Board 72: Discourse Moves and Engineering Epistemic Practices in a Virtual Laboratory

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Introduction

Laboratory activities have long held a central place in the engineering curriculum. These activities allow students to engage in valued disciplinary practices that are difficult to replicate in a classroom environment and are considered important to the formation of professional engineers (Balamuralithara & Woods, 2009; Brinson, 2015; Feisel & Rosa, 2005; Hofstein & Lunetta, 2004). Due to advancements in technology and other factors, such as the COVID-19 pandemic, new modes of laboratories have gained momentum in the engineering education space (Agustian et al., 2022; Feisel & Rosa, 2005; Koretsky & Magana, 2019; Ma & Nickerson, 2006; Van den Beemt et al., 2022). Virtual laboratories, where the activity is accessed through the internet and data is generated through simulation and not experimentation, are one such example.

What can be achieved in a laboratory can be conceptualized as the laboratory's affordances. Affordances, as defined by Gibson (1986), refer to the perceived and actual properties of a thing, particularly as related to functional properties that define how such things could potentially be used. This concept describes the contribution to student learning a specific laboratory can provide. Because many of the constraints of physical and virtual laboratories are better addressed by the other mode, they are often seen as having complementary affordances (Alkhaldi et al., 2016; de Jong et al., 2013; Kapici et al., 2019; Wörner et al., 2022). For instance, the virtual mode allows for remote access to content, quick generation of data, and new representations not possible in the physical mode (such as visualizing the movement of molecules). However, the mode also has drawbacks, including a lack of sensory feedback, often considered an important aspect of laboratory learning (Lazonder & Ehrenhard, 2014; Zacharia et al., 2012).

In addition to the affordances and constraints of the laboratory mode, the instructional design and resultant outcomes in a laboratory activity will depend on the conceptualization of what students will learn in the laboratory, which we term the learning orientation. The most common orientation in the analysis of learning during laboratory activities frames learning as the acquisition of skills or knowledge during the activity (Altmeyer et al., 2020; Farrokhnia & Esmailpour, 2010; Flegr et al., 2023; Gumilar et al., 2019; Kapici et al., 2019; Muilwijk & Lazonder, 2023; Olympiou & Zacharia, 2012, 2014; Zacharia & Michael, 2016). Acquisition can then be assessed after the fact, typically, using a test. The study presented here utilizes a different orientation which frames learning as participation in valued disciplinary practices. This orientation follows the "practice turn" in the learning sciences (Forman, 2018; Passmore et al., 2014) and frames participation in engineering practices (such as analyzing data, developing and revising experiments, and breaking down open-ended problems) as the crux of engineering learning.

The virtual laboratory investigated in this study was designed with such an orientation. The laboratory was designed to target the engineering practices the virtual mode afforded. This meant eliciting engineering practices by building opportunity for iteration into the laboratory, allowing students to perform multiple trials in a single laboratory period which wouldn't be possible in the physical mode.

Conceptual Framework

In this paper, we take the sociocultural view that learning is realized through more central participation in engineering disciplinary practices, such as designing experiments, analyzing results, and working effectively in teams. This approach contrasts with a common orientation taken in education research which views learning as the acquisition of conceptual understanding (Brinson, 2015; Muilwijk &

Lazonder, 2023; Wörner et al., 2022). Our approach therefore views learning as an active process in which students' habits, behaviors, and dispositions are changed through their engagement in practice (Duschl, 2008; Kelly & Licona, 2018). Therefore, we need a framework to characterize both practice and interaction. To do this, we look at practice through the lens of engineering epistemic practices (Cunningham & Kelly, 2017; Kelly, 2008) and interaction through the lens of discourse moves with practical epistemological analysis (PEA) (Wickman, 2004; Wickman & Östman, 2002). Epistemic practices are used to characterize what practices students are engaging while PEA situates this practice by identifying the specific need that students are addressing at that moment as they progress in their work.

First, we identify the *engineering epistemic practices* in which students engage in the laboratory activity. Engineering epistemic practices are the socially organized and interactionally accomplished ways in which engineers develop, justify, and communicate ideas when completing engineering work (Cunningham & Kelly, 2017; Kelly, 2008). Epistemic practices can be divided into three categories: material, conceptual, and social (Chindanon & Koretsky, 2023; Koretsky et al., 2023; Pickering, 1996). Material practices refer to interactions with the material world, such as through observation, measurement, and production of design artifacts (Bogen & Woodward, 1988; Furtak & Penuel, 2019). Conceptual epistemic practices refer to interactions with theory and the development of models (Giere, 1999; Pickering, 1996; Windschitl et al., 2008). Social practices refer to interactions with other humans in the context of completing engineering work (Bucciarelli, 1988; Cross & Clayburn Cross, 1995; Trevelyan, 2014). Others have developed lists of specific engineering epistemic practices, such as: investigating uses of materials, applying science knowledge to problem-solving, and communicating effectively (Cunningham & Kelly, 2017). These practices can be thought of as examples of material, conceptual, and social practices, respectively. By aligning instructional design with the affordances of a given laboratory mode, our past work showed we were able to target a desired subset of engineering epistemic practices (Gavitte, in review).

