brevity rather than integrating them into the text; a more expansive set of quotations for each practice is available in Pembridge (2011; because this paper describes an earlier version of the model, function and practice names differ slightly from those used here). To provide an audit trail, quotations are identified by participant ID number and transcript paragraph number (i.e., 71242/68 is participant number 71242, paragraph 68). Finally, we conclude with an analysis of patterns based on participant experience level.

3.1 | Challenge

At the heart of the capstone courses, participants described intentionally creating, soliciting, and shaping projects that will challenge students to help them develop as engineers and prepare them for the workforce. To do so, participants created projects to meet three practices, illustrated in Table 4, which coalesced into subcodes for this function: (a) integrate previous learning, (b) prompt new learning, and (c) provide realistic experiences that address full project cycles, incorporate authentic constraints, and are open-ended.

TABLE 3 Teaching functions in capstone design

Function	Operational definition: Practices designed to . . .
Challenge	. . . develop students' technical and professional skills by providing them with complex projects that push students to both apply and further develop their engineering knowledge and skills.
Protect	. . . proactively guard students from failure through the structure and administration of the course.
Coach	. . . impart knowledge regarding technical and professional skills directly related to the capstone project through a variety of pedagogical approaches.
Promote employability	. . . provide access, opportunities, experiences, and/or materials designed to assist students in attaining employment.
Provide exposure	. . . provide students with diverse opportunities to exhibit their skills and knowledge in ways that facilitate acclaim and feedback.
Provide role models	. . . demonstrate for and/or elicit from students the attitudes, values, and behaviors expected of engineering professionals.
Accept and confirm	. . . provide experiences and feedback that help develop students' confidence and identity as practicing engineers.
Counsel	. . . guide teams and individuals through difficult interpersonal and personal problems.
Build rapport	. . . develop interpersonal relationships with students that establish an environment in which students feel comfortable approaching the instructor.

TABLE 4 Challenge practices

Practice	Representative quotations
Integrate previous learning	Students basically combine everything they have learned in all the other courses in order to design, build, and fly aircraft. 71242/68
Prompt new learning	You know most of these projects end up stretching them beyond what they have done before. So this is one where they had had the course and the background modeling technique simulation, but they had not, uh, used, you know, the [client context] problem. So they had a lot of things in that domain that they did not know. 50946/81
Provide realistic experiences	But these projects are all reality based in nature and we always search for 2 to 3 large objectives, often competing objectives, that the students can work on as a team. [. . .] So, my approach is to get real world projects that have good potential for actually being implemented and used by the company. 50831/47

3.1.1 | Integrate previous learning

As specified by ABET (2017), engineering curricula must "culminat[e] in a major design experience based on the knowledge and skills acquired in earlier coursework" (p. 6)—typically the capstone course. Not surprisingly, participants described selecting or designing projects that afforded opportunities to integrate prior learning as well as challenged students to adapt that knowledge to new contexts.

3.1.2 | Prompt new learning

Faculty also intentionally created assignments that challenged students to develop new knowledge and skills. In some cases, this new knowledge included technical concepts or techniques, but often it also included professional skills such as dealing with clients and stakeholders and managing economic or social constraints.

3.1.3 | Provide realistic experiences

Finally, even when projects were simulated rather than client-based, faculty focused on making the projects as realistic as possible, drawing from their own experiences or the experiences of colleagues as well as local or global challenges. Key elements included (a) a full project cycle that moved from conception to realization; (b) ambiguous goals that required students to define and scope the problem before solving it; (c) open-ended problems to sharpen students' engineering judgment and decision-making; and (d) multiple, often conflicting, nontechnical requirements and constraints.

Notably, these challenging assignments are at the heart of all other functions: they necessitated protection and counseling; they were the focus of coaching and role modeling; and they provided the vehicle for employability, exposure, and acceptance and confirmation, as illustrated in the discussion of the remaining functions.

3.2 | Protect

Faculty balanced challenging assignments with practices to protect students from failure. In part, this protection involved intervening in difficult interactions with project sponsors or clients to limit damage. But more importantly, faculty protected students from two context-specific failures: learning failures and project failures.

Participants' desire to protect students from learning failures reflects the overall goal of any class, which is to support student learning; as a result, faculty structured activities to facilitate learning. At the same time, they sought to ensure that the projects succeeded both to support the students' sense of accomplishment and, when external sponsors were involved, to preserve positive relationships with them. Factors that threatened success included inappropriate project scope, poor time management, dysfunctional team dynamics, lack of sponsor responsiveness, or poor technical execution. Participants indicated, however, that successful learning and successful projects could be at odds because learning often occurs through failure; thus, they often described weighing how far down a failing path they allowed students to travel before intervening.

Participants described four distinct practices to protect students from failures, as seen in Table 5: (a) selecting projects and teams, (b) ensuring accountability, (c) knowing the status of the project and team, and (d) mediating between students and external individuals. The first three focus on course design and administration as faculty structured activities to both limit the potential for failure and identify emerging failures quickly.

3.2.1 | Select projects and teams

First, faculty developed projects with scopes appropriate for the students' skills, learning goals, and available time, and then matched team abilities and interests to project needs. To that end, faculty frequently worked with sponsors (external or internal) well before the start of the course to negotiate project scope and ensure that sponsors understood both students' capacities and their own responsibilities regarding feedback, information, and resources. Faculty also described using various approaches to team formation that they believed would support successful project work. Approaches included balancing teams based on past academic performance and/or personality types, matching projects to student interests to support sustained engagement, and matching skill sets to project requirements.

