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Implementation of Challenge-Based Instruction via an Open Lab Concept in Undergraduate Fluid Mechanics Lab Course

Dr. Jun Chen, Purdue University – West Lafayette (College of Engineering)

Professor of Mechanical Engineering at Purdue University

Prof. Sally Bane, Purdue University at West Lafayette (College of Engineering)

Sally Bane is an Associate Professor in the School of Aeronautics and Astronautics at Purdue University. Her teaching interests focus on experimental fluid mechanics, aerodynamics, and the development of engaging laboratory experiences that connect theory with hands-on practice. She has led innovations in undergraduate laboratory instruction, including the use of virtual wind tunnel environments and inquiry-based learning approaches to enhance student understanding of fluid mechanics concepts. Her broader research interests include high-speed aerodynamics, flow diagnostics, and plasma-based flow control.

Dr. Sean P Brophy, Purdue University – West Lafayette (College of Engineering)

Dr. Sean Brophy is a learning scientist and mechanical engineer who develops, and research engineering learning environments enhanced with technology. His work spans multiple disciplines including aerospace, biomedical, civil, electrical, and mechanical engineering. His focus has been on the use of physical computing to enhance students' design and computational thinking. His latest research involves the integration of artificial intelligence for improving pedagogy, assessment, and learning goals in engineering learning environments.

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Introduction

In the past ten years, undergraduate enrollment has surged in engineering majors across the USA. Multiple factors contribute to this trend. According to the U.S. Bureau of Labor Statistics, engineering fields have consistently shown strong demand and job growth, attracting students seeking stable and lucrative careers. Rapid technological advancements attract students who want to work on cutting-edge developments. Initiatives promoting STEM education in schools have motivated more students to pursue engineering degrees [1]. The increased collaboration between engineering programs and industry partners offers practical exposure and networking opportunities that entice more students (see, e.g., [2] and references therein). This awareness of pressing issues such as the environment, healthcare, and infrastructure development stimulates potential engineers to solve real-world problems by pursuing engineering careers (e.g., [3]).

To cope with increased enrollment, lecture courses are offered as either larger sessions or multiple small sessions. The former practice has been criticized for resulting in higher withdrawal rates and deficits in students' academic achievement due to impeded student engagement in course activities [4–6] while the latter demands more teaching resources. Another set of unique challenges exists for laboratory and hands-on courses with large enrollment, primarily due to limited instructional lab support (lab space, equipment and instruments, supporting staff, etc.). For lab courses that involve large-scale equipment, this challenge becomes even more severe. The limited availability of equipment and physical space usually results in unmanageably large groups and hinders student engagement. It further forces many students to be observers of the experiment, thus forfeiting the opportunity for meaningful hands-on experience and learning.

Historically, instruction of undergraduate fluid mechanics courses begins with lectures to introduce concepts, which are supported with experiments that replicate the theory used to describe fluid mechanics. This arrangement thus has merit in its efficiency to share knowledge with large populations of students and familiarize them with experimental methods and skills. Well-designed lectures typically use contexts to illustrate the potential application of the knowledge and provide some organization to the knowledge the students are trying to learn how to apply. When students are engaged and inquisitive, they can actively generate questions for things they need to know. This creates a time for telling [7] that develops students' prior knowledge so they have a more effective engagement with lectures, readings, and laboratory experiences.

Laboratory experiences in the fluid mechanics courses provide students with the opportunity to engage their thinking about interesting past discoveries, the skills needed to conduct experiments, and the opportunity to collaborate with others. Ultimately, these students should be able to transfer their knowledge and skills to their own discoveries. Achieving these goals and objectives requires that students participate in a sense-making process to identify problems and participate in learning activities to develop their conceptual understanding of domain knowledge. When done well, learners will be able to transfer what they learned in their studies to novel problems they encounter on the job or in their design activities. Studies of *Challenge-Based Instruction* (CBI) provide evidence of the effectiveness of these learning environments in improving learning in domains like biomechanics [8], biotransport [9, 10], dynamics [11], and fluid mechanics [12, 13], to name a few.

Implementing CBI in fluid mechanics lab courses involves crafting a sequence of authentic challenges that guide students through a series of meaningful learning activities. The instructional task is identifying the appropriate learning resources for the target learners and scheduling them appropriately. We aim to implement CBI and advanced assessment methods to improve the quantity and quality of important learning outcomes.

The work presented in this paper is part of a joint effort within the College of Engineering at Purdue University to renovate the instruction of fluid mechanics lab courses in the School of Mechanical Engineering (ME) and the School of Aeronautics and Astronautics (AAE) since 2020. These core courses are required for all ME/AAE students. Offering these lab courses usually needs large-scale equipment (wind tunnel, water tunnel, etc), which cannot be duplicated easily with limitations from budget and space. In Fall 2023, the enrollment for the AAE course (AAE33101, fluid mechanics lab) reached 335, while in Spring 2023, the enrollment for the ME course (ME30801, fluid mechanics lab) reached 560. Both numbers set the historic records.

This paper reports on the design, implementation, and multi-semester evaluation of a challenge-based "open lab" model in a large-enrollment undergraduate fluid mechanics laboratory course. Unlike prior CBI implementations that focus on small or lecture-based settings, this work examines scalability, student autonomy, and learning perceptions across six semesters (N = 1,907). Using survey and course evaluation data, we investigate how open-ended lab projects influence students' critical thinking, experimental design skills, and transfer of laboratory competencies.