Epistemic practices allow us to classify the types of practices that students engage in, but alone do not connect students' engagement to a larger narrative of learning throughout the laboratory task. This analysis provides information about what epistemic practices are being used but lacks context of how those practices serve the team's progress in the engineering task. To better understand how students apply these practices, PEA is used to identify the discourse moves students use to address their identified needs as they attend to the goals of the activity (Wickman, 2004; Wickman & Östman, 2002). PEA revolves around four concepts: relations, gaps, standing fast, and encounters. *Relations* are the connections built between actions and pieces of knowledge in the process of learning. *Gaps* arise when relevant relations must be established to make meaning and progress in the activity. Relations that are established beyond doubt and do not need to be explained are thought of as *standing fast.* Many gaps are implicit and immediately filled with relations that stand fast, while explicit gaps are those that are socially acknowledged and require new relations to fill. Social or material interactions in which gaps are identified and filled with new relations are *encounters.* By looking at how epistemic practices are used by students to identify and fill gaps during the task, we look to characterize how students are using practices to progress and learn moment to moment in the laboratory. The practices students engage in during the laboratory task may change and evolve to address different gaps.

This analysis looks to observe how engineering epistemic practices are used by students to identify and fill gaps when completing a virtual laboratory activity. We seek a characterization that more expansively interrogates laboratory activity than the acquisition of knowledge and skills. In this work we will seek to answer the following research questions:

1. What epistemic practices does a team of undergraduate engineering students utilize during an industrially situated environmental engineering virtual laboratory task?
2. What gaps does the team identify in order to complete the task?
3. In what ways do the epistemic practices support the team to address the gaps?

Methods

Participants and Setting

The virtual laboratory was delivered to junior and senior engineering students in an upper-level engineering laboratory course. It was delivered during a three-hour laboratory period to four groups of three students. All students provided informed consent. The laboratory was completed in a dedicated room where all students in each group worked on the same computer while communicating in-person.

The virtual laboratory was designed to be industrially-situated, placing students in the role of engineers being contracted by a drinking water plant to address concerns caused by a recent storm event. In this situation, students are tasked with running jar tests to calibrate the dosages of chemicals to optimize removal of contaminants from the water impaired by stormwater runoff. Jar testing consists of a bench-scale analysis of coagulation, flocculation, and sedimentation, three of the major unit processes in a common drinking water treatment approach. To do this, a coagulant (in this case aluminum sulfate, alum for short) along with a pH controlling substance (in this case hydrated lime) are added to contaminated water and rapidly mixed. In this step the coagulant reacts with the water contaminants, neutralizing their surface charge. The water is then slowly mixed for thirty minutes, this is the flocculation step where the contaminants collide and form into larger flocs. Finally, mixing is stopped and the large flocs that formed are allowed to settle to the bottom, leaving cleaner water on top. The effectiveness of these processes will depend on the initial conditions of the water and the dosage of chemicals added.

The stated objective of the laboratory activity is for students to find an optimal dose of alum and lime for the water sample provided in the problem statement. Students are given an imagined workday to complete this task, allowing for a maximum of four jar tests to be run. The virtual laboratory simulates the results for each test, allowing for data to be provided immediately when students run a test. This feature allowed for multiple jar tests to be run in a single laboratory period. In a physical laboratory environment, a single jar test would take almost three hours to complete. Students were not given any explicit recommendations for which doses they should run, but rather needed to use engineering skills, and results of their past tests to iteratively develop an experimental plan capable of obtaining and justifying an optimal dose of chemicals for the process.

Data Collection and Analysis

Data were collected in the form of audio and video recordings of students during the entire time working on the laboratory. Audio was collected with speaker phones placed in the center of the desk. Video was recorded of both the computer screen running the virtual laboratory and the students as they worked. Other forms of data were collected for the larger project, including the written reports groups submitted and transcripts of individual interviews with participants. For the purpose of the analysis presented here, these forms of data were not considered; however, they did influence our thinking about how students approached the laboratory activity.

Video transcripts of laboratory work were transcribed verbatim and broken into thematic episodes. In previous work (Gavitte, in review), episodes were systematically coded to quantify and categorize the types of engineering epistemic practices that were elicited by students while completing the laboratory work. In this study, we build on that analysis by elaborating on the nature of those epistemic practices and seeking to connect the practices to the temporal context in which they appear through the opening and closing of explicit gaps. For this analysis, we focus on a single group's virtual laboratory record; the intent is to provide a methodological and theoretical anchor to approach the remaining data corpus.

