Complementary affordances of virtual and physical laboratories for developing engineering epistemic practices

Overview

Professional engineering demands more than the ability to proficiently carry out engineering calculations. Engineers utilize other practices; for example, they need to approach problems with a holistic view, make decisions based on evidence, collaborate effectively in teams, and learn from setbacks. Laboratory work plays a crucial role in shaping the professional development of university engineering students as it enables them to cultivate these essential practices [1, 2]. A successful laboratory task design should provide students opportunities to develop these practices but also needs to adhere to the constraints of the educational environment.

In this project, we explore how both virtual (simulation-based) and physical (hands-on) laboratories, based on the same real-world engineering process, develop the practices students will need in their future careers. In an engineering virtual laboratory, students work within computer simulations of an experiment where they provide values to process variables and the computer provides them realistic data which they can then analyze [3-5]. Specifically, we seek to determine whether the virtual and physical laboratory modes foster different yet complementary *epistemic practices*. Epistemic practices refer to the ways in which group members propose, communicate, justify, assess, and validate knowledge claims in a socially organized and interactionally accomplished manner [6, 7]. This project builds upon our prior work in developing virtual laboratories in chemical engineering and biological engineering [8], and on our learning research on professional discourse [9], gendered interactions [10], modeling [11], creativity [12], and disciplinary engagement [13, 14].

The goals of this NSF Research Initiation in Engineering Formation (PFE: RIEF) project are to:

1. Build on preliminary work to develop the Virtual Jar Test Laboratory for Water Treatment and develop a corresponding Physical Jar Test Laboratory for Water Treatment.
2. Compare student engagement and demonstration of epistemic practices in the virtual laboratory and physical laboratory modes to develop transferable knowledge about the development of epistemic practices in the laboratory.
3. Develop capacity in PI Nason as an engineering education researcher through a deliberate mentoring plan and research activities.

To accomplish these objectives, we are conducting a microgenetic analysis of student teams engaging in both the virtual and physical versions of the same laboratory exercise, the Jar Test for Drinking Water Treatment. The central hypothesis guiding this research is that physical laboratories emphasize social and material epistemic practices, while virtual laboratories highlight social and conceptual epistemic practices. The goal is to gain transferable knowledge about how the laboratory format and instructional design influence students' engagement in epistemic practices.

Laboratory Development

Jar testing is a standard laboratory procedure used by design engineers and water treatment plant operators to optimize the physical and chemical conditions for the effective removal of particulate contaminants from water through coagulation, flocculation, and settling. We have developed instructional laboratories in both virtual and physical modes. Often, virtual laboratories are designed to directly replicate a corresponding physical laboratory, imposing the constraints of the physical laboratory on the virtual laboratory [15, 16]. Here, rather than having the virtual laboratory design mirror the physical laboratory, we developed designs independently to take advantage of the affordances of each mode. Affordances refer to the perceived or actual properties of a thing [17]. Industrially situated problem statements and associated activities were developed for each mode.

Virtual Laboratory: A new html-based user interface has been developed that interfaced with a mathematical model and adds realistic process error. The mathematical model is based on the work of Weber-Shirk and co-workers [18-21] with added functionality to simulate changes in aqueous inorganic chemistry and to account for the removal of natural organic matter [22]. In addition, random noise was added to the output. An instructor interface where problem parameters can be entered for each student group has also been developed. Finally, work towards incorporating the virtual lab into the Concept Warehouse platform [23] has been initiated. This allows controlled student access as well as storage of student inputs and results for further analysis.

Physical Laboratory: A physical lab procedure was developed and tested, and an industrially-situated assignment was developed based on the laboratory. Results of the physical lab were compared to simulation results indicating broad agreement. Data collection from the physical lab informed the process error and noise included in the virtual laboratory.

Learning Research

Data collection

After developing laboratories and industrially-situated assignments for each mode, we completed two rounds of data collection as follows:

Round 1: We delivered the laboratories to four groups (3 students each) in a 3rd-year chemical engineering laboratory course. Two teams completed the virtual laboratory first and the physical laboratory second. The other two teams completed the physical laboratory first and the virtual laboratory second. All lab sessions were video and audio recorded. Video recordings of the teams' working sessions out of class were collected for some teams and eight recorded interviews with individual students were conducted after they completed both laboratories. Laboratory reports for all teams have been collected in each mode.

Round 2**:** We delivered the labs to three groups (3 students each) in a 4th-year environmental engineering laboratory course. All teams completed the virtual laboratory first and the physical laboratory second. The physical laboratory activity was modified to include an incomplete data set which groups used to devise an experimental plan. All lab sessions were video and audio recorded. Nine (9) recorded interviews with individual students were conducted after both labs were completed. Laboratory reports for all teams have been collected in each mode.

