Resolving Epistemological Tension in Project-Based Introductory Engineering

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Introduction

A class of inductive teaching and learning methods—case-based, inquiry-based, problem-based, and project-based learning—are characterized by students' self-guided, open-ended engagement in ill-defined tasks designed to mimic authentic, domain-specific contexts (Prince & Felder, 2006). Rather than explicit introduction to content-specific principles and learning objectives, "instruction begins with…a set of observations or experimental data to interpret, a case study to analyze, or a complex real-world problem to solve," each of which serves to contextualize students' study of a given topic (Prince & Felder, 2006). As students navigate the open-ended, ill-defined task, they look up information and develop skills necessary for the successful completion of the task at hand and ultimately gain exposure to discipline-specific content. Inductive teaching and learning methods afford students the freedom to identify what information and approaches they deem pertinent to the successful completion of the task and the space to develop both their own methods of acquiring and representing this information and their own procedures for engaging in content-specific practice.

The student-driven nature of inductive teaching and learning methods is notably consistent with constructivist learning theory (Prince & Felder, 2006), which maintains learning is filtered through students' prior knowledge and new information is incorporated into students' already existing cognitive structures (Bransford & Schwartz, 1999). As such, pedagogies that afford students opportunities to engage and grapple first-hand with content through their participation in open-ended tasks are often more effective than traditional instructional methods in which students are introduced to content through lecture (Barron et al., 1998). Whereas students are passive recipients of information when attending lecture, when they actively engage with and construct knowledge by virtue of participation in open-ended tasks, they are motivated to learn information that will promote successful completion of the task. Importantly, this new information is connected more meaningfully to what students already know, as students have the opportunity to actively construct their understanding of new content in a contextually rich instructional environment.

Project-based learning (PBL) differs from other inductive teaching and learning methods in that students are assigned to engage in a number of smaller tasks as they work towards developing a final product (Prince & Felder, 2006). Whereas problem-based learning is a relatively narrowly focused pedagogical practice in which students are exposed to and develop a solution for a specific real-world problem, project-based learning is larger in scope and may encompass a number of problem-based elements, thus requiring more time to implement (Prince & Felder, 2006). Barron et al., (1998) suggest successful implementation of PBL can be accomplished by ensuring the following elements are incorporated: "1. Learning appropriate goals, 2. Scaffolds that support both student and teacher learning, 3. Frequent opportunities for formative self-assessment and revision, and 4. Social organizations that promote participation and result in a sense of agency" (p. 273). When successfully implemented, PBL is reported to increase students' interest in and motivation for studying content (Blumenfeld et al., 1991) in addition to promoting collaboration with peers, providing experiences in which students engage in authentic discipline-specific practice, and offering students latitude to develop their own models and representations of content (Krajcik & Shin, 2014).

Given the aforementioned benefits of the open-ended, student-centered nature of PBL, PBL is particularly suitable for implementation in engineering courses because its benefits are consistent with student learning outcomes specified by the Accreditation Board for Engineering and Technology (ABET), specifically the following strands from criterion 3 (ABET, 2015):

(b) an ability to design and conduct experiments, as well as to analyze and interpret data;
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;
(d) an ability to function on multidisciplinary teams;
(e) an ability to identify, formulate, and solve engineering problems.

As a pedagogical practice that supports these student outcomes, PBL fosters students' acquisition of skills necessary for industry employment (Kolmos & de Graaff, 2014; Mills & Treagust, 2003). Further, PBL is reported to improve student motivation, increase student retention, and enhance students' process skills in engineering (Kolmos & de Graaff, 2014).

Despite the reported advantages of implementing PBL in engineering coursework, it is also important to consider potential drawbacks. Given both the student-driven nature of PBL and the hierarchical nature of engineering knowledge, students may learn target content incorrectly and develop misconceptions that negatively impact their future study (Mills & Treagust, 2003). As such, although students may be better equipped to apply their knowledge of engineering content in a practical sense, PBL may lead to students "[having] a less rigorous understanding of engineering fundamentals" (Mills & Treagust, 2003). The nature of the differences between the advantages and disadvantages of implementing PBL in engineering coursework are epistemic in nature: students' success in a PBL environment, in which the onus of identifying and learning content relevant to a given discipline-specific task is on the student, is a function of how students consider, identify, and construct knowledge in instructional contexts designed to mimic engineering practice. As such, research into students' epistemological stances in PBL is instructive and can elucidate the ways in which PBL can be successfully implemented in engineering courses.

