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Work-in-Progress: A Living Laboratory: Inquiry-Based Learning in Chemical Engineering

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Abstract

This work-in-progress paper investigates how incorporating inquiry-based learning laboratories into core chemical engineering courses affects students and faculty at a large, private university in the Northeast United States. Traditional chemical engineering curricula first engage students with the theory behind real-world processes and reserve hands-on applications for the upper-level Unit Operations laboratory course. However, existing literature suggests that redesigning the curriculum to have students learn theory and immediately apply it to real-world equipment could benefit student motivation and knowledge retention. Toward this end, we are currently deconstructing the existing Unit Operations course into self-contained experimental "inquiry labs" and implementing these inquiry-based labs into courses in the second and third years of the curriculum. At this point, we have incorporated four inquiry labs into the first required course of the curriculum, mass and energy balances. To assess the impact of these labs, we employed a mixed-methods study with pre-surveys to gather baseline data for both students and faculty and conducted interviews and focus groups with students engaged in the inquiry labs. Specifically, this study describes initial findings on the impact of these labs on student learning, motivation, and engineering identity as well as faculty attitudes towards curriculum change and engagement with active learning. Future work will continue to assess the impact of incorporating inquiry labs in subsequent courses on student's and faculty's attitudes toward these changes through a longitudinal study. By understanding the effect of active learning implementation on this department, we can better understand the potential for curriculum improvement across all engineering disciplines.

Introduction

The field of chemical engineering has consistently transformed and evolved over time to address the novel needs presented in society. From its beginnings in the petrochemical industry to current applications in nanotechnology, clean energy, and biomolecular engineering, chemical engineering has emerged as a discipline at the forefront of technological and industrial advancement [1], [2]. Despite the ease and swiftness at which the field has evolved its content towards novel applications, similar evolution in chemical engineering pedagogy is sluggish in comparison [3], [4].

Traditional chemical engineering curricula often feature instructor-centered, lecture-based courses that engage with theory, followed by discussion sections to solve close-ended problems. Student application of the knowledge learned in these core courses with real-world equipment and data analysis is usually reserved for the canonical upper-level Unit Operations (UO) laboratory that engages theory through real-world process equipment applications. Due to the synthesizing nature of this course across all core courses, students are required to recall learning from prior years to successfully complete it, and thus, it has a reputation for being particularly challenging while also serving an important role in the curriculum. While recall of prior course material can improve retention, students can struggle to connect and apply lessons learned years ago to their present day, leading to higher levels of stress, frustration, and impeded learning [5], [6], [7], [8].

The theory of social constructivism contrasts with this existing learning structure as it argues that learning is not a passive process of information absorption but rather an active process of collaboration and reflection [9]. Through this framework, the traditional curriculum structure can lead to student demotivation by passively teaching chemical engineering knowledge and skills first and reserving the challenge of application for after these skills are gained [10]. By contrast, a curriculum that appropriately challenges students to apply their newly gained skills can push them into their zone of proximal development, motivating students and improving knowledge retention [7], [11]. Furthermore, social constructivism asserts that student learning is contextual, where students are inspired by and learn better from applications of theoretical concepts grounded in real problems [12]. As such, students would benefit from opportunities to actively apply their knowledge to solve problems connected to the real world throughout the curriculum. This redesigned curriculum would both contextualize course material and actively engage students with each subject, improving student motivation and learning retention [13], [14]. Therefore, adjusting the curriculum to provide opportunities to actively apply course material could benefit students.

Inquiry Lab Design, Implementation, and Assessment

To begin implementing these curriculum changes, we designed four inquiry labs for the third-semester required course, mass and energy balances. We chose the objective of each lab based on the course instructor's guidance on key content to emphasize and reinforce, as well as the integration of existing equipment. As such, we adapted two existing UO labs into inquiry labs using heat exchanger and distillation column units. We also developed two new inquiry labs concerning process economics and dimensionless numbers. We designed each inquiry lab's structure around Kolb's experiential learning model [15], [16], in which students engage in concrete experience, reflective observation, abstract conceptualization, and active experimentation to engage in learning.

In this development and testing phase, the labs were offered as an additional one-credit module to all students. A total of 23 students enrolled in the course. For each lab, students were first formed into teams and presented with a challenging open-ended question. As a team, they were asked to plan their strategy for data collection, collect data with relevant equipment, analyze their data with chemical engineering theory, and communicate their results. This active learning framework motivates students by encouraging them to connect their course knowledge to the problem and challenging them to collaborate, gain, and disseminate new knowledge, strengthening attention and memory consolidation [17], [18], [19]. Furthermore, the inquiry labs were conducted as close as possible to when the content was introduced in lecture, reinforcing course concepts immediately as opposed to two years later in the current UO lab structure. Details regarding each lab's learning objectives and components are summarized in the table below (Table 1).

