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Leveraging the Capstone Design Experience to Build Self-Directed Learning*

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Capstone design courses, an established component of undergraduate engineering curricula, offer students the opportunity to synthesize their prior engineering coursework and apply professional and technical skills towards projects with practical application. During this experience, capstone faculty enable mentored exploration, coaching students to navigate the design process to complete complex, open-ended projects. These projects typically require specific knowledge and skills that students need to independently identify and develop. Findings from our study of recent graduates during their first year of work suggest that this self-directed learning experienced through the capstone design process provides critical preparation for professional practice. In this paper, we examine self-directed learning in capstone and at work in detail, highlighting critical challenges in managing both knowledge and time. The findings point to important ways that capstone design educators can design projects and mentor students to help promote this critical skill.

Keywords: self-directed learning; professional preparation; capstone design; school-to-work transition; design process

1. Introduction and Background

Capstone design courses provide a critical opportunity for students to experience the design process in an authentic manner, serving as a dress rehearsal for engineering practice. These courses are meant to synthesize and expand prior technical coursework and promote practical application by enacting the design process in an extended (often full-year) real-world project [1–5]. Capstone experiences typically seek to replicate a professional engineering workplace [5], allowing faculty to coach students through a full design cycle and help them understand that design is a social process [6–9], with an emphasis on interpersonal and teamwork skills, technical communication, and project management abilities [4, 6, 7]. At the heart of these experiences are complex, authentic (often client-based) projects that require students to draw upon fundamental discipline-specific knowledge from previous courses, but also require them to seek out and learn new knowledge and skills relevant to their specific project [5, 10].

In the context of such projects, capstone faculty and project advisors provide students with an experience of mentored exploration through a full design cycle, guiding students to seek out and develop the knowledge needed to scope problems and generate, test, and refine solutions. Davis et al. highlight this information-seeking (or what previous ABET criteria referred to as life-long learning [11]) as a critical outcome of capstone design [6]. And indeed, capstone faculty intentionally seek to promote such learning; in their recent taxonomy of capstone teaching practices, Pembridge and Paretti [5] describe ways in which capstone educators both design projects to "prompt new learning" and intentionally help students develop strategies for finding needed information, including both searching for print/electronic sources and seeking out experts. That is, faculty not only create opportunities for students to learn and apply new material through the design process, but also provide guidance to help students identify what they need to learn and how to locate appropriate resources. Paralleling these expected outcomes and faculty intentions, students completing capstone experiences identify self-directed learning, or "learning how to do independent research, find and vet resources, and leverage contacts with other professionals to learn about project details" as a primary outcome of the course [10].

While engaging in ongoing learning is central to

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students' experiences in their capstone courses, questions remain about how and to what extent these practices transfer to professional work since most prior research stops at the end of the capstone course. Toward that end, in our recent study of individuals' transition from capstone design through their first year at work, self-directed learning (defined as as individuals' ability to manage and monitor their time and activities [12, 13]) emerged as the most common significant challenge reported during participants' first three months on the job [14, 15]. Equally important, our results also indicate that it was one of the most prominent practices our participants transferred from their capstone courses, particularly in their first three months of work [14].

Elsewhere we have reported these patterns at a general level [14]; in this paper, we unpack the data more deeply to better understand the ways in which students' experiences of mentored design practice in capstone courses support their ability to engage in self-directed learning at work. Two research questions frame our study:

- RQ1: What aspects of self-directed learning are most salient to new engineers as they transition from school to work?
- RQ2: What aspects of self-directed workplace learning are supported by the design process in the capstone course?

2. Methodology and Research Framework

This study is drawn from a broader research project that systematically examines the effectiveness of capstone design experiences relative to students' transitions from school to work. Specifically, we use a case study approach [16] to understand how and to what extent students' experiences with the design process in year-long, professionally-oriented capstone courses prepare them to enter engineering workplaces. As we have reported previously [14, 15, 17, 18], this large multi-case study [16] utilizes a longitudinal mixed methods design. Quantitative and qualitative survey data were collected during participants' first 12-weeks of work, in conjunction with interviews at the conclusion of capstone design, as well as after 3, 6, and 12 months of work.