Data Analysis

Video data and interviews were transcribed verbatim. The video recordings of laboratory activity were divided into episodes bounded by a change in strategy or change in topic. Then, discourse analysis was used to identify the types of epistemic practices the teams engaged in and the ways those practices moved the work forward. Coding was performed using the software Atlas.TI 9 and lending from past work [24]. As the analysis progressed, coding was done over several iterations, with existing codes being refined and emergent codes being added as new phenomena were identified. The codes were grouped into larger categories of conceptual, material, and social epistemic practices.

Findings

We have several initial findings, as follows:

- Physical and virtual laboratories have different affordances and constraints. Instructional designs that leverage each mode's particular affordances allow them to scaffold the development of different engineering epistemic practices.
    - Through Round 1 analysis [25], we identified an average of 76 instances of material practices, 7 conceptual practices, and 139 social practices in teams completing the physical laboratory; we identified an average of instances of 36 material practices, 69 conceptual practices, and 161 social practices in teams completing the virtual laboratory. Thus, more material epistemic practices were elicited in the physical mode, while more conceptual practices were elicited in the virtual mode, and approximately the same amount of social practices were elicited in each mode.
- Physical and virtual laboratories can be complementary, each targeting a specific set of epistemic practices, creating a learning outcome more reflective of real engineering practice.
- The instructional design, instructor framing, and student activity need to align with the affordances of the laboratory modes to produce a complementary outcome. This means implementing the laboratories in a way that positions the affordances of each to be maximally leveraged by students.

Broader Impacts

We have the following broader impacts:

- This research project has supported the professional development of a MS student in chemical engineering (2nd Author) who defended his MS thesis in August 2023. He attended the 2023 ASEE annual conference in Baltimore. Through his experience on this project, he has decided to pursue a doctoral degree focused on engineering education. He will continue work on this project as a PhD student at Tufts University.
- PI Nason has gained knowledge and experience in qualitative research methods through collaboration with and mentoring from the third author. He has expanded his professional network through engagement with the project advisory board and also achieved sustained exposure to engineering education research and methods through regular meetings with the other two authors.

Acknowledgements

The work reported here was supported in part by a grant from the National Science Foundation (EEC 2204885 and EEC 2204933) and the Oregon State University Center for Research in Engineering Education Online (CREEdO). We appreciate the cooperation of Profs. Skip Rochefort and Tyler Radniecki for supporting the delivery of these laboratories. The views represented here are those of the authors.

References

[1] L. D. Feisel and A. J. Rosa, "The role of the laboratory in undergraduate engineering education," *Journal of engineering Education,* vol. 94, no. 1, pp. 121-130, 2005, doi: 10.1002/j.2168-9830.2005.tb00833.x.
[2] B. Balamuralithara and P. C. Woods, "Virtual laboratories in engineering education: The simulation lab and remote lab," *Computer Applications in Engineering Education,* vol. 17, no. 1, pp. 108-118, 2009, doi: 10.1002/cae.20186.
[3] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *ACM Computing Surveys (CSUR),* vol. 38, no. 3, pp. 7-es, 2006, doi: 10.1145/1132960.1132961.
[4] M. D. Koretsky, D. Amatore, C. Barnes, and S. Kimura, "Enhancement of Student Learning in Experimental Design Using a Virtual Laboratory," *IEEE Transactions on Education,* Article vol. 51, no. 1, pp. 76-85, 2008, doi: 10.1109/te.2007.906894.
[5] M. D. Koretsky, C. Kelly, and E. Gummer, "Student Perceptions of Learning in the Laboratory: Comparison of Industrially Situated Virtual Laboratories to Capstone Physical Laboratories," *Journal of Engineering Education,* Article vol. 100, no. 3, pp. 540-573, 2011, doi: 10.1002/j.2168-9830.2011.tb00026.x.
[6] C. M. Cunningham and G. J. Kelly, "Epistemic practices of engineering for education," *Science Education,* vol. 101, no. 3, pp. 486-505, 2017, doi: 10.1002/sce.21271.
[7] M. D. Koretsky, E. J. Nefcy, S. B. Nolen, and A. B. Champagne, "Connected epistemic practices in laboratory-based engineering design projects for large-course instruction," *Science Education,* vol. 107, no. 2, pp. 510-550, 2023, doi: 10.1002/sce.21769.
[8] M. D. Koretsky, C. Kelly, and E. Gummer, "Fundamental Research in Engineering Education. Student Learning in Industrially Situated Virtual Laboratories," *Chemical Engineering Education,* vol. 45, no. 3, pp. 219-228, 2011.