3.2.2 | Ensure accountability

Faculty established a variety of structures to keep both teams and individuals accountable. Drawing on their own experiences, they embedded steps required for project success into their courses in structured ways. Most often, team accountability came

TABLE 5 Protection practices

Practice	Representative quotations
Select projects and teams	If it's a good project nobody knows the answer, and so you have to look at what are you trying to accomplish and what is the complexity of the process look like and make a judgment call as to how much one team can accomplish in a semester given their level of knowledge and also given how much information seems to be available. 10169/50 I ultimately assign the teams. [. . .] I put together a team that, well, have interests, have sufficient aptitude, and have the personality types that can probably get all the job done. 50946/81
Ensure accountability	I try to manage [the complexity] with mileposts through these memoranda. [. . .] And so you've given them a task. You've given them a deadline. You know, it's in the memoranda form so they don't see it as milestones. But I have the course arranged so there's these milestones throughout that keeps them actually on a path somewhat. 30452/128
Know status of projects and teams	Well, we have an oral presentation progress reports once every 2 weeks. And so on a, every other week I hear what they're working on, where they're going for the next week and when I start seeing those kind of issues coming up, what, I usually won't last more than a week at a time before I know about them. 61097/51
Mediate	It was clear from the memos that there was a, what's the right word, difference in expectation from the student to the, what the company was expecting. And, pretty much came down to the company expected the students to be out there a lot more, grabbing a lot more data than what was happening. Being the intermediary here, they were both out of line; the students weren't out there enough, and I let the company know, look you're asking them to be out there too much, this is not, these kids don't work for you, this isn't a full time job. 50895/55

through scheduled milestones such as preliminary design reviews and regular updates to ensure that teams were making appropriate progress. At the same time, participants used these reporting structures together with grades to ensure that all team members were either contributing equally or being rewarded differentially (e.g., through lower grades for lower-contributing students). Reporting structures were key, with students documenting individual tasks, reporting percent contributions of each team member, and/or completing regular peer evaluations.

3.2.3 | Know the status of projects and teams

Participants used multiple approaches to monitor teams and projects, including the formal reporting structures noted above as well as regular meetings with individual teams, observations of teamwork sessions, and comparisons across teams. Understanding team dynamics, workload distributions, and project status allowed faculty to identify potential failures quickly and act accordingly. Regular written reports, for example, allowed faculty to observe issues in student work warranting specific coaching. Oral reports provided similar insights but also allowed for direct questioning to check actual progress against the written reports. Meetings were frequently cited as useful ways to accurately track progress, monitor team dynamics, or identify individuals who may not be contributing. Faculty also intentionally triangulated across these sources, for example, by using discrepancies between written reports and informal meetings as an indicator of potential problems.

3.2.4 | Mediate

In most cases when failures began to emerge, some faculty acted more directly. Faculty described, for example, stepping in between students and project sponsors to renegotiate scope, obtain critical company data, or resolve miscommunications.

3.3 | Coach

Coaching describes the practices faculty used to directly or indirectly guide students' project work and develop project-specific technical and professional skills. This function included four practices, listed in Table 6, that represent a continuum from direct to indirect knowledge transfer: (a) provide direct instruction and feedback, (b) model tasks, (c) direct to resources, and (d) listen/question. Faculty often framed these practices by contrasting what they do with what they do not do: participants consistently explained that they did not tell students what to do, even when providing direct instruction; instead, they sought to guide in ways that supported independent learning.

TABLE 6 Coaching practices

Practice	Representative quotations
Provide instruction and feedback	We review reactors and separators, we talk a lot about design altruistic: What is the maximum size of a design heat exchanger, what is the maximum height for a distillation column, all that stuff. We talk a lot about how to use ChemCad/ASBN, what to be careful of, just basically how to use the program properly. 50918/23
	If I see an obvious problem I will give them some hints that there is a problem and what they might do about it. I try not to give them the answer. But what I'll say is that this approach is probably not going to work because . . . and then let them go from there. 50902/110
Model tasks	I try to pick problems where there are 3 or 4 different ways you could solve the problem and then we'll talk about how you might evaluate and choose a particular way to do it. 40760/23
	So I showed him an example . . . like if I'm meeting, this is how I would take notes. 10104/91
Direct to resources	In some cases they may have, be stuck on a topic that maybe I don't know much about and I'll ask them to go to another expert, maybe here in the college of engineering and say, “Why don't you get advice from professor X or professor Y and see what they say.” 61135/90
Listen and question	It's not a formal process as much as letting them talk. They think I'm solving the problem for them, but I'm not. I'm there and they're talking out loud and explaining things to me. Basically when you hear yourself verbalize all the things you're thinking about, for some reason that it seems to help people move off of from zero speed. 20307/54
	[I act] as a catalyst simply by being there, listening to them, and you know, asking the right questions and having them address the right, relevant, issues of the project. 30423/23

3.3.1 | Provide instruction and feedback

At one end of the continuum, faculty provided direct instruction by teaching concepts related to the project and providing feedback on students' work. Such instruction occurred most often near the beginning of the course, when faculty lectured to convey content or assigned exercises to train students on key technical practices. More rarely, faculty directed students to take specific steps or apply certain approaches, typically in response to an impending failure that seriously threatened desired learning or project outcomes. Even then, however, participants typically described identifying flaws or problems but allowing students to decide how to handle them.