2.1 Study Sites

Study participants were recruited from four universities, including three mechanical engineering programs and one engineering science program. Mechanical engineering provides access to one of the largest disciplines, nationally, with a strong post-graduation industry focus, and as our data demonstrates, students can move from mechanical engineering degrees into a range of engineering industries (land development, electronics, manufacturing, and more) and roles (project management, systems integration, research and development, consulting). The engineering science program, with equally diverse work paths, provides an important site for theoretical replication across cases [16]. The study includes two cohorts of students, spanning two academic years. Table 1 provides an overview of these four sites, including course duration, number of students, number of projects and sources, course assignments, pre-requisites, intern/co-op experience, and the employment sectors of study participants.

The four research sites share similar course structures that follow national trends [4]: 2-semester (or longer) course length, project partnerships with industry/government and faculty, and course deliverables that reflect engineering practice (e.g., reports, technical presentations, design reviews, and demonstrations of prototypes). Additionally, consistent with common practice among capstone faculty [5], each site focuses on simulating a professional workplace culture and includes leadership and teamwork instruction and feedback, multiple stakeholder coaching/advising models, a blend of formal and informal written and oral communication, and individual student responsibility and accountability.

2.2 Data Collection and Analysis

As detailed in full elsewhere [14, 18], to investigate transfer from capstone courses to engineering workplaces, we collected weekly short quantitative surveys of perceived preparedness and weekly reflective journals about challenges and strategies during the first three months of work. Hour-long semi-structured interviews were also conducted at the end of the capstone course and after 3, 6 and 12 months of work. Appendices 1 and 2 provides the weekly reflective survey questions and the interview protocol for the workplace interviews.

For this paper, we focus on the weekly reflective journals and 3-month interviews from Cohort 1. For this cohort, 60 participants completed interviews at the end of their capstone course, and 47 completed interviews after 3 months of work; between 34 and 51 participants responded to the reflective journal prompt each week. To analyze the data, we used both *a priori* and emergent coding [19] to understand what skills or strategies transfer from capstone to work. Prior publications highlight transfer in the four categories represented by the *a priori* codes: self-directed learning, teamwork and communication, technical engineering work, and identity development [14]. Emergent sub codes

Table 1. Capstone Course Logistics at Participating Research Sites [9]

Capstone Features	**Site A**	**Site B**	**Site C**	**Site D**
Course Duration	2 semesters	4 semesters	2 semesters	2 semesters
Discipline	Mechanical Engineering	Mechanical Engineering	Engineering Science	Mechanical Engineering
Advising Structure	Course instructor oversees; faculty advisors mentor teams (instructor also advises some teams)	Course instructor oversees; faculty advisors mentor teams	Course instructor oversees and advises all teams	Course instructor oversees; faculty advisors mentor teams
Number of Capstone Students	417 (20 in Study)	131 (18 in Study)	25 (11 in Study)	244 (13 in Study)
Number of Capstone Projects	51 (15 in Study)	20 (13 in Study)	7 (5 in Study)	29 (12 in Study)
Project Sources (in capstone class and in Study (S))	Industry: 16 (S = 7) Faculty: 19 (S = 5) Competition: 9 (S = 2) Humanitarian: 7 (S = 1)	Industry: 6 (S = 4) Government: 4 (S = 3) Faculty: 7 (S = 6) Competition: 2 (S = 0) Entrepreneurial: 1 (S = 0)	Industry: 6 (S = 4) Government: 1 (S = 1)	Industry: 24 (S = 10) Government: 2 (S = 1) Faculty: 1 (S = 0) Competition: 2 (S = 1)
Major Assignments	Reports (3) Presentations (4) Poster (1) Design Reviews (4) Product Demo (1) Expo (1)	Reports (6) Presentations (4) Poster (2) Design Reviews (2) Expo (2)	Reports (3) Presentations (3) Poster (1) Design Reviews (3)	Reports (5–8) Negotiated Reports (3) Presentations (6–9) Negotiated Presentations (3) Poster (1) Design Reviews (4) Expo (1)
Previous Design Experiences of participants	First Year Design Course, Sophomore Design Elective	First Year Design Course	First Year Design Course, Possible Electives with Design	First Year Design Course, Junior Design course, Sophomore and Junior Design Electives
Internship/Co-op Experience*	Optional (Study = 95%)	Optional (Study = 94%)	Optional (Study = 91%)	Optional (Study = 92%)
Employment Sector of participants*	Automotive (4) Defense (3) Consumer Products (3) Electronics (2) Design/Manufacturing (1) Other (7)	National Research Lab (4) Defense (3) Aerospace (1) Consumer Products (1) Electronics (1) Other (8)	Consulting (1) Electronics (1) Energy (1) Aerospace (1) Defense (1) Other (6)	Automotive (2) Structural Engineering (2) Defense (1) Aerospace (1) Electronics (1) Robotics (1) Other (5)