Open Lab in ME30801: a Practice of Challenge-Based Instruction

The open lab component was designed to implement CBI within the constraints of a large-enrollment undergraduate fluid mechanics laboratory. Rather than prescribing narrowly defined experiments, the open lab requires student teams to formulate, design, and execute an original experimental investigation grounded in fluid mechanics principles, using shared departmental facilities. This shift intentionally transfers responsibility for problem formulation, experimental planning, and interpretation from instructors to students, aligning with core CBI principles of learner autonomy, authentic challenges, and iterative refinement.

While the open lab operates within logistical constraints typical of large laboratory courses (shared facilities, limited equipment availability, and fixed scheduling), it was deliberately

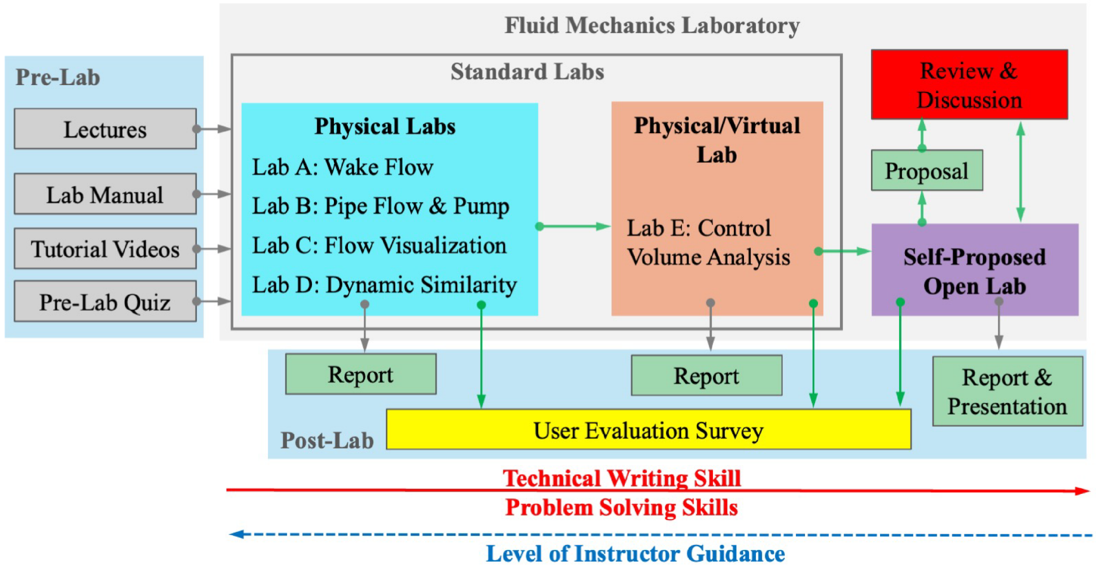

Figure 1: A typical teaching plan of ME30801.

structured to preserve the essential features of CBI. The design therefore represents a scalable approach to implementing challenge-based learning in resource-constrained, high-enrollment laboratory settings.

Study Context

This study was conducted in ME30801, a required one-credit undergraduate fluid mechanics laboratory course for mechanical engineering students at Purdue University. Figure 1 illustrates a typical teaching plan of ME30801. The course is taken after completion of a three-credit lecture course in fluid mechanics and enrolls several hundred students per semester, reflecting the scale typical of large public engineering programs. ME30801 focuses on experimental methods, data analysis, and the application of fluid mechanics principles through hands-on laboratory activities. Since Spring 2022, the course has incorporated a challenge-based open lab project as a required component for all enrolled students. Data for this study were collected across six consecutive semesters (Spring 2022–Spring 2025) under a common curriculum implemented by multiple instructors. Because enrollment in ME30801 is required for all mechanical engineering majors, the participant population broadly represents the undergraduate mechanical engineering cohort at Purdue.

A 25% team score is assigned for the open lab project: 5% for the revised project proposal, 12% for project report, and 8% for the project presentation. This allocation is proportional to the overall time commitment during the entire semester.

Challenge-Based Instruction Framework for the Open Lab

The open lab project was structured around six phases of challenge-based instruction (CBI), adapted from the Legacy Learning Cycle [14], to support student autonomy, iterative learning, and transfer of experimental skills. Rather than functioning as a linear set of prescribed tasks, these phases collectively scaffold students' progression from problem formulation to public dissemination of findings, with instructional support intentionally shifting over time from guided feedback to independent execution, as detailed below.

The Challenge initiates the learning cycle by positioning students as problem formulators. Student teams identify a self-defined, real-world challenge grounded in fluid mechanics principles and articulate clear objectives and constraints. This phase establishes ownership and relevance, key features of CBI that motivate engagement and frame subsequent learning activities.

Generate Ideas emphasizes exploration and planning. Teams brainstorm potential approaches, consult relevant literature, and develop an initial experimental concept. Through proposal drafting, students begin to align objectives, test methods, and available resources, encouraging early sense-making about feasibility and experimental design.

Multiple Perspectives introduces structured feedback to refine student thinking. Instructor review and revision of proposals expose teams to expert perspectives, prompting reconsideration of assumptions, clarification of objectives, and refinement of methods. This phase provides targeted scaffolding while preserving student control over project direction.

