Epistemological Tension in Project-Based Learning: Fabricated and Propagated Knowledge Through Practical and Formal Lenses*

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Similarities between the characteristics of project-based learning (PBL) and those of engineering practice make curricula incorporating PBL ideal for undergraduate engineering coursework. Given the suitability of PBL for engineering coursework, the present work explores students' epistemological stances within a PBL environment. Through semi-structured interviews with students enrolled in a project-based introductory civil engineering course, the present work explores how students mediate their engagement through practical and formal epistemological lenses. In particular, this report finds that students initially struggle to find academic authenticity in the project-based learning environment, suggesting there are tensions between both propagated and fabricated knowledge and between students' formal and practical epistemologies in engineering during their engagement in PBL. By the conclusion of the course, however, many students resolve this epistemological tension, finding value in active learning and identifying learning outcomes from the course syllabus.

Keywords: project-based learning; civil engineering; personal epistemology

1. Introduction

Project-based learning (PBL) is characterized by students' self-directed, collaborative, and open-ended engagement in academic tasks designed to mimic authentic, discipline specific practice [1] and aligns with constructivist learning principles [1, 2]. PBL also aligns with sociocultural learning theory [3], as students are required to engage collaboratively to address a task [4, 5]. A large body of work has explored the advantages and disadvantages of implementing PBL in engineering coursework with the general consensus that it has the potential to yield positive student learning outcomes when properly implemented [1, 6–9].

A number of studies have explored student response to the "active" learning required of students engaged in student-centered, collaborative curricula [10–13]. Notably, Yadav et al. [10] report students engaging in self-directed learning perceive that they learn less than they would in a traditional, lecture-based course. Felder and Brent [11] also acknowledge student resistance to active learning, citing literature likening the student experience in an active-learning environment to the psychological experience of dealing with trauma or grief. Felder and Brent [11] describe the source of students' negative response to active learning: "students, whose teachers have been telling them everything they needed to know from the first grade on, don't necessarily appreciate having this support suddenly withdrawn" (p. 43).

In contrast, Oakley et al. [12] provide a more encouraging picture of students' experience with self-directed, collaborative learning in the engineering classroom, concluding that working in teams is "positively associated with students' self-assessed quality of learning" (p. 271) and offering a number of suggestions for fostering effective teamwork in engineering coursework. Moreover, in a recent study on student response to active learning, Nguyen et al. [13] present survey data highlighting the relationship between students' responses to active learning and their expectations for and experiences with different types of instruction in addition to in class activities. They find little evidence to support the notion that student resistance to active learning stems from expectancy violation, or students' unwillingness to engage in active learning because of a general expectation that STEM coursework should be passive and lecture-based.

Given the importance of understanding student response to active learning curricula like PBL, we draw upon epistemological theory to explore student engagement with the PBL pedagogy in a more nuanced way. Specifically, we explore students' epistemic stances (beliefs about knowledge) in a project-based introductory civil engineering course. The use of personal epistemological theory to evaluate student engagement in PBL allows us to characterize student responses to active learning with greater attention to the subtle, context-specific ways in which students' engagement in PBL aligns

with their expectations for learning in STEM courses.

Data for this study were collected as a part of a broader research endeavor to evaluate the efficacy of a project-based curriculum in an introductory civil engineering course at a large, research university in the Southwestern United States [14]. Analysis of student interview data collected during this project reveals an epistemological tension in which students perceive their engagement in PBL tasks to be authentic to engineering practice but struggle to articulate what they have learned and fail to identify or acknowledge enhanced understanding of introductory engineering principles. Upon completion of the course, however, students articulate learning outcomes both specified on the course syllabus and expected in established standards for engineering programs [15], suggesting that at least some students are able to overcome this epistemological tension during their participation in the course and ultimately identify how their engagement in PBL is relevant to their study of, and future professional engagement in, civil engineering. Through our analysis, we propose *epistemological tension* (ET) as a construct that can help researchers frame student engagement in "active learning" with greater sensitivity to the nuanced ways in which students navigate these pedagogies and rectify such experiences with prior experiences in more traditional coursework.

2. Literature review

In philosophy, epistemology is the study of the construction, transfer, and validation of knowledge [16]. Goldman [17] explains, "epistemology deals with . . . the whole range of efforts to know and understand the world" (p. 13). Beyond purely philosophical considerations, understanding the cognitive mechanisms responsible for an individual's knowing in addition to the social processes through which people construct knowledge together is critical for understanding epistemology [17]. Toward that end, researchers are concerned with personal epistemology (PE), "the set of beliefs that individuals hold about the nature of knowledge and its production" [16, p. 636]. The nature and form of PE at a cognitive level, however, has been described in several different ways within the literature [18–20].

Predominant theories characterize PE's as existing in different forms: developmental stages; beliefs; and resources [18]. The developmental stage view of PE is analogous to Piaget's cognitive stage theory. Individuals' epistemologies evolve, becoming increasingly complex, as they mature through well-defined stages [18, 21–24]. Broadly, stage-based epistemological models maintain that individuals, initially viewing "knowledge as comparatively certain and gained from authority or direct observation" when they are children, ultimately "reach expert stages in which they see knowledge as constructed yet subject to scrutiny, judgment, and synthesis" [19, p. 58].

The beliefs view, put forth by Schommer [25], characterizes an individual's PE as a system of relatively independent beliefs organized into five distinct dimensions [25, 26]. Individuals' epistemic beliefs in each of these dimensions exist along a continuum, ranging from relatively simple views, such as the belief that knowledge is absolute, to complex views, such as the belief that knowledge can evolve and change [18]. Within the beliefs framework, an individual's epistemic belief system is a relatively stable, extensive structure that must first be broken down in order to stimulate epistemological growth.