3.3.2 | Model tasks

Faculty also modeled approaches for solving technical and professional problems. They described "thinking aloud," or explaining to students how they might approach the situation at hand or how they had approached similar situations in the past, including not only what actions they might take but also their rationales. In several cases, modeling included walking students through a series of steps to illustrate a process or technique.

3.3.3 | Direct to resources

A more indirect practice involved directing students to resources to help them acquire knowledge on their own. Faculty directed students to search the literature, sometimes explicitly identifying articles or journals, but more often suggesting multiple resources or showing students how to search (e.g., offering useful databases or search terms), and encouraging students to read about a topic to develop their own knowledge. Faculty also directed students to people with pertinent expertise; in some cases, faculty connected students to people they knew, but in other cases, participants described helping students learn strategies for finding such experts on their own.

3.3.4 | Listen and question

The least directive coaching practice involved providing students a chance to talk through issues while asking probing questions as a means to encourage students to reach decisions using their own reasoning, a practice multiple participants described as being a "sounding board." Some participants described questioning as a mechanism to challenge students to achieve excellence, while others saw it as a gentle form of guidance. In some cases, the questioning was Socratic in that faculty knew what they wanted students to discover, but in other cases, it was more open-ended as faculty helped students think through critical issues.

While we have described these coaching practices independently for simplicity, in practice, participants described linking them, for example, using feedback to identify a problem, then directing students to resources they could use to develop a solution. At the same time, participants explained that where and how they used these practices depended on the project, the status of the team, and the amount of time left in the course; they often relied on protection practices to identify when and what kind of coaching students needed.

3.4 | Promote employability

Participants also used the capstone course to promote employability by directly linking the course to students' job search. Importantly, this approach differs from faculty's nearly ubiquitous belief that the capstone course was preparing students for the workplace broadly, with segments coded under this function describing specific support for students' job *searches*, rather than general job *preparation.* As listed in Table 7, faculty who supported students' employability explicitly used the capstone course to (a) provide access to potential future employers; (b) provide marketable skills, experiences, and materials; and (c) provide verbal or written recommendations.

3.4.1 | Provide access to potential employers

Direct access to employers was typically linked to industry-sponsored projects as faculty sought clients who would be likely to recruit employees from the capstone course or who offered types of work students were interested in pursuing. Faculty described such projects as ways to provide students with opportunities to experience working either with a particular employer or, more broadly, in a particular industry sector or type of firm to support a subsequent job search.

TABLE 7 Employability practices

Practice	Representative quotations
Provide access to potential employers	I do have students who have taken the class that are now working for those same agencies. 2038/82 I also get their input on what type of companies/entities do they want to work for such as, manufacturing or logistic supply chain or banking finance, or health care, so on and so forth, what type of sponsor they would like to work with, whether it's a large company, or for profit, small company for profit, government, government contractor, not for profit, these types of things. 50895/59
Provide marketable skills, experiences, and materials	They have to invest extra time to and extra efforts to make good results, but this is the sense really that I was discussing, and if they do that then they definitely produce very good projects and projects that they can take with them to their job interviews and definitely get much better interviews, much better jobs. 40756/172
Provide recommendations	And then what I need to do is write really strong letters of recommendation for them to get them to go to these really good schools. And I have a pretty strong track record of being able to do that. Or getting them to be accepted to one of the selective design companies, because I'm giving them design experiences. 10104/284

3.4.2 | Provide marketable skills, experiences, and materials

Several faculty also described ways in which they saw capstone projects as explicit components of students' job applications. These participants discussed providing opportunities to produce deliverables and develop skills that students could list on résumés and discuss during job interviews.

3.4.3 | Provide recommendations

Finally, two participants cited providing recommendations as part of their capstone teaching.

3.5 | Provide exposure

Where employability supports the job search, exposure captures the ways faculty showcase students' work and provide opportunities to interact with professionals more broadly, both of which serve to socialize students into the profession, as indicated in Table 8.

3.5.1 | Showcase student work

Participants created multiple opportunities for students to demonstrate their accomplishments to academic, industry, and community members. These showcases, which frequently appeared at the end of the term, typically involved presentations or

TABLE 8 Exposure and visibility practices

Practice	Representative quotations
Showcase student work	I will invite in faculty, sponsors, parents, people from industry. I sort of liken it to a trade show or science fair. [. . .] If they have something where they can demonstrate a working prototype then they demonstrate it. If they have not got a working prototype—they've done really just a paper or case study of the problem, you know—they will have a poster where they describe the project. 71240/10
Foster interactions with professionals	To the maximum extent possible we have external sponsors for the projects, for the problem. So they have to learn how to interact with the sponsor. 20274/10 The experience there is the students actually meeting with the village manager, they're meeting with their supporting engineering service, they're defining the task, they're scheduling it, they're budgeting it, she's probably gonna meet with the city council. 40772/89 Another deliverable as part of the class is a professional meeting attendance. They need to attend a professional society meeting, such as American Society of Civil Engineers, National Society of Professional Engineers, American Concrete Institute. 50897/48

poster sessions where students explained their work to other students, faculty, external review panels, departmental advisory boards, competition judges, clients, and/or the public. They occurred either at the home institution or at client or competition sites. Participants described such showcases as opportunities for students to gain experience in situations they were likely to encounter in the workplace; to obtain professional feedback on their work; and, linked to the accept and confirm function, to take pride in their accomplishments.