Research and Revise shifts responsibility decisively to students. Teams fabricate models, conduct experiments, and iteratively adapt their procedures in response to practical constraints and data quality. Instructional staff primarily serve supervisory and advisory roles, allowing students to navigate uncertainty, manage trade-offs, and apply prior laboratory skills in an open-ended context.

Test Your Mettle focuses on data analysis and interpretation. Students process experimental data to address their original objectives, confronting the ambiguity and variability characteristic of authentic engineering data. This phase reinforces analytical reasoning and supports the transfer of foundational skills developed in earlier structured laboratories.

Go Public culminates the cycle through communication and reflection. Teams synthesize their work into a formal report and presentation, requiring them to justify methods, interpret results, and communicate findings to an external audience. Public dissemination reinforces accountability and consolidates learning by integrating technical, analytical, and communication competencies.

Taken together, the framework is designed to promote critical thinking, experimental design competence, and the transfer of laboratory skills to novel problems—outcomes that are examined in the subsequent research questions and analysis.

Team and Lab Settings

In ME30801, every student must voluntarily join a team of three. The same team should work together for all lab efforts for the entire semester. All members will receive the same scores (team score) for open lab while they will receive different individual scores for portions of the standard labs.

In ME30801, there are three test facilities with two duplicated sets for each: low-speed wind tunnel, soap film system, and pipe flow system. For the open lab, every team may choose to work on one of the test facilities, or another facility provided availability is justified. Their selection should be described in the proposal together with the selection of instrumentation and test plan. The instructor and teaching assistants serve mostly as advisors so they do not give direct instructions to the teams during the open lab season. An open scheduling system is posted online for every team to reserve their lab hours for the open lab projects.

Current Study

The current study examines whether the open lab improves students' learning experience in fluid mechanics, with the hypothesis that the newly introduced CBI will have a positive impact on students' learning experiences in large STEM lab courses. In particular, the following research questions (RQs) are examined:

RQ1. To what extent do challenge-based open lab projects enhance students' critical thinking, problem-solving autonomy, and independence in applying engineering knowledge?

RQ2. To what extent does challenge-based instruction through mandatory proposal writing and revision enhance students' self-reported understanding of experimental design, core engineering principles, and tools selection in open-ended engineering projects?

RQ3. To what extent does challenge-based instruction in open-ended lab projects improve students' self-reported proficiency in data processing, technical reporting, and the transfer of foundational laboratory skills?

Method

Participants

Participants were recruited from students in ME30801, from 2022 to 2025, in six semesters. All students taking ME30801 were encouraged to participate in this study by completing a user evaluation survey released near the end of the semester. Over these semesters, three different instructors taught the course using the same curriculum. Purdue University also requests the students to complete a course evaluation, which is independent of the teaching team. The statistics of students attending this study are summarized in Tab. 1.

As of Fall 2025, a total of 3,180 undergraduate students (sophomore to senior) were enrolled in Purdue ME, the largest mechanical engineering program in the USA. Among them, 20.4% are female while 10.3% are underrepresented minority (URM). 11% of the enrolled undergraduate students are international. Since every ME student is required to take ME30801, these demographics approximately describe the participants of this study. One is reminded that the open-lab concept was first introduced into the curriculum from Spring 2022 and there was no historical data serving as a control for direct quantitative comparison.

User Evaluation

The present study is primarily based on a questionnaire survey after students complete their open lab projects. This questionnaire employed a Likert-type scale [15], with a 6-point scale from 1

		User Evaluation Survey	
Semester	Enrollment	Response Received	%
Spring 2022	304	241	79.2%
Spring 2023	325	275	84.6%
Fall 2023	192	166	83.4%
Spring 2024	461	416	90.2%
Fall 2024	236	212	89.8%
Spring 2025	389	344	88.4%
Total	1,907	1,654	86.7%

Table 1: Statistics of students participating in this study.

(strongly disagree) to 6 (strongly agree). The questionnaire survey was delivered to students via a web-based survey tool. The questionnaire collected students' responses to the following eight survey questions (SQs):

SQ1: The open lab allowed me to think critically about an actual engineering problem and allowed me to organize my own thoughts on how to solve it.

SQ2: Writing the project proposal helped me understand how to design lab tests to achieve the project objective.

SQ3: Identifying the project idea helped me to better understand the principle of fluid mechanics.

SQ4: Designing the test plan helped me to better understand the working principle of different instruments.

SQ5: Our team finished the lab tests independently (without TAs' help).

SQ6: Our team understood what to be included in the report of the open lab.

SQ7: Our team understood how to process the data for the report.

SQ8: Completing the open lab has increased my ability to use the knowledge and skills learned in standard labs.