Prior work exploring students' personal epistemology throughout students' participation in PBL identified an epistemological tension in which students valued the opportunity to engage in tasks authentic to engineering practice, but struggled to identify what engineering competencies they learned (David & Marshall, 2017). Students' expectations for "doing school" were often discordant with PBL teaching methods, resulting in tension between how students considered knowledge production as "engineers" and how students considered knowledge production within a classroom context. Specifically, this epistemological tension arose as students navigated *practical* and *formal* epistemological foci in which they considered knowledge construction within academic settings and within authentic, discipline-specific practice, respectively. Students' understanding of what it meant to "know" engineering by virtue of their engagement in PBL was mediated by their expectations for "doing school" in traditional coursework.

Expanding upon this work, the present research paper draws from interview, observation, and survey data to explicate students' resolution of this tension after completing a project-based introductory civil engineering course. Specifically, during end-of-semester interviews, students articulate learning outcomes aligned with both course goals, such as understanding how to "[break] down complex problems into well defined sub-problems," and "Student Outcomes" specified by ABET such as "an ability to function on multidisciplinary teams" (ABET, 2015). Additionally, students describe how their understanding of these engineering concepts will impact their engagement in future coursework. This differs significantly from concerns students express during mid-semester interviews in which students were unsure as to what they learned through engagement in PBL and how their participation in PBL would aid them in future coursework. Such shifts in students' epistemological stances come about as students negotiate course requirements, such as quizzes and other assessments, and tailor their engagement in project-based tasks to meet these formalized course requirements. In making these adjustments, students develop strategies for engaging in project-based tasks such that they can navigate the practical requirements of the course and continue to find relevance in the tasks.

Literature Review

Most generally, epistemology is the branch of philosophy concerned with the study of knowledge (Sandoval, 2005). Psychologists and educators, however, are concerned with personal epistemology, which Sandoval (2005) defines as "the set of beliefs that individuals hold about the nature of knowledge and its production" (p. 636). Specifically, educational researchers seek to understand "how a student's underlying *beliefs about knowledge and knowing* are a part of the process of learning, and how these beliefs affect or mediate the knowledge-acquisition and knowledge-construction process" (Hofer, 2001, p. 354).

Personal epistemology has been hypothesized to take a variety of forms (for an overview of theories on personal epistemology, see Hofer, 2001; Hofer & Pintrich, 1997; Louca, Elby, Hammer, & Kagey, 2004). Perry (1970), one of the first scholars to theorize about the form of personal epistemology, argued that individuals progress through a series of well-defined stages in which they gradually come to view knowledge with greater complexity. Specifically, young children, in initial stages, view knowledge as fixed, and gradually mature to understand and view knowledge as flexible and subject to debate and revision. Expanding upon Perry's conception of personal epistemology, the reflective judgement theory of personal epistemology similarly describes epistemic development as an individual's progression through a series of well-defined stages (King & Kitchener, 1994, 2004). In the reflective judgement model, individuals progress through pre-reflective, quasi-reflective, and reflective stages, ultimately viewing knowledge as contextually-dependent and open to evaluation.

Schommer's (1990) beliefs view of personal epistemology purports individuals have a multi-dimensional view of knowledge and that each dimension varies in complexity and sophistication. According to this theory, there are five dimensions that can be used to describe individuals' beliefs about knowledge: "the structure, certainty, and source of knowledge, and the control and speed of knowledge acquisition" (Schommer, 1990, p. 498). According to Schommer's (1990) framing, these dimensions of personal epistemology are independent of one another, and an individual's beliefs about the nature of knowledge are relatively stable, making it difficult to change through instruction.