3.5.2 | Foster interactions with professionals

Participants also sought to socialize students into typical professional interactions by having them work with external clients and encouraging them to join professional societies. Participants described the ways in which such interactions helped students become familiar with goals and practices in industry and learn how to interact with the different people involved in a project (e.g., different types of engineers, government officials, and other stakeholders).

3.6 | Provide role models

Beyond guiding students through projects, capstone faculty saw themselves enculturating students into the profession broadly. As a result, they provided role models designed to help students develop attitudes, values, and behaviors associated with professional practice. Unlike the modeling practice in coaching, which focuses on project-specific skills, this role-modeling function encompasses practices faculty used to foster general workplace behaviors and attitudes, though faculty often described moving from modeling a specific project skill to generalizing it into an expected workplace behavior. Role modeling included four practices: (a) describe professional engineering experiences; (b) share personal values; (c) model professional behaviors, and (d) mimic engineering workplaces. These practices, illustrated in Table 9, move from cognitive to situative approaches as they offer opportunities to listen, observe, and act.

3.6.1 | Describe professional engineering experiences

In cognitive terms, faculty helped students understand professional life via straightforward description using narratives of their own and others' experiences. Many participants had work experiences they could share with students; when their own experiences were limited, they brought in industry professionals—both those with extensive experiences and recent graduates. These opportunities allowed students to hear firsthand accounts from current engineers about their workplaces, including expectations

TABLE 9 Role modeling practices

Practice	Representative quotations
Describe professional engineering experiences	And so, the class time is spent bringing in guest speakers. Mostly our alumni, you know, who are working in all sorts of aspects of chemical engineering. And they come in and talk about their career, professional issues, graduate school, professional school, that sort of thing. 30407/51
Share values	So what they wanted to do was see if they could make the bridge less sturdy or conform to less loading. And so that's where we have a meaningful discussion. Alright well we're talking about ethics. What is your responsibility? Is your responsibility in life to only make the client happy or do you have a higher calling or a higher responsibility as engineers to make sure things are safe, and a duty to inform their client that their budget is unrealistic, and then propose to them what it would really cost. 50879/81
Model behaviors	One of the most [important] things that I do is model the behavior that I expect, so I absolutely 100% of the time expect my students to be professional, to communicate efficiently and effectively, to be 100% engaged and working as hard as they can possibly work all the time. You know if I did something wrong I apologize, and I make it clear that I'm sorry. So I think the very most important thing I can do is model the behavior that I expect from them. 20307/84 My overarching goal is to model for students how they need to handle this in the workplace. So if they have a conflict with a team member or a conflict with someone who is working for them or with them, [I] to try to model how to confront that person and address conflict head on rather than either ignore it or handle it in a non-productive way. 30407/52
Mimic the workplace	I look at my role as role of the supervisor. When the student leaves the university, they're going to be working for somebody. And my role is the supervisor. 20345/56

for new graduates, descriptions of daily engineering work, and current industry trends. In some cases, these descriptions occurred during class lectures, but faculty also described sharing stories from their experiences informally throughout the course.

3.6.2 | Share values

Faculty also shared personal values and attitudes with students that ranged from helping students understand industry economics and engineers' corresponding responsibility for contributing to company profitability to confronting ethical issues that arise as scheduling and budget constraints push engineers to weight safety versus cost or company versus consumer interests. Several also described trying to impart values with respect to facing challenges, managing relationships, balancing workloads, and other facets of professional life. These values encompass attitudes toward people and work that participants hoped to instill in students regardless of their future careers.

3.6.3 | Model behaviors

In addition to describing professional behaviors, faculty explicitly sought to show students how to behave through their own actions. They described, for example, modeling how to treat colleagues with respect and to ensure that all voices are heard, how to interact with clients and suppliers, how to handle mistakes or failures, or how to be open to new ideas. By intentionally displaying behaviors they valued, participants saw themselves giving students an opportunity to learn by example.

3.6.4 | Mimic the workplace

Finally, to help students to adopt professional identities and enact professional behaviors, participants positioned themselves as engineering managers and established workplace expectations for students' work quality, interactions, and attitudes. Thus, where faculty used realistic experiences to challenge students, they carried that realism into the structure and ethos of the course to help students think and work like practicing engineers. Importantly, participants balanced this workplace mimicry with protection and coaching to support student development.

3.7 | Accept and confirm

Faculty included acceptance and confirmation among their core functions as a means to sustain students through the challenges of an extended project and to build their confidence as practicing engineers. As shown in Table 10, faculty built this confidence through three practices: (a) promote ownership and responsibility, (b) create a sense of accomplishment as students complete tasks, and (c) encourage students as they encounter difficulties.

3.7.1 | Promote ownership

To help students see themselves as engineers, faculty fostered students' sense of responsibility for their projects; participants repeatedly used the term "ownership" as they described pushing students to explore options, make decisions, and take

TABLE 10 Acceptance and confirmation practices

Practice	Representative quotations
Promote ownership	I really want it to be their own thing, and so I really do wait for the students to come to me and tell me what it is they need and I think it's their chance to really take ownership and not just be the student in the classroom. It's their chance to go and really make the project their own. 61086/123
Foster a sense of accomplishment	I kind of lead them along and I try to bring out in them stuff they know, but they don't have confidence in the fact they really know it. That's the big issue with some of the young engineers. They just don't have confidence in making a decision. And so, I've got to push them, and bring it out of 'em, and finally at the end they understand that they really know this stuff, but they didn't know that it had any value. 20345/68
	I'm [. . .] also making them realize, "Hey you've done a really good job here. You should be proud of your effort; let's get up and present this professionally at the final defense." 50831/59
Encourage	The main goal has always been for these open ended problems to not let them get too discouraged or overwhelmed because then you have, you can go into a rebellion mode and that doesn't help anyone either. 40690/42

actions independently. Taking ownership was closely linked to building confidence and helping students recognize their capabilities.