The students also can give improvement suggestions and/or comments by answering one open question: *"What would improve your learning from the open lab project?"*

Data Collection & Analysis

The data presented in this paper were collected from the anonymous user evaluation survey. The statistics of data collection are indicated in Tab. 1. A total of 1,654 (86.7%) responses to the user evaluation survey were received, out of 1,907 students in these six semesters, and 901 responses (47.2%) to the course evaluation. The mean and standard deviation (SD) of the user evaluation survey are computed by

$$\mu = \frac{\sum(\text{Likert Scale}\times\text{Count})}{\text{Total Responses}}$$

and

$$\sigma = \sqrt{\frac{\sum \left((\text{Likert Scale - Mean})^2 \times \text{Count}\right)}{\text{Total Responses}}}.$$

Results

Students' Overall Learning Experience — RQ1

Students' responses to SQ1 and SQ5 shed light on their overall learning experience, as summarized in Figs. 2 and 3. Response rates (Tab. 1) are high, averaging 86.7% across six semesters, lending credibility to these findings. The data show strong evidence of positive student perceptions associated with CBI, meriting further adoption in large laboratory courses.

SQ1 assesses the open lab's impact on critical thinking and problem-solving autonomy. Responses show consistently positive trends, with the majority of students agreeing or strongly agreeing across semesters. Negative responses (1-3, strongly disagree to somewhat disagree/neutral) are minimal, never exceeding 10% in any semester and dropping to 4% overall. Positive responses (5-6, agree and strongly agree) dominate at 76.3% overall, peaking in Spring 2025 (92.8%). Mean scores hover around 5, indicating strong agreement, with a slight upward trend over time (from 4.79 to 5.35). Standard deviations suggest moderate consistency in opinions, tightening in later semesters, which is consistent with the continuous improvement over the years.

SQ5 evaluates student independence in executing lab tests, a key marker of skill application and self-reliance. Responses are even more skewed toward agreement, reflecting high confidence in team autonomy. Disagreement is rare (below 10% in all semesters, 8% overall for levels 1-3). Strong positive responses (5-6) account for 75.9% overall, with a notable spike in Spring 2025 (86.3%). Means are consistently above 4.9, showing steady improvement, though standard deviations indicate slightly more variability than in SQ1, possibly due to team dynamics.

Impact of Proposal Writing — RQ2

SQ2, SQ3, and SQ4 are designed to evaluate the students' perception of the mandatory proposal writing. These questions, directly tied to the proposal process, involve articulating project ideas, designing tests, and planning, which are often refined through revisions. Across six semesters, responses show consistently high agreement, suggesting that the proposal writing contributes positively to learning outcomes such as conceptual understanding, design skills, and knowledge of instrumentation (tool selection) for real-world applications.

Understanding of Experimental Design (SQ2, Fig. 4): Students across six semesters (Spring 2022–Spring 2025) reported that writing the project proposal significantly helped them understand how to design lab tests to achieve project objectives. Positive responses (5-6) comprised about 74% overall, with negatives (1-3) below 10%. This indicates that proposal writing enhances students' ability to align tests with objectives, a key learning outcome in engineering design.

Understanding of Core Engineering Principles (SQ3, Fig. 5): Across six semesters, students

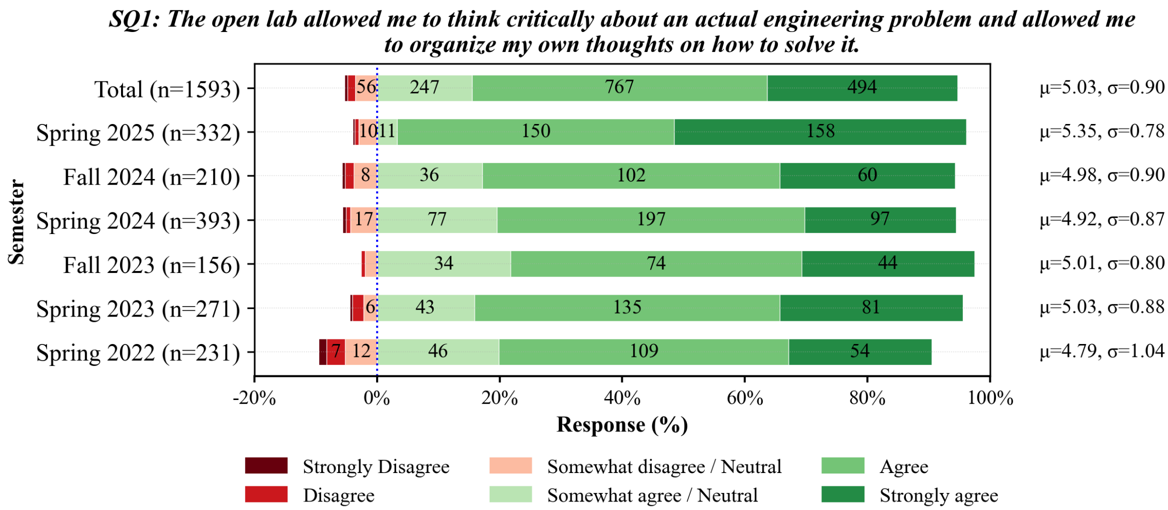

Figure 2: Summary of the Likert level distributions of SQ1 (raw counts and percentages, aggregated per semester for clarity) with key metrics.