In contrast to the stage (King & Kitchener, 1994, 2004; Perry, 1970) and beliefs (Schommer, 1990) views of personal epistemology, which frame personal epistemologies as relatively stable structures that are difficult to change through instruction, the epistemological resources framework offers a flexible account of personal epistemology as "a collection of resources, each activated and appropriate in familiar contexts" (Hammer & Elby, 2003, p. 56). The resources framing of personal epistemology maintains that an individual's epistemological structure consists of a set of fine-grained, context-dependent elements that are cued in familiar contexts, much like the phenomenological primitive in the knowledge in pieces cognitive framework (diSessa, 1993; diSessa, Elby, & Hammer, 2003; Hammer & Elby, 2002). Hammer and Elby (2002) postulate "a framework of epistemological resources, smaller and more general than theories or traits, that can accommodate contextual dependence and provide an account of productive resources" (p. 415). According to the epistemological resources framing of personal epistemology, individuals have a variety of resources for understanding the nature and source of knowledge, epistemological activities, epistemological forms, and epistemological stances (Hammer & Elby, 2002). Since these resources are cued in different contexts, this theoretical framing allows for students to have coherent epistemologies that vary between these different contexts (Elby & Hammer, 2010).

Sandoval (2005, 2009) acknowledges the utility of the resources framing of personal epistemology and adopts this theoretical framing in his (2005) work exploring student epistemology in inquiry settings. Sandoval (2005) writes, "given the discrepancy between what students seem able to do during inquiry and the difficulty they have in articulating epistemological aspects of formal science, it seems more likely that epistemological beliefs are contextualized rather than coherent frameworks" (p. 648). The present work similarly favors the epistemological resources framework, as previously reported tension in PBL environments presupposes the context-dependence of students' epistemological stances and foci (David & Marshall, 2017). Moreover, this epistemological framing is useful to our purposes here, as we seek to characterize how students resolve tensions between various epistemological foci throughout their engagement in PBL.

Methodology

Participants in the present study were enrolled in one of two PBL sections of introductory civil engineering offered during the spring 2016 semester at a large research university in the Southwestern United States. Prior to the spring 2016 semester, introductory civil engineering, a requirement for all students seeking to major in civil engineering, consisted of two one-hour lectures per week supplemented by one three-hour laboratory meeting during which students completed standalone labs meant to supplement content introduced during lecture. In the traditional version of introductory civil engineering, guest lecturers specializing in one of the sub-disciplines of engineering—structural engineering, environmental engineering, transportation engineering, water resources engineering, geotechnical engineering, and construction engineering—were invited to offer students a general overview of their areas of expertise.

The curriculum for the PBL sections of introductory civil engineering was developed as a collaborative effort between civil engineering faculty and faculty in the university's college of education. Although the PBL sections of introductory civil engineering followed a schedule identical to the traditional version of the course (i.e., two one-hour lecture meetings and one three-hour lab session per week), the focus of the PBL sections of introductory civil engineering differed significantly from that of the traditional course. Rather than consisting of lectures that served to introduce students to information and separate lab meetings designed to allow students to apply these principles, participation in the PBL version centered around a semester-long cornerstone project in which students designed a multi-purpose event center. For the duration of the semester, students worked in teams of four during lab sessions to complete a series of activities that served to give students first-hand experience with the various sub-disciplines of civil engineering and contextualize their study of civil engineering. Lecture meetings similarly revolved around students' participation in the cornerstone design project and served as a space in which students could discuss their projects with their professors in greater detail. Indeed, students report that lecturers encouraged their participation and discussion, making the lectures take a conversational tone.

The multi-purpose event center design project consisted of five activities, summarized below:

1. *Overview of design project*. Students were tasked with developing two general designs of a multi-purpose event center, considering maximum capacity, ways for people and vehicles to enter and exit the property, and a layout of a general plan for the property.
2. *Water runoff*. Students created a 100-year flood plan in which they calculated the total runoff for a 100-year flood plan and designed two drainage systems, describing the advantages and disadvantages of each.
3. *Structures*. Students designed a simple 3D model of the building and produced elevation sketches for the front, side, and back of the building. Additionally, students were tasked with incorporating novel features to make the structure eco-friendly.
4. *Transportation engineering*. Students developed a comprehensive transport access plan detailing challenges of providing access to large quantities of people, constraints for the transportation access plan, and changes to the surrounding infrastructure necessary to accommodate the plan.
5. *Foundation design*. Students were tasked with using geotechnical principals to design a foundation that could support the structure of the multi-purpose event center.