A chief short-coming of the developmental stage and beliefs views of PE is that they conceptualize an individual's epistemology as a stable cognitive structure, resistant and slow to change. Moreover, work drawing upon these models reinforces the notion that epistemological development is difficult to achieve and positions students as resistant to changes and growth in their PE's [26, 27]. The epistemological resources framework challenges the stages and beliefs frameworks by viewing an individual's PE as consisting of a "Manifold Ontology of Resources" that depend upon context. The resources model is akin to diSessa's [32, 33] knowledge in pieces framework for cognition, in which individuals have subconscious cognitive units, phenomenological-primitives, that are cued when they encounter familiar situations. Similarly, rather than theorizing a stable belief system about knowledge that does not vary across context, Hammer and Elby [30, 31] postulate that individuals have a system of epistemological resources that are cued in appropriate and familiar contexts.

Louca et al. [19] also argue that the way in which an individual considers knowledge generation and evaluates the legitimacy of knowledge depends fundamentally on the context surrounding that knowledge. These authors illustrate the context dependent nature of an individual's PE in the following example:

> Consider a 6-year-old child's views about the source of knowledge. When asked how she knows what's for dinner, the child says, "Because Daddy told me!" This answer reflects an understanding of knowledge as something that can be transmitted from one person to another.
>
> However, asked how she knows her mommy brought her a present, the same child says, "I figured it out, 'cause it's my birthday and I saw you hide something

under your coat!'' This answer reflects a rudimentary awareness of knowledge as something constructed out of other knowledge. (p. 58)

Sandoval [20] critically analyzes all of these epistemological frameworks, noting that empirical evidence does not support the developmental stage and beliefs theories. Rather, Sandoval [20] acknowledges that the resource framework accounts for a possible effect of context on individuals' PE's and, as a result, for variation found in empirical data. Given the flexible nature of the epistemological resources framework and the ability of this framework to account for differences and changes in students' epistemological thinking from context to context within a classroom, the resources framework is used in the present analysis. We will argue that the tensions between students' PE's in a project-based introductory engineering course emerge due to resources being cued differently in varying contexts within the course. The discrepant ways in which resources are cued causes students to challenge what they know in some contexts yet still find legitimacy in project-based tasks.

3. Methodology

This study draws upon data collected as a part of a larger research endeavor initiated to evaluate the implementation of a project-based curriculum in an introductory civil engineering course at a large, public research university in the Southwestern United States [14]. Introductory civil engineering, traditionally taught as a lecture-based course, is a requirement for all students pursuing a major in civil engineering. In the Spring 2016 semester, two out of six sections of the introductory level civil engineering course piloted a project-based curriculum, described below. The curriculum was developed by two faculty members in civil engineering, who also instructed the course. Authors of the present work were tasked with monitoring student engagement in civil engineering in order to evaluate the efficacy of the project-based curriculum. The next section describes the development and scope of project-based introductory civil engineering, followed by a description of data collection and analysis.

3.1 Project-based introductory civil engineering

A primary goal of introductory civil engineering is to familiarize students with the six sub-disciplines of civil engineering: geotechnical engineering; water resources engineering; transportation engineering; structural engineering; environmental engineering; and construction engineering. During the present study, both lecture-based and project-based sections of introductory civil engineering held two 1-hour meetings and one 3-hour laboratory session each week. Since the curricular differences between the two courses were not published in the university's course catalog, students' self-selection into the project-based sections of the course did not reflect either favorable or unfavorable views of PBL curricula, but instead resulted from tangential considerations, such as section availability, constraints in students' schedules, or students' preferences for meeting times.

In the lecture-based sections of introductory civil engineering, faculty members with expertise in each of the aforementioned civil engineering disciplines delivered guest presentations introducing students to these sub-disciplines. Laboratory sessions, loosely correlated with lectures, provided students with opportunities to engage hands-on with select content introduced in lecture. Although labs were designed to supplement content presented in lecture, they were "stand-alone" in nature, lacking cohesion with other laboratory sessions throughout the semester. In addition to generating reports describing their lab work, students were assigned to read chapters from the course textbook and articles pertaining to specific civil engineering topics.

By contrast, students enrolled in project-based sections of introductory civil engineering rooted their study of civil engineering content around engagement in a semester-long cornerstone project, in which they were tasked with creating a design for a multi-purpose event center to replace the one currently on campus. In the cornerstone project, students completed a series of five activities structured to give them opportunities to explore the sub-disciplines of civil engineering. For each activity, students worked in groups to consider aspects of the design challenge and were ultimately required to prepare reports outlining how their design specifications addressed given constraints. Figure 1 depicts instructional material for *Activity 1*, in which students were introduced to the scope of the cornerstone project and tasked with sketching two "concepts" for a multi-purpose event center. A list of the five activities constituting the cornerstone project is provided in Table 1. These activities took place during weekly lab meetings, and 1-hour whole-class meetings were designed to supplement lab sessions by allowing students and instructors to discuss content relating directly to the project.

The development of project-based introductory civil engineering was motived by low retention in civil engineering in addition to a lack of vertical alignment of coursework required for the major. At the time the course was developed, civil engineering had one of the lowest retention rates among all engineering programs at the university in which

ACTIVITY 1

Acme Inc. is a corporation that is interested in buying a piece of land just South of Colorado river in Austin and turning it into a multi-purpose event center (see figure below for site location and layout). They have turned to your consulting firm to conduct a preliminary assessment of what can be built at this site. Your first activity is to develop a preliminary report with two potential concepts for this project.

Figure 1: Location of the proposed site

Constraints

1. This site is very close to the Capital view corridor and the client requires that no structure should exceed an elevation of 520 feet above MSL.

Requirements for the Report

As a minimum the concept report must address the following attributes:

1. The maximum number of visitors that the event center can accommodate along with the rationale and any calculations used to arrive at this number (for each option if needed).

2. A plan of how people would enter and leave the premises. Will everyone be able to park on site? How much parking would be available on site? How will excess parking, if any, be handled? (for each option if needed).

Fig. 1. Activity 1 for project-based introductory civil engineering.