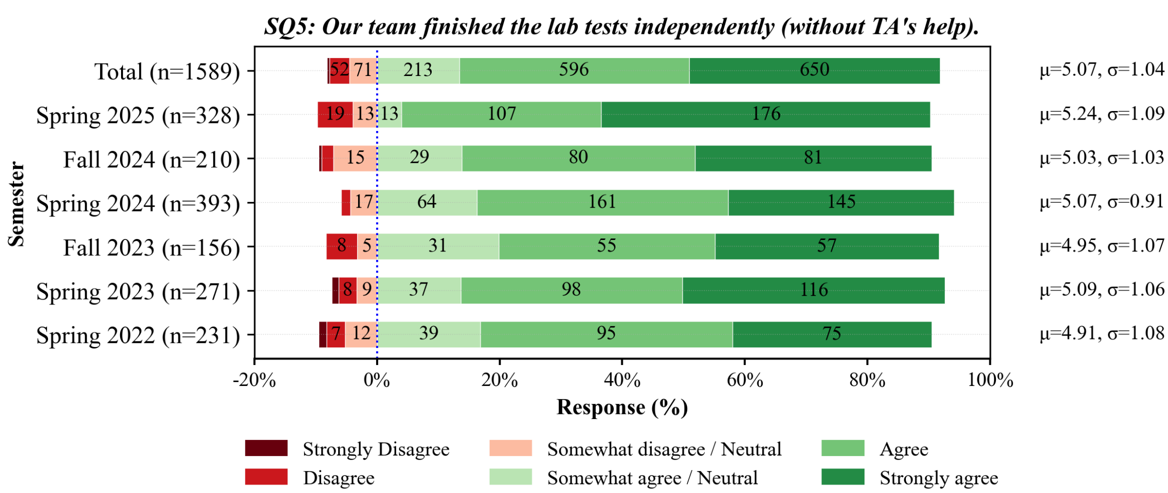

Figure 3: Summary of the Likert level distributions of SQ5 with key metrics.

reported that articulating their project idea in the proposal improved their understanding of core fluid mechanics principles. Responses to SQ3 yield slightly lower but still favorable means, from 4.64 (Spring 2022) to 4.89 (Fall 2024), averaging around 4.75 overall. Positive responses hovered at 68%, with a dip in Spring 2025 (mean 4.70, possibly due to higher neutrality at 24%). This suggests that idea identification in proposals aids understanding of core principles like fluid mechanics, though with more variability ($\sigma \sim 0.90$–1.18), perhaps reflecting differences in project complexity.

Understanding of Instrumentation Principles (SQ4, Fig. 6): Students reported that designing the test plan as part of the project proposal notably improved their understanding of the working principles of different instruments used in the open lab. Fig. 6 shows means from 4.63 (Spring 2022) to 5.10 (Spring 2025), with an overall average of about 4.84. Positive agreement reached 73%, reinforcing that test plan design and integral to revisions improve instrument comprehension (tool selection in real-world applications). The upward trend in later semesters (e.g., 5.10 in Spring 2025) may indicate benefits from iterative feedback in the proposal process.

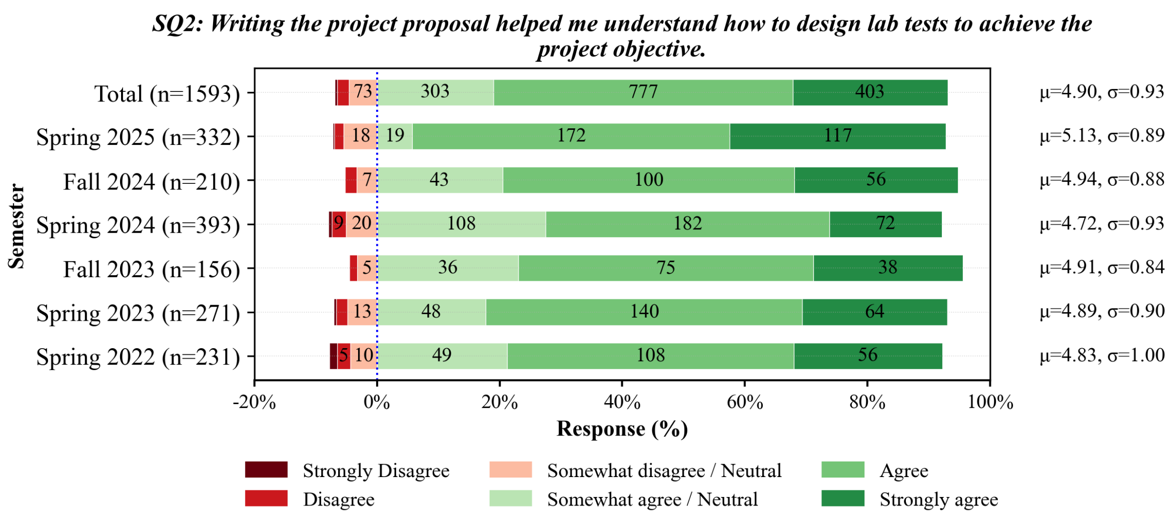

Figure 4: Summary of the Likert level distributions of SQ2 with key metrics.

Students' Self-reported Improvement due to Open Labs — RQ3

SQ6, SQ7, SQ8 directly capture self-perceived improvements in data processing, technical reporting, and the application of lab skills within the context of open lab projects, which embody CBI. The data indicate that CBI in these open labs improves students' self-reported proficiency to a substantial extent (Figs. 7-9), aligning with CBI's strengths in fostering reflective application through real-world challenges, where students must adapt foundational skills to ambiguous, team-based projects.