Results

In this section, we first present the specific conceptual, material, and social epistemic practices that the group demonstrated while completing the laboratory. We then present two examples which exemplify how epistemic practices were used by students to identify and fill explicit gaps that arose as they progressed through the laboratory activity. The first example addresses how students determined the process parameters for their first run of tests. In the second example, students reason through the coagulation and flocculation mechanisms for different chemical doses.

Engineering Epistemic Practices

In our past work (Gavitte, in review) we looked at the engineering epistemic practices students engaged in when completing the laboratory. Specific practices were identified and grouped as either conceptual, material, or social. In total, the group studied here engaged 112 conceptual, 54 material, and 215 social practices during the two hours they spent working on the virtual laboratory activity. The overall practice counts are useful for getting a general idea of what is occurring in the laboratory, but seeing the specific types of practices engaged provides deeper meaning. Figure 1 shows the distribution of the specific code types for conceptual, material, and social epistemic practices.

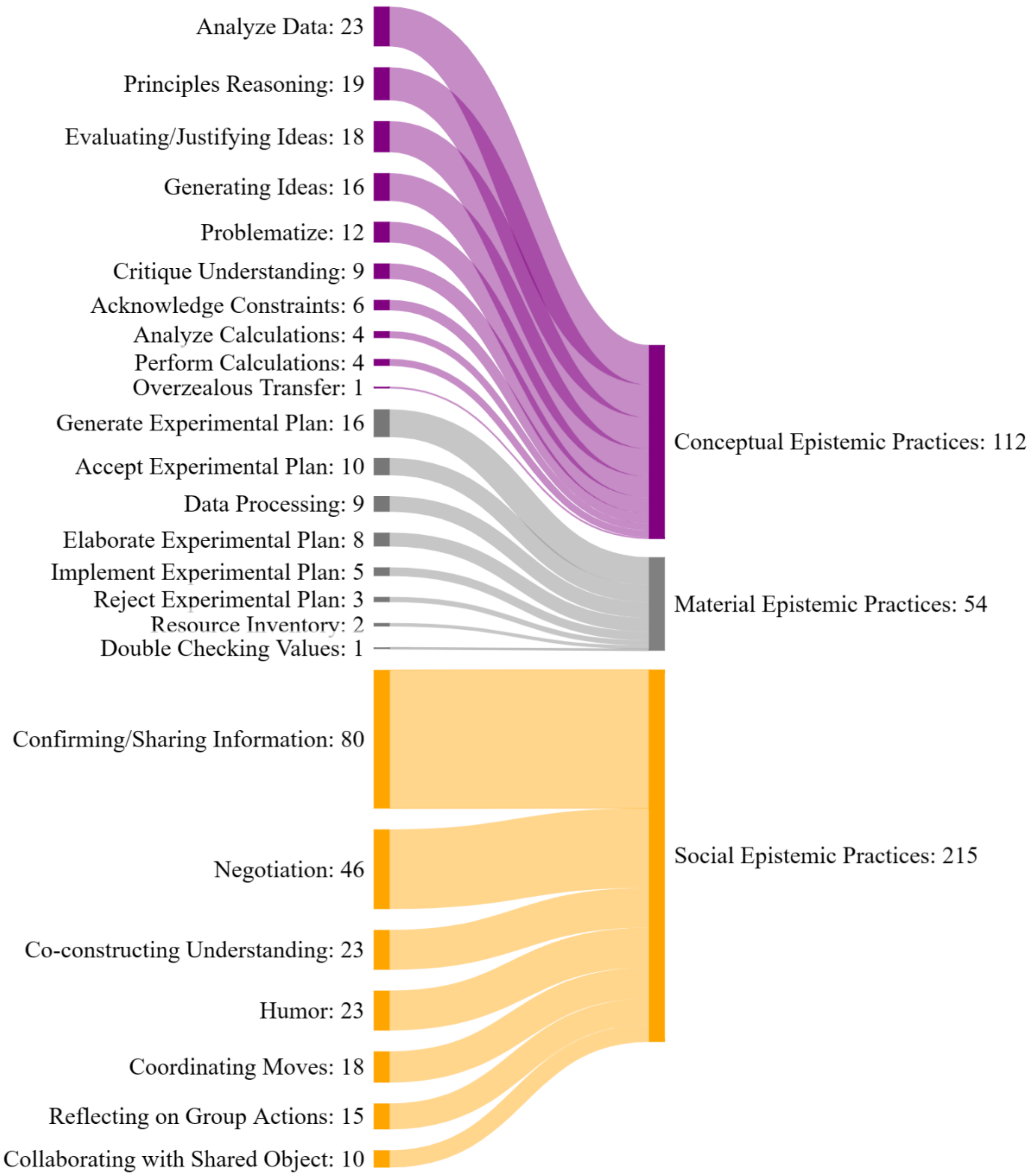

Figure 1: A Sankey diagram showing the distribution of specific epistemic practices of the three categories: conceptual, material, and social. The numbers represent the number of episodes that were coded for a specific epistemic practice. The figure was made with www.sankeymatic.com.