* Data for full graduating class is not available; data is reported here for study participants only.

provide a more nuanced understanding of each category. As noted, in this study we focus on self-directed learning; Table 2 summarizes the code and sub-code definitions for this category; we then grouped these sub-codes into two broad themes: managing knowledge and managing time, as indicated in the table.

2.3 *Trustworthiness*

To support trustworthiness of the analysis, all coders were trained on the codebook, with norming sessions conducted over multiple meetings to ensure inter-rater reliability and stabilize code definitions. Coders reviewed commonly-coded interviews to

Table 2. Description of Self-Directed Learning and Sub-Codes

Self-Directed Learning		Autonomous learning skills and dispositions, including doing independent research, finding and vetting resources, and leveraging contacts with other professionals.
Managing Knowledge	Finding Resources	Knowing what resources are needed for a task and/or where to find them
	Lack of Knowledge	Not having the information, skills, background, etc. to take on tasks; not knowing enough
Managing Time	Finding Work/ Keeping Busy	Finding things to do at work (e.g., during slow times or between projects)
	Time Management	Balancing time among different work tasks
	Time Pressure	Dealing with short/tight deadlines and/or a fast pace at work

compare results; discrepancies were negotiated to consensus and code definitions were modified as needed. The coding team also held regular meetings to ensure ongoing consistency, and the project leads also reviewed coded excerpts across coders as a further check. For a detailed explanation of the coding process, please see [14].

3. Results

3.1 RQ1: Salient Aspects of Self-Directed Learning at Work

As we have reported elsewhere [14], self-directed learning was the most frequently reported challenge in participants' reflective journals, with 92% of the Cohort 1 participants citing it at least once. Drawing on the three-month interviews, we present excerpts relative to the two broad themes within self-directed learning that were most salient during this period: managing knowledge and managing time. (Numbers in brackets after the excerpts refer to participants' ID numbers, site labels correspond with Table 1.)

3.1.1 Managing Knowledge

With respect to managing knowledge, participants described challenges in gaining new knowledge and finding resources.

Gaining New Knowledge. Self-directed learning was prompted for our participants when they experienced a lack of knowledge; virtually all of our participants described needing to learn new information rapidly in order to do their jobs as a significant challenge. The types of knowledge needed ranged from company-specific terminology or equipment to new technical concepts. For example, one participant talked about the need to learn all of the various pieces of equipment in her company:

> "I think the most challenging thing has been all the new material. So when I first got there, I knew nothing about the power plant or anything like that and very little about manufacturing processes at all. Since I got there, I had to learn about those two things. My first couple weeks, I felt like they were speaking a different language or something. They had all these different acronyms and everything, and I had no idea what they were saying. I think that was a really steep learning curve, just knowing different parts of the power plant." [3150, Site C]

Similarly, another participant described the biggest challenge in her transition to work as follows:

> "[. . .] getting up to speed on how the company runs and how our specific product line works has been the main challenge that I've been working at because we have four, five, six, seven, eight, nine, 10, 18 . . . I think we have about 12 different machines that have anywhere from 50 to 150 parts each in them, and everybody has the part numbers memorized and knows that, 'Oh, this machine runs with this pressure and this flow and has this combination of nozzles.' Like, there's so many different options that can go into each one of these 12 different machines. It's been staggering to try to keep up with all of it and start to learn, 'Okay. You're talking about the [part number]. That's the part that goes here and does this thing and oh, the problem's with that.'" [3151, Site C]

Another situated this need to learn in terms of the design work:

> ". . . we call them [sales] drawings, and they're pretty much like a model of a 20-foot truck or 40-foot truck, however big the truck is, that weighs like 30,000 pounds. And having that in a model and then looking at it with almost zero CAD design experience from school can be overwhelming. So I pretty much had to learn that, as well as my job at the same time." [1117, Site A]

This participant needed to learn both the equipment and the process of designing something he'd never learned to design.