Technical Reporting Proficiency (SQ6, Fig. 7): With an overall mean of 5.07 and 72.3% positive responses, students report high understanding of report elements (e.g., objectives, methods, results, discussions). In CBI, reporting is a critical phase (*Phase VI: Go Public*), where synthesizing challenge outcomes reinforces communication skills. The upward trend over the

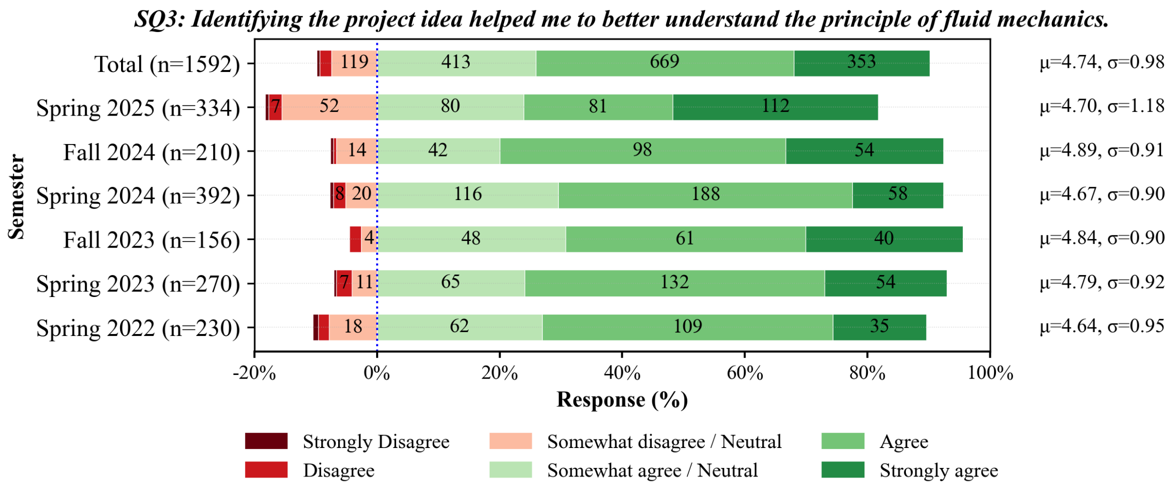

Figure 5: Summary of the Likert level distributions of SQ3 with key metrics.

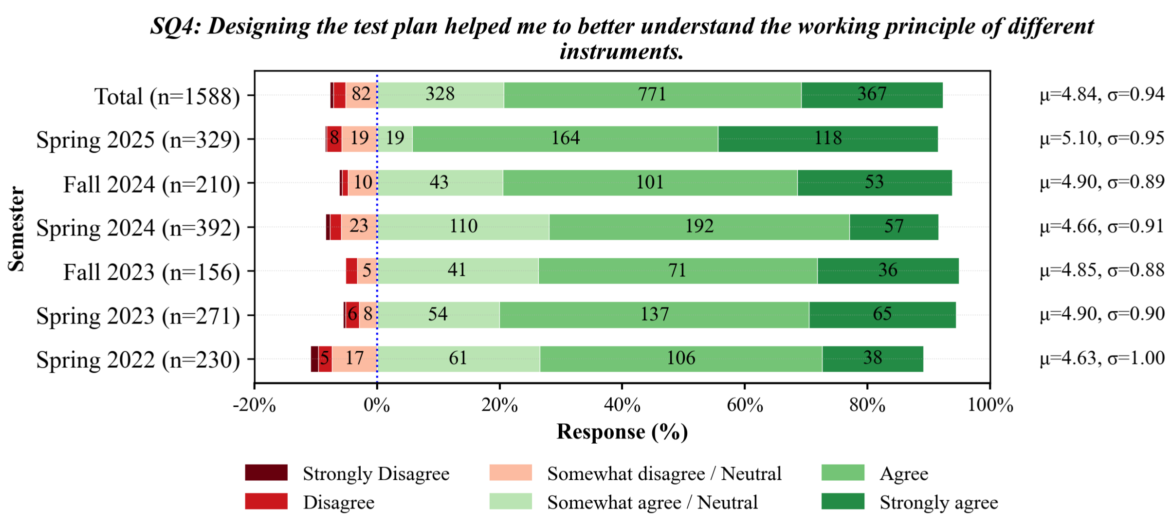

Figure 6: Summary of the Likert level distributions of SQ4 with key metrics.

years suggests iterative refinements of CBI enhance this proficiency over time, possibly due to improved guidelines or peer feedback. Low variability ($\sigma \sim 1.0$) implies consistent benefits.

Data Processing Proficiency (SQ7, Fig 8): The highest mean (5.10 overall, 79% positive) points to strong self-reported gains in independently handling the collected data (analysis, visualization, and interpretation). CBI excels here by exposing students to noisy, real-challenge data (vs. sanitized standard lab datasets), promoting iterative processing to derive insights. Negligible negatives ($<4\%$) underscore that most students feel equipped, aligning with CBI's goal of building analytical resilience.

Transfer of Foundational Laboratory Skills (SQ8, Fig 9): An overall mean of 4.99 and 74.4% positive responses directly evidence perceived skill transfer from standard labs (e.g., test plan, data processing, and report writing) to open lab projects. CBI facilitates students to apply those skills in new challenges, fostering metacognition and integration. The overall positivity affirms CBI's role in bridging guided and open-ended experiences.