The most common conceptual epistemic practice observed was analyzing data. This epistemic practice is essential to having success in the laboratory to improve upon results in subsequent iterations. The second most common practice was principles reasoning. When faced with the open-endedness of the problem, this group often turned to their fundamental understanding of science and engineering concepts to progress in the laboratory. Generating and evaluating ideas were also frequently elicited, often in conjunction with material practice as the groups generated and debated different experimental strategies. In the following section, we discuss example encounters and show how some of these epistemic practices were used to fill gaps. For material epistemic practices, the most common involved the groups' experimental plan. The ability to perform multiple iterations of the experiment led to the group designing, evaluating, and redesigning their experimental plans several times. Data processing was also tied to this process to analyze data after each iteration. These material practices were often intertwined with conceptual practices which would inform the group's decision making when planning experiments. Finally, the most common social epistemic practices were about negotiating and sharing information within the group. These types of practice are essential for the group to stay on the same page and organize their efforts as they progress through the laboratory.

Encounters: opening and filling of gaps

In this section, we present two encounters students had while completing the laboratory. In each encounter, we discuss the gaps that were opened and closed and the epistemic practices that were enacted to address them.

Encounter 1 - Determining a Starting Point

The first major decision that the group encountered in the virtual laboratory was to decide what parameters to use for their first experiment. In this encounter, the group is confronted with and addresses this gap.

1 Blue: So, now we have to pick the range.
2 Red: So, the first six, do you want to do a higher range?
3 Green: 5, 10... 15, 20, 25-
4 Red: Well, it would be up to 25 because one's a control. Right? So, we only have five.
5 Green: Well, we want to go up to a maximum of 100, right? That's the goal?
6 Red: We can do that. So, do you want to do obviously 10, but... 20's? That would give us the wide range for zero to 100 for the first run.
7 Green: We could reduce it from there.
8 Red: But we'd want to see the general trend, right? Just to see... I don't know.
9 Green: Yeah. I think with those increments… because if we don't fall within the range right off the bat then we are kind of screwed. I think we should do just 10, 20, 30, 40, 50.
10 Red: You want to just go up to 50 then? What was the... because in our project report you said from 30 to 100 or something was the dosage?
11 Green: Yeah, but-
12 Blue: We need to be tracking how much we're using of our stock.
13 Red: But we have to calculate that, right?
14 Blue: Yes.
15 Red: Considering these, it's 0.1.
16 Blue: Okay.
17 Red: So, what do we want to go up by? 10's? 20's?
18 Green: I think 10.

19 Blue: That's what they had on the sample. 10, 20, 30, 40.
20 Red: Okay. So, that would be our first set of samples.
21 Blue: Mm-hmm (affirmative).

The group first identifies the relation they need to develop, the *gap* they need to fill, this gap being what parameters should they input in their first set of experimental runs. However, more specifically they are deciding how they will first enter the parameter space of the problem and how it will set them up to achieve the goals of the assignment. The group first makes the gap explicit when Blue says “now we have to pick the range.” This epistemic practice is both social and conceptual where Blue coordinates the group's focus and determines the problem at hand. Red then proposes a higher range for their first six doses before correcting themselves to five since one dose is a control. During this time, Green lists out five possible values for the range and a hypothetical maximum dose of 100 (the units here being milligrams of chemical per liter of water). Here, Red and Green are engaging in material epistemic practice developing their experimental plan. Furthermore, Green is performing a subtle conceptual epistemic practice when discussing the maximum dose. This value of 100 comes from the pre-lab materials that were provided where this was an optimal dose for an example case. However, this example was from a different water sample and for some waters the optimal dose of alum could be above 100 mg/L. The group's interpretation of information from the pre-lab materials is standing fast here. The group then returned to the idea of testing a larger range because it would show more of the general trend; therefore, giving them more information to design further experiments. The group engages in social epistemic practice negotiating this reasoning, eventually agreeing on inputs for their first runs, closing the gap.

Encounter 2 - Understanding the Process Mechanisms

For the fourth and final jar test in the virtual laboratory activity, at the end of the virtual workday, this group wanted to investigate how changing the pH could give them better drinking water. In this encounter, the group members are consulting a figure that shows how the process mechanisms change as functions of pH and aluminum concentration. They had not realized that multiple coagulation mechanisms could occur and attempted to reason through these mechanisms conceptually to fill this gap.