Table 1. The five design activities in project-based introductory civil engineering

Activity	Description
1	Overview of design project—Sketch two concepts for a multi-purpose event center.
2	Water runoff—Develop a plan to handle run-off from a 100-year flood.
3	Structures—Design "modern looking" building and supporting frames.
4	Transportation engineering—Develop plan for how event attendees arrive and depart.
5	Foundation design—Design foundation to support the building load.

this intervention was implemented. Specifically, 55% of students entering the civil engineering major between 2005 and 2008 graduated with a civil engineering degree, and the three-year retention rates in civil engineering for students entering the major between 2007 and 2010 and between 2008 and 2012 were 59% and 65%, respectively. In addition to low retention in the civil engineering major, there was a general lack of vertical alignment between upper and lower division coursework required for the major in addition to a lack of cross-disciplinary integration between the various specializations within the major. Project-based introductory civil engineering was developed and implemented to remedy these problems. The civil engineering faculty who developed and instructed the project-based sections of introductory civil engineering conducted interviews with upper-division faculty and referenced published student learning outcomes for post-secondary engineering programs [15, 34] in order to develop course goals. Ultimately, the civil engineering faculty included the following student learning outcomes on the syllabus for project-based introductory civil engineering:

(1) understand breaking down complex problems into well defined sub-problems,

(2) understand the process of collecting information required to solve each sub-problem,

(3) find approximate solutions to each sub-problem,

(4) develop an inventory of knowledge compo-

nents that would be needed to perform a thorough optimal design,

(5) learn to work in a team,
(6) communicate effectively, and
(7) develop a context to better understand subsequent civil engineering base level courses.

3.2 Data collection

Data on student participation in project-based introductory civil engineering include in-class observations of laboratory sessions, results from an adapted *Engineering Attitude Survey* [35] administered at the beginning and at the conclusion of the semester, and group interviews conducted at the midpoint of the semester and again at the conclusion of the semester.

Laboratory session observations occurred four times throughout the course of the semester (twice for each section). They served primarily to provide us with an idea of the ways in which students engaged with the various activities and the factors influencing that engagement. Field notes generated during laboratory session observations focused on student collaboration, student interpretation of activity instructions, how students defined constraints within such activities, and how students worked to design final products within these constraints.

The *Engineering Attitude Survey* consists of a series of Likert scale questions assessing students' perceptions of both the civil engineering discipline and the engineering discipline writ large, their perceptions of their social and STEM-specific competencies as compared to peers, the degree to which students identify as engineers, and students' demographic information. Exploratory factor analysis was used to organize survey items according to five constructs: math self-efficacy, design self-efficacy, engineering interest, communication skill, and creativity. In evaluating the efficacy of project-based introductory civil engineering, Marshall et al. [14] compare pre-test and post-test results for PBL students in addition to comparing survey results for students enrolled in project-based and lecture-based sections. Although a total of 32 students were enrolled in project-based introductory civil engineering during the Spring 2016 semester, survey data represents 28 students who submitted both pre-test and post-test surveys. While survey data are not the central source in the present analysis, statistically significant differences between pre-test and post-test data, as reported by Marshall et al. [14], corroborate findings stemming from qualitative data analysis.

Semi-structured interviews at the midpoint and end of the semester served to gauge students' experiences and perceptions about their participation in PBL coursework. Although the interview protocol was not initially designed specifically to assess epistemic stance, it was structured in order to allow for a variety of student responses. Allowing for such flexibility in the interview protocol afforded researchers the opportunity to infer students' epistemic stances by virtue of students' explicit and implicit discussion of knowledge and learning in a PBL environment [18, 36]. Table 2 gives the interview protocol for the mid- and end-of-semester interviews. Students were interviewed in groups ranging from 3 to 6 students, which allowed for students to interact with and respond to one another in evaluating their personal and collective engagement in project-based introductory civil engineer-

Table 2. Interview protocol for mid- and end-of-semester interviews

No.	Question	Mid-semester	End-of-semester
1	Has Project-Based Introductory Civil Engineering* been what you expected from the introductory course in Civil Engineering? If not, what surprised you?	√	√
2	What has been the most valuable part of the course so far?	√	√
3	Is there anything that has not been valuable or something you would recommend the instructors change or delete?	√	√
4	Are there more things about being an engineer or about the Civil Engineering major you would like the course to cover? If so, what?	√	√
5	Have you had to use any physics, mathematics and chemistry for this course? More than you expected? Did you know or were you able to learn the physics, math and chemistry that you needed?	√	√
6	What have you learned so far (if anything) about how engineers solve problems?	√	√
7	In previous interviews, students mentioned access to resources would be helpful. Is this still something you think? How did a lack of "required" resources impact how you've participated in the design challenge?		√

* Modified in order to keep the course title anonymous.

ing. Group interviews lasted between 10 and 30 minutes. Generally, interviews followed the scripted questions in Table 2 with occasional follow-up questions to seek clarity regarding student responses and to ask students to expound upon ideas expressed in their initial responses to scripted questions.

Interviews were transcribed and coded independently by two researchers, and differences in interpretation were negotiated until researchers were able to reach consensus. All students participating in interviews gave informed consent to be recorded according to IRB protocol for the project. Of the 32 students enrolled in project-based introductory civil engineering, twenty-two students gave informed consent to participate in interviews. Twenty students were present on the days during which mid-semester interviews were conducted and nineteen students were present on the days during which end-of-semester interviews were conducted. Seventeen of the twenty students who participated in mid-semester interviews also participated in end-of-semester interviews.

4. Analytical framework

The analytical framework and coding scheme used to analyze interview data operationalized constructs outlined in the *Literature Review*. Specifically, we used three criteria to evaluate the nature of students' epistemologies in project-based introductory civil engineering: students' epistemological focus (their perception of the context through which they evaluated knowledge) [16], students' understanding of the "nature and source" of knowledge [30], and students' expressed epistemological stances [30]. Coding for epistemological focus allowed us to ascertain whether students considered their engagement in PBL an academic endeavor or akin to engineering practice. Coding for the "nature and source" of knowledge gave us insight into how students categorized knowledge they encountered in the PBL course. Finally, coding for epistemological stance served to gauge students' awareness of their own relationship to knowledge.