In navigating and collaboratively engaging with these tasks, students' study of civil engineering sub-disciplines was contextualized by the multi-purpose event center design project. At the conclusion of the course, students prepared presentations showcasing their designs and mock-ups for the multi-purpose design center.

In total, thirty-two students were enrolled in the two PBL sections of introductory civil engineering. Of these thirty-two students, twenty-one gave informed consent to participate in interviews. Students were interviewed in groups of three to six at the mid-point and at the conclusion of the semester. On the day during which mid-semester interviews were conducted, twenty-one students were present, and on the day during which end-of-semester interviews were conducted, nineteen students were present. Interviews were semi-structured in order to allow for the facilitator to ask follow-up questions to students' answers. Moreover, the group interview afforded students the opportunity to engage with one another and to mutually evaluate their co-participation in the multi-purpose design project. Students' responses were coded using an analytical framework described in the next section. Two researchers coded student interview responses independently. Any discrepancies in coding were negotiated until researchers arrived at a consensus.

In addition to interview data, laboratory session observations were conducted four times throughout the duration of the semester. These sessions served primarily to provide researchers with an opportunity to evaluate students' engagement in the multi-purpose event center design project, and field notes generated during these observation sessions focused upon how students navigated the requirements for each activity and upon student interactions with group members.

An adapted version of the *Engineering Attitude Survey* (Prybutok, Patrick, Borrego, Seepersad, & Kiristis, 2016) also served as a way to evaluate the efficacy of implementing PBL in introductory civil engineering. The survey was administered at the beginning and end of the semester in order to gauge how students' conceptions of engineering changed throughout their participation in the course. Of the thirty-two students enrolled in the course, twenty-eight completed both the pre-and the post-surveys. The survey consisted of a series of Likert scale questions assessing students' perception of their own social and STEM-specific competences, identities as engineers, and prior experience with engineering and engineering professionals. Factor analysis of survey items resulted in five analytical constructs: mathematics self-efficacy, design self-efficacy, engineering interest, communication skill, and creativity. Comparisons between students enrolled in PBL and traditional versions of introductory civil engineering are reported elsewhere (Marshall et al., 2017), and survey results are used here primarily to support findings from interview data. Epistemological theorists and researchers note the close relationship between identity and epistemology (Boaler & Greeno, 2000; Danielak, Gupta, & Elby, 2014; Hofer & Pintrich, 1997), and factors of the *Engineering Attitude Survey* pertaining to students' identities and perception of their own competences within engineering serve as an important indicator of student epistemology in the course.

In initially analyzing student interview data, students' epistemic conflicts became evident as a central theme. As such, researchers turned to epistemological research in order to develop an analytical framework with which to evaluate interview data. A description of the analytical framework developed is provided in the following section. Moreover, a summary of the tension that students described during mid-semester interviews is provided. Finally, end-of-semester interview data, in which students describe that they achieve specific learning outcomes aligned with course goals, are presented and discussed.

Results

Epistemological Tension in PBL. Prior work describing epistemological tension in PBL introductory civil engineering operationalized features of the theoretical framings presented in Sandoval (2005) and Hammer and Elby (2002). Specifically, researchers identified the ways in which students use "resources for understanding the nature and source of knowledge" and "resources for understanding epistemological stances" (Hammer & Elby, 2002, p. 175 & p. 178). In identifying how students understand the nature and source of knowledge, David and Marshall

(2017) focus on how students consider knowledge as *propagated*—transmitted directly from a source—and knowledge as *fabricated*—deduced from other knowledge—within PBL (Hammer & Elby, 2002). In describing students' epistemological stances, David and Marshall (2017) analyze whether or not students describe *understanding* or *not understanding* information. Borrowing from Sandoval (2005), David and Marshall (2017) differentiate between students' *practical* epistemology, "the set of ideas that students have about their own knowledge production in school," and students' *formal* epistemology, "the set of ideas about [content-specific] knowledge and its production that students appear to have" in regards to "professional (formal)" practice (Sandoval, 2005, p. 636). Using this framework enabled researchers to analyze how students' stances toward knowledge depended upon their epistemological focus—*practical* or *formal*—and upon students' consideration of the source of knowledge.