1 Blue: Oh, yeah. We're not considering, I guess, the two. There's two mechanisms here. There's sweep, and adsorptions. Adsorption onto the surface area of the coagulate, right? But then what is the sweep?
2 Red: But he said the optimal sweep... So it is a solid, though. That's what I'm confused by. Is that... So we want the solid?
3 Blue: But is the sweep... Is referring to what, again? Where are my notes?
4 Red: He talked about sweep flock. About...
5 Green: What is the max? What is the max dose on that scale?
6 Red: I don't know if I can... Where is it?
7 Blue: Sweep. Sweep flock. I can assure you my notes were bad on that.
8 Red: I think it's down.
9 Blue: Down where?
10 Red: Down one more. There you go, sweep flocs. Coagulation.
11 Blue: Where? Right here?
12 Red: There. [Pointing to Blue’s notes]
13 Blue: Forms. My guess is, so formed solids can adsorb, right?

14 Red: What are those on it? So it's the $AlOH_3$. So that's the solid. That's the precipitate.
15 Blue: Mm-hmm (affirmative)-
16 Red: So we want as much of that as possible.
[The group reads through Blue's notes for a bit]
17 Blue: Yeah. Okay, so yeah. You have to form the positive particles to adsorb for the charge neutralization as the first step, right?
18 Red: Mm-hmm (affirmative)-

Once again, the group begins by identifying a gap, that they weren't considering the two mechanisms that could occur (sweep and adsorption). Blue again makes this gap explicit with both social and conceptual epistemic practice, calling the group's understanding of the coagulation mechanisms into question and focusing them on rectifying it. The group determines that they understand the mechanism for adsorption but not sweep coagulation. The first step they take in filling this gap is consulting the notes they had about the process. Using this material resource and science principles they reason through each mechanism, performing a conceptual epistemic practice. As the group works through this process they collaborate with their shared resources and co-construct an understanding collectively, both social epistemic practices. Through these epistemic practices the group is able to close this gap, agreeing on their shared understanding of the process mechanisms. This gap opened when the group investigated the effects of pH; however, it leads them back to the original strategy they had of increasing alum concentration.

19 Blue: Also... Oh, this is low dose and high dose.
20 Red: Yep.
21 Blue: Why is this-
22 Red: But that's just with more Al^{2+}. Or that's with more alum being added.
23 Blue: Oh, because you actually, you have to for-
24 Red: Because this is the product. Yeah, this is just the product of the low dose, and then this is the product of the high dose.
25 Blue: Yeah, adding more.
26 Red: So this will happen, I think, right? At high dose.
27 Blue: This floc will occur at high dose.
28 Red: Should occur at low dose, right? Because they're just going to bump together.
29 Blue: Yeah.
30 Red: And then once we add more...
31 Blue: Yeah. Okay.
32 Red: And then as we add more we're going to perform the... Or, not perform. Coagulation.

Here the group makes a connection between the alum concentration and the process mechanisms, making a conceptual connection that supports the results they've seen in their previous trials. Here the groups conceptual epistemic practice is leading to relations standing fast, developing a new relation between the alum concentration and the process mechanisms.

Discussion

In our analysis of two encounters, we have shown that students engaged certain engineering epistemic practices to address gaps that were opened. Through the engagement of these epistemic practices, they developed new relations that allowed them to progress towards the engineering goal. In each encounter the epistemic practice and gaps they addressed were situated in engineering practice, which was encouraged by the laboratory's design. The gaps which opened stemmed from the overall objective of developing an optimal dose of chemical and were often pragmatic in nature. In the first encounter, the group sought to choose parameters they believed would help them progress toward their goal. In the second encounter, they develop their conceptual understanding of process mechanisms to try and better their results. Interestingly, they were motivated by an apparent desire to understand the process mechanism rather than the need to demonstrate understanding that was expected.

PEA was developed to understand science learning, often in introductory classes, and, therefore, focused on the science classroom (Wickman, 2004; Wickman & Östman, 2002). These studies focus on much shorter interactions where students try to understand and solve science problems (Hamza & Wickman, 2013; Hardahl et al., 2019; Lidar et al., 2010). In this work, we are looking at a larger grain size and a different context, where the goal of the activity is engaging engineering disciplinary practices as opposed to developing conceptual science understanding. This application of PEA, therefore, is fundamentally different because the pursuit of different goals inherently leads to different gaps and approaches to address them. In our industrially-situated engineering laboratory context, conceptual practice serves as a *tool* to progress towards the larger, open-ended engineering goal of the activity – to provide clean drinking water. In contrast, in a science classroom, conceptual understanding itself, represents the goal.