4.1 Personal epistemology and personal pedagogy

Prior to describing each component of the analytical framework in detail, it is important to address the potential conflation of students' beliefs about learning (personal pedagogies) and their beliefs about knowledge (epistemologies). Whereas Elby [37] maintains it is difficult, and limiting, to disentangle PE and personal pedagogy when framing and analyzing empirical data, particularly from certain theoretical perspectives, Sandoval [16, 35] contends that a theory of personal epistemology should be

distinct from an individual's beliefs about learning. Despite debating the degree to which an individual's ideas about learning overlap with an individual's ideas about knowledge, both Elby and Sandoval highlight the importance of distinguishing between individuals' PE's and their ideas about navigating expectations in school contexts [16, 34, 35]. Students' ideas about how best to succeed in an academic setting are not the same as their ideas about the nature of knowledge.

Chinn, Buckland, and Samarapungavan [39] define epistemic aims as the "goals related to finding things out, understanding them, and forming beliefs" (p. 146), suggesting students' comments about learning can be reasonably interpreted as articulations of their epistemic aims. In analyzing interview data, it is important to dissociate participants' comments regarding the ways in which they navigate course requirements and cater their participation within the course to align with their own and their instructor's expectations from participants' commentary on how their knowledge and understanding evolve throughout their participation in the course. Participants' discussion of their learning in a project-based environment was not immediately interpreted as being distinct from their PE as Sandoval argues [16, 35]. Rather, some student responses regarding learning were interpreted as epistemic in nature and coded as such. In these cases, students' commentaries on learning were indicative of their goals with respect to knowledge acquisition and reflective of their understanding of how to acquire this knowledge, activities that are epistemic in nature.

4.2 Epistemological focus

Coding for students' epistemological focus, defined here as a student's awareness or description of the context in which he or she considered knowledge, served as a way to discriminate how students framed a certain piece of knowledge. When evaluating students' epistemologies in educational contexts, Sandoval [16] distinguishes between how individuals consider knowledge and its production within specific academic or professional disciplines and how individuals consider knowledge and its production within the classroom. Specifically, Sandoval [16] identifies *formal epistemology*, defined as "the set of ideas about [content-specific] knowledge and its production that students appear to have" in regards to "professional (formal)" activity, and *practical epistemology*, "the set of ideas that students have about their own knowledge production in school" (p. 636).

Following this convention, student responses were coded as being *formal* if they described knowledge as being authentic to engineering practice or as

being *practical* if students described knowledge construction as it pertained to academic activity. Although coding for students' *practical* epistemology as that which concerns scholastic endeavors rather than professional endeavors may seem, at first, counterintuitive, this convention makes sense when considering that, for students engaging in coursework, evaluating knowledge in academic contexts is quite a pressing practical matter. By categorizing student responses according to students' epistemological focus with regard to the knowledge and/or form of knowledge production expressed during the interview, we could subsequently analyze students' epistemic beliefs in a PBL environment and attend to the context-specific focus evoked, namely whether students considered participation in a PBL task as academic in nature or as congruent with professional engineering.

4.3 "Nature and source" of knowledge

Among the variety of epistemological resources described by Hammer and Elby [30] are resources for understanding the "nature and source" of knowledge. These resources allow students to "understand what sort of thing knowledge is and how it arises" [30, p. 179]. Although students have a number of resources for understanding the nature and source of knowledge, the analytical framework used here adopted two constructs in particular: knowledge as *propagated* and knowledge as *fabricated*. Whereas *propagated* knowledge refers to students' understanding that knowledge is transmitted directly from a source, *fabricated* knowledge is deduced from already existing or expressed knowledge [30]. For example, if students discussed knowledge they obtained from a textbook or an instructor, that comment was coded as *propagated* knowledge. Alternatively, if students expressed obtaining knowledge by constructing or deducing it (i.e., through participation in the cornerstone project), the excerpt was coded to reflect *fabricated* knowledge.

Choosing to focus on students' awareness of *fabricated* or *propagated* knowledge was a deliberate decision meant to uncover how students considered knowledge generation within PBL. Specifically, focusing upon these two constructs afforded us the opportunity to understand whether or not students considered certain types of knowledge to be tied to certain instructional tasks (e.g., whether or not engaging in PBL was associated with *fabricated* knowledge).

4.4 Epistemological stance

Hammer and Elby [30] include resources for understanding epistemological stances in their framework. During interviews, students often expressed
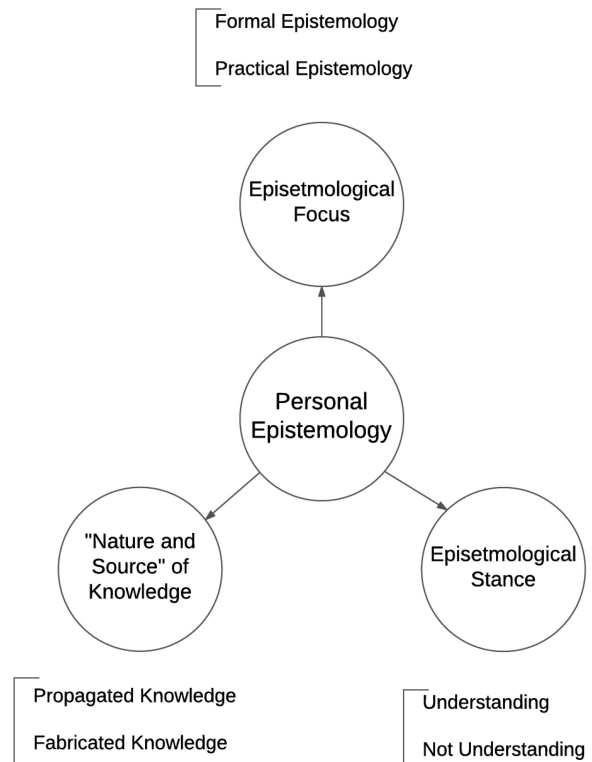

Fig. 2. Schematic diagram of the framework used to analyze interview data.

understanding or *not understanding* either factual or procedural knowledge. Students' comments pertaining to their epistemological stances towards knowledge were coded to reflect this *understanding* or *not understanding*. Doing so provided insight into whether or not students considered a given piece of knowledge to be effectively transmitted. Moreover, this allowed us to gauge whether students considered certain forms of knowledge to be more or less accessible. Fig. 2 provides a diagram of the analytical framework used to code interviews.