When focusing on their *practical* engagement in PBL, students valued opportunities to *fabricate* knowledge afforded to them by virtue of their engagement in PBL. Moreover, students described that opportunities to engage in tasks that allowed them to *fabricate* knowledge ultimately resulted in their *understanding* of content. This finding also holds true for students' *formal* engagement in PBL. Students viewed their participation in the multi-purpose event center as authentic to engineering, and students described *understanding* the knowledge by *fabricating* it in ways contextualized by their design project. In contrast to these findings, however, students described that a lack of *propagated* knowledge—since students did not have a textbook assigned for the course and since professors and teaching assistants did not give students explicit information in response to their questions—resulted in students thinking they did *not understand* information as it pertains to their *practical* engagement in the course. Such a finding suggests that students expect that knowledge within a course should be able to be verified from a source, either a textbook or knowledgeable instructor, which serves to help students identify what, specifically, they learn. Without *propagated* knowledge, students were unsure of what they understood as it pertained to their success educationally, both in introductory civil engineering and in anticipating future courses, despite the fact that students viewed the opportunity to *fabricate* knowledge as enhancing their understanding of information as it related to their *formal* engagement with engineering practice.

Epistemological tension in PBL introductory civil engineering is also supported by survey data. Analysis of pre- and post-survey results revealed statistically significant changes in students' mathematical self-efficacy and design self-efficacy across the course of the semester (Marshall et al., 2017). Specifically, students' mathematical self-efficacy decreased and students' design self-efficacy increased over the course of their engagement in PBL introductory civil engineering. Although students used mathematical models in several of the activities of the multi-purpose event center design project, students reported their use of math was not challenging and instead intuitive. We argue students' use of math within a contextualized PBL environment is discordant with their expectations of school math, and students therefore do not perceive their use of math as valid. Contrastingly, because students engage in a robust design project, which they perceive as authentic to civil engineering practice, their design self-efficacy increases. The reported changes in mathematics and design self-efficacy are indicators of how students identify with these aspects of engineering practice and also their epistemic stances with respect to mathematics and design in engineering.

Resolving Epistemological Tension. Despite encountering an epistemological tension during their engagement in the multi-purpose event center design project, students ultimately come to value their participation PBL *formally* and *practically*. Rather than perceiving a lack of knowledge *propagating* resources as something that limits students' *practical understanding*, students more often describe *fabricating* knowledge through PBL as meaningful learning, both *practically* and *formally*. This is evident in two key findings from students' responses during end-of-semester interviews:

1. Students foreground their engagement in the multi-purpose event center, emphasizing its value in promoting their participation in engineering, and they focus less on the role of traditional tools of *propagation* play in their learning.
2. Through their participation in the multi-purpose event center design project, students identify that they have achieved learning goals specified on their syllabus and in ABET Criterion 3.

In substantiating these findings, interview data is presented with the date on which the interview was conducted, the group designation, the speaker, and the time stamp of the excerpt.

Although students' engagement in PBL introductory civil engineering centered on their participation in the multi-purpose event center design project, there were also formal assessments that were administered during the semester. Part of students' difficulty in articulating what they learned *practically* in PBL stemmed from their lack of familiarity with how they would be held accountable through traditional educational assessments, such as quizzes. After taking quizzes, however, students had a metric by which to measure the degree to which they learned *practically* by *fabricating* knowledge in PBL:

<u>April 27, 2016 – Group 1</u>

1:02	S3	I feel like after these tests, I think…I've learned more than I felt like I learned before because before when we… did the interview, we hadn't had exams.