3.7.2 | Foster a sense of accomplishment

Participants also built confidence by helping students recognize that they had the knowledge, skills, and abilities to successfully complete the work. To foster this recognition, participants helped students remember what they knew and then identify how that knowledge applied to their projects. They also helped students see the tangible outcomes of their work as sources of pride.

3.7.3 | Encourage

Finally, faculty reported that part of their work included keeping students motivated in light of the challenges. As participants explained, conflicts, failures, delays, and similar challenges often make it difficult for students to remain engaged; as a result, participants described ways they helped students remain positive and focused as they experienced failures, sometimes for the first time in their undergraduate experiences. Participants thus intentionally helped students develop the ability to manage and recover from setbacks.

Several faculty considered acceptance and confirmation especially important for historically low-performing students who may not have excelled on traditional homework problems and tests. These faculty saw capstone as a final opportunity for such students to succeed at a project and gain confidence as engineers. More broadly, faculty also saw capstone as an opportunity to reinvigorate student enthusiasm for the profession and for the things that inspired them to pursue engineering.

3.8 | Counsel

Faculty counseled both entire teams and individual students through personal and interpersonal problems that inhibited successful project work and learning. Counseling was often a primary response to problems identified through the protective function; it reflects ways in which faculty intervened directly with individuals to help them (a) negotiate difficult team relationships, (b) address personal challenges that hindered performance, or (c) explore career decisions, as illustrated in Table 11. Counseling differs from coaching in that it focuses on emotional or interpersonal dynamics rather than project-specific skills. Approaches varied depending on the situation as well as the capabilities of the participant.

3.8.1 | Negotiate team relationships

Faculty described counseling teams or team leaders when interpersonal dynamics were hindering performance, for example, when team members were not getting along, when personality clashes created unproductive stalemates, or when poor

TABLE 11 Counseling practices

Practices	Representative quotations
Negotiate team relationships	I'm one that keeps asking the questions of both sides if they understand and to have them paraphrase what was said into their own words so that I'm sure that the ideas are being heard and the intent is being heard on both sides, to try and minimize the misunderstandings due to language or whatever else, terminology differences or whatever. 61097/131
Address individual performance	I help the students work through personal problems, there's always issues with they won't do their fair share whatever those might be, so we deal with personal problems. 20307/24
	I meet with the team but I'll look each student in the eye and try to get a feeling from there where they are and what they're doing and what kind of problem they're having and if they're encountering road blocks and that. I did that with this student also. [. . .] I tried to do some one on one counseling with him. 61135/151
Explore career options	It would be easier sometimes when a student comes to me for help, say, what . . . which job should I take, or what summer internship should I pursue, or should I change my major, it would be easier for me to just tell them the answer. But, I try approach it . . . you know, my role in advising is more of a coach in asking questions that sort of prompt that person to figure it out for themselves or identify what the main issues are. 30407/56

communication hampered productivity. In many cases, faculty first tried coaching a team leader or other member in conflict resolution to enable teams to resolve issues on their own. When such coaching failed, however, faculty actively stepped in, counseling the team through the issues to help them resolve differences and develop more effective ways of interacting.

3.8.2 | Address individual performance

In other cases, faculty counseled individual students who were struggling, as evidenced by indicators such as poor performance, disengagement, or conflicts with team members. Faculty described meeting with individuals one-on-one to uncover underlying issues, develop coping strategies, negotiate performance expectations (and grades), and provide referrals to outside resources when warranted. Faculty who used this practice recognized that poor performance often stems from other issues in a student's life, and they used counseling to help identify and resolve those issues or, when warranted, to direct students toward appropriate resources such as university counseling centers.

3.8.3 | Explore career options

Finally, in a few cases, faculty extended counseling beyond the course as students came to them for advice about applying to graduate school, choosing among job possibilities, or negotiating job offers. This counseling focused on helping students sort through such decisions themselves.

3.9 | Build rapport

Rapport describes the interpersonal dynamic between faculty and students that establishes an environment in which students feel comfortable approaching faculty with questions, problems, challenges, and concerns. As such, it enabled many of the other mentoring functions. Participants built rapport as a means to enhance students' receptiveness to instruction, their openness to faculty as role models, and their trust in faculty efforts to support students' confidence. As listed in Table 12, participants described two key practices: (a) cultivate a sense of availability and approachability and (b) know students individually.

3.9.1 | Cultivate availability and approachability

Participants highlighted ways in which they made themselves available to students through frequent interactions (e.g., regular team meetings to openly discuss the project) and verbal and visual cues (e.g., being in the office or the lab when students are working, providing phone numbers, responding quickly to emails). Importantly, several participants explicitly noted that it was not simply students' responsibility to initiate interactions; instead, faculty took it upon themselves to be visibly open and available, particularly because the capstone dynamic is often so different from the student–teacher relationships in previous courses. Such openness facilitated protection by creating an environment in which students were likely to approach their faculty when problems arose; it simultaneously facilitated coaching or counseling by increasing students' receptivity to feedback.