5. Findings

Using the framework outlined above, analysis of mid-semester interview data revealed an epistemological tension in which students perceived their engagement in PBL tasks to be authentic to engineering practice but questioned their academic understanding of introductory engineering principles. Specifically, students valued the opportunity to engage in open-ended exploration of engineering content but did not see how the cornerstone project would help them acquire the knowledge and skills they would need to be academically successful. By contrast, during end-of-semester interviews, students expressed satisfaction with their participation in the cornerstone project, both as it prepared them for the engineering profession and as it prepared

them for future academic study, emphasizing the benefits that self-directed engagement afforded to them on account of the PBL curriculum. Additionally, students discussed achieving learning goals set forth both in the course syllabus and in standards for engineering programs [15]. Such a transition is achieved, in part, as students navigated elements of traditional coursework, such as quizzes, and modified their engagement in the cornerstone project accordingly. In navigating these traditional course elements, students saw how PBL aligned with their expectations of traditional "schooling" and tailored their engagement in PBL to meet these requirements. Epistemological tension revealed during mid-semester interviews and the resolution of this tension are discussed in the next two sections with excerpts from interview transcripts provided to support our findings. Excerpts of interview transcripts are labeled with the interview date, interview group number, audio time stamp, and speaker label.

5.1 Epistemological tension in project-based learning

Three primary themes emerged from mid-semester interview analysis in regard to epistemological tension: (1) as it pertains to their *practical* engagement in introductory civil engineering, students described *understanding* content by *fabricating* knowledge; (2) relating to their *formal* epistemologies, students expressed *understanding* by *fabricating* knowledge; and (3) with a *practical* epistemic focus, students described that lack of

access to *propagated* knowledge resulted in *not understanding* content. Figure 3A consists of a Venn diagram displaying the percentages of students expressing views that align with one (or several) of these epistemic stances, described in detail below. The figure is meant to help visualize the prevalence and nature of epistemological tension during mid-semester interviews.

5.1.1 Practical understanding through fabricating knowledge

Generally, students valued opportunities to engage in the cornerstone project because it allowed them to explore content in a self-directed manner and to *fabricate* knowledge, which resulted in *understanding*. When responding to questions about the most valuable part of the course and about how the course differed from their initial expectations, students offered the following:

Day 1—Group 1
2:39 S2 The most valuable thing with having a class like this is having to figure out everything on your own. [The instructors] don't give you much guidance or instruction or examples. You just have to kind of figure it out.

Day 1—Group 2
1:14 S3 I love the fact that the class is more interactive. It's not just lecture based, just listening. I like how they make us all participate. The time when he [assigned] homework was pretty cool, because he made us take the lesson that we learned and apply it to everyday life.
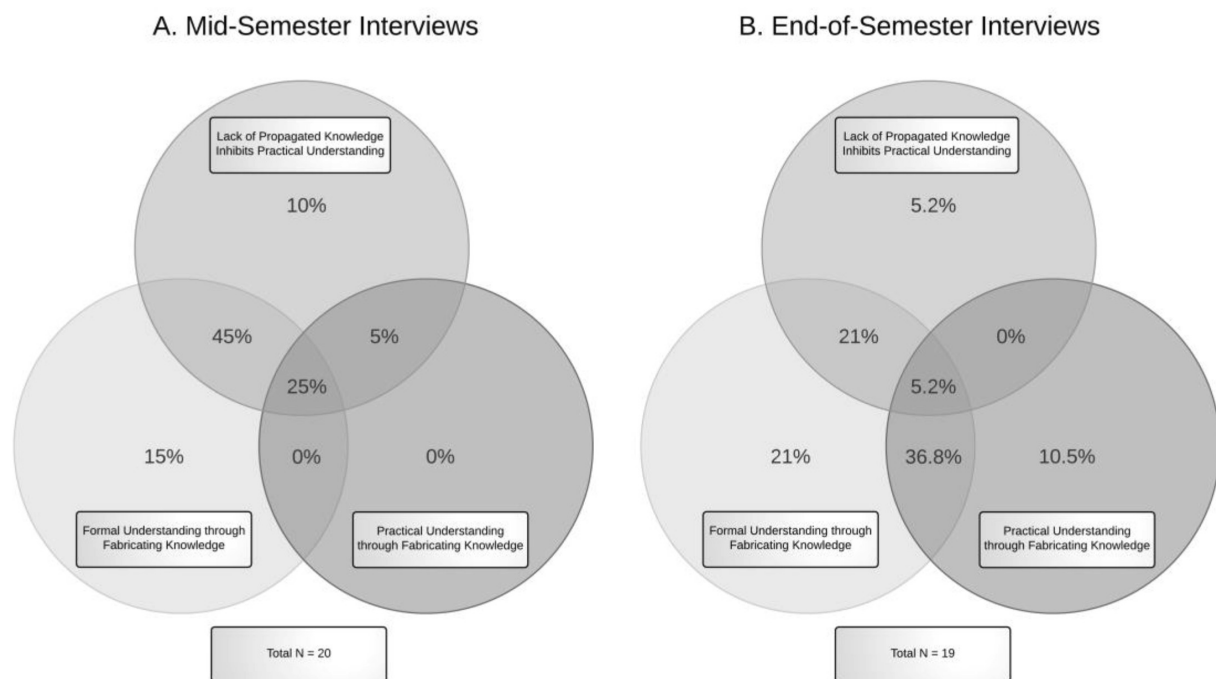

Fig. 3. Distributions of epistemological views during mid-semester interviews (A) and during end-of-semester interviews (B).

The opportunity to *fabricate* knowledge (e.g., "figure it out" or "apply [the lesson] to everyday life") is viewed favorably by students and considered a positive feature of PBL.

More specifically, several students (6 of 20) viewed their engagement in the multi-purpose event center project as an effective way to construct engineering knowledge such to successfully navigate course requirements (i.e., *practical* epistemological focus). When focusing on their *practical* engagement in the course, several students expressed that *fabricating* knowledge within the context of the multi-purpose event center project resulted in *understanding*:

Day 1—Group 2
2:01   S4   [In] normal lectures you just learn about [content], then hopefully you'll remember it for the test. Here it's kind of like, "Learn about it, now go apply it almost immediately," so you can remember easy . . . how all these things that we're learning take effect into what you're going to do.