<u>April 28, 2016 – Whole Group</u>

18:40	S3	I think they made a really good point with that: giving us the quizzes. I really actually appreciated it, the two quizzes. Now…understanding, especially after the first one, because I think everyone went into the first one pretty blindly, because we didn't have any structure beforehand, so were like, "Oh, we've been doing stuff for a really long time, but what stuff do we actually have to know? Like, what stuff is..."
18:59	S2	Yeah, what matters?
19:00	S3	Yeah, it was a bunch of stuff, you just didn't really compartmentalize it, or organize it for yourself, and really break it down and learn it. Not until after the first quiz, where you're like, "Okay, I see what I should know about different foundations and different history points, and landmarks in civil engineering" Or, you know, the different parts of the quiz. And then especially after when they let us re-take it, and then I was pretty ready for the second quiz. I felt like throughout that whole time, I kind of new how to organize what they were saying and really learn it. So I think, even just those two quizzes [have] completely changed how I learned from this course and thought about this course and handled it.

Quizzes served to validate PBL for students. Engagement in PBL required epistemological activity that was at odds with students' notion of how to construct knowledge in a traditional academic setting. Assessments, a key feature of traditional education, gave students a reference for how their engagement in PBL aligned with course goals and specified learning outcomes. As such, quiz-taking afforded students a metric by which to measure their own learning in PBL, and henceforth find value in their epistemological activity in *fabricating practical* and *formal* knowledge without *propagated* knowledge resources. Students' appreciation of opportunities to engage in self-directed learning through *fabricating* knowledge within the multi-purpose event center design project is evident in the following excerpts:

<u>April 27, 2016 – Group 2</u>

3:06 S3 Um, I think this class…we were dropped into a very simulated project thing…it's a situation where things we learned [are] different from just lectures and stuff, and we…learn from our mistakes, and figure out what to do with other people on our team. And just, I think that's a valuable learning style, learning environment.

<u>April 28, 2016 – Whole Group</u>

3:31 S3 I definitely thought, I guess when I signed up, when I first actually signed up for the class, I was thinking it would be textbook guided. So more of like, different section assigned each week. Because I think that's how the regular class is, right? I think it's more like that, where it's chapter by chapter, section by section, and that's what I thought it would be like. But yeah, I like how we started with [a] really vague big project, and you're like, "Oh, it's, you know, designing a building structure or whatever." It can go many ways. And we kind of scoped in each week and focused on a different aspect to see the different systems of civil engineering and to figure out how broad it is and how big it can be.

During end-of-semester interviews, students did not consider the lack of access to *propagated* knowledge as inhibiting, but rather characterized their open-ended engagement with the multi-purpose event center design project as an important aspect of their learning in the course. Moreover, open-ended engagement in the project afforded students opportunities to explore the breadth of civil engineering, rather than limiting their engagement with topics introduced to whatever information was provided during a lecture.

In addition to placing greater value in *fabricated* knowledge as a means for achieving *practical* and *formal understanding* (and in acknowledging that lack of *propagated* knowledge did not diminish learning), students also articulated that they understood civil engineering principles articulated on the course syllabus and in ABET Criterion 3. The following exchange is in response to a question asking students to explain what they know about how engineers solve problems.

April 27, 2016 – Group 2

10:29 S4 [W]ell they use models, and then the different methods that we talked about were analytical and numerical, where…you can just do straight up calculations, or you can actually gather information and infer something based on what you know.

10:56 S2 Uh, there's a lot of ethical and moral values that you need to consider of the community and of yourself. Especially this recent part of information that we're going over, that comes into play more than just what you're doing, because if the community doesn't like something, you have to change your entire problem and that solution could work here, but you move 20 minutes south, it works a different way over there because wherever you are, there's a different mentality and different values. So I think that was something that hit me big, it was like I can be working in this city, move to [a different] city and have to re-learn and re-process everything just for the solution itself.

11:47 S1 Just basing off that…I learned there's just a lot of more, there's many other factors that you have to consider for every activity we've done. There's just, "Oh, I didn't think of this, you have to include that." And it just, I don't know, I didn't think there was that much that went into it, factor wise, I guess.