Collectively, the high means and low disagreements imply CBI enhances these proficiencies considerably, with 75-80% of students reporting agreement. Trends across semesters (e.g., Spring 2025 highs) may indicate refinements like enhanced scaffolding or resources, further amplifying CBI benefits. This supports the effectiveness of CBI in STEM education, where challenge-driven reflection deepens skill mastery beyond traditional labs.

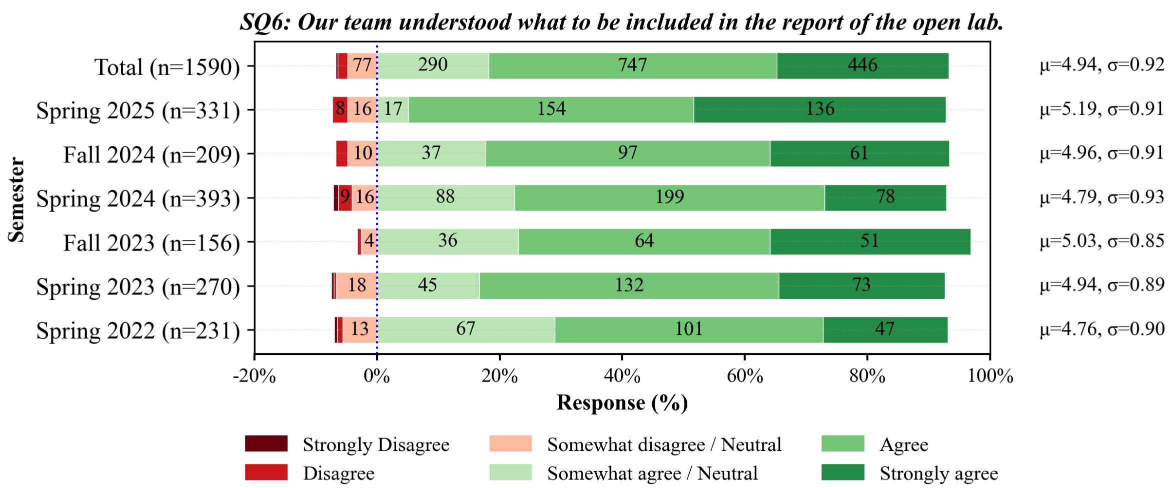

Figure 7: Summary of the Likert level distributions of SQ6 with key metrics.

Discussion

The open lab component in ME30801 embodies challenge-based instruction to engage students in open-ended, real-world challenges. The survey data across six semesters provide compelling evidence to address all three RQs. Students overwhelmingly self-reported the learning experience positively from their responses to survey questions. Their feedback comments also highlight CBI's strengths: high engagement from autonomy and relevance, with praise for instructor

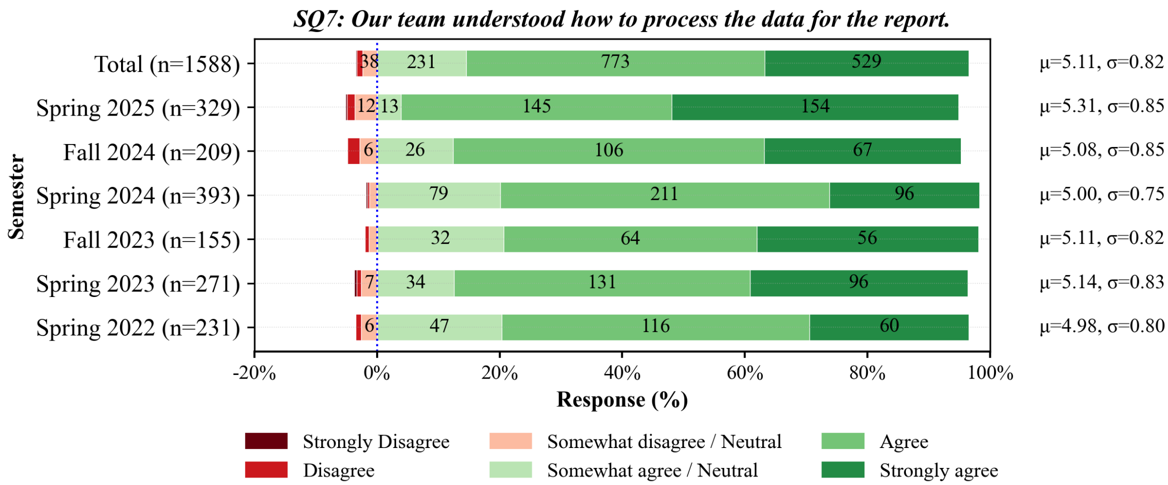

Figure 8: Summary of the Likert level distributions of SQ7 with key metrics.