Day 1—Group 4
2:36   S2   Instead of just studying for tests and learning about stuff, we have activities where we kind of do it; not completely in depth, but it's more hands on than it would have been. That kind of helps it sink in better. Later it'll be easier to reflect back on, because you're like, "Okay, I worked on a project for that [and] that's what you do when you're working in the field."

Day 2—Group 3
1:41   S3   I think that the way that they're teaching, I'm almost actually paying attention and getting the material into my brain instead of reading something that I'm probably never going to look at again.

In these excerpts, students described that *fabricating* knowledge by virtue of their engagement in the multi-purpose event center project led to *understanding* in such a way that supported their successful participation in the course. Specifically, students perceived their engagement in PBL to be more effective than "traditional" coursework, as it resulted in better *practical understanding* through first-hand engagement with content (i.e., *fabrication*).

5.1.2 Formal understanding through fabricating knowledge

In addition to considering *fabrication* of knowledge as an effective way to learn content necessary for navigating *practical* course requirements, students (17 of 20) also described the ways in which participation in the cornerstone project aligned with professional civil engineering and generated *formal understanding* of the engineering profession. Engagement in the cornerstone project gave students experience with engineering design, activity they perceived to be authentic to the civil engineering profession, and students highlighted the ways in which their participation helped them glean insight into the authentic work and activity of professional civil engineers:

Day 1—Group 2
2:35   S3   This project makes us think and learn how to work together as a group. It's a challenge because we're not actual engineers yet, we're not even seniors. You have to think about everything that some engineers have to think about. I like the challenge.

3:40   S2   It kind of puts us out there without necessarily giving us everything we need, so when we encounter problems, each problem we have is something we're going to experience.

Day 2—Group 2
3:26   S2   I think the lab is definitely the most useful thing, because when you hear about things that civil engineers have accomplished, or these are the kinds of jobs you can hold as a civil engineer, it's a lot harder to picture yourself doing it than if you're actually given a task where they tell you, "You are a civil engineering firm. Make us a building."

Day 2—Group 3
4:45   S2   I like doing the project and having to . . . sort of think like an engineer and come up with the ways we do things, like create the drainage systems and stuff like that. In the normal class . . . I probably would have just sat there and tried to memorize stuff, but not really think about how to make things work.

5:51   S3   I like the fact that we get to struggle like actual engineers, because engineers create; they don't just look at a piece of paper that has a list of things that you have to do and you do it. They actually figure out what we want to do with it and how to do it, and I think that's really important.

In these excerpts, students expressed that *fabricating* knowledge within the context of the multi-purpose event center project resulted in *formal understanding* of professional engineering. A major benefit of PBL for students was the opportunity to participate in a manner consistent with professional engineering, which afforded students the opportunity to foster *understanding* of professional practice. Whereas the first set of excerpts highlights students' epistemological stances as *practically* related to their engagement in the course, here students' responses are interpreted as acknowledgement that their engagement in the cornerstone project promoted *formal* epistemological growth. It is significant to note, however, that far more stu-

dents acknowledged the ways in which PBL was conducive to *formal understanding* than *practical understanding*.

5.1.3 Lack of propagated knowledge inhibits understanding

Although students found value in the opportunity to *fabricate* knowledge by virtue of their participation in PBL and acknowledged that *fabrication* led to *understanding* both *formally*, as it pertains to their conception of professional engineering, and *practically*, within an academic context, most students (17 of 20) expressed that not having access to *propagated* knowledge (e.g., direct instruction during a lecture or assigned readings from a textbook) resulted in students *not understanding* engineering content in a *practical* sense. Without *propagated* knowledge, students questioned whether or not they were learning content necessary for their academic success and were dubious of the academic authenticity of PBL:

Day 1—Group 1
5:20   S2   As far as the lecture goes, everything they talk about is super interesting, and it's engaging and stuff, but I don't know how much I'm really learning from their discussion. I don't know because I don't have something to study, and I'm not really necessarily taking notes, so . . . I don't know, it's just different, and I don't want to say that I wish we had the textbook to read, because that would be a lot more work, but—I don't know—I feel like maybe I would learn more with a set lesson.

6:46   S3   I would like it if they said buy this specific textbook about civil engineering projects so I can have something to go off of.

Day 1—Group 4
0:33   S3   I don't think they've completely gone into everything yet, but they do go into all the different aspects. But I think readings and stuff would have at least given us a bit more insight. Because we just kind of go in blind a little bit.

6:21   S3   I feel like it's a bunch of stuff we already kind of knew, and we're learning that that kind of thing has to do with civil engineering. There are some things that are new, like the different types of failures and the nomenclature for engineering. But other than that, I'm not sure how challenging they are wanting it to be. It's kind of nerve wracking that you don't know, like, am I just not absorbing what I'm supposed to? I'm not sure what's to be considered important or not.

Day 2—Group 3
4:45   S2   I wish we had little assignments so you know that you're learning some of this stuff at the same time. But, I guess, nothing difficult; just to make sure you are understanding the material that is taught.

5:29   S1   Generally when you leave a class, you have a textbook at your house, you have a Power-Point presentation to look over, you have some notes, you might even have a worksheet that you have to fill out. From the lecture class, I feel when I leave, I have some scribbled down notes, because it felt more of a conversation than actually like a presentation in a lecture setting. So, not really like, "Okay, this is, the objective for today." It's more like, "Hey, here's some more information about civil engineering." . . . But you're not really like, "this is what I should be taking; here's how it all breaks down, at the end of the week there's going to be a small assignment or a quiz." I feel like for a class like this, [that'd] be really helpful.

11:55   S1   [The course] has the points of a good lecture, a good presentation . . . I don't know if the actual material is there necessarily. Because you still leave empty handed, you know. The class, you still feel like it was nice to go—it's fun, it's engaging, it's a good time—but it's not necessarily like, "this is what I learned today," like leave with something in your hand.