Bernhard and Carstensen (2018) used PEA as an analytical tool to investigate learning in a university level circuits laboratory with and without the inclusion of simulations in the activity. Here they identified salient concepts within the activity (such as the real circuit, differential equations, and Laplace transforms). Their analysis consisted of the student's process of linking the conceptual elements, where a gap corresponded to a non-established link and a relation corresponded to an established link. Here we are similarly looking at which gaps students address as they complete a laboratory task but connect the filling of gaps to engineering practices instead of the linking of concepts. It would be interesting to look at Bernhard and Carstensen's data from the lens of epistemic practices.

Our study looks at student interactions primarily within their group and not with an instructor, as other work with PEA has done (Carlos et al., 2023; Karch et al., 2024). In this work, we instead primarily look at student's interactions within their group and with the virtual laboratory. In the second encounter, students deeply engaged with conceptual practice with a desire to understand the multiple process mechanisms, a gap which had opened within another gap, an investigation of how changing pH could better their results. The activity does not mandate that the group to do this and it is not explicitly necessary, but the group still engages this practice because they see it as a way to progress towards their goals and satisfy their curiosity. Thus, the authentic engineering activity studied here affords students the opportunity to engage in conceptual understanding in ways that are motivated by and respond to the engineering context. An important contribution of this work is applying PEA to an open-ended industrially-situated engineering problem which seeks to understand gaps and how they are filled in a much different context than the science classrooms that PEA has been applied. We argue that the opening and filling of gaps is intimately linked to the essential nature of engineering practice, and more detailed investigations in different authentic contexts could be generative in identifying instructional designs and practices that support students' professional formation.

Limitations

This analysis reported here is limited. For one, the analysis is not complete enough to develop continuity through the entire laboratory; certain meaningful gaps were analyzed to exemplify our framework, but all the gaps were not identified. Something that holds fast at one point in time may not hold fast at a different point in time. For instance, the relation that 100 mg/L was the maximum dose they could run held fast when the group determined their starting point but this later changes and the group considers doses above 100 mg/L. Developing a continuous description of gaps and the epistemic practices elicited to fill them would allow for a more complete description of learning in the laboratory.

Mapping the gaps and epistemic practices throughout the whole laboratory would serve as a pilot example. It would then be beneficial to perform the same analysis for the other laboratory videos in the data corpus and other realistic engineering activities, such as internships and student clubs. This data includes three other groups' work in the virtual laboratory. Additionally, the four groups completed a jar test laboratory in the physical mode which was also recorded. Comparing the results of this group's analysis to other groups and other modes would expand on our understanding of the ways the laboratory design and laboratory affordances and constraints influence the opening and filling of gaps. In other work, we quantified the epistemic practices in all the laboratory videos and found students engaged in more conceptual practices in the virtual laboratory versus more material practices in the physical laboratory. However, this analysis only connects epistemic practices to the laboratory mode and implementation, larger characteristics of the laboratory that don't give information about when and why epistemic practices are being used. Comparing the types of gaps that appear in each mode and how students use epistemic practices to address them would provide information about the types of learning that occur in specific moments throughout the physical and virtual laboratories.

Conclusions

While still preliminary, this analysis showed that students elicit engineering epistemic practices to identify and fill gaps that occur during the completion of laboratory work, and the nature of those gaps was different than those reported in the science education literature. Rather than serving as vehicles to make progress on understanding challenging contexts, gaps served as a way to make progress on an engineering project. By engaging in meaningful engineering epistemic practices students were able to build relations that stood fast for the purpose of progressing towards their project goals.

References

Agustian, H. Y., Finne, L. T., Jørgensen, J. T., Pedersen, M. I., Christiansen, F. V., Gammelgaard, B., & Nielsen, J. A. (2022). Learning outcomes of university chemistry teaching in laboratories: A systematic review of empirical literature. *Review of Education*, *10*(2), e3360. https://doi.org/10.1002/rev3.3360

Alkhaldi, T., Pranata, I., & Athauda, R. I. (2016). A review of contemporary virtual and remote laboratory implementations: Observations and findings. *Journal of Computers in Education*, *3*(3), 329–351. https://doi.org/10.1007/s40692-016-0068-z

Altmeyer, K., Kapp, S., Thees, M., Malone, S., Kuhn, J., & Brünken, R. (2020). The use of augmented reality to foster conceptual knowledge acquisition in STEM laboratory courses—Theoretical background and empirical results. *British Journal of Educational Technology*, *51*(3), 611–628. https://doi.org/10.1111/bjet.12900

Balamuralithara, B., & Woods, P. C. (2009). Virtual laboratories in engineering education: The simulation lab and remote lab. *Computer Applications in Engineering Education*, *17*(1), 108–118. https://doi.org/10.1002/cae.20186

Bernhard, J., & Cartensen, A.-K. (2018). *"Real" Experiments or Simulated Experiments in Labs – Opposties or Synergies?: Experiences from a Course in Electric Circuit Theory*. 6:e UTVECKLINGSKONFERENSEN för Sveriges ingenjörsutbildningar.