12:06 S3 Yeah, I was going to pretty much say that…there's many different factors you have to take into consideration…all the people…organizations that are affected by a project, or budget concerns, environmental, or ethical concerns. It's everything that has to be factored in. It's like a complex problem every time.

In this exchange, students express that they understand differences between analytical and numerical models in addition to the importance of considering constraints on a project, including social, environmental, ethical, and budgetary constraints. Whereas students had trouble articulating expressly what they learned about engineering practice during mid-semester interviews, they articulate how they achieve understanding of these principles at the end of the engagement in the multi-purpose event center design project. In addition to these learning outcomes, students also express how engineering requires iteration, systems-level thinking, and the need to break larger problems into smaller problems in order to solve them, learning outcomes specified in the course syllabus:

April 28, 2016 – Whole Group

7:39 S1 They sort of mentioned this when the project started, but, um, they did mention that things were going to be really broad at first, or could be really broad at first, but then eventually had to scope in as we went through the project. And I think that's sort of how we dealt with the open-endedness. Um, it was sort of kind of broad, you know, just like, "this is essentially what, the design we want to make for the stadium," like, "this is where we want to place the stadium on the property, and…this area is going to be covered in actual land, this part's going to be concrete." But then from there, we say, "Well if we start with that, then where could we go or what would we have to change to still sort of keep that, but also continue trying to solve what we have to.…" So just using each previous point as a reference, I guess, sort of helped to solve the open-endedness, but also keep the systems approach.

8:39 S3 With that open-ended portion, like [S1] was saying, you kind of just had to start somewhere. Kind of just make a decision, and then do all the work, and then kind of use all that work to go back and justify or change the first initial assumption. So…you kind of just jumped past that open-endedness and you're just like, "this is what we're going to do." Decide on something, go from there, and then come back and kind of fix it.

Both students in the exchange above describe the iterative process of design in explaining the need to return to fix or alter elements of their design based on initial assumptions. Moreover, students describe how each aspect of their design fits with other aspects, and that even though it is important to break large problems down into smaller elements, it is also necessary to consider how these smaller elements function within the broader context of the project.

That students both acknowledge the role that *fabricating* knowledge plays in their learning and express their understanding of outcomes articulated on the course syllabus and in ABET Criterion 3 indicates students become more comfortable with the open-ended nature of PBL and resolve notions that engagement in PBL (*fabricating* knowledge without access to course sanctioned *propagated* knowledge) prevents valid learning. To the contrary, students articulate that open-ended engagement in the multi-purpose event center design project bolstered their understanding of engineering content and come to view their success on formal course requirements (e.g., quiz-taking) as a by-product of effective engagement in PBL.

Conclusion

Participation in PBL can be epistemologically unsettling: students are often accustomed to knowledge being produced and verified in a quite systematic (and arguably narrow) way after having participated traditionally in school. The *fabrication* of knowledge, which is encouraged in PBL, is discrepant with students' expectations of how to orchestrate their own learning in school, namely that students are recipients of *propagated* knowledge from a textbook or instructor. When students engage in PBL, they are forced to readjust their goals in learning and accordingly shift their epistemological framing of what knowledge is valued in a PBL environment and what steps are necessary in order to learn this knowledge. Ultimately, students come to view PBL favorably, and do not express the same level of epistemological tension that is reported during their earlier engagement in PBL. This is a favorable result that suggests students' epistemological shifts throughout the course of the semester promote a positive view of PBL both as it pertains to their *practical* and *formal* knowledge in the coursework.

While the results reported herein suggest that implementing PBL is advantageous, at least on the time-scale of students' immediate participation in the course, it is also necessary to evaluate how students' engagement in PBL impacts their future coursework. Moreover, as PBL continues to gain traction in engineering education, it will become necessary to determine the extent to which it prepares students for professional practice. If PBL can implemented such that it shrinks the gap between students' conception of school knowledge and professional knowledge, it is likely that implementing PBL more broadly can better equip students for careers in engineering.

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