These excerpts highlight that students expected *understanding* in a *practical* sense to be achieved with access to *propagated* knowledge rather than through the *fabrication* of knowledge (e.g., wishing for "little assignments" to ensure that "learning" is happening). Students questioned what they learned and what knowledge was to be considered important with respect to their *practical*, in class, engagement (e.g., unsure as to whether or not "actual material is there") because they were not told explicitly what to learn (e.g., "[leaving] empty handed"). Participants' expressed lack of *understanding* likely stems from the expectation that canonical engineering knowledge should be *propagated* rather than *fabricated*, leading students to question what they knew within the project-based learning environment. Students' discussion of *not understanding* content *practically* was coupled with an awareness of their lack of access to *propagated knowledge*, but did not holistically define their epistemic stance in PBL. Rather than persistent resistance to active learning in PBL, students found value in the cornerstone project, particularly as *fabrication* fostered *formal understanding* of engineering.

5.2 Resolving epistemological tension in project-based learning

In contrast to mid-semester interviews, during which students expressed an epistemological ten-

sion between achieving *understanding* through *fabrication* in PBL, but *not understanding* content due to a lack of access to *propagated* knowledge, responses of some groups indicated that this tension resolved by the conclusion of the semester. Fig. 3B gives a Venn Diagram of students' expressed epistemological views during end-of-semester interviews. Notably, the distribution of students' epistemological views shifts and becomes more concentrated in regions characterized by *practical* and *formal understanding* achieved through *fabrication* of knowledge. Such a shift supports the notion that students' epistemological tension resolved by the conclusion of the semester. While this resolution is by no means universal, it is notable that such a large number of students interviewed shifted their epistemological views over the course of the semester.

Two additional themes from end-of-semester interviews also support the notion that students' epistemological tension resolved by the conclusion of the semester:

1. Rather than emphasize how a lack of access to *propagated* knowledge hindered their learning in PBL, students described the advantages of *fabricating* knowledge during the cornerstone project.
2. Students described having achieved learning outcomes specified both on the course syllabus and in established outcomes for engineering programs.

Evidence supporting these two findings is provided below. Then mechanisms by which resolution of epistemological tension was achieved are explored.

5.2.1 Foregrounding the fabrication of knowledge

During end-of-semester interviews, students did not discuss the lack of access to *propagated* forms of knowledge (or how such a lack of access resulted in *not understanding* content). Contrastingly, several students (14 of 19) instead emphasized the benefits of *fabricating* knowledge by virtue of their engagement in the cornerstone project. In the following interview excerpts, students described how the *fabrication* of knowledge (e.g., "figuring it out") enhanced their ability to learn and led to deeper *understanding* of content:

Day 3—Group 2
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.

Day 4—Whole Group
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.

In reflecting upon the cornerstone project, students often expressed that they perceived participation in the project as distinctly more effective than participation in traditional coursework. Furthermore, students articulated that their participation in the cornerstone project resulted deeper *understanding* of civil engineering principles both *practically* and *formally*. This is further supported by the fact that students identified learning outcomes specified both in the syllabus and in established standards for engineering programs [15].

5.2.2 Identifying learning outcomes

During interviews, students were asked what, if anything, they had learned about how civil engineers solve problems. Notably, without referencing the course syllabus or any other materials (e.g., [15, 34]), most students (15 of 19) articulated learning outcomes specified on those documents in addition to aspects of engineering epistemology (as articulated by Grimson and Murphy [40] and de Figueiredo [41]) they considered to be typical of engineering practice:

Day 3—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 twenty 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 are] 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.

The excerpt provided above highlights students' awareness of several aspects of civil engineering practice: 1) that engineers engage different modalities when solving problems (e.g., "analytical or numerical"); 2) the importance of considering community needs (e.g., "if the community doesn't like something, you have to change your entire problem"); and 3) that engineers must consider a multitude of constraints when engaging in design. Moreover, students acknowledged that larger projects can be solved by first defining and considering smaller problems of that project (e.g., "[there are] many other factors that you have to consider for every activity we've done").

Students' awareness of these themes not only aligns with learning outcomes specified on the course syllabus, such as "breaking down complex problems into well defined sub-problems," but also with learning outcomes commonly used for engineering programs in the United States (the Accreditation Board for Engineering and Technology), for example the "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" [15]. That students independently identified learning outcomes specified on the course syllabus and in established outcomes for engineering programs, in addition to aspects of engineering practice that are consistent with engineering epistemology, such as engaging in "systems thinking" [41] or integrating engineering knowledge with general knowledge to engage in the design process [40], suggests that student participation in the cornerstone project resulted in *understanding* of civil engineering both *formally* and *practically*.

5.2.3 Mechanisms of epistemological resolution

Students' awareness of their learning over the course of the semester is achieved, in part, by seeing their projects come to fruition and reflecting upon their engagement in the cornerstone project holistically:

Day 3—Group 1
2:20   S3   Throughout the year I feel like we've all become more comfortable with the projects because everyone—in our group, at least, we all started out not really knowing what we were supposed to do—but it's gotten somewhere.

Day 4—Whole Group
1:59   S1   Also. . . this is something I just realized, I guess, recently because [the instructor] talked about systems. The title of the course is "———— Systems," and I guess I didn't really think of that part of the course—the fact that everything would eventually tie together. I didn't really expect that coming in. Even when we started the first project . . . I didn't see how it would go full circle by the time we reached the end. So that was also pretty impressive. Just the systems part of the course, I wasn't really expecting that, but, I guess from the get go it was a pretty extensive theme that went on throughout the class, and I don't think I'd be able to see it until the end.

As students engaged with the cornerstone project over the course of the semester, not only did students become more familiar with the cornerstone project but they also realized how component activities fit within the larger project. As expressed in the quotes above, such a realization served to elucidate, for students, the learning that had occurred over the course of the semester.

Students also cited formal assessments as course elements that helped them to see how their engagement in the cornerstone project aligned with traditional coursework. Prior to mid-semester interviews, students had not had any quizzes or exams, which some students considered disconcerting. By the end of the semester, however, students had completed two quizzes. The role these quizzes played in resolving epistemological tension described during mid-semester interviews is evident in the following interview excerpts:

Day 3—Group 1
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.