For many of our participants, the sheer volume of information they needed to learn was overwhelming. As one reported,

> "The amount of work really surprised me and was very tough initially to overcome. The considerations, I never even considered for designing a plan. Just in order to get a quote for a product you have to know so many different things. You have to know [list of multiple criteria needed]. Just the mass of information that I didn't already know from school was surprising in the sense that there was so much I didn't know, if that makes any sense. That was surprising, that was tough, just having so much information thrown at me and just me being expected to know or at least being taught in minor ways, 'Hey you need to know this. Hey, make sure you know this. Hey make sure you get this,' was very tough to follow." [1111, Site A]

Finding Resources. As the comments above illustrate, our participants continually encountered situations that prompted them to learn extensively and come up to speed quickly in order to do their jobs. In the context of being confronted with so many knowledge gaps at so many levels, participants also noted that it could be challenging to locate the resources they need to learn or to complete their assigned tasks. One framed the challenge this way:

> "I guess taking initiative I guess is pretty big, at least in the job I'm in. You kind of get used to in school being kind of spoon fed. Even when you are taking hard classes you are spoon fed the problems, you have to solve, and then the way you need to solve them, like if it's in a textbook or Googling it or something. When you get out in the real world or get out in a job, literally it's like here is the job, and when it's kind of due, maybe, I don't know it might change. And even the job, like you don't even get the full, I have to scratch and claw to find CAD drawings. I have to scratch and claw to find details on what I actually, you know, specifications like

> you almost got to work to figure out what the question is then you work on solving it. The taking initiative part is really kind of tricky, at least in my opinion." [4137, Site D]

As evidenced by another excerpt from the same participant, a related issue involves the challenge of accessing the tacit knowledge that more experienced members of a company possess, and the frustration of considering a task complete only to find that gaps still remain.

> "Then I show it to him again, and he was like 'It looks good. Oh wait I forgot, you can't open the door like this, we are going to need hinges there or something.' So I have to go back and it just seemed like I made this table almost like seven times. I thought I was going into this just like, 'I'm making a table and I know you not going to know the details,' but I feel like asking people stuff and they were just like, 'I forgot this critical detail about this.'" [4137, Site D]

At the same time, the ability to locate resources to support learning was critical in helping participants fill their knowledge gaps. Most often, learning happened through talking with people, and our participants needed to learn to reach out, as the following comment illustrates:

> "'Go talk to people. If you need to learn something, the person's here. It's a big company. We've got a bunch of really smart people. Just find the right guy to talk to and they'll tell you what you need to know.' So that kinda forces a lot of conversation. I've ended up setting up a lot of meetings, going out and just, sometimes I'll even send a meeting like, 'I don't really need to know anything specific. I just wanna go talk to you about what you know' kind of meetings, and just talking to people, so doing that a handful of times, I've gotten pretty comfortable with it." [1119, Site A]

But not all resources were people; participants also reported using resources such as training videos, manuals, or company websites, which also posed challenges. As one explained,

> "In terms of my training, it's been all self-perpetuated. In any and all of the spare time I had when I first started working, which was a lot because no one really gave me stuff to do for the first few weeks, [Company] has this [internal online] page where they have a ton of videos and tutorials about [specific software], and energy modeling, and low calculations, and anything related to my work. I took a bunch of those. It's just so much harder learning from those, than it is in a personal setting with someone who's actually training you on specific things related to our office and what our office does. But they also have a subscription to Lynda, so any video that you ever find on there, you can request and they will download for you." [3145, Site C]

Summary

Across the board, our participants found both the need to gain new knowledge and the ability to find resources were central in their transition to work. One, responding to a question about advice for capstone students, summed it up as follows:

> "I think the first thing that comes to mind is don't lose or don't be afraid to ask questions and admit that, 'Hey. I don't know something.' Like, go into it being willing to ask questions 'cause I think I've learned the most so far by saying, 'No. I didn't quite understand that.' And you don't have to know everything. Like, they don't expect you to know everything right off the bat. So, that would probably be the primary piece." [3151, Site C]

3.1.2 Managing Time

In addition to managing their (lack of) knowledge, participants in our study also identified significant challenges related to monitoring and managing their time.