[9] D. M. Gilbuena, B. U. Sherrett, E. S. Gummer, A. B. Champagne, and M. D. Koretsky, "Feedback on Professional Skills as Enculturation into Communities of Practice," *Journal of Engineering Education,* vol. 104, no. 1, pp. 7-34, 2014, doi: 10.1002/jee.20061.

[10] L. Hirshfield and M. D. Koretsky, "Gender and participation in an engineering problem-based learning environment," *Interdisciplinary Journal of Problem-Based Learning,* vol. 12, no. 1, p. 2, 2018.

[11] B. U. Sherrett, E. J. Nefcy, E. S. Gummer, and M. D. Koretsky, "An Expert Solution to Assess an Industrially Situated, Computer-Enabled Design Project," *Journal of Engineering Education,* vol. 102, no. 4, pp. 541-576, 2013, doi: 10.1002/jee.20027.

[12] L. J. Hirshfield and M. D. Koretsky, "Cultivating creative thinking in engineering student teams: Can a computer-mediated virtual laboratory help?," *Journal of Computer Assisted Learning,* vol. 37, no. 2, pp. 587-601, 2021.

[13] M. Koretsky, S. B. Nolen, D. M. Gilbuena, G. Tierney, and S. Volet, "Productively engaging student teams in engineering: The interplay between doing and thinking," in *Frontiers in Education 2014*, Madrid, Spain, October 22-25 2014, Piscataway, NJ: Frontiers in Education Clearinghouse, pp. 2684-2691.

[14] M. D. Koretsky, M. Vauras, C. Jones, T. Iiskala, and S. Volet, "Productive disciplinary engagement in high-and low-outcome student groups: Observations from three collaborative science learning contexts," *Research in Science Education,* vol. 51, pp. 159-182, 2021.

[15] T. F. Wiesner and W. Lan, "Comparison of student learning in physical and simulated unit operations experiments," *Journal of Engineering Education,* vol. 93, no. 3, pp. 195-204, 2004.

[16] V. J. Bhute, P. Inguva, U. Shah, and C. Brechtelsbauer, "Transforming traditional teaching laboratories for effective remote delivery—A review," *Education for Chemical Engineers,* vol. 35, pp. 96-104, 2021.

[17] J. J. Gibson, "The theory of affordances," in *The Ecological Approach to Visual Perception*, J. J. Gibson Ed. New York and London: Psychology Press, 1986, pp. 119-136.

[18] Y. Du, W. H. Pennock, M. L. Weber-Shirk, and L. W. Lion, "Observations and a geometric explanation of effects of humic acid on flocculation," *Environmental Engineering Science,* vol. 36, no. 5, pp. 614-622, 2019, doi: 10.1089/ees.2018.0405.

[19] W. H. Pennock, M. L. Weber-Shirk, and L. W. Lion, "A hydrodynamic and surface coverage model capable of predicting settled effluent turbidity subsequent to hydraulic flocculation," *Environmental Engineering Science,* vol. 35, no. 12, pp. 1273-1285, 2018, doi: 10.1089/ees.2017.0332.

[20] K. A. Swetland, M. L. Weber-Shirk, and L. W. Lion, "Influence of polymeric aluminum oxyhydroxide precipitate-aggregation on flocculation performance," *Environmental Engineering Science,* vol. 30, no. 9, pp. 536-545, 2013, doi: 10.1089/ees.2012.0199.

[21] K. A. Swetland, M. L. Weber-Shirk, and L. W. Lion, "Flocculation-sedimentation performance model for laminar-flow hydraulic flocculation with polyaluminum chloride and aluminum sulfate coagulants," *Journal of Environmental Engineering,* vol. 140, no. 3, p. 04014002, 2014, doi: 10.1061/(ASCE)EE.1943-7870.0000.

[22] M. Edwards, "Predicting DOC removal during enhanced coagulation," *Journal-American Water Works Association,* vol. 89, no. 5, pp. 78-89, 1997, doi: 10.1002/j.1551-8833.1997.tb08229.x.
[23] M. D. Koretsky *et al.*, "The AIChE Concept Warehouse: A Web-Based Tool to Promote Concept-Based Instruction," *Advances in Engineering Education,* vol. 4, no. 1, p. n1, 2014.
[24] K. Chindanon and M. D. Koretsky, "Group Practice in Engineering: Productive Interactions during a Realistic, Open-Ended Task," *Studies in Engineering Education,* vol. 4, no. 2, pp. 144-175, 2023, doi: 10.21061/see.112.
[25] Gavitte S. B., M. D. Koretsky, and J. A. Nason, "Connecting Affordances of Physical and Virtual Laboratory Modes to Engineering Epistemic Practices," *in review,* 2024.