TABLE 12 Rapport practices

Practice	Representative quotations
Cultivate availability and approachability	Usually I make myself available to them. I show up in the computer lab in the evenings when I get done with work and get an overall pulse of how things are going and answer any questions that they might have. Made myself available via email, committed to them that I'd respond to any email question within 24 hours and try and address any questions, concerns, or comments that they might have if they arose. 40754/221
	Most important things I do . . . I mean, the thing . . . probably the most impactful thing I do is meet with each team every week. I think that really makes a big difference. 30522/153
Know students individually	I don't actually get to know the students until they're seniors, but then I've typically had them in the first design course and the [technical] lab, the senior lab, in the fall, and so I begin to get to know them individually and what their capabilities are then. And then in the spring I typically teach the capstone design and [another technical] course and they're taking that one either as juniors or seniors. So, I get to know them quite well individually by the time that year is over. 10169/39

3.9.2 | Know students individually

Participants also got to know students as people, seeking to understand not just their knowledge and skills but also their interests and personalities. Faculty described a variety of strategies for getting to know their students both inside and outside the course. In several cases, participants taught prerequisite courses and leveraged those encounters to build their knowledge of students. In cases where the capstone course was their first meeting, faculty talked with students formally and informally to get to know their habits, capabilities, interests, and work.

3.10 | Summary

Interviews with a broad spectrum of capstone faculty resulted in an operational taxonomy of nine functions with 28 associated practices, summarized in Table 13, that provide a comprehensive description of the current state of capstone teaching.

This taxonomy has subsequently been used in semester-long ethnographic work (e.g., Lutz et al., 2015) and a multi-case study that combined field observations with student and faculty interviews (Lutz & Paretti, 2017). In each study, the taxonomy proved sufficient to describe faculty practices and provided a fruitful framework for understanding student's learning experiences.

TABLE 13 Summary of functions and practices

Function	Associated practices
Challenge	Integrate previous learning
	Prompt new learning
	Provide realistic experiences
Protect	Select projects and teams
	Ensure accountability
	Know status of projects and teams
	Mediate
Coach	Provide instruction and feedback
	Model tasks
	Direct to resources
	Listen and question
Promote employability	Provide access to potential future employers
	Provide marketable skills, experiences, and materials
	Provide recommendations
Provide exposure	Showcase student work
	Foster interactions with professionals
Provide role models	Describe professional engineering experiences
	Share values
	Model behaviors
	Mimic the workplace
Accept and confirm	Promote ownership
	Foster a sense of accomplishment
	Encourage
Counsel	Negotiate team relationships
	Address individual performance
	Explore career options
Build rapport	Cultivate availability and approachability
	Know students individually

TABLE 14 Percent of participants reporting functions

	Challenging assignments	Protection	Coaching	Employability	Exposure	Role modeling	Acceptance and confirmation	Counseling	Rapport
Total ($n = 42$)	88	100	100	31	60	93	88	79	74
High ($n = 10$)	80	100	100	40	70	80	90	80	80
Mid ($n = 25$)	92	100	100	32	64	100	96	80	76
Low ($n = 7$)	86	100	100	14	29	86	57	71	57

3.11 | Patterns across participants

While the primary goal of this study was to develop an operationalized taxonomy of teaching practices, it is useful to highlight emerging patterns across functions and participants. First, while the taxonomy describes the functions independently for clarity, in reality they are tightly interwoven. In particular, the challenging nature of the assignments elicits the need for most other functions—particularly protection, coaching, acceptance and confirmation, and counseling. Similarly, the practices associated with protection are often the basis by which faculty determine subsequent interventions such as coaching or counseling. At the same time, the realistic nature of these projects, grounded in the role of capstone as a fulcrum between school and work, enables faculty to support students' professional and career development through role modeling, employability, and exposure. Finally, the rapport faculty build with students plays a key role in facilitating the other functions.

Second, though the size of the data set and the subgroups limits the significance of statistical analysis, several patterns based on experience level merit attention. As noted earlier, experience is a composite measure that included years of teaching, years in industry, and scholarly activity, with the levels being relative to the survey response population as a whole. Table 14 lists the percentage of participants in each category who reported practices associated with each of the nine functions.

Notably, eight of the nine functions were described by a majority of the participants across all experience levels, and seven were described by 70% or more. Only employability was described by fewer than half the participants. Most participants, moreover, described using at least six of the functions; both the mean and median number of functions by participant were 7, and no participant interview included fewer than five functions. These distributions suggest that the functions address the full breadth of work involved in teaching in capstone design, and that the functions and practices are used widely and integratively by faculty.

It is worth noting, however, that participants with less experience were markedly less likely to focus on both employability and exposure across all practices. Only one of the seven low-experience participants described a showcase event, for example, in contrast to 14 of the 25 mid-experience participants (56%) and 6 of the 10 high-experience participants (60%). Those with less experience were also less likely to describe practices associated with building rapport and with providing the acceptance and confirmation needed to keep students engaged throughout the project. In particular, at the practice level, no low-experience participants described knowing individual student characteristics, compared to approximately half of the medium (11) and high (5) experience participants. Similarly, only one low-experience individual described giving students a sense of accomplishment. In contrast, two-thirds of the participants in mid- and high-experience groups did so. And while low-experience participants reported role-modeling at the same level as other groups, at the practice level that role modeling focused on mimicking the workplace; none cited sharing values and only two cited describing workplace behaviors and practices, in contrast to 18 (72%) and 7 (70%) of the mid- and high-experience groups, respectively. Finally, while all faculty reported some form of coaching, faculty with low experience were markedly less likely to describe listening and questioning (2, or 29%, in contrast to 12 (44%) mid- and 6 (60%) high-experience participants).