Time Pressure. One of the key challenges participants faced is related to the pressure of meeting tight deadlines, particularly when the deadlines were unexpected, as one participant explains:

> "I will be working on something and I will think I have a month to do it. And then we will sit down and they will be like we need this done by the end of the week. I'm like oh shoot, that would have been nice to know like two or three weeks ago or something like that." [4137, Site D]

In other cases, time pressure came in the form of emergent events, as another says:

> "Yes. So it was in the middle of a welding project, where I was sitting at my desk and, all of a sudden the principal engineer comes over and is like, I'm on this conference call with [inaudible], do you want to come over and help explain the project? And I was like, oh gosh. So that was the time where I felt completely unprepared, and he basically took me in and told somebody to explain to them what's been going on. So that was kind of difficult for me to remember everything all at once, without having that time to prepare before talking to them." [1122, Site A]

Unlike their structured college courses, participants routinely found themselves confronted with shifting deadlines and time pressures that required them to continually manage and re-adjust their work.

Balancing Multiple Tasks. Participants also reported significant challenges in managing multiple projects and deadlines and identifying priorities. As one explained,

> "Right now I'm getting pulled in like six different ways, which is a little challenging. I got in a meeting today at 7:00 am, and we got out at 5:00. Didn't even open my laptop until 5:00 today, and that's just a couple different things going on, so that's really coming down to prioritizing. I've got a couple big projects. I don't have a whole lot of time left in the rotation, so I've decided I'm gonna focus on those. The smaller tasks that are getting asked of me, I'm being pretty upfront in saying, 'I'll get these done if I have spare time, but if not, we're both in agreement that the big project is more important than getting these smaller tasks done,' so just

being upfront about where my priorities are, and realistic about what I'm gonna get done." [1119, Site A]

Similarly, another reported,

"I have a notebook where I'll write down everything from meeting notes to what I'm currently working on, measurements off of drawings that I'm updating. And so long as I keep a fairly up-to-date list of what I'm supposed to be working on, it's not too difficult to be self-directed, 'cause there's just enough check-in during meeting times to say, 'Oh, our priority should probably be on this project right now.' But, I haven't run into any issues where my boss will say, 'Why are you working on this and not this? This is more important.' I think, as far as prioritizing goes, it's gone pretty well 'cause it's usually fairly clear from the meetings what should be the most important task at any given time." [3151, Site C]

As these comments suggest, our participants needed to develop strategies to both track and prioritize their assigned tasks. But they also noted that time management at work differed from college because of the constraints of the work day. As one participant explained,

[In college] "I was able to stay up late working on something, whereas I can't bring my work home. I have to do it on a specific server. Then not necessarily working on the computer that much 'cause a lot of the work we were doing was hand[s] on, and pen to paper." [3153, Site C]

Staying Focused. While balancing time and attention across competing tasks was a challenge for many of our participants, many also struggled to stay focused on single tasks that were time-consuming and or tedious. They described challenges pertaining to boredom or the stamina required for workplace projects. In some cases, this challenge can result from the time participants have to spend on one or two projects, as in the following comment:

"I guess I would say the biggest challenge is just staying focused sometimes. [. . .] I only have two projects. And so I can kind of cycle through both of them, but at the same time it doesn't feel as refreshing. It's like doing the same thing. And also, these projects last about a year to a couple years. So just going through that for so long can really I guess in a way, it's not a stimulating. And so yeah I guess that's my biggest struggle just to stay on track and keep focused." [1123, Site A]

Challenges around focus also reflect the differences between college and industry schedules, as this participant explained:

". . . with school, I was so used to homework and stuff taking a couple hours here or there, but some of the things I'm doing now take multiple days or weeks to get done, where it's just an eight or nine hour slog every day working on the same thing. I think the reason why it's boring for me is because I'm not used to working on something for so long. Even if you look at most people's every day, they're on their phone, they're on this, they're on that, so they only have a certain amount of attention before they get bored. That's a struggle that I'm facing right now is just that it gets boring working on the exact same thing." [4126, Site D]

In still other cases, participants struggled to stay focused because, in contrast to those balancing multiple projects, they had little assigned work and did not know how to find meaningful tasks, as the following comments suggests:

"Work is pretty slow. The position I'm in is very mundane and very boring. I mean, if you talk to like anybody around, that's in the same like position that I am [. . .], they'll tell you straight out there's a lot of downtime. It's pretty boring. It's not what I was expecting at all." [1115, Site A]

"I guess the biggest difference, the one that I wasn't expecting, is how to deal with boredom, like when work is going slow, that's not something I anticipated necessarily, just because I mean there really wasn't a break senior year [of college], and now I have quite a few breaks. It's just interesting trying to pace myself differently and thinking of new projects to do when I have some free time and just, yeah, continuously keeping myself occupied." [3155, Site C]

Managing time at work thus involved both distributing time across competing tasks and filling time appropriately when tasks are routine or non-existent.

3.2 RQ2: Transferring Self-Directed Learning from the Capstone Design Process

As the previous section demonstrates, our participants described an array of self-directed learning challenges during their first three months at work as they struggled to manage knowledge and time. But they also reported multiple ways in which the extended open-ended design process that they experienced in their capstone course provided critical grounding for meeting these challenges. Drawing on capstone experiences was one of the most prevalent strategies used by participants to address self-directed learning challenges in the first three months at work. One participant summed it up as follows:

"I would say the best three things about capstone would be that it teaches you to manage your time and your resources really well. It teaches you to work with other people in a team to get a goal accomplished . . . third is learning how to find information that you don't already have, research, basically. Looking how to find information to get what you need done." [2159, Site B]

3.2.1 Managing Knowledge

One of the critical practices students found salient in their capstone design process was the need to continually and rapidly accumulate new knowledge, as the following comment illustrates:

"I guess the general . . . just being able to absorb new information very quickly, that's been the biggest similarity [between capstone and work], I think, and being able to retain that information and apply it to different systems. Just the general trying to figure out the next step before . . . Professor [Capstone] would always tell us to instead of waiting for your [industry partners], just jump into it, and then ask them what to do differently and how to improve the process and to essentially guide us into the right direction after we've attempted it. I think that's been a big part of the job as well, just because there are only like three leads, and there are like 20 of us, so it's hard for them to be everywhere all at once. It's like moving onto the next step, if I have a question to ask it, but also if I can't ask someone, just to try to figure it out, think through it logically, and just go through that process. I guess that's been the biggest similarity." [3155, Site C]

The capstone design process played a key role in helping many of our participants learn how to gain the knowledge they needed to address an unfamiliar problem. At the same time, it also helped build participants' confidence in this practice. As one participant explained,

> "I feel like in [Capstone], I got to learn a lot for the project because there was a lot of things I didn't know, and so I feel like it's helped me to realize that it's possible to learn everything and to complete a project even though I don't know much about it going into it. I feel like it's helped me to know how to ask questions and how to research things and to know what questions I need . . . it's helped me in that I feel like it's been similar. I feel like at work it's a lot faster because I'm working on projects for less time, and so I have to learn everything in couple of days rather than like the first two months of the project like [Capstone], but I feel like the process is similar. In [Capstone], I sort of went through a process of trying to figure out the project and then asking my liaisons and then try to figure out more about the project and going back. I feel like that sort of process is really similar because I get a project and think about it, figure out what my questions are and ask somebody. And once I get the answers back, look more at it, and it's sort of an iterative process in that way." [3150, Site C]

Participants also explicitly pointed to the practice of reaching out to experts as a key part of the capstone design process that transferred to work:

> "Right so in capstone design, our mentor was our technical contact at [Company] so if we had any questions we would contact [. . .] our technical lead or our technical advisor at [Company] and asked him, 'Hey, we don't know anything about this chemical hydrazine; can you give us more information, maybe give us a booklet on compatible materials?' and they'd point us in the right direction and we would go from there. It's almost exactly the same [as the process at work]." [2159, Site B]

As these comments suggest, the mentored design process in the capstone course helped students learn to recognize when they needed new knowledge and to seek out that knowledge. Notably, though, our participants also highlighted the ways in which the capstone experience developed their confidence in self-directed knowledge-building. That is, through the mentorship of their capstone faculty and industry partners, students learned that "it's possible" to rapidly come up to speed in ways that enable them to tackle unfamiliar projects.