Table 1. Descriptions of inquiry labs implemented and assessed.

Lab	Objective	Real-World Context	Deliverable	Reinforced Course Concept
Heat Exchanger (HX)	Characterize the heat transfer efficiency of a water-fed concentric pipe heat exchanger	Engineering consulting firm aiding a chemical company's reaction mixture heating to avoid unwanted side products	Individually-written memorandum communicating experimental protocol, results, and recommended flow rates to maximize efficiency	Energy balance calculations between streams of a heat exchanger
Process Economics (Econ)	Maximize company value by allocating "yearly" funds towards capital, operating, and research costs	Hair-loss drug manufacturing company in competitive market	Highest value company after 6 "years" wins and receives prize	Spreadsheet models, return-on-investment calculations, depreciation, and scaling of price/production capacity
Total Reflux Distillation (TRD)	Characterize the Murphree efficiency of each tray in an eight-tray distillation column operating in total reflux	Engineering consulting firm aiding a chemical company's separation of methanol and water for reagent recycling	Individually-written memorandum comparing ideal and real-world column temperatures and calculating Murphree efficiency	McCabe-Thiele graphical analysis, column pinching, and Murphree efficiency calculations
Dimensionless Numbers (Dimensionless)	Determine the value of a dimensionless number (Froude) at which humans transition between walking and running	Research team adding to existing literature of biped and quadruped gaits	15-minute group presentation to graduate students and faculty communicating results	Manipulating dimensionless numbers, experimental design, and plotting techniques

Due to the nature of this course being an introduction to chemical engineering theory, we adapted the two existing UO lab experiments to the appropriate level of complexity. In the heat exchanger inquiry lab (HX), students were asked to characterize the heat transfer efficiency of a water-fed concentric-pipe heat exchanger, determining the operating conditions that both maximized efficiency and heated the cold "reaction mixture" to a desired temperature to avoid reaction side products. In teams of 3-6 students, they created and executed experimental procedures to vary the hot and cold water flow rates and collect inlet and outlet temperatures to calculate and compare heat gained and lost by each stream. They submitted individually written memorandums describing their purpose, experimental protocol, results, recommendations, and conclusions, simulating a potential future role as an engineering consultant. They were also given feedback on their technical writing to help improve their written communication skills.

Similarly for the distillation inquiry lab (TRD), teams of 6-8 students were asked to characterize the Murphree efficiency of each tray in an eight-tray distillation column operating in total reflux, separating a mixture of methanol and water to aid a chemical company's reagent recycling. Before their lab, the students used McCabe-Thiele analysis to predict the temperatures of each tray in the column given constraints on the distillate and bottoms compositions, revealing the potential for pinching in either corner of the diagram and providing an ideal reference state for comparison of the real column operating conditions. Again, they submitted individual memorandums to disseminate their findings. This structure follows Kolb's experiential learning model by having students engage with an open-ended problem grounded in real-world contexts (concrete experience), connect their prior course knowledge to the problem (abstract conceptualization), develop a working hypothesis and procedure to investigate the problem (active experimentation), and reflecting on their experience and communicating their newly gained knowledge through a written report (reflective observation). Furthermore, this structure aligns with social constructivism, encouraging students to exchange ideas and knowledge with each other and motivating them to engage with the material by leveraging real-world contexts.

For the new inquiry labs, we adapted activities previously implemented for earlier iterations of this course into the experiential learning structure mentioned above. The process economics inquiry lab (Econ) asked students to form teams or "companies" of 2-3 students and create spreadsheet models to decide their yearly expenditures of capital cost for new drug manufacturing equipment, operating cost to produce their drug product, and research funding subsidies to lower their costs or increase their revenue. Each company could negotiate with others to exchange research patents, production capacity, or cash, and the company with the highest net value at the end of 6 "years" was declared the winner. The final inquiry lab on dimensionless numbers (Dimensionless) asked teams of 5-6 students to craft and execute an experimental procedure to determine the value of the Froude number, a dimensionless number, at which humans naturally transition from walking to running. Given tape, a tape measurer, and hallway space, students performed trials moving with different gaits and collected data on velocity, stride length, and leg length. They disseminated their results in a 15-minute group presentation to graduate students and faculty in the department and were given feedback on their presentation skills.