Importantly, although we note these patterns for further exploration, we do so with caution; the goal of the study was to build the taxonomy rather than explore such patterns, and the number of participants in each group is too small to support statistically significant differences by any variable. Although we used stratified sampling to build a diverse pool across multiple factors, a wide range of variables beyond discipline and experience might account for these variations (e.g., programmatic factors such as size, types of project, typical post-graduation trajectories of students; faculty characteristics such as industry vs. academic experience). Moreover, participants may have used practices in their teaching that they did not articulate in the interview. As a result, more work is needed to understand variations in practices across individuals and contexts.

4 | DISCUSSION

Our research sought to identify and categorize concrete teaching practices used in capstone design courses from a functional perspective, and our analysis of interview transcripts with a diverse pool of 42 faculty both provides such practices and illustrates the complexity of teaching in this dynamic environment. The resulting taxonomy intersects with and enhances findings from prior research, capturing both the breadth of work suggested by Pérez et al. (2012) and the discursive complexity highlighted by Adams, Radcliffe, Forin, and Chua (2014); Adams et al. (2016); Yilmaz and Daly (2014); and others. For example, the practices outlined here not only address the six content domains identified by Pérez et al. (2012) (technology, arrangements, motivation, execution, meetings, and management), but also extend that work beyond course logistics to highlight the ways in which capstone faculty prepare students for professional work by creating environments that simulate work as well as through role modeling, exposure, and employability practices geared explicitly toward students' post-graduation roles.

At the same time, the taxonomy complements the richly detailed accounts of design review coaching sessions such as those provided by Tolbert et al. (2016) and Daly and Yilmaz (2016) by situating that coaching within the capstone experience as a whole. The coaching practices identified through our interviews encompass and extend the discursive practices identified in these earlier studies. Our work includes practices such as direct instruction that align with Daly and Yilmaz's (2016) characterization of feedback that promotes convergent thinking, as well as practices such as listening and questioning that align with feedback that supports divergent thinking; as Daly and Yilmaz (2016) explain, both types of discourse are central in design teaching and learning. Several of the practices, most notably in coaching, also echo the feedback categories defined by Gilbuena, Sherrett, Gummer, Champagne, and Koretsky (2015) that faculty use to address professional skills in a capstone course. Their discussion of corrective/directive feedback parallels the practice of direct instruction, whereas the practices of modeling, directing to resources, and listening/questioning offer more specific modes of what Gilbuena et al. call facilitative feedback. Finally, these practices echo those identified in problem-based learning research as supporting learning, motivation, and assessment (Barron et al., 1998; Savery, 2006; Thomas, 2000).

The data from this study also highlight the ways in which these localized discourse practices are embedded in the larger context of the capstone course as a place between school and work. Coaching practices derive from and depend on the ways in which capstone faculty solicit or create realistic projects and employ protective measures to support accountability and provide critical knowledge about student and project development. The ways in which these practices are applied, moreover, are shaped by the ways in which capstone faculty build rapport with students and create an environment that is simultaneously supportive and reflective of professional expectations.

The complexity of these interactions across functions and practices intersects with work by Adams et al. (2014, 2016) on the pedagogical content knowledge (PCK) enacted within design reviews, which are often key milestones in capstone courses. Broadly, PCK refers to the context-specific integration of domain knowledge and generalized pedagogical knowledge (Shulman, 1987). Adams et al. (2014, 2016) used a purposely selected set of design review sessions from three disciplines (choreography, industrial design, and mechanical engineering) to capture the ways in which faculty or other experts integrate multiple teaching techniques with content and procedural knowledge to support student learning. Their results illustrate a complex interplay among the needs of the students, the quality and status of the design under review, and the reviewers' knowledge of both design and teaching, an interplay they term "integrated knowing" (Adams et al., 2016, p. 34). Across the review sessions, the design coaches enacted this integrated knowing in ways that were highly adaptive and "improvisational" (their term) based on the local context.

Given the range of context-specific variations seen across a single type of interaction, the design review, it is not surprising, then, that across the entire span of a capstone design course, participants in this study frequently described designing courses (i.e., identifying projects, forming teams, setting milestones, planning showcases, identifying guest speakers) and interacting with students (coaching, counseling, role modeling, encouraging) in ways that were consistently tuned to the local context and the needs of individual teams and students. While a full analysis of participants' decision-making processes is beyond the scope of this article, even the small sample of quotations included highlight the centrality of context as participants described practices in terms of specific teams and situations. The functions and practices identified in this study thus illustrate the ways in which the capstone course embeds the already complex process of design teaching described by Adams et al. (2014, 2016) within an equally complex process of socializing students to professional engineering practice. In doing so, they reflect the rich, highly contextualized social interactions at the heart of situated learning and LPP (Lave & Wenger, 1991).