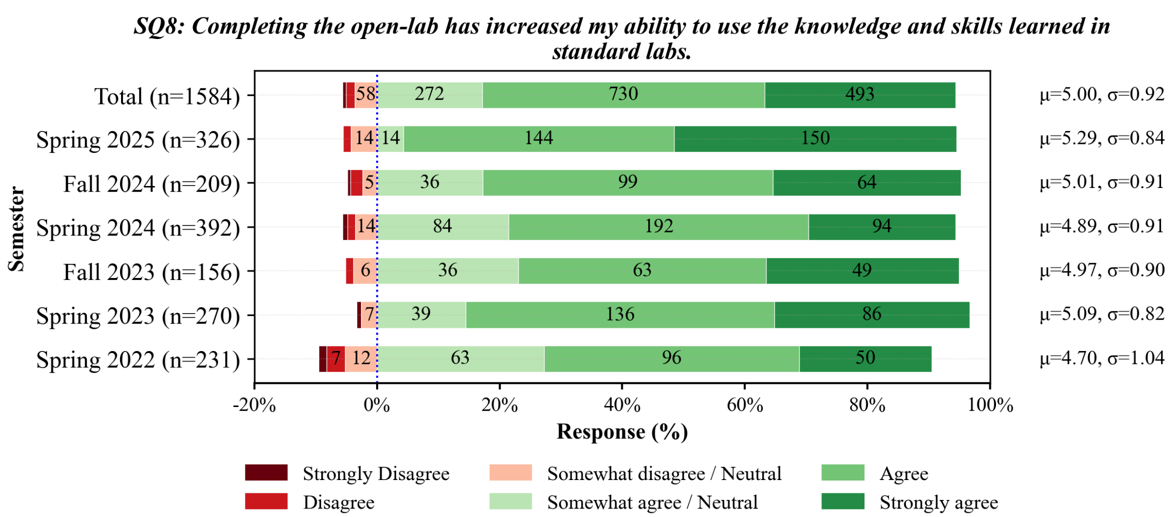

Figure 9: Summary of the Likert level distributions of SQ8 with key metrics.

guidance. Challenges were also identified in this study for improvement of this CBI practice.

Limitations of the present study

Several limitations should be considered when interpreting the findings of this study. First, the analysis relies primarily on students' self-reported perceptions collected through surveys, which may overestimate learning gains and do not directly measure performance or skill development. Second, because the open lab was implemented as a required component of the course beginning in Spring 2022 with the course renovation, no pre-intervention or non-CBI control group was available for direct comparison, limiting causal claims about the effects of challenge-based instruction. Third, variations in enrollment size across semesters and external factors associated with course growth may have influenced response patterns and perceived trends over time. Finally, the study is situated within a single large-enrollment fluid mechanics laboratory course at one institution, which may constrain the generalizability of results to other disciplinary contexts or instructional settings. Future work incorporating objective learning measures, comparative designs, and multi-institutional implementations would strengthen the evidence base and further clarify the impact of challenge-based open labs.

Concerns from responses to survey questions

Although overall student sentiment toward the challenge-based open lab remained strongly positive across six semesters, several recurring concerns emerged from survey responses that highlight structural and pedagogical tensions inherent in scaling CBI to a large-enrollment laboratory course. Most consistently, students called for clearer proposal and reporting guidance, including more explicit rubrics, earlier deadlines, and more detailed formative feedback, underscoring the central role of proposal writing as a scaffold for experimental design and tool selection. Resource access and time constraints—particularly limited availability of wind tunnels, fabrication services, and testing slots—also appeared repeatedly (e.g., *"wind tunnel so booked out"*), suggesting that while CBI promotes autonomy and iteration, its effectiveness is bounded by physical infrastructure in hands-on settings. Team dynamics constituted a third prominent concern (e.g., *"force the team to rotate roles," "hold teammates accountable,"*, *"a way to get an unhelpful teammate to do their work."*), reflecting both the benefits and challenges of team-based inquiry as cohort sizes grow. Finally, students frequently expressed a desire for greater diversity in project ideas and clearer connections to core fluid mechanics principles, indicating that while the open-ended format supports critical thinking, the range of accessible, principle-rich challenges may require further expansion or inspiration. Collectively, these concerns do not contradict the perceived benefits of the open lab but instead point to specific design refinements—enhanced scaffolding, expanded resource transparency, and structured team support—that are critical for sustaining effective challenge-based instruction at scale.

Conclusion

The implementation of challenge-based instruction through the open lab concept in Purdue's undergraduate fluid mechanics laboratory course (ME30801) demonstrates significant potential for enhancing student learning in large-enrollment STEM settings. Addressing RQ1, the self-driven open lab projects have positively improved students' overall learning experience, as evidenced by qualitative feedback highlighting increased engagement, autonomy, and hands-on application of fluid mechanics principles over six semesters. For RQ2, the mandatory proposal writing and revision process has supported better experimental design and skill development, though persistent calls for clearer rubrics, more detailed feedback, and earlier deadlines indicate opportunities for refinement to maximize its scaffolding benefits. Regarding RQ3, students perceive CBI via the open lab as valuable for fostering real-world problem-solving and collaboration, with evolving themes in suggestions—such as improved resource access (e.g., wind tunnel availability), team accountability mechanisms, and greater project idea diversity—reflecting both the strengths of open-ended inquiry and the challenges of scaling it amid enrollment growth and facility constraints.

Overall, these findings affirm the hypothesis that CBI positively impacts every student's learning in large lab courses, while highlighting the need for iterative enhancements to address structural bottlenecks and ensure equitable participation across diverse groups (e.g., 100% Engineering school affiliation but varying class standings). Ongoing research includes extracting data from the formal course evaluations over these semesters and trends from their comments. Future work should incorporate student-suggested refinements, such as expanded project examples, flexible scheduling, enhanced TA training, and longitudinal assessments of knowledge transfer and skill retention, alongside comparative analyses with non-CBI laboratories.

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