We employed a mixed-methods study (IRB0148897) to assess the effect of these inquiry labs. For students, we administered a pre-survey to measure students' engineering identity, motivation, and attitudes toward active learning. We also conducted one-on-one interviews to learn more about student's perceptions of their learning, growth, and belonging. We further conducted focus groups with 4-6 students to gather feedback on the inquiry labs. For faculty, we surveyed all faculty in the chemical engineering department to assess their attitudes and engagement toward this active learning initiative. Additionally, after each lab, students who participated were asked to complete a post-lab feedback survey to assess the effect of each lab on both student learning and motivation.

Preliminary Results

We provide our initial results of the quantitative student feedback on each inquiry lab and selected qualitative quotes from focus groups conducted with the students. For the quantitative data, the students were asked to complete a short feedback survey no more than 24 hours after their inquiry lab session to promote immediate reflection on their experience. In addition to qualitative questions about the main takeaways, skills gained, best aspects, and suggested improvements for each lab, students rated their agreement with various statements on a 7-point anchored numeric scale (Table 2).

Table 2. Inquiry lab feedback survey questions.

#	Question	Purpose
1	The problem statement for this lab was clear.	Design
2	The deliverable assignments for this lab were clear.	Design
3	I felt prepared to successfully complete this lab.	Design
4	I felt confident while participating in this lab.	Performance/Competence
5	I learned something new from this lab.	Learning
6	Concepts I learned in lecture were reinforced by this lab.	Learning
7	I enjoyed this lab.	Motivation
8	I see the value in participating in this lab.	Motivation
9	I recommend this lab be instituted next year.	Learning
10	I tried my hardest to do well in this lab.	Motivation

We included each question to determine the degree to which each lab was well-constructed (Design), enhanced student learning (Learning), impacted engineering identity (Performance/Competence), and influenced motivation (Motivation). The Design questions (#1-3) all resulted in mean values greater than 5 for each lab, confirming successful construction of inquiry labs at the appropriate level of complexity. The results for questions #4-10 further suggest students had successful lab experiences (Figure 1).