Given the situated, contextual nature of capstone teaching, the taxonomy presented here does not posit a set of "best" practices nor, we argue, would such a set be possible. Even the possibility of delineating "effective" practices is one that should be undertaken with caution because as the participants in our study repeatedly explained, no single practice is always good or bad; it might be tempting, for example, to suggest that to promote self-directed learning, capstone faculty should always direct students to resources, but some tasks, as our participants noted, are so far beyond students' current capacity that they require direct instruction. Providing students with a sense of accomplishment may help them move forward with decisions, but it might also leave them complacent about design flaws. One guest speaker might be an effective role model who helps students understand what to expect in the workplace, but a different speaker could easily become simply another lecture to check off before graduation.

Instead of "best practices," then, this taxonomy offers a common, concrete language for describing teaching in the context of the capstone design course as students learn not only to "do design" but also to "be engineers" in ways that encompass a full range of professional practices. Moreover, the functional orientation of this taxonomy, which organizes individual practices based on goals, provides a useful framework to help identify why capstone faculty might choose certain structures, assignments, and interactions; at the same time, by identifying concrete practices, the taxonomy describes specific ways in which a broad spectrum of current capstone instructors seek to achieve those goals.

5 | IMPLICATIONS FOR PRACTICE

While the taxonomy presented here has not been validated as a set of "best" practices, nonetheless we believe it has the following useful implications for capstone faculty nationally:

1. Capstone education moves beyond teaching design to include socializing students into the norms and expectations of professional work environments; faculty should account for this socialization in both the course structure and their interactions with students. Practices associated with challenging students, promoting employability, providing exposure, and providing role models are particularly salient.
2. To support the transition to work, faculty need to balance practices that challenge students with practices that protect them from project and learning failures. Such protection requires substantial attentiveness from faculty with respect to both the progress of the project and the dynamics of the team. In smaller classes, a single instructor may be able to maintain such attention through meetings and assignments, but in larger classes, individual project advisors are critical.
3. In preparing students for engineering workplaces, capstone faculty themselves serve as role models of practicing engineers. In a sense, all faculty are role models, but the emphasis on creating a professional environment makes this function particularly salient for capstone courses. Capstone faculty must learn to balance acting as engineering teachers to facilitate learning and acting as engineering managers to model professional workplaces.
4. Most of the teaching in capstone is not direct instruction but rather guiding students to learn, explore options, and reach decisions on their own. Capstone faculty need to become adept at questioning, listening, and guiding, and in doing so, they need to develop adaptive expertise to assess each team and issue individually and respond improvisationally to each situation. Such expertise typically develops over time as faculty work with different teams and projects.
5. Capstone teaching is highly relational, as evidenced by the rapport building, counseling, and acceptance and confirmation functions. While our participants enacted these functions differently based on context and personality, capstone faculty should be willing to engage with students individually and move beyond being only purveyors of information.

The functions and practices provided by this taxonomy offer faculty a concrete set of potential tools for addressing these implications. Moreover, given the increasing emphasis on large-scale program redesigns (e.g., through the National Science Foundation-funded Revolutionizing Engineering and Computer Science Departments program) that emphasize continuity across the curriculum, the taxonomy may also be helpful in identifying practices that can be embedded across all four years, particularly for project-based pedagogies, to enhance students' holistic professional preparation.

6 | LIMITATIONS

As with any project, this study has several limitations. First, while sampling strategies were designed to maximize variation, the initial survey pool represented only 40% of all accredited engineering programs, and participants volunteered for interviews. Although the data analysis reached saturation and the taxonomy has been subsequently validated through student surveys, student interviews, and observations (Lutz et al., 2015; Pembridge, 2011), there may be practices missing, and some practices included here may be less common nationally than in the sample population. Second, the taxonomy was developed based on retrospective self-reports of faculty practices and goals and, as such, may not accurately capture practices that could be identified through intensive ethnographic observation and in situ interviewing. Finally, the results represent a descriptive functional taxonomy, and neither the functions nor the practices have been studied to understand their effectiveness relative to student learning.

7 | CONCLUSIONS AND FUTURE WORK

The functional taxonomy presented here is, we argue, a useful comprehensive description of capstone teaching. At the same time, it represents only a first step in better understanding how and why expert capstone teachers integrate and adapt these functions and practices to individual student and team needs to promote learning. As the taxonomy makes clear, faculty roles in the capstone class move beyond conveying information and facilitating design learning. Functions such as rapport, acceptance-and-confirmation, and counseling, along with practices such as listening, encouraging, and knowing students individually, highlight the relational nature of teacher–student interactions in this course. Similarly, the importance of realistic projects and the prevalence of role modeling—and particularly the emphasis on creating a professional work environment—highlight faculty beliefs about the role the capstone course serves in transitioning students from technical coursework to industry practice.

At the same time, the complex interactions among functions and practices point to the need for more research to understand how course coordinators and project advisors use these practices to support learning in a variety of contexts. Subsequent research on this or similar data sets, for example, could use the taxonomy to explore faculty decision making around the integration and adaptation of the functions and practices. Case studies such as those developed around design review sessions could use the taxonomy to map the decision processes of expert capstone educators and potentially identify patterns linking faculty practices to student learning. Finally, because in large part the "effectiveness" of a capstone course is most evident in students' transitions to engineering workplaces, we need studies that follow participants from school to work to understand both what new engineers transfer across contexts and how that transfer happens. Capstone courses provide a key bridge between students' school experiences and their professional careers, and faculty who teach in these courses are the central architects of those bridges.

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