Bogen, J., & Woodward, J. (1988). Saving the Phenomena. *The Philosophical Review*, *97*(3), 303–352. JSTOR. https://doi.org/10.2307/2185445

Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education*, *87*, 218–237. https://doi.org/10.1016/j.compedu.2015.07.003

Bucciarelli, L. L. (1988). An ethnographic perspective on engineering design. *Design Studies*, *9*(3), 159–168. https://doi.org/10.1016/0142-694X(88)90045-2

Carlos, C. M. L., Maggiore, N. M., Dini, V., & Caspari-Gnann, I. (2023). Characterizing facilitation practices of learning assistants: An authoritative-to-dialogic spectrum. *International Journal of STEM Education*, *10*(1), 38. https://doi.org/10.1186/s40594-023-00429-4

Chindanon, K., & Koretsky, M. (2023). Group Practice in Engineering: Productive Interactions during a Realistic, Open-ended Task. *Studies in Engineering Education*.

Cross, N., & Clayburn Cross, A. (1995). Observations of teamwork and social processes in design. *Analysing Design Activity*, *16*(2), 143–170. https://doi.org/10.1016/0142-694X(94)00007-Z

Cunningham, C. M., & Kelly, G. J. (2017). Epistemic Practices of Engineering for Education. *Science Education*, *101*(3), 486–505. https://doi.org/10.1002/sce.21271

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and Virtual Laboratories in Science and Engineering Education. *Science*, *340*(6130), 305–308. https://doi.org/10.1126/science.1230579

Duschl, R. (2008). Science Education in Three-Part Harmony: Balancing Conceptual, Epistemic, and Social Learning Goals. *Review of Research in Education*, *32*(1), 268–291. https://doi.org/10.3102/0091732X07309371

Farrokhnia, M., & Esmailpour, A. (2010). A study on the impact of real, virtual and comprehensive experimenting on students' conceptual understanding of DC electric circuits and their skills in undergraduate electricity laboratory. *Procedia - Social and Behavioral Sciences*, *2*, 5474–5482. https://doi.org/10.1016/j.sbspro.2010.03.893

Feisel, L., & Rosa, A. J. (2005). The Role of the Laboratory in Undergraduate Engineering Education. *Journal of Engineering Education*, *94*. https://doi.org/10.1002/j.2168-9830.2005.tb00833.x

Flegr, S., Kuhn, J., & Scheiter, K. (2023). When the whole is greater than the sum of its parts: Combining real and virtual experiments in science education. *Computers & Education*, *197*, 104745. https://doi.org/10.1016/j.compedu.2023.104745

Forman, E. (2018). The Practice Turn in Learning Theory and Science Education. In *Constructivist Education in an Age of Accountability* (pp. 97–111). https://doi.org/10.1007/978-3-319-66050-9_5

Furtak, E. M., & Penuel, W. R. (2019). Coming to terms: Addressing the persistence of "hands-on" and other reform terminology in the era of science as practice. *Science Education*, *103*(1), 167–186. https://doi.org/10.1002/sce.21488

Gibson, J. (1986). The Theory of Affordances (Chapter 8). In *The Ecological Approach to Visual Perception* (pp. 119–136). Psychology Press.

Giere, R. N. (1999). *Science without Laws*. University of Chicago Press.

Gumilar, S., Ismail, A., Budiman, D. M., & Siswanto, S. (2019). Inquiry instructional model infused blended experiment: Helping students enhance critical thinking skills. *Journal of Physics: Conference Series*, *1157*. https://api.semanticscholar.org/CorpusID:151092423

Hamza, K. M., & Wickman, P. O. (2013). Supporting students' progression in science: Continuity between the particular, the contingent, and the general. *Science Education*, *97*(1), 113–138. https://doi.org/10.1002/sce.21042

Hardahl, L. K., Wickman, P.-O., & Caiman, C. (2019). The Body and the Production of Phenomena in the Science Laboratory. *Science & Education*, *28*(8), 865–895. https://doi.org/10.1007/s11191-019-00063-z

Hofstein, A., & Lunetta, V. (2004). The Laboratory in Science Education: Foundations for the Twenty-First Century. *Science Education*, *88*, 28–54. https://doi.org/10.1002/sce.10106

Kapici, H. O., Akcay, H., & de Jong, T. (2019). Using Hands-On and Virtual Laboratories Alone or Together―Which Works Better for Acquiring Knowledge and Skills? *Journal of Science Education and Technology*, *28*(3), 231–250. https://doi.org/10.1007/s10956-018-9762-0

Karch, J. M., Maggiore, N. M., Pierre-Louis, J. R., Strange, D., Dini, V., & Caspari-Gnann, I. (2024). Making in-the-moment learning visible: A framework to identify and compare various ways of learning through continuity and discourse change. *Science Education*, *37*(1). https://doi.org/10.1002/sce.21874

Kelly, G. J. (2008). Inquiry, activity and epistemic practice (Chapter 8). In *Teaching Scientific Inquiry: Recommendations for Research and Implementation* (pp. 99–117). Sense Publishers.