Day 4—Whole Group

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 we're 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 knew 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.

Whereas during mid-semester interviews, students experienced an epistemological tension between their *formal* and *practical* epistemological foci as they pertained to their engagement in the course, by the end of the semester students had quizzes to see how engagement in PBL aligned with their expectations for *practical*, in class engagement. In this sense, quizzes served to validate PBL for students because students were able to concretely understand how their engagement in the multi-purpose event center project aligned with their experiences of traditional coursework. Rather than struggling to articulate how to navigate PBL such to achieve *practical*, academic success during their initial engagement in PBL, after taking quizzes and seeing their projects come to fruition, students were able to articulate how their participation in the multi-purpose event center project helped them *practically* and *formally*.

6. Discussion

The nature of the epistemological tension identified in mid-semester interview data is one in which students valued the opportunity to engage first-hand in an engineering design task and perceived their participation as an opportunity to *fabricate understanding* of engineering knowledge, particularly *formally*, as participation in the project was likened to professional engineering. However, stu-dents did not engage in an experience in which knowledge was directly transmitted, or *propagated*, to them through lecture or access to resources (e.g., textbooks), which left students questioning whether or not they had acquired *practical* knowledge throughout their participation in PBL and unsure about what knowledge was to be privileged *practically* (in the academic context).

At the beginning of the course, students valued PBL in as much as they perceived it to be authentic to the civil engineering profession, however, students could not articulate the specific civil engineering concepts they *understood*. More specifically, students thought that there was more that they *should* be learning in order for their immediate and future academic success, but they could not identify what exactly it was they were not learning. The tension students experienced in finding *formal* worth in, but questioning the *practical* benefits of, PBL, was likely due to the fact that students were accustomed to a classroom experience in which knowledge is *propagated* from an established source, such as the instructor or a text. By participating in an unfamiliar PBL environment, students equated the lack of access to *propagated* knowledge with a lack of *practical* learning, despite finding *formal* value in an authentic design experience.

As demonstrated by the shift in the distribution of students' epistemological views between mid- and end-of-semester interviews (i.e., Fig. 3A to 3B), students increasingly came to value PBL both *practically*, as it related to their academic engagement in the course, and *formally*, as it replicated authentic civil engineering practice. Additionally, students commented favorably about the self-directed nature of participation in PBL, acknowledging the benefits of engaging in active learning. Finally, students also identified learning outcomes specified both in established outcomes for engineering programs [15, 34] and on the course syllabus and described aspects of engineering practice rooted in engineering epistemology [40, 41].

Although not universally acknowledged, students alluded to mechanisms by which epistemological tension is resolved during end-of-semester interviews. First, students acknowledged learning after seeing how each activity fit holistically within the broader cornerstone project.

Additionally, students discussed becoming more familiar with the project throughout the progression of the semester, which undoubtedly helped students to find value in PBL. Finally, students explicitly acknowledged the role that quizzes played in resolving epistemological tension. For some students, quizzes served to validate PBL by helping them to see how engagement in initially unfamiliar instruction aligned with their expectations for more tradi-

tional coursework. With this familiarity, students were able to tailor their engagement in the multi-purpose event center such that they could successfully navigate course requirements.

The qualitative analysis presented herein is also supported by survey data reported by Marshall et al. [14]. Specifically, Marshall et al. [14] report survey data suggesting that PBL students' design self-efficacy (perceived ability to engage in design) increases over the duration of the course, but that their mathematical self-efficacy (perceived ability to engage with mathematics) decreases. This is likely a reflection of the epistemological tension students described during mid-semester interviews. More explicitly, students perceived that their engagement in the multi-purpose event center project aligned with the civil engineering profession, and thus they reported increased design self-efficacy. However, given both that students likely experienced STEM coursework in a "chalk and talk" format and that PBL did not allow for the direct *propagation* of mathematical knowledge, students perceived their mathematical capabilities as being lower than that of peers.

While survey data serves to substantiate the nature of the epistemological tension described herein, it is limited in its capability to account for the resolution of this tension by the end of the semester. Though students acknowledge some mechanisms by which epistemological tension is resolved, it is also important to acknowledge that opportunities to reflect on their engagement in PBL afforded to students on account of this project may have played a role in the resolution of epistemological tension. Specifically, the timing of interviews was such that mid-semester interviews occurred when students were navigating the various activities that constituted the project as a whole, whereas end-of-semester interviews occurred when students had completed the project and could reflect on their experiences. In asking students about their understanding of engineering knowledge and their perceptions of the course, they were given a space to consider how smaller activities fit more holistically with the entirety of the cornerstone project. As such, interviews themselves may have played a role in prompting students to consider the academic (*practical*) and professional (*formal*) legitimacy of project-based coursework.

7. Conclusions

Epistemological tension provides a useful construct for understanding how students struggle to rectify their familiarity with traditional STEM coursework with the relatively unfamiliar open-ended, self-directed nature of PBL. That students think they are not learning fundamental engineering knowledge in PBL by the midpoint of the semester substantiates concerns articulated by authors exploring student resistance to active learning. However, that this tension can be resolved by the conclusion of the semester is promising, particularly considering the benefits of project-based coursework in ultimately reinforcing both *practical* and *formal* aspects of civil engineering. Understanding mechanisms by which this resolution occurs can inform design and implementation of PBL curricula in engineering.

This study is limited in that it investigated a small sample of students and only looked at two sections of one introductory civil engineering course. Additionally, this study is limited in that it was not designed specifically to investigate student epistemology. Rather, students' considerations of knowledge emerged during semi-structured interviews, prompting us to develop an analytical framework suitable for understanding students' reflections on their knowledge development and learning. Due to the limited sample size, generalizing findings about student's epistemological engagement in PBL is not possible. However, data indicate that students experience tension in navigating PBL, a finding consistent with other studies. Studying this tension using personal epistemology can serve to elucidate student engagement in PBL with greater sensitivity to the context dependent nature of their very engagement and can provide insight into "student resistance" to active learning reported in the literature.

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