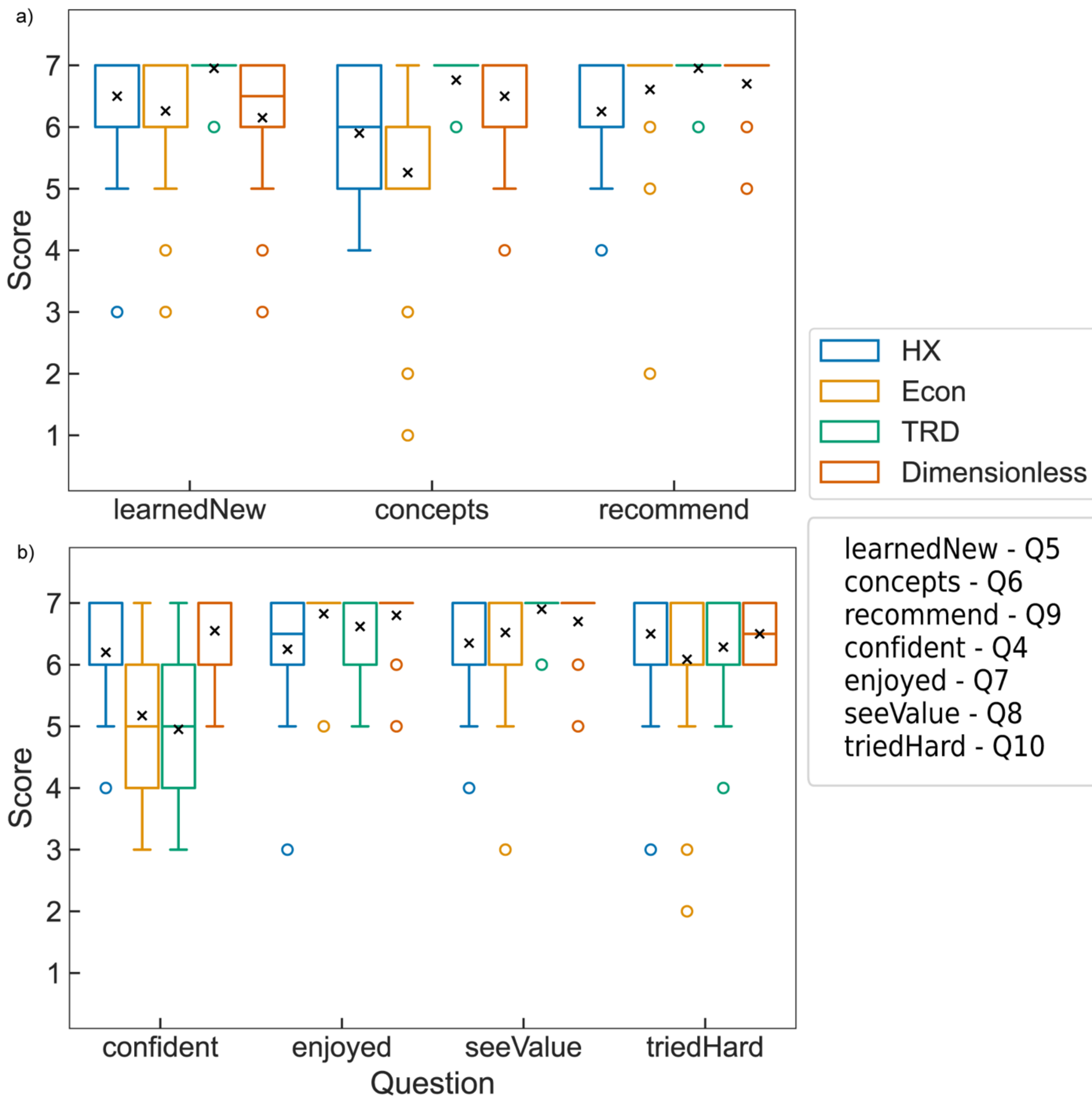

Figure 1. Quantitative results of inquiry lab feedback survey questions #4-10 (a) Learning-focused question responses demonstrate achievement of learning objectives for all labs. Students expressed that they learned something new (learnedNew, Q5), reinforced concepts from lecture (concepts, Q6) and recommend the lab be instituted in the future (recommend, Q9) for all labs. (b) Identity and motivation question responses show high degrees of enjoyment (enjoyed, Q7), seeing value in the lab (seeValue, Q8), and motivation to try hard (triedHard, Q10). Confidence in each lab varied, with students feeling less confident in the Econ and TRD inquiry labs compared to the HX and Dimensionless inquiry labs (confident, Q4). Boxes represent the upper quartile, median, and lower quartile of responses for each lab and outliers are represented as open circles. Response count n = 20, 23, 21, and 20 for HX, Econ, TRD, and Dimensionless inquiry labs, respectively. Mean values are plotted as "x" markers over their respective boxes.

We observed high degrees of learning expressed by students in all labs (Figure 1a). This trend is particularly evident in the TRD inquiry lab responses, which showed the highest means for learning new concepts, reinforcing lecture concepts, and recommendation for future implementation. The Econ inquiry lab showed the lowest level of course concept reinforcement, likely due to the structure of the lab emphasizing teamwork and negotiation over the basic return on investment calculations highlighted in lecture. Despite this lower level of reinforcement, almost all students recommended the lab be instituted in the next iteration of the course and most learned something new from the experience.

The responses to the identity and motivation questions of the survey highlighted a discrepancy between the confidence level and the enjoyment and motivation students experienced during the lab (Figure 1b). The Econ and TRD labs received the lowest scores for confidence yet received some of the highest scores for enjoyment and learning something new. This result suggests that these labs challenged the students, as they did not feel as confident in their abilities, and that their uncertainty did not impede their learning or cause them to view the lab negatively. Previous research supports this suggestion, as students have been shown to achieve enhanced understanding and enjoyment levels when given autonomy during experiments [20]. Furthermore, students expressed high motivation levels for all labs, acknowledging the value of each lab in their learning journey and trying their hardest to succeed in each lab. This could be attributed to the labs being grounded in real-world applications, which existing literature supports as a strong motivator for students [12], [13].

Qualitative data was collected through 60-minute individual interviews and 90-minute focus groups at the end of the semester. Several student quotes in focus groups support the conclusions found in the quantitative feedback. Regarding the HX inquiry lab, one student remarked that the best aspect of this first lab was the ability to engage with a real-world system:

> *Physically handling and manipulating the flow rates of the heat exchanger [was the best aspect]. It was cool to see and touch something I've learned so much about in class, in real life.*

In other words, participating in the HX inquiry lab helped this student contextualize and reinforce concepts from lecture. This sentiment was echoed in response to the TRD inquiry lab:

> *When being taught about this during class, I was confused how it actually looked, but this lab cleared that confusion up.*

Another student responded in agreement, emphasizing the positive impact of the lab on their performance:

> *Being able to, like, actually put your hands on stuff and, see how it operates, really helps clear up any, like, fogginess in your brain of what's actually going on in [mass and energy balances] and it was definitely, like, I understood concepts a lot like. When I was reviewing for an exam, it helped me understand how the actual like, how a [McCabe-Thiele] graph actually would work, because I knew how the distillation column actually worked because I operated one.*

The students in our focus groups also expanded upon the high enjoyment level of the Econ inquiry lab expressed in the quantitative data:

> *I really enjoyed it. It was one of the most fun things I did for a class at [institution]. This lab was like a game which made it fun while being educational.*

Further, the discrepancy between the Econ inquiry lab's connection to the course content and the overall positive response was indeed due to the lab emphasizing the competition aspect:

> *I think Econ, we just didn't know what to expect. Yeah, because it was just like we'd only been given simple, like, baseline problems [in lecture]. So, when we were tasked with keeping a company afloat for like, multiple years, I think people didn't know what was going to happen when we came into the lab. I, like, really enjoyed that lab. And I felt like it was one of the best ones, because it was just so fun. Like, we were learning, but we were also just having a good time. So, I totally get why people were like, Yeah, I didn't feel quite prepared when coming in because it felt really random, because we'd never done anything like it before.*

When students were asked about their confidence level during the TRD inquiry lab, one student responded:

> *I think there could have been more instruction at the start of the lab because it was not very clear on what everything was and what to start with.*

Another student followed, suggesting that the autonomy given in the lab was not prohibitive with adequate support from lab teaching assistants:

> *But there was enough guidance that it didn't take long to figure out what we were doing.*

One student further expanded on their low feelings of confidence during the TRD inquiry lab, highlighting the initial uncertainty they felt at the beginning:

> *Mostly, I think the distillation one is just like we have never seen these things, like actually in use. So it's very eye opening and like, a little shocking when we actually do it for the first time. It's an opportunity for growth. It's like, the whole thing basically like, this is so low stakes. Come in and, like, try your best, and you'll, you'll get something out of it.*

A different student agreed with their view of uncertainty being a positive aspect:

> *I feel like, like doing something like this is really helpful to see that like, even if you don't know, it's probably better that way for collaboration and like learning.*

These responses illustrate that students still felt motivated to learn during these labs despite feeling unsure of themselves and their competence, viewing them as an opportunity for growth. Overall, student reception of the inquiry labs was positive in interviews and focus groups and supported the observed trends in the quantitative results. Both qualitative and quantitative data suggest these labs be implemented in future versions of the mass and energy balances course and bode well for future inquiry lab implementation in subsequent chemical engineering courses.

Conclusions and Future Work

In this work-in-progress study, we designed, implemented, and assessed the impact of four active-learning inquiry labs for a third-semester required chemical engineering course, mass and energy balances. Students were appropriately challenged to reflect on, apply, and disseminate their course knowledge in real-world situations. Using a mixed-methods approach of quantitative feedback scores and qualitative focus group data, we determined that all four labs succeeded in having students reinforce course concepts and learn something new, all while having fun and feeling motivated. Students overwhelmingly expressed their satisfaction with this experience and recommended it for continued implementation in future course iterations.

This is the first semester of inquiry lab implementation in this department's curriculum. As such, there is more to be learned from the data collected. For example, demographic information from the student pre-survey would enable breakdowns of each student's responses to the inquiry labs and potentially identify differences in effects on students of different gender, ethnicity, or socio-economic status. Additionally, the pre-survey was completed by students further along in the curriculum and students enrolled in the mass and energy balances course who were not engaged in the inquiry labs. Their survey responses and interview data would help establish a baseline of this department's perception of the curriculum to compare to the new inquiry-based curriculum at the end of the study. Furthermore, analysis of the faculty pre-survey would elucidate the current perceptions of active learning among those who teach with the traditional instruction model. Together with faculty interviews scheduled for after their courses are modified as demonstrated, we would be able to assess the effect of incorporating active learning on faculty perceptions. Finally, the following courses in this department's chemical engineering curriculum are slated for inquiry lab implementation: Physical Chemistry II, Fluid Mechanics, Heat and Mass Transfer, Thermodynamics, Separations, Process Dynamics and Control, and Kinetics and Reactor Design. As such, a longitudinal study collecting more quantitative and qualitative data after each implementation would enrich the findings from this first iteration. If this semester's success continues to be replicated as the project evolves, we hope to encourage chemical engineering departments at other institutions to consider similar curriculum adjustments, benefiting even more students, faculty, and the field.

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