Kelly, G. J., & Licona, P. (2018). Epistemic Practices and Science Education. In *Science* (SCOPUS:85118780797; pp. 139–165). Springer Nature. https://doi.org/10.1007/978-3-319-62616-1_5

Koretsky, M., & Magana, A. J. (2019). Using Technology to Enhance Learning and Engagement in Engineering. *Advances in Engineering Education*.

Koretsky, M., Nefcy, E. J., Nolen, S. B., & Champagne, A. B. (2023). Connected epistemic practices in laboratory-based engineering design projects for large-course instruction. *Science Education*, *107*(2). https://doi.org/10.1002/sce.21769

Lazonder, A. W., & Ehrenhard, S. (2014). Relative effectiveness of physical and virtual manipulatives for conceptual change in science: How falling objects fall. *Journal of Computer Assisted Learning*, *30*(2), 110–120. https://doi.org/10.1111/jcal.12024

Lidar, M., Almqvist, J., & Östman, L. (2010). A pragmatist approach to meaning making in children's discussions about gravity and the shape of the earth. *Science Education*, *94*(4), 689–709. https://doi.org/10.1002/sce.20384

Ma, J., & Nickerson, J. (2006). Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Comput. Surv.*, *38*. https://doi.org/10.1145/1132960.1132961

Muilwijk, S. E., & Lazonder, A. W. (2023). Learning from physical and virtual investigation: A meta-analysis of conceptual knowledge acquisition. *Frontiers in Education*, *8*. https://www.frontiersin.org/articles/10.3389/feduc.2023.1163024

Olympiou, G., & Zacharia, Z. C. (2012). Blending Physical and Virtual Manipulatives: An Effort to Improve Students' Conceptual Understanding through Science Laboratory Experimentation. *Science Education*, *96*, 21–47.

Olympiou, G., & Zacharia, Z. C. (2014). Blending Physical and Virtual Manipulatives in Physics Laboratory Experimentation. In C. Bruguière, A. Tiberghien, & P. Clément (Eds.), *Topics and Trends in Current Science Education: 9th ESERA Conference Selected Contributions* (pp. 419–433). Springer Netherlands. https://doi.org/10.1007/978-94-007-7281-6_26

Passmore, C., Gouvea, J. S., & Giere, R. N. (2014). *Models in Science and in Learning Science: Focusing Scientific Practice on Sense-making*. https://api.semanticscholar.org/CorpusID:59812136

Pickering, A. (1996). The Mangle of Practice: Time, Agency, and Science. *Bibliovault OAI Repository, the University of Chicago Press*, *38*. https://doi.org/10.2307/3106908

Trevelyan, J. (2014). *The Making of an Expert Engineer*. CRC Press.

Van den Beemt, A., Groothuijsen, S., Ozkan, L., & Hendrix, W. (2022). Remote labs in higher engineering education: Engaging students with active learning pedagogy. *Journal of Computing in Higher Education*. https://doi.org/10.1007/s12528-022-09331-4

Wickman, P.-O. (2004). The practical epistemologies of the classroom: A study of laboratory work. *Science Education*, *88*(3), 325–344. https://doi.org/10.1002/sce.10129

Wickman, P.-O., & Östman, L. (2002). Learning as discourse change: A sociocultural mechanism. *Science Education*, *86*(5), 601–623. https://doi.org/10.1002/sce.10036

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941–967. https://doi.org/10.1002/sce.20259

Wörner, S., Kuhn, J., & Scheiter, K. (2022). The Best of Two Worlds: A Systematic Review on Combining Real and Virtual Experiments in Science Education. *Review of Educational Research*, *92*(6), 911–952. https://doi.org/10.3102/00346543221079417

Zacharia, Z. C., Loizou, E., & Papaevripidou, M. (2012). Is physicality an important aspect of learning through science experimentation among kindergarten students? *Early Childhood Research Quarterly*, *27*(3), 447–457. https://doi.org/10.1016/j.ecresq.2012.02.004

Zacharia, Z. C., & Michael, M. (2016). Using Physical and Virtual Manipulatives to Improve Primary School Students' Understanding of Concepts of Electric Circuits. In M. Riopel & Z. Smyrnaiou (Eds.), *New Developments in Science and Technology Education* (pp. 125–140). Springer International Publishing. https://doi.org/10.1007/978-3-319-22933-1_12