3.2.2 Managing Time

At the same time, the capstone course also helped students develop time management skills for large, complex projects. In part, the process helped them simply learn to manage and meet deadlines in a professional context, as one participant explained:

> "So pretty much almost being able to work under the deadline; the stress of the deadline, I guess, is really what you got out of Capstone." [2170, Site B]

But experiencing the full design cycle also helped students build strategies for managing a long project over time, including breaking down and prioritizing tasks, as illustrated by the following comments:

> "With Capstone you're just kind of given an idea, take these semesters, come back with a product. We have guidelines, but at the end of the day you have to make it happen. I think that initiative, that you have to develop if you don't already have it, in senior design definitely translates to R&D. Because you have people throwing questions at you, you kind of have to decide what is the most important at any given time, go with it, but also find time to get the other things done." [1113, Site A]

> "At first it was a bit overwhelming but once you learn to just take a step back, take a breath and realize that it's the same thing that I was doing in college in Capstone, but just larger and I just did it the way I did it there. I took it piece by piece, I chopped it up, you know the saying how do you eat an elephant, bite by bite, keep your head down and keep moving forward and hope for the best." [2159, Site B]

> "I definitely think that, specifically my experience with [Capstone] really helps me excel in this job. Simply because, I was in the product manager position with my project. I really got that exposure to managing my time, managing the team's time. Did all things skill sets, regarding to scheduling, and a having constant communication with a point person at a customer site; as well as, just having those email skills, or those talking to people skills, that I developed over my senior year, through the senior design program." [4135, Site D]

The complexity of the projects and the need to manage time, tasks, and people over an extended period throughout the capstone design process provided critical workplace preparation for our participants as they transitioned from their capstone experiences to the demands of industry.

Notably, however – and perhaps not surprisingly – participants did not draw on their capstone course (or any other school experience) to help maintain focus during mundane or routine tasks. As they noted, the nature of university life, with multiple courses and extra-curricular activities interspersed through the day and into the evening makes it difficult to replicate this dimension of workplace experiences.

4. Discussion

As our participants moved through their first three months of work, many of their most significant challenges involved managing their own (lack of) knowledge relative to the tasks they were assigned and managing their time as they faced company deadlines, multiple projects, mundane work, and the constraints of an 8–5 workday. And in many respects, the capstone design process laid a critical foundation for this transition. It helped them learn to recognize and accept the need to learn new knowledge with each new project, to develop the skills and the confidence needed to seek out resources and question experts to build that knowledge, and to prioritize and coordinate tasks to accomplish long-term goals in a team environment.

These learning gains align closely with the learning goals of many capstone faculty, including those at the four sites from which our participants were drawn, in creating a professional work environment for the capstone course. By intentionally and explicitly structuring and guiding students through the design process, capstone faculty play a critical role in supporting self-directed learning for students, and, as our participants explained in their interviews, for new graduates beginning their careers. This intentionality mirrors findings from previous studies of design educators [20, 21]; in doing so, it points to important recommendations for faculty in structuring the design process, particularly in longer-term settings such as the capstone course that seek to build transferable workplace skills:

- Because a critical component of the design process for our participants was ongoing knowledge acquisition, design projects should be structured to intentionally promote new independent technical learning throughout the design process such that students have the opportunity to both recognize their need to acquire new knowledge and develop skills in directing that learning themselves.
- Mentors, including both course faculty and project advisors (industry and academic) should explicitly model and guide students in the process of seeking out and learning new information, particularly through engaging individuals with relevant expertise. While many students are used to looking up information on the internet, they may have less experience identifying and talking with experts to build their knowledge. Capstone mentors can play a key role throughout the design process in helping students develop the skills and the confidence needed to ask questions of key individuals, both by modeling that behavior and by guiding students through the process.
- Project management, now an explicit outcome in the current ABET criteria [22], is an essential component of the design process in capstone courses. Here, too, design faculty need to build ongoing accountability into the design process and provide students with both structures and strategies that build their capacity to manage and prioritize tasks across multiple people over time, and to manage their own time in the context of multiple, sometimes competing, aspects of a project.

5. Conclusions

The findings from our study suggest that self-directed learning is an essential workplace skill, one that can and should be supported and developed through the design process in capstone courses. Complex open-ended projects situate self-directed learning within the kinds of realistic contexts that students will experience when they become practicing engineers, and capstone design educators are well-positioned to scaffold this critical learning as they mentor students through the process.

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Appendix 1: Weekly reflective survey questions

1. What was your biggest challenge this week?
2. What made it so challenging?
3. How did you approach this challenge?
4. To what extent did you feel prepared for this challenge based on your capstone design experience? Based on other experiences?
5. Is there anything you think your education might have done that would have better prepared you?
6. Are there any other workplace activities this week that you felt particularly well or poorly prepared for? If so, please explain.

Appendix 2: Interview Protocol Early Employment (3, 6, and 12 months)

The interview will employ a semi-structured protocol, below, to prompt participants to reflect on the ways in which their capstone experience did and didn't prepare them for their current workplace experiences. Interviews will explore participants' experiences in the first few months of their job following graduation. Because this interview will come after previous data collection (initial interview, weekly workplace surveys, and, for 6 and 12 month interviews, after earlier workplace interviews), prompts may be tailored to follow up on comments or experiences identified in previous data.

The interview will begin with a review of the Informed Consent.

The protocol will follow the pattern below, but is semi-structured to allow for flexibility and exploration of potentially salient but unanticipated topics.

Introduction: As I mentioned when we reviewed the informed consent, what I'm really interested in today is exploring your recent experiences in your job and how they might relate to your capstone design experience.

1. Tell me a little bit about your job.
   a. What are your typical responsibilities?
   b. On a scale of 1–10, how prepared do you feel for these responsibilities?
   c. Please explain your rating. (Prompt participant to discuss capstone course versus other sources of preparation)
2. How much or what kind of training have you received for this work?
   a. If they had training: Tell me a little bit about that experience?
3. How do your work responsibilities compare to what you experienced in your capstone course?
   a. In what ways were your experiences aligned with your capstone course?
   b. In what ways were they different?
4. Thinking broadly, what has been challenging about this new job?
   a. What do you think makes that so challenging?
   b. How are you dealing with those challenges?
   c. In what ways did your capstone experience prepare you for those challenges? [Anywhere else?]
5. [Referencing short surveys] What skills have been necessary for you to do your job? Where did you develop those skills?
   a. Can you elaborate on those skills as they happened at work?
6. Based on your experiences so far, can you provide a definition or description of engineering work?

Now I'd like to talk in a little bit more detail about some things that you described in your weekly responses:

7. Based on [interesting survey response or prior interview comments], it looks like [this time] was pretty important for your transition. Can you elaborate a bit more on what was going on then?
   a. Researcher will have participant-specific prompts based on journal entries

Now I'd like to step back a little and talk more broadly about the transition from your capstone/senior design class to work.

8. Knowing what you know now, is there anything that you wish you would have learned about in capstone?
   a. Why would that have been important?
   b. Was there anything in capstone that you would take out or change?
9. If you could give advice to the next class of graduating seniors about what to expect when they enter their jobs, what would that be?
10. If you could give any advice to your capstone design instructor - including not only what to change, but what to keep doing – what would you say?
11. How was the process of responding to either survey? Was it boring? Worthwhile? What motivated you to respond?
12. Did you receive performance reviews from a supervisor?
    a. Would you be comfortable sharing those performance reviews with us or describing the feedback?
    b. Would you be comfortable with us sending [supervisor questionnaire] to your supervisor?

Thank you for your time, is there anything else you would like to add that we maybe haven't covered, as I try to understand how individuals experience this transition